Universidade Federal do Pará

ENERGY GENERATION BY RENEWABLE HYBRID SOURCES WITH PUMPED STORAGE

Gilton Carlos de Andrade Furtado

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Gilton Carlos de Andrade Furtado

Doctorate Thesis presented to Postgraduate Program in Natural Resources Engineering of the Amazon, ITEC, of Federal University of Pará, as a partial fulfillment of the requirements for the degree of Doctor of Science in Natural Resource Engineering.

Advisor: André Luiz Amarante Mesquita

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" GERAÇÃO DE ENERGIA POR FONTES HÍBRIDAS RENOVÁVEIS COM ARMAZENAMENTO BOMBEADO”

Gilton Carlos de Andrade Furtado

TESE SUBMETIDA AO CORPO DOCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE RECURSOS NATURAIS DA AMAZÔNIA - PRODERNA/ITEC/UFPA COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA OBTENÇÃO DO GRAU DE DOUTOR EM ENGENHARIA DE RECURSOS NATURAIS.

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To Benjamin,

His hair is the color

Of liquid gold.

Eyes of a summer sky

Reflected in an Amazon River.

Body with the scent of an unknown flower

Dewy with a lymph from heaven.

Touch with the strength of an atom

And the attraction of a sun.

Pure smile, breath of dawn

That brings the hope of beginnings.

Hands of rare and gentle bond,

Eternal handcuff in disguise

In simple embrace of love.

MY WORDS

Our gratitude must be cultivated in every moment of life. In moments like these, which represent important milestones, however, we remember with joy and emotion, circumstances, events and people who were by our side, keeping us company on this journey, making it more pleasant.

I must remember, first of all, God. To whom I recognize in every detail the care and discreet conduct of my existence.

My parents, inspired by sacrifice, have always supported my spirit, encouraging me to study, which here receives the crown of an achievement that, with humility, I recognize the symbolic value it has for this house.

My wife Márcia, since the beginning, has accompanied me in this phase among the joys, incentives and reconciliations, strengthening our union with the maturity that a common purpose and their experiences provide. And of the good things that these doctoral years have given me, certainly the greatest was the arrival of our son Benjamin who, with his river eyes, inspires me to do good, without the need for words.

Even though I have been in the industry since graduating, UFPA has always been present in my life, as in many others. Therefore, its importance for our region, as a mainstay of education and development, is to be praised.

Professor André Mesquita is a friend that I meet again. His leadership in this work and the mutual trust were the basis for the success of this stage, and we must also remember his support and commitment so that the opportunity to work in direct partnership with Prof. Patrick Hendrick and Dr. Alessandro Morabito at the Université Libre de Bruxelles, in Belgium.

Far beyond the degree are the values and lessons learned during these doctoral years. The work, the meeting with so many important people, the humble contribution and, in particular, the maturation provided by entering the scientific world... all this is unforgettable, and along with responsibility, the desire to continue contributing to progress.

To all, thank you very much.

For that and much more.

Resumo da Tese apresentada ao PRODERNA/UFPA como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

GERAÇÃO DE ENERGIA POR FONTES HÍBRIDAS RENOVÁVEIS COM ARMAZENAMENTO BOMBEADO

Gilton Carlos de Andrade Furtado
Outubro/2022

Orientador: André Luiz Amarante Mesquita
Área de Concentração: Uso e transformação de recursos naturais

Com o aumento do uso das fontes renováveis, a necessidade de armazenamento energético se torna importante para garantir que a geração de energia possa atender a demanda por eletricidade. Este trabalho visa explorar o potencial de geração e armazenamento de energia existente em usinas hidrelétricas e barragens. É analisado o caso de Tucuruí, no qual as Eclusas e as ilhas formadas no reservatório superior oferecem oportunidade de implantação de sistemas renováveis. São pesquisados, em revisão de literatura, os sistemas similares existentes no hemisfério sul, com destaque para os casos do Brasil e África. Para as Eclusas, inicialmente, é avaliada a viabilidade de implantação de um sistema híbrido solar com armazenamento bombeado, comparando-se com uma proposta puramente fotovoltaica. Logo após, um sistema otimizado é proposto considerando as diferenças tarifárias previstas nas regras do setor elétrico brasileiro. Na ilha estudada, são analisadas as vantagens do uso de bombas funcionando como turbina como meio de produção e armazenamento energético. Os casos estudados mostraram resultados interessantes do ponto de vista técnico e econômico, apresentando tempo de retorno do investimento abaixo da média, investimentos iniciais reduzidos e facilidade de manutenção. A estrutura física das Eclusas e barragens já existente mostra-se favorável a sistemas desta natureza demonstrando que a expansão do transporte hidroviário no Brasil e no mundo deve ser planejado para prover armazenamento energético em sincronia com fontes de geração renovável.

Palavras-chave: Energias renováveis, sistemas híbridos, bombas funcionando como turbina, armazenamento bombeado

Abstract of Thesis presented to PRODERNA/UFPA as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

ENERGY GENERATION BY RENEWABLE HYBRID SOURCES WITH PUMPED STORAGE

Gilton Carlos de Andrade Furtado

October/2022

Advisor: André Luiz Amarante Mesquita

Research Area: Use and transformation of natural resources

With the increase in the use of renewable sources, the need for energy storage becomes important to ensure that energy generation can meet the demand for electricity. This work aims to explore the potential of energy generation and storage existing in hydroelectric plants and dams. The case of Tucuruí is analyzed, in which the locks and the islands formed in the upper reservoir offer the opportunity to implement renewable systems. In a literature review, similar systems existing in the southern hemisphere are researched, with emphasis on the cases of Brazil and Africa. For the locks, initially, the feasibility of implementing a solar with pumped storage hybrid system is evaluated, comparing it with a purely photovoltaic proposal. In sequence, an optimized system is proposed considering the tariff differences provided in the rules of the Brazilian electricity sector. On the studied island, the advantages of using pump as turbines as a means of energy production and storage are analyzed. The cases studied showed interesting results from a technical and economic point of view, presenting below average payback times, reduced initial investments and ease of maintenance. The physical structure of the already existing locks and dams is favorable to systems of this nature, demonstrating that the expansion of waterway transport in Brazil and in the world must be planned to provide energy storage in sync with renewable generation sources.

Keywords: Renewable energies, hybrid systems, pump as turbine, pumped hydro energy storage

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND NOMENCLATURE

Symbols

ψ	Head coefficient
β	Optimization variable
η	Efficiency
ϕ	Flow coefficient
Q	Flow rate
N	Rotational speed
D	Impeller diameter
E	Energy
g	Acceleration of gravity
H	Head
n_S	Specific speed
f	Frequency
pol	Number of poles
P	Power
t	Time
V	Volume
h	Head ratio
q	Flow ratio

Subscript

p	Pump
t	Turbine
BEP	Best Efficiency Point

1. INTRODUCTION

1.1. General considerations

The environmental impacts of fossil fuels, the associated costs, the availability of natural sources, and the increase in energy demand, have favored the interest in renewable energy systems [1]. Scientific research, in the same way, has accompanied the development of these solutions, especially when associated with other sources [2–4]. This research addresses different topics within the field of renewable energy and hybrid generation systems, such as pumps-as-turbine, pumped storage, variable speed operation, cost analysis and return on investment, and the optimal sizing of these systems.

The use of pumps-as-turbines (PATs) has been increasingly explored as a practical, low-cost, easy-access, and maintenance solution [5], although it encounters difficulties in its applications. These machines are not designed for operation in reverse mode and, among others, manufacturers do not provide their curves in turbine mode [6]. Thus, there is a need to make use of theoretical, analytical, computational, and/or experimental methods to predict the behavior of the pump in reverse mode [5,7–9]. In addition, due to the characteristics and need for adaptations, PATs can be used in different configurations, for example, in a parallel arrangement, with fixed and variable speeds, aiming at the generation and storage of energy. This is one of the areas developed in this work.

The literature review, presented in chapter 2 and the scientific production of this research, shows that the most used renewable energy sources are wind and solar and the energy systems designed and researched in the world aim to exploit resources according to the availability and feasibility of each location where they are applied. Generation systems from renewable sources, such as those mentioned, present a technical characteristic that resides in the variability of production due to the intermittence of solar irradiation and wind speed [10].

Thus, there is a need to combine with other resources, storage, or complementary sources, to ensure that the electrical energy produced is delivered to the consumer in the desired or contracted characteristics of quality, availability, and reliability. This association of sources characterizes a hybrid power generation system.

Regarding energy storage systems, there are several technological solutions already developed, such as batteries, capacitors, superconducting magnetic coils, heat storage, compressed air, flywheels, and pumped storage [11]. Each system is selected according to its characteristics and the system to which it will be connected.

In this work, the hybrid system conceived associates the energy sources naturally available in the place and the storage technology of easy access and development. Thus, the photovoltaic solar source is combined with a pumped storage system using PATs at variable speeds, aiming to guarantee the quality standards of the energy produced and the operation of the hydraulic machine at points of better efficiency.

Within the dimensioning of these systems, this work discusses issues related to cost analysis, and payback time, compared with several results in the literature [12–15], in addition to, in the following steps, optimization of the project to obtain the best dimensional, operational and cost conditions related to the project.

Hybrid systems, as a renewable and clean energy solution, have been applied in different cases around the world, as shown in the literature reviews of published and submitted articles. In Belgium, they are present in administrative buildings whose facades, composed of solar panels, integrate smart power generation grids [16], and in abandoned mines that are being reused as a lower reservoir for pumped storage systems using PATs [17].

In Germany, the potential of waterways as a reservoir for pumped systems is being researched [18]. In Italy, research on the use of PATs in water distribution networks shows promising development [19,20]. In Spain, Greece, and several other countries these systems are being proposed as a solution to the energy issue of isolated islands of the distribution grid [21,22].

1.2. Motivation

Although in the field of renewable energies and hybrid systems, the aforementioned works are being fruitfully developed, there is a gap in the research that relates energy generation and storage systems applied to locks. For the case of Tucuruí, research opportunities are added for the islands formed in the lake and the influence of the spillway of the hydroelectric plant on the project studied. These transposition systems, although present in many countries, are little explored as a means of generating and storing energy.

In this work, therefore, we present the structures of the Locks as an innovative means for generating and storing energy by exploiting the solar availability on site and the hydraulic head, which already exists due to the structure itself. This approach aims to demonstrate the positive financial impacts, regarding the investment in the proposed system, guaranteeing the energy demand for the reliable operation of the facility, in line with the worldwide trend of use of clean and renewable energy.

1.3. Objectives

1.3.1. General Objective

Demonstrate the potential for the use of infrastructure related to hydroelectric plants, such as the physical structure of the dam, locks and islands in the reservoir to generate energy from renewable hybrid solar and hydraulic sources.

1.3.2. Specifics

i. Verify the feasibility of taking advantage of the available solar and hydraulic potential, to meet the energy demand of the UHE Tucuruí Locks.
ii. Study the hybrid energy potential solar with pumped storage in the islands of Tucuruí lake.
iii. Propose an optimized hybrid system solar with pumped storage, for energy generation and meeting the energy demand for operation of the Tucuruí Locks.

1.4. Thesis contributions

i. Demonstrates the feasibility of using renewable energy systems in Locks.
ii. It gathers important information, not yet explored regarding the applications of renewable systems in Locks, considering the rules of the Brazilian electricity sector, making use of the tariff rules
iii. Contributes to the affirmation of the potential and benefits of using renewable sources in the world, from a technical, environmental and economic point of view.
iv. Provides other researchers with crucial results to analyze the energy options offered by solar and hydraulic sources applied in locks, helping to promote the debate on energy sustainability.

The contributions are in the articles listed as follow that have been published at international conferences and high-impact journals in the area.

Item	Article	Published in
1	Variable speed regulation for pump as turbine in a micro pumped hydro energy storage application	38th IAHR World Congress 2019
2	Energy Alternatives for the Operation of Tucuruí Locks	11th International Conference on Applied Energy 2019
3	Hybrid energy system with pumped hydro storage for off-grid applications – Case study of Tucuruí Lake islands	12nd International Conference on Applied Energy 2020
4	Using hydropower waterway locks for energy storage and renewable energies integration	Applied Energy
5	A Solar photovoltaic energy and pumped hydro storage system coupling in Southern Countries	Encyclopedia of Energy Storage
6	Sedimentary Basin Water and Energy Storage: A Low Environmental Impact Option for the Bananal Basin	Energies – MDPI
7	Spillway operation effects on the feasibility of a hybrid solar pumped storage system for supplying energy to a lock	19th Brazilian Congress of Thermal Sciences and Engineering
8	Optimization of hybrid system solar-pumped storage with pump-as-turbine using the rules of the Brazilian electric sector: case study of Tucuruí hydropower locks (*submitted to journal*)	Journal of Energy Storage

1.5. Work structure

This document is according to the proposal for the presentation of the thesis in the form of aggregation of scientific articles and is organized as follows: in the initial part, a general introduction contextualizes the area of research explored, the motivation, the objectives of the work and the contributions of this thesis. Section 2 presents a review of the literature within the fields covered in the research. In part 3, the methodology used in the evaluations proposed in the objectives is presented. Research applications are presented in chapter 4. Section 5 shows the conclusions of the thesis and, in the final part, opportunities for future research are also presented and the appendix contain main published article.

2. LITERATURE REVIEW

2.1. General introduction

In 2020, renewable energy sources accounted for almost 38% of the installed power in the world, with a total supply of 2,989 GW. This was driven by a sharp reduction in technology costs from these sources and by support policies that led to a growth in installed capacity of around 50% in the last year [23], even within the scenario of changes imposed by the COVID-19 pandemic.

However, in that scenario, an important question arises: solar and wind energy present intermittent production due to variations in availability, seasonality, or daily weather conditions. As a result, there is often a mismatch between energy production and instantaneous demand. On the other hand, in isolated areas of the interconnected system, this characteristic leads to the use of fossil fuels to supply the demand, through diesel engines [24].

In this context, in addition to large-scale energy systems, microsystems have shown promise as an alternative to serve isolated communities. A hybrid energy system can be used to ensure the integration of energy sources in order to guarantee compensation due to the variability of solar or wind sources. Thus, the diversification of renewable energies using wind, solar and hydraulic potential, in particular, has gained prominence in the world energy scenario with technological solutions and viable proposals presented by several researchers. In the context of hydroelectric plants, for example, the energy from the downstream flow of the dam can be used, with low environmental impact, to generate energy through hydrokinetic turbines [25,26], while the upper reservoir can be used for a photovoltaic generation with floating panels [27,28], including for complementation at peak demand times [29].

The important and successful experience of the application of micro hydropower plants as a localized solution for isolated communities is presented in [30], highlighting the key factors for the project.

Due to the diversification and variability of renewable sources, their exploitation, nowadays, is generally in the form of hybrid generation and storage systems. The design of a photovoltaic-wind system with pumped storage is evaluated [31] in the Egyptian electrical system, in [32] the authors seek to optimize the daily operating costs of a photovoltaic system with pumped storage connected to the grid.

A clean and renewable system consisting of a wind-photovoltaic source with pumped storage is proposed [33] for a coastal community in Nigeria.

An optimized project, analyzed from several technical and economic points of view, is studied [34] in a remote Chinese island composed of solar, wind, and hydroelectric sources with pumped storage.

Regarding the optimal energy dispatch of a hybrid solar-wind-diesel system with pumped storage, [35] elaborates a generation programming model that considers the variability of sources and demand, seeking to minimize the use of diesel.

2.2. Energy storage

Energy storage is one of the central issues within the operation and technical-economic feasibility of hybrid systems with renewable sources. Within current technologies, pumped storage is known as the most cost-effective one due to its known operational characteristics, reliability, reduced environmental impact [36], ease of operation and maintenance and therefore it is present in many proposed solutions [37,38], this includes comparison with other storage technologies [39].

In addition, pump-as-turbine (PaT) operating at variable speeds have also been studied as an effective means of achieving high operational efficiencies in generation and storage systems [40,41] and in water distribution networks, for energy recovery and leak prevention, including parallel machine operation [42,43].

An integrated project of a hybrid system with solar and wind power sources with batteries for storage, considering the saturation limits for each source, based on economic and technical indices is also presented in [44].

A hybrid system with pumped storage and batteries is proposed for an off-grid renewable energy system, in which the authors [2] use a new operating strategy based on maximum extraction of stored energy at the turbine's best efficiency point (PaT), the battery is used only to meet very low load levels. To evaluate the system, an indicator of storage performance, energy utilization rate, and storage utilization factor is used. In this way, the need to know the limiting characteristics of each source proposed as a solution is highlighted.

These systems are cited to exemplify the different types of solutions that combine different storage technologies, summarized in Figure 1. However, among the technologies for large-scale energy storage, *pumped hydro energy storage* (PHES) is the most adopted [11] because of the potential energy that can be stored, the efficiency in energy conversion, the cost per unit of power, and the flexibility provided to the transmission system operator [45].

In addition, due to mass production, they are available in different sizes and patterns, wide range of flow and head, low response time, long service life, easy installation, operation and maintenance, in addition to the ease of spare parts [8].

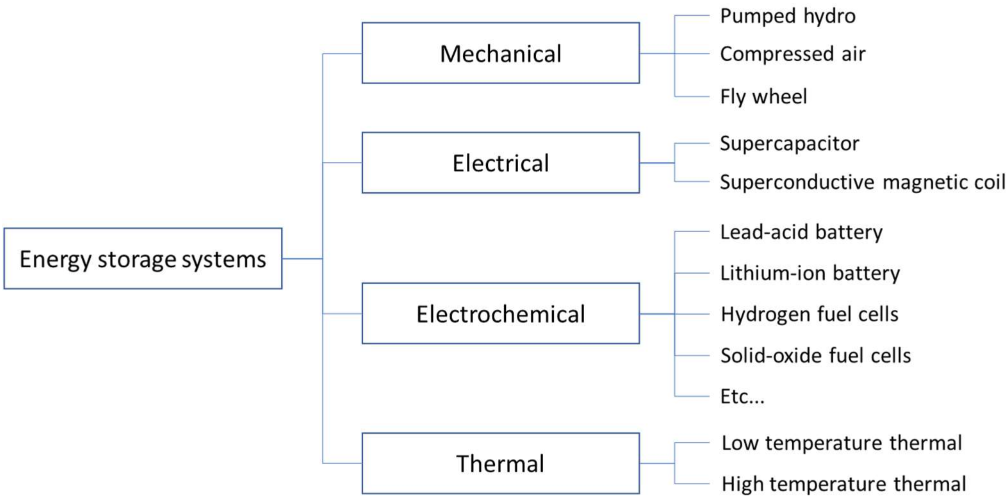


Figure 1. Energy storage technologies.

Another interesting aspect to be pointed out is related to the possibility of exploring the potential of sedimentary basins for energy storage due to the absorption capacity and natural flow control of rivers. We highlight the potential of the Bananal sedimentary basin for water and energy storage[46] as follows:

The article addresses the issue of energy storage through water, taking advantage of existing natural conditions in a sedimentary basin. This work proposes two water management solutions for the Bananal river basin. The first one is the construction of a dredged channel that can increase the cross-section flow at the currently restricted outlet of the basin, preventing annual flooding episodes and allowing the use of the basin for agricultural development. The second one is the construction of a low-head dam that will generate hydroelectric energy in the basin and can also control the flow of water and thus store water without the need to create a surface reservoir.

The methodology for the study is based on three main steps. First, estimate the storage capacity of the sedimentary basin. Secondly, the proposition of two solutions for the control of water that allow the use of the basin for agriculture and water storage.

Finally, the estimation of the gains from the hydroelectric generation downstream, in the sense of the influence on the other cascade plants in the river.

The basic principle of the proposed solution for energy and water storage in the sedimentary basin is the impact of river level variation on the amount of water stored. This concept is presented below. During the wet season (Figure 2a), rainfall in the basin fills the sedimentary basin with water, and due to the rise in the level of the Araguaia River by up to 5 meters, the river water percolates into the soil, being stored in the pores of the sedimentary basin of sponge-like shape. In the dry period (Figure 2b), the river water leaves the Bananal basin with the natural flow of the river, with the stored water contributing to the high flow of the river for a longer time. By controlling the outflow from the basin through a dam, the river level during the dry season remains high and the basin can store significant amounts of water (Figure 2c). This control in sedimentary basins is intended to use them as water and energy storage reservoirs, reducing the vulnerability of floodplains to global warming and climate change.

By the proposed methodology, the volume of water stored in the sedimentary basin is estimated at approximately 33.5 km³. Also, considering the operation of this new reservoir and the better sediment management results in the reduction of the river level by one or two meters from its minimum altitude, the estimated volume of water storage in the sedimentary basin with this solution increases to 41 and 48 km³, respectively.

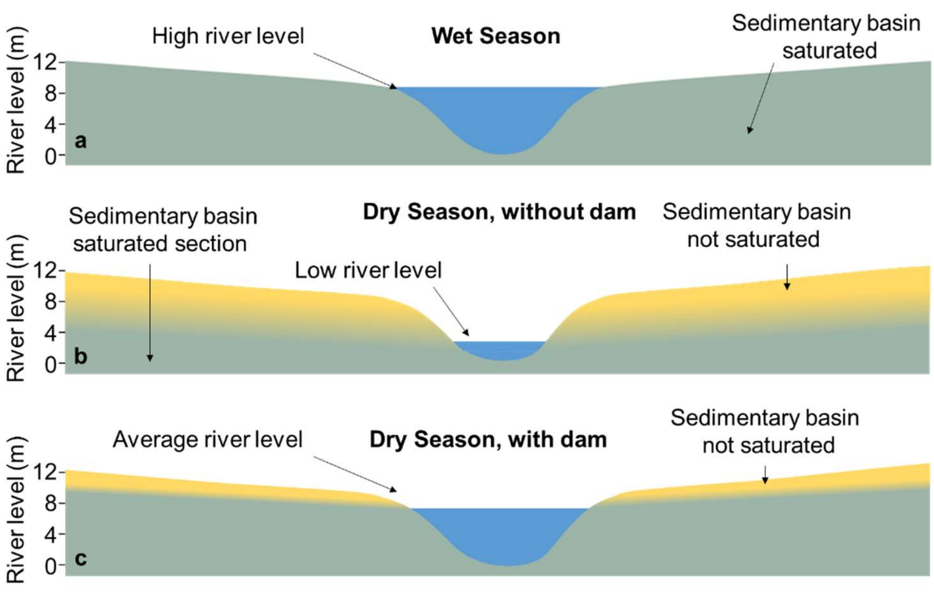


Figure 2. Representation of basin saturation and influence on river level.

Regarding the gains in hydroelectric generation capacity, currently only the Tucuruí plant would be affected by the operation of the proposed sedimentary basin storage project, as shown in blue in Figure 3. This is because the Marabá, Santa Isabel and São José dams are still proposals, whose constructions run up, mainly, in environmental issues and in the lack of energy generation in the dry season.

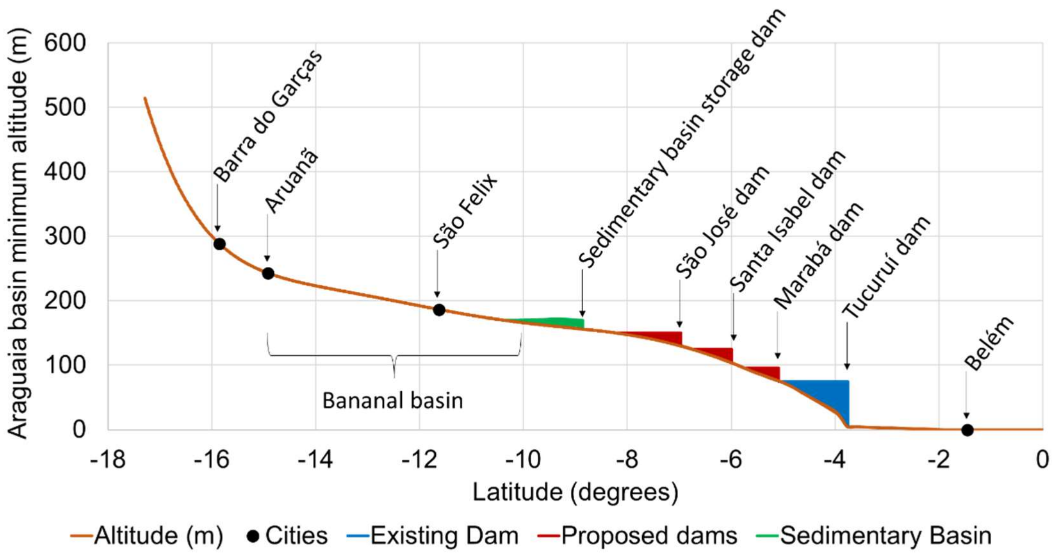


Figure 3. Cascade hydroelectric plants on the Araguaia and Tocantins rivers.

In this article, the proposal of storage in the sedimentary basin of Bananal can significantly increase the hydroelectric generation capacity of the dams downstream with the regulation of the flow of the Araguaia River, through the storage of rainwater in the soil, during the wet period, being able to reach up to 42.3 TWh of electricity added to the Brazilian energy matrix annually.

2.3. Pump-as-turbine

Pumped storage consists of pumping water from a lower reservoir to an upper one and storing energy in potential form, to be used by a hydraulic turbine, when necessary. The performance of a plant that uses pumped storage of this type, therefore, is strongly dependent on the type of turbomachine selected, which, in the case of pumps and turbines to be installed, depends on the flow rate to be explored, available head and loss of pressure due to the hydraulic circuit of pipes and accessories.

Although in the design, a pump or turbine is sized to operate at a specific flow and head point, the pumping process and variation in reservoir levels cause changes at this point, thus determining an operating range for the hydraulic machine.

The literature records that the first use of pumps in reverse mode became known by the publication of Thoma and Kittredge, in 1931. While evaluating the characteristics of pumps, they accidentally realized that the machines could operate quite efficiently in turbine mode. Ten years later, Knapp made public a complete study of pump characteristics based on experimental investigations.

In the ’50s and ’60s, the concept of pumped storage plants, in the range of 50 to 100 MW, emerged mainly in developed countries, to meet the peaks of energy demand. Then, the chemical industry starts to use PATs for energy recovery, which are found today in numerous applications [47].

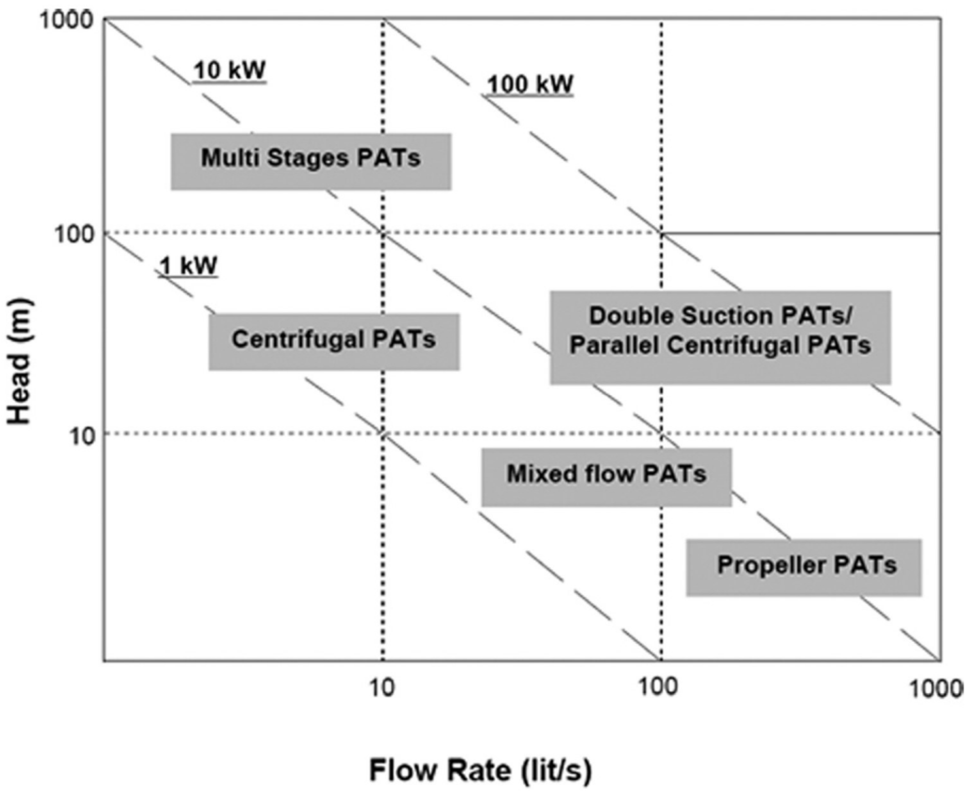


Figure 4. Applications of PATs according to head and flow [48].

An overview of the use of pump-as-turbine is presented [48] according to the characteristics of the installation and the machine. The authors suggest that centrifugal pumps can be used in the head range of 15 to 100 m and a flow rate of 5 to 50 L/s. Mixed flow impeller pumps are indicated for the range of 5 to 15 m of head and 50 to 150 L/s of flow. Finally, for heads in the range of 15 to 100 m and flow rates between 50 and 1000 L/s, systems composed of pumps operating in parallel are applicable, as shown in Figure 4.

Since pump manufacturers normally produce centrifugal and mixed flow machines on a large scale, there is a great availability of pumps at a low cost, when compared to conventional turbines. In Figure 4, the authors also highlight the possibility of using the pump impeller as a turbine for a head from 1 to 5 m and flow rates in the range of 50 to 1000 L/s. However, for these cases, the pumps are not normally found on the market, being manufactured and sold on demand and, therefore, at much higher costs than the previous ones.

Pump performance curves are usually presented in a chart that relates head and flow. In this way, the operations as a turbine and as a pump can be shown in a single graph, in which the negative flow is represented in the reverse mode, as shown in Figure 6.

This graph describes the general behavior of the pump and turbine for the same rotational speed. Note that the important quantities of the machine present some differences in behavior [49], as shown in Figure 5.

PARAMETER	PUMP	TURBINE
Flow rate	Decreases with increasing of head, reaches zero at shut-off value.	Continuously increases with head
Power	It has its minimum value at the maximum head, increasing with the reduction of the head (radial flow).	Power generation starts after a minimum flow value, continuously increasing, even beyond the nominal head.
Efficiency	Start at zero, when there is no flow, reaching a maximum value at the rated point, decreasing again to higher flows.	Increases from zero, at the minimum flow rate, reaching the maximum value at the nominal point and subtly decreases to high flows.
Best efficiency point	Head and flow are smaller compared to turbine mode.	Output power is higher than in pump mode.

Figure 5. Comparison between direct and reverse modes.

Furthermore, experience and records in the literature show that the operation of a pump as a turbine, in mechanical terms, is smooth and noiseless; maximum efficiency is approximately equal in both modes; the power consumed at the best efficiency point (BEP) in pump mode is less than the power generated at the same point [50].

Although Figure 6 shows the general behavior, this relationship varies among different types of machines in their sizes and types [49].

This depends on the flow patterns in the machine, reflected by the specific speed, and the losses involved, expressed by the efficiency of the machine, the losses not being the same in both modes of operation.

For this reason, it is observed in experiments that for the same specific velocity the relationship between the head and flow for each mode (h and q) can be considerably different.

The use of PAT as a solution for energy generation and storage, as expected, presents advantages and disadvantages. If, on the one hand, its operation reaches a reasonable value of efficiency in the BEP, it allows adjustment of the head/flow point with changes in the rotor or in the speed, and it operates continuously with reduced noise level with vibrations at acceptable levels and, in terms of mechanical assembly, has the flexibility to allow the use of belts for coupling to the generator for changes in speed.

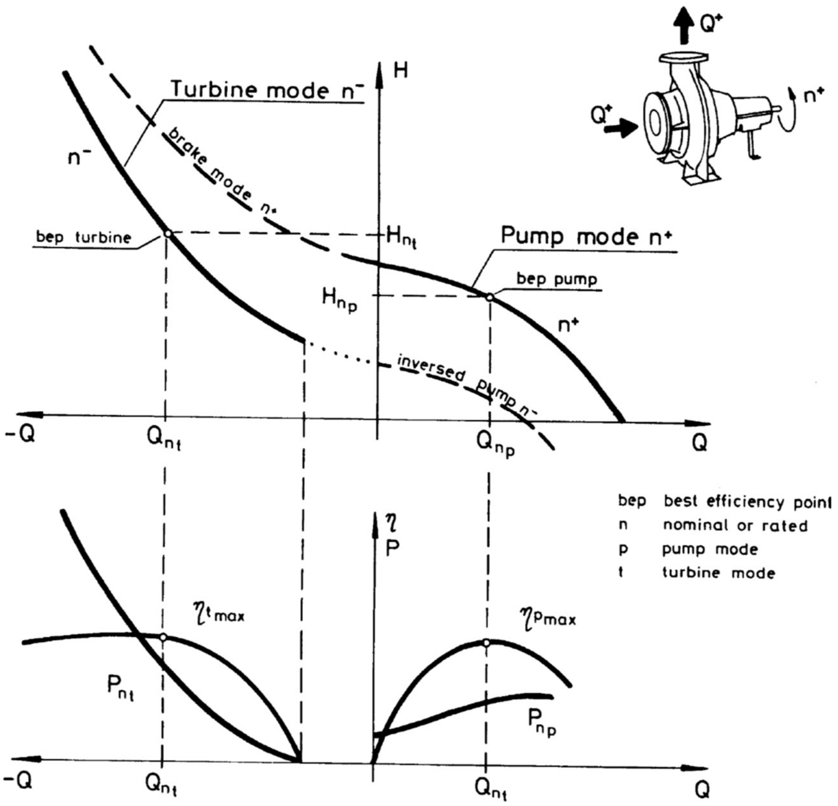


Figure 6. Expected general theoretical behavior for pumps and PATs [49].

On the other hand, however, reinforcements may be needed in the shaft and coupling, the bearing life cycle is shorter due to the higher efforts, and there is a need to use a mechanical seal due to higher leakages, in addition to the costs related to the form of varying the speed [50].

There are a variety of methods developed in the field of hydraulic turbomachinery to predict the performance of pumps operating in reversible mode.

In general, methods are developed based on two considerations: efficiency or specific speed. Stepanoff, Childs, Hancock, Sharma, Schmiedl, and Alatorre-Frenk establish their relationships based on the best efficiency point in pump mode. On the other hand, researchers Groover and Hergt formulate relationships considering the specific speed in turbine mode in their BEP, as shown in Table 1, adapted from [51].

Table 1. Historical development of prediction methods for PATs.

Year	Name	Criteria	h	q	Notes
1957	Stepanoff	BEP	$\frac{1}{\eta_p}$	$\frac{1}{\sqrt{\eta_p}}$	n_S: $40-60$
1962	Childs	BEP	$\frac{1}{\eta_p}$	$\frac{1}{\eta_p}$	-
1963	Hancock	BEP	$\frac{1}{\eta_t}$	$\frac{1}{\eta_t}$	-
1980	Grover	Specific speed	$2.693-0.0229n_{ST}$	$2.379-0.0264n_{ST}$	n_S: $10-50$
1982	Hergt	Specific speed	$1.3-\frac{6}{n_{S_t}-3}$	$1.3-\frac{1{,}6}{n_{S_t}-5}$	-
1985	Sharma	BEP	$\frac{1}{\eta_p^{1.2}}$	$\frac{1}{\eta_p^{0.8}}$	n_S: $40-60$
1988	Schmiedl	BEP	$-1.4+\frac{2.5}{\eta_p}$	$-1.5+\frac{2.4}{\eta_p^2}$	-
1994	Alatorre-Frenk	BEP	$\frac{1}{0.85\,\eta_p^5+0.385}$	$\frac{0.85\,\eta_p^5+0.385}{2\,\eta_p^{9.5}+0.205}$	-
1998	Sharma	BEP	$\left[\frac{N_t}{N_p}\right]^2\frac{1.1}{\eta_p^{1.2}}$	$\frac{N_t}{N_p}\frac{1.1}{\eta_p^{0.8}}$	$N_p=240\frac{f}{pol}-N$

Since then, considering the works of the aforementioned classical authors, other approaches have been developed with the objective of improving this field of knowledge, using experimental, theoretical-statistical, numerical, and computational analysis techniques.

For example, the performance of a pump operating in turbine mode is experimentally analyzed at different speed rotations [52], in which it is possible to establish, through the dimensionless parameters, an approximate relationship with the theoretical prediction in the BEP.

In the field of pumps-as-turbines, one of the most cited works [53], performs an experimental study of four pumps operating as turbines, with different specific speeds and, from the dimensionless parameters, the authors establish a correlation to predict the behavior in points beyond the BEP.

The application of pumps operating as turbines has been studied in rural and mountainous areas [54] as an economic alternative to turbines, especially for microgeneration, and applied to small hydroelectric plants [55], via numerical method aiming at pump prediction in reverse mode.

Computational methods have also been used [56,57] looking for the prediction of pumps in reverse mode, including the analysis of hydraulic losses, and partial load at points outside the rated condition.

A theoretical, numerical, and experimental approach was carried out [58] seeking a determination of the performance curve in reverse mode. Despite the small differences in relation to the experimental one, the methodology presented more coherent results, in the theoretical and numerical approaches, than those used as a reference (Sharma and Stepanoff).

The analytical, numerical, and experimental solutions presented focus their efforts on finding the behavior of the PAT at the point of maximum efficiency. However, in real applications, it is of interest to predict behavior at off-design points. It is in this sense that an interesting proposal [6] seeks to predict the complete performance curve in turbine mode, based only on the BEP in pump mode.

For this, a method that predicts the turbine mode at its best efficiency point must be used. The authors establish a normalized mathematical correlation between the dimensionless coefficients of pressure, flow, and efficiency to plot the pump performance curve in reverse mode, according to equations (1) to (5).

$$\psi/\psi_{BEP_t} = 0.2394R^2 + 0.769R \tag{1}$$

$$\eta/\eta_{BEP_t} = -1.9788R^6 + 9.0636R^5 - 13.148R^4 + 3.8527R^3 + 4.5614R^2 - 1.3769R \tag{2}$$

$$R = \phi/\phi_{BEP_t} \tag{3}$$

$$\phi = Q/(ND^3) \tag{4}$$

$$\psi = gH/(ND)^2 \tag{5}$$

The use of pumps operating as turbines has been widely explored in industrial facilities due to numerous advantages over conventional turbines. The rising price of energy, the limitations, and complexity of other sources when compared to pumps find low investment and maintenance costs allied to the simplicity of operation. Energy in systems with PATs installed can be consumed or stored for use in the process itself or supplied to the grid as credit for later use, sale, or transfer between consumers, depending on local regulatory rules.

Its viability as a source of energy is widely demonstrated in the literature when compared to diesel engines, commonly suggested and used due to the ease of compensation they provide, despite the associated pollution and fossil fuel costs. Due to the flexibility of sizes, capacities, and mounting positions, PATs can be used in different cases to take advantage from 1kW up to megawatts [48,59], with payback, mainly influenced by low O&M costs, around five years [59,60].

In on-grid applications, a special case that offers the use of PATs a valuable advantage, is the possibility of taking advantage of the tariff differentiation, which varies throughout the day as a result of the demand profile, consuming energy from the grid for pumped storage and in the peak time, when the price of energy is higher, operate as a generator supplying the demand, profiting from the supply, as long as the local regulatory rules allow this transaction.

2.4. Solar systems with pumped storage

The combination of photovoltaic with pumped storage is shown in a simplified form in Figure 7 and basically consists of an upper and a lower reservoir, the hydraulic machine, piping for connection between them, and a power element that, depending on the operation in direct or reverse mode, can be a source to supply energy (solar panels or the grid, for example) or for storage. This element represents all electrical components connected to the hydraulic machine, panels, and grid [61].

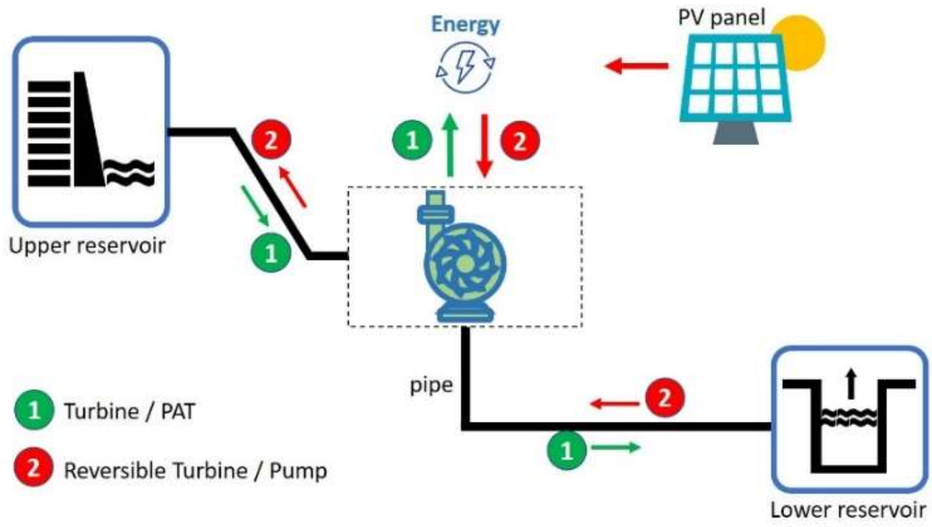


Figure 7. Representation of a photovoltaic system with pumped storage.

As for the hydraulic machine, depending on the size of the plant, it can be a reversible turbine, also called a reversible pump-turbine or pump functioning as a turbine (pump-as-turbine). Commercially, reversible turbines are sold with power above 10 MW [62]. For smaller powers, in the range of 1 to 10 MW, special designs of reversible turbines are necessary and for powers below 1 MW, the use of PATs is possible [63].

Pumps-as-turbines offer a low-cost configuration, suitable for the feasibility of projects in this power range. These machines, although they have well-known advantages and facilities, the main problem in using pumps in reverse mode is the selection of a suitable machine for each working condition. In addition, there is the practical difficulty of reliably predicting the pump performance curve in reverse mode. For this problem, a variety of analytical, numerical, experimental and hybrid methods are present in the literature to answer these two questions [6,64].

A review is carried out in the article *"Solar photovoltaic energy and pumped hydro storage system coupling in Southern Countries"*[61], about the applications of renewable hybrid systems that combine solar source with pumped storage in the countries of the southern hemisphere, highlighting the projects in Brazil in Africa.

Considering systems in the format shown in Figure 7, there are several pumped storage applications as viable means for the energy issue in African countries. Initially, in Figure 8 are shown proposals for seasonal pumped storage systems (SPHS), combined long-term and short-term (CCSPHS), hydroelectric combined pumped storage (CHPHS) [65].

Although water storage is the main objective of the proposed plants, to make them economically viable and socially acceptable, energy storage services are also considered for grid management. Given the need for energy for pumping water storage, it is important to analyze the renewable energy potential existing in the region.

The average wind speed along the watershed is small. However, the region has solar energy potential reaching an annual average of 2,300 kWh/m² (Figure 9). Solar energy could be used to pump water into pumping plants (PHES) which in turn could reduce the intermittency of solar power generation.

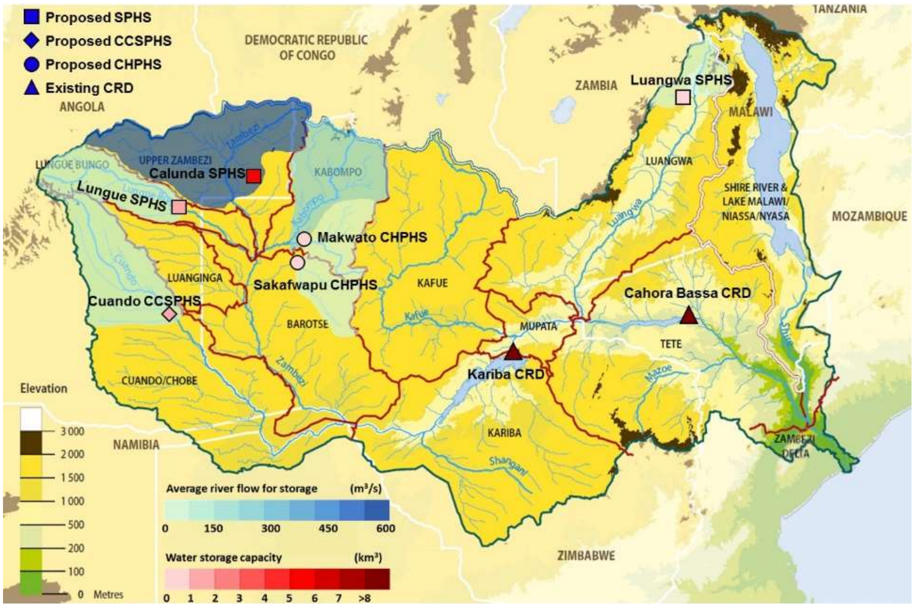


Figure 8. Pumped storage potential into the Zambeni River basin.

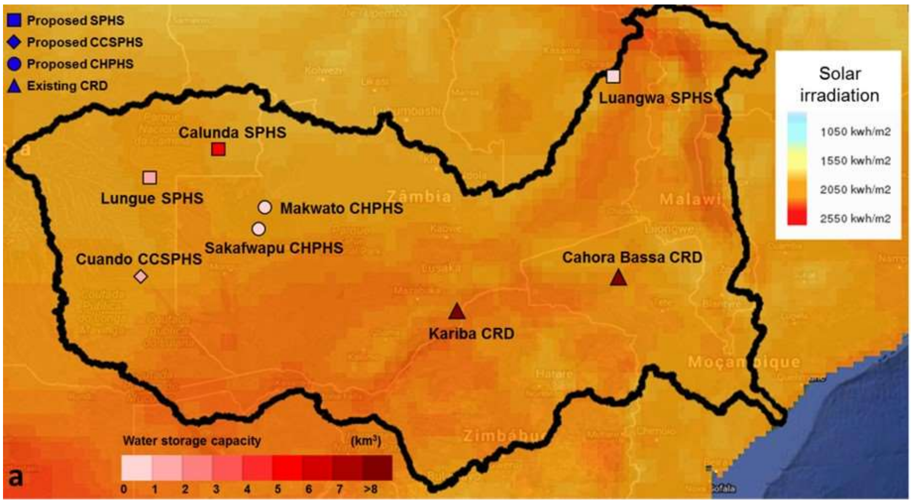


Figure 9. Photovoltaic potential in the Zambeni river basin.

In Brazil, there are several projects of hydroelectric power plants capable of operating in pumping mode (reversible): the Pedreira project (78.5 MW of generation and 42.6 MW of pumping), Edgar de Souza (with power in turbine mode of 14 .8 MW and 13.3 MW in pump mode, disabled), Traição (with 7.3 MW to turbine, and 9.4 MW to pump) and Vigário (with power of 90.8 MW in turbine mode and 72.0 MW in pump mode) [66], with only the last three in operation in the country. However, despite the reduced number of projects of this nature, there are currently many projects under study. Most of them with photovoltaic and hydroelectric integration (PV-HPP), and it can be considered that the true hybrid coupling between PV-HPP, in the PHES context, is still under initial development in Brazil.

2.5. Optimized solutions for hybrid systems

The studies developed for the optimized solution of renewable hybrid systems are broadly addressed in relation to the use of sources, subsystem sizing, production management, etc. Such analysis to approach the optimization decision, for example, from the point of view of minimizing the Leveled Cost of Energy (LCOE) [67,68], the use of fossil sources [69,70], payback time [71,72] and also controlling the power flow in the system [73]. Regarding the optimization methods for calculating hybrid systems, different tools and methodologies have been explored in the literature, such as genetic algorithm [69,74], particle swarm [75,76], flower pollination [77], fruit fly [70], and other combined methods [78].

Further investigations on the use of renewable energy systems combined with energy storage can be found in the literature. For example, [79] study the optimal design of a renewable energy system for the electrification of isolated areas without access to the grid, highlighting the importance of storage for the success of the project, aiming at continuity and reliability due to the intermittence of the solar source.

A mathematical analysis is performed [80] in a hybrid system with solar, wind, and diesel as backup sources, within a year, with hourly changes in source availability and energy demand.

Considering that hybrid power systems are increasingly used in isolated or energy-deficient areas, it is shown that an optimized system is more economical and reliable than a single-source power system [81].

The optimization of a hybrid solar-wind system with pumped storage is studied in order to serve an isolated grid with a capacity of about a few hundred kW [82].

A new configuration of a hybrid system with wind and water sources is proposed for rural and isolated areas [83]. By connecting wind turbines directly to energy storage, the authors highlight cost savings and improvements in simplicity and reliability regardless of wind power fluctuations.

Thus, the application of hybrid systems, even considering the peculiarities of each situation, can be useful in different scenarios of energy needs [84].

In the energy systems scenario, researchers have dedicated special attention to solutions with renewable sources linked to pumped energy storage, which is considered a more suitable technology for long-term projects with a need for flexibility, for which strong growth for the next decade is expected [85].

A combination of solar, wind, diesel, and pumped storage sources is modeled to meet a variable demand profile, through an optimized dispatch [15]. This modeling addresses the seasonality and intermittence of renewable sources, which represents a continuous challenge for the management of these types of energy, which for hybrid solutions is even more complex due to the diversity and variability of different sources [81–83,86–89].

The application of a hybrid solar system with pumped storage is proposed as a viable, continuous, and economical solution to the problem of low water availability in power plant reservoirs, demonstrating it as a good option to restore the performance of the reservoir [86].

Some difficulties in relation to the use of renewable sources in the electrical system are studied from the point of view of wind and solar variability that, on a large scale, can cause threats to stability and security in the electrical grid, in addition to instabilities in the connection and disconnection in the system due to pump shaft vibration in the storage process [89].

Hybrid systems may be viable in other types of power generation, for example, the application of the concept as a new form of pumped storage using federal waterways as a lower reservoir in Germany, where was identified a potential of 400 MWh [18].

A suitable economic approach to energy systems can be carried out by considering the annual cost and return of the systems [90,91] or the effective cost using the net present value (NPV) method [92], including availability, efficiency, installation, operation, and maintenance costs.

2.6. Applications in hydropower locks and the case study

In the city of Tucuruí-Brazil, the dam of the hydroelectric plant on the Tocantins River creates a water difference of 61.7 m. Two locks, shown schematically in Figure 10, allow water transport and the passage of local goods in the state of Pará.

The operation of these locks is the responsibility of the National Department of Transport Infrastructure (DNIT), which operates independently of the adjacent hydroelectric plant. In addition to the primary purpose, reversible plants can be built in these transposition systems together with intermittent sources of energy, presenting themselves as an innovative opportunity to, using the head available in the facility, meet the energy demand for its operation.

Figure 10. Schematic representation of Tucuruí locks.

The locks, as facilities associated with the construction of hydroelectric plants, share their results between the benefits and the impacts caused by their implementation.

It is in this sense that investments and improvements in the locks take place, aiming at their efficiency, and considering their fundamental role in water transport.

In the case of the Tucuruí project, studies have been carried out regarding the effects on fish and population health [93], forest alterations [94], and riverine fishing [95]. While other authors highlight advantages arising from the construction of the project, with regard to the emission of greenhouse gases [96], including the ease of stabilization of the transmission system and integration with other renewable sources [97].

Environmentally, the importance of reducing the carbon footprint related to hydroelectric plants and locks, points to renewable energy sources as an important and strategic means of ensuring the sustainability of projects [84,86] and the combination with energy storage systems contributes to the optimal exploitation of resources in terms of reliability [98,99], operational [99,100] and return on investment [101].

Studies applied to locks and waterways address the method of controlling vessels in locks [102], and optimization of vessel flow [103], including the case of cascading locks [104,105]. Others study the resistance of the structure due to impacts from vessels [106] and materials for retrofit in locks gates [107], tourist use [108], and the navigability of vessels in lock channels [109]. From an environmental point of view, changes along the waterways due to the existence of locks, dams, and channels [110] and impacts on ichthyofauna [111] are also analyzed.

In terms of energy systems, an energy solution for the transposition system is proposed in [112], in which the authors present a potential energy exploration project using head and flow in filling and drainage operations. They also demonstrate viable applications that seek the maximum use of energy availability, even in installations or places destined for other purposes. The costs involved in design, installation, and maintenance are decisive in adoption and determine the viability of renewable energy systems.

The varied research and applications of hybrid energy systems show the viability of these solutions for energy supply in isolated areas, integrated into the grid, etc. However, the implementation of renewable energy systems in locks presents an interesting opportunity that can be investigated, given the very few studies in the literature. In the Brazilian case, there are more than 20 locks and more than a hundred other dams [113], in which the combination of head and solar radiation is very frequent, thus allowing the use of both sources for energy generation and storage. The results can be easily applied to hydropower plants and transposition systems around the world.

In the case study presented, the energy exploitation is proposed based on the possibility of interconnecting the upper and lower reservoirs through an existing pipe (Figure 11), intended for use when filling the intermediate channel. Locks, in general, have in common the possibility of using the energy contained in the filling and drainage process for energy generation. This evaluation was included as an opportunity for research and future work (Chapter 6) as it is not included in the scope of this research.

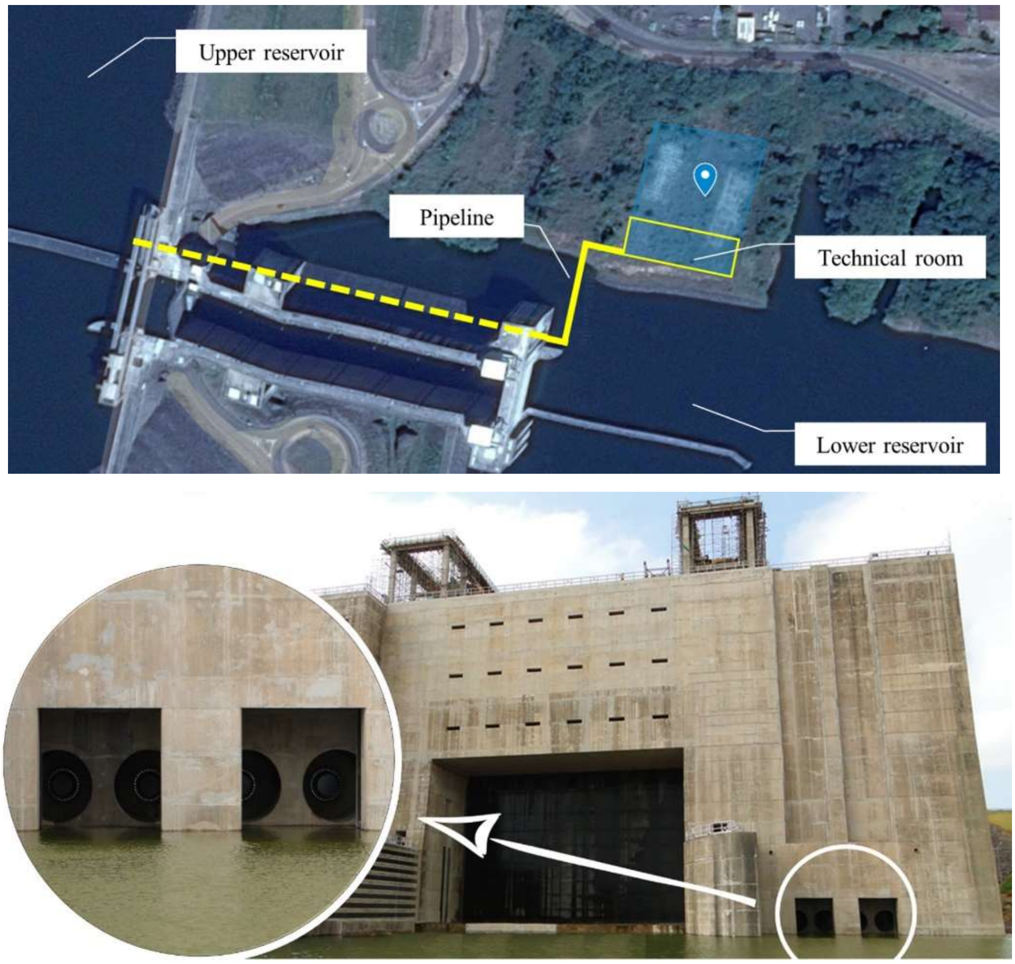


Figure 11. Overview on the proposed facility and constructive datailes.

3. METHOD

In the development of the research, some aspects form the basis of the evaluations carried out. Applied to the case of the Brazilian electricity sector, in this topic we present the method used for studies and feasibility assessments that reside within the normative context determined by the National Electric Energy Agency (ANEEL).

3.1. Tariff aspect and storage on the grid

In the Brazilian electric sector, the access of self-generation energy systems to the distribution grid, so-called micro or mini-distributed generation, is regulated by several standards. In this sense, the ones which impact the studied project, Normative Resolutions numbers 414 [114], 482 [115], 687 [116,117], and 1000 [117] delimit the rules of purchase, sale, charge, and, in cases of self-generation, the use of energy in the form of credit and debit (compensation).

Among the numerous guidelines of the aforementioned standards, we highlight the guiding ones of the project. The main characteristic explored for the analysis is the variation of the energy tariff throughout the day (Figure 12).

i) Distributed mini-generation is defined as a power generating plant with an installed capacity between 75 and 3000 kW for hydro sources, or less than 5 MW for hybrid systems and other renewable sources of electricity.

ii) The energy from a generating plant injected into the grid is provided by using a free loan to the local energy distribution company and subsequently compensated with the consumption of this same energy.

iii) For each consumer unit, the compensation must first take place at the tariff station where the generation took place and, later, at the other tariff stations, observing the list of energy tariff values. This rule assesses the feasibility of replacing energy with pumped storage, in which energy is purchased at a lower rate and sold at a higher rate.

iv) As in the case of the Locks, consumers who receive the supply with a voltage below 2.3 kV are classified as units of group B (commercial/industrial) whose applicable tariffs are those described in Table 2.

v) The energy distribution company must charge group B for the highest value obtained from the consumption of electric energy or the cost of availability, which refers to the use of the grid [117].

Table 2. Energy tariff in the region.

Tariff station	Pick time	Intermediary		Off pick time
Hour (h)	18:30-21:29	17:30-18:29	21:30-22:29	22:30-17:29
Tariff ($/kWh)	0.3364	0.2123		0.1112

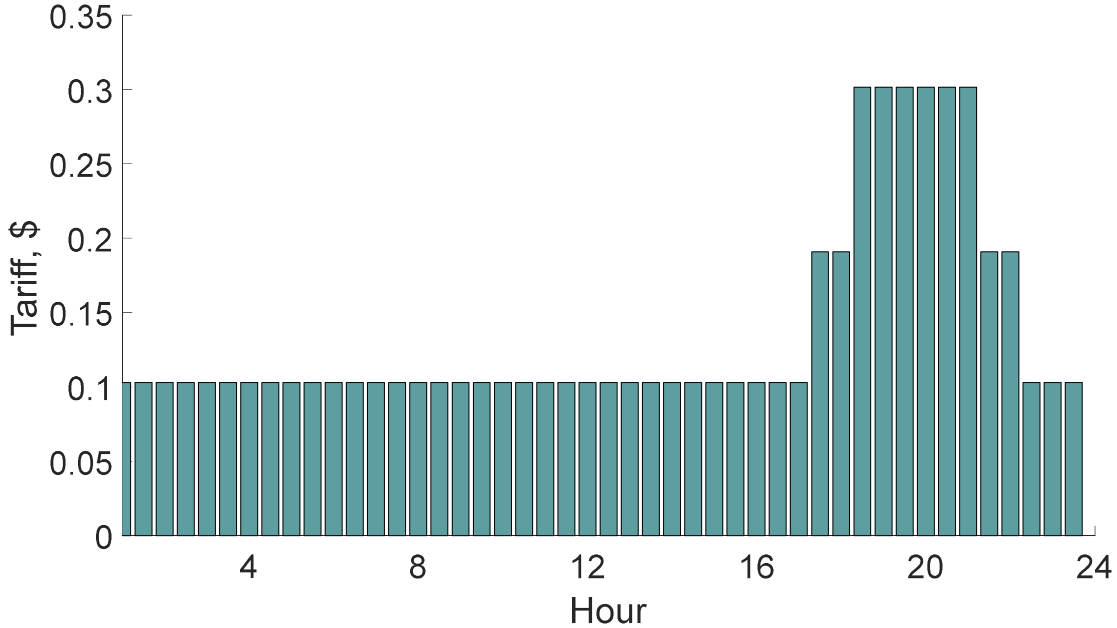


Figure 12. Energy tariff according to the hour.

The normative rule stating that "*The energy from a generating plant injected into the grid is provided using a free loan to the local energy distribution company and subsequently compensated with the consumption of this same energy*", gives a character to the distribution system of storage. This aspect is crucial in the analyzes carried out in this research and the feasibility of the proposed projects.

3.2. Simulation Method

This topic presents the details for dimensioning through simulations of project parameters such as photovoltaic power, number of PATs/pumps, LCOE, costs, credit, and debit, etc. The calculations were performed using the MATLAB R2020a® software, based on the equations presented in each subtopic. The optimal design performed, both for the purely photovoltaic and hybrid systems, is considered as the condition that meets the criteria and limits of the parameters established in the simulation.

a) Optimum photovoltaic system

Initially, a purely photovoltaic optimized system was designed to meet the operating demand of the Tucuruí locks, considering the balance of energy credit and debit, under the aforementioned rules.

The dimensioning sought to find the photovoltaic power that guarantees the balance of energy purchase and sale costs, which according to mini-generation rules in Brazil are equivalent to energy credit and debit in the system. Thus, the energy balance, given by the flowchart in Figure 13, is calculated at each instant i of 30 minutes of a typical day, with $i = 1,2,3, \ldots 48$.

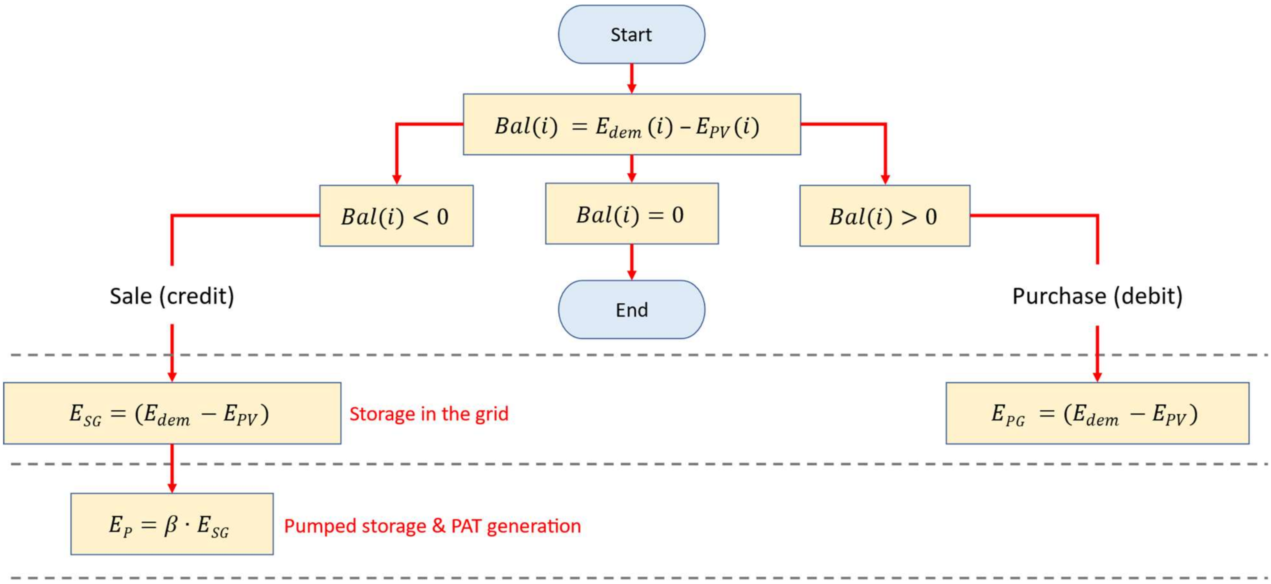


Figure 13. Flowchart of the proposed study with different storage ways.

The simulation for calculating the system considers variation of the parameters instant of time (i) and photovoltaic power (P_{PV}), as follows:

$$Bal(i) = E_{dem}(i) - E_{PV}(i, P_{PV}) \quad (6)$$

Where

$0 \ll P_{PV} \ll 2000$

$1 \ll i \ll 48$

Thus, Equation (6) expressed in matrix form takes the form:

$$[Bal]_{2000x48} = [E_{dem}]_{2000x48} - [E_{PV}]_{2000x48} \tag{7}$$

$$E_{dem} = \begin{bmatrix} E_{dem_{11}} & E_{dem_{12}} & E_{dem_{13}} & \cdots & E_{dem_{148}} \\ E_{dem_{21}} & E_{dem_{22}} & E_{dem_{23}} & & E_{dem_{248}} \\ & \vdots & & \ddots & \vdots \\ E_{dem_{20001}} & E_{dem_{20002}} & E_{dem_{20003}} & \cdots & E_{dem_{200048}} \end{bmatrix}_{2000x48} \tag{8}$$

Regarding the E_{dem} matrix, corresponding lines were added so that it became the same type as the E_{PV} matrix, allowing the subtraction operation. The lines, therefore, from 2 to 2000 are equal to line 1, which is the initial vector.

$$E_{PV} = \begin{bmatrix} E_{PV_{11}} & E_{PV_{12}} & E_{PV_{13}} & \cdots & E_{PV_{148}} \\ E_{PV_{21}} & E_{PV_{22}} & E_{PV_{23}} & & E_{PV_{248}} \\ & \vdots & & \ddots & \vdots \\ E_{PV_{20001}} & E_{PV_{20002}} & E_{PV_{20003}} & \cdots & E_{PV_{200048}} \end{bmatrix}_{2000x48} \tag{9}$$

$$Bal = \begin{bmatrix} Bal_{11} & Bal_{12} & Bal_{13} & \cdots & Bal_{148} \\ Bal_{21} & Bal_{22} & Bal_{23} & & Bal_{248} \\ & \vdots & & \ddots & \vdots \\ Bal_{20001} & Bal_{20002} & Bal_{20003} & \cdots & Bal_{200048} \end{bmatrix}_{2000x48} \tag{10}$$

From the matrix (10), which represents the amounts of energy sold or purchased, depending on the positive and negative values, to calculate the cost of purchase and sale (credit and debit), the following matrices were established:

$$\begin{gathered} E_{SG} = \left[Bal_{ij}\right]_{2000x48} ; \begin{cases} \text{If } Bal_{ij} > 0 \ ; \ Bal_{ij} = 0 \\ \text{If } Bal_{ij} < 0 \ ; \ Bal_{ij} = Bal_{ij} \end{cases} \\ E_{PG} = \left[Bal_{ij}\right]_{2000x48} ; \begin{cases} \text{If } Bal_{ij} < 0 \ ; \ Bal_{ij} = 0 \\ \text{If } Bal_{ij} > 0 \ ; \ Bal_{ij} = Bal_{ij} \end{cases} \end{gathered} \tag{11}$$

Finally, the costs of buying and selling energy, that is, credit and debit, are given by multiplying the energy by the tariff:

$$C_{SG} = [E_{SG}]_{2000x48} \cdot [Tarif]_{48x1}$$

$$C_{PG} = [E_{PG}]_{2000x48} \cdot [Tarif]_{48x1} \tag{12}$$

The above products result in the matrices $[C_{SG}]_{2000x}$ and $[C_{PG}]_{2000x}$ whose solution is given by the position where the elements of the vectors are equal. This element gives the balance value between credit and debit COE_{bal} and the position is the photovoltaic power P_{PV} that meets the equilibrium condition.

b) The optimized hybrid system

The proposed hybrid system design is evaluated from the optimal sizing of the photovoltaic system. Inserting the hydraulic component in the project, pump, and pump-as-turbine (PAT), the objective is to evaluate the advantages of this system to the purely photovoltaic proposal. The design of this system is based on the use of pumped storage instead of using the grid as storage, as in the previous case. In addition to this, other criteria are established such as:

i) rational use of water resources, keeping the pumped and turbined volumes the same.
ii) storage process at the lowest tariff times and generation at the highest tariff.
iii) use of pump and PAT in variable speed aiming at high-efficiency operation.

c) The parameter $\boldsymbol{\beta}$ in the hybrid system

As shown in Figure 14, from the already dimensioned photovoltaic system, it is simulated what percentage β of the energy that would be sent to the grid could be pumped in order to guarantee the credit and debit balance and the lowest LCOE. The number of pumps/PAT for application in the case studied is also evaluated. A graphic summary of the studied problem is presented in Figure 14 in which the design criteria are shown. The simulation of the best value for the β parameter implies an equivalent reduction in the installed photovoltaic power, which economically justifies the hybrid proposal. Thus, in Figure 14, the pumping portion occupies the upper region (consumed from the grid), while the generated portion (PAT) represents what will be sent to the grid. We emphasize that the approach, with the insertion of the β factor, focuses only on the portion of the additional generation sent to the grid. The remaining quantities are maintained in the energy balance of the system.

Furthermore, this approach presented above (β) is applied only to the case of the on-grid system, due to the need for the system to be connected to the grid, which is where the credit/debit rules apply. For the case of isolated systems (island case study) this optimization is not applicable, thus requiring a particular study, suggested in Chapter 6.

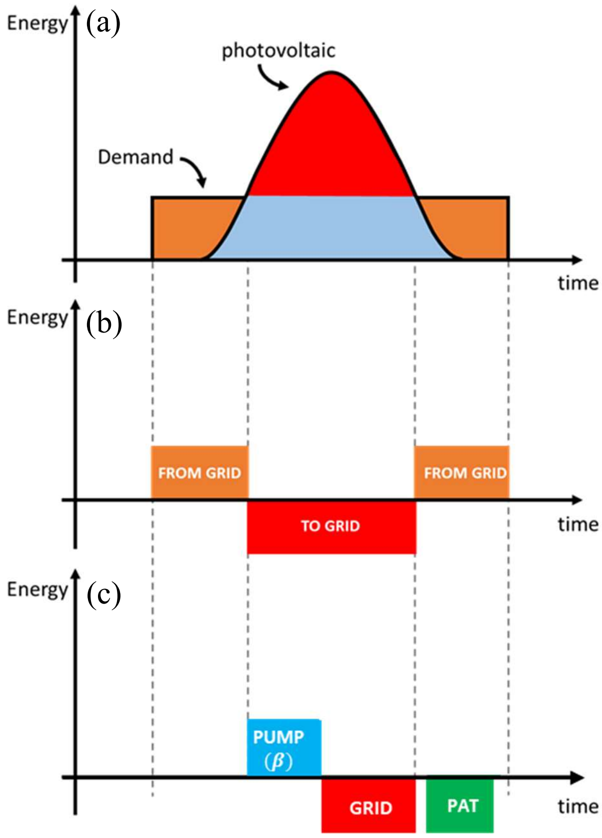


Figure 14. Outline of the approach to the problem.

In Figure 14a is shown a classical system where photovoltaic production is sizing to meet demand. A storage medium is needed so that the energy surplus is used in periods of deficit in the production/demand ratio. An important aspect of this configuration is that in the Brazilian electricity sector rules, grid can be used as intermediate storage (in the form of credit and debit of energy), bypassing the issue of variability of photovoltaic production in meeting demand (Figure 14b). In this section, the problem analyzed is as follow: from a photovoltaic system (b) what amount of energy could be stored via pumping in the lower tariff period, instead of using the grid, and turbined in the higher tariff period, satisfying the following conditions: i) energy balance, ii) mass balance (pumped volume and turbined the same), iii) purchase and sale cost balance (credit and debit) and iv) efficient PaT/Pump operation?

The approach of the proposed system and the calculation of the hydraulic system, for the pump mode, was carried out through Equations (13) to (21), considering the pumping time $t_P = 10$ hours, given by the solar production period, with the lowest tariff, as follows:

The energy evaluated in the hybrid system is based on the β factor that varies from $0 \ll \beta \ll 1$, as follows:

The energy to be stored via pumping is given by:

$$E_P = \beta \cdot E_{SG} \tag{13}$$

With the cost of energy for pumping:

$$COE_{pump} = \beta \cdot COE_{bal} \tag{14}$$

The cost of energy sent to the grid, in this configuration, becomes:

$$COE_{grid} = COE_{bal} - COE_{pump} \tag{15}$$

Relating Equations (14) and (15):

$$\begin{aligned} COE_{grid} &= COE_{bal} - \beta \cdot COE_{bal} \\ COE_{grid} &= (1 - \beta) \cdot COE_{bal} \end{aligned} \tag{16}$$

The design condition of the hybrid system provides for the maintenance of the balance between costs, as follows:

$$COE_{PAT} + COE_{grid} = COE_{bal} \tag{17}$$

The pumping power is given by the energy in Eq. (13) related to the set pumping time.

$$P_P = E_P/t_P \tag{18}$$

From the pump performance curve, given by the manufacturer, the operating point is defined as the maximum efficiency. In this (BEP), the flow and head are defined, which allows, thus, the calculation of the volume in the pumping operation, as follows:

$$Q_{Pbep} = Q(\eta = \eta_{max}) \tag{19}$$

$$H_{Pbep} = H\big(Q = Q_{Pbep}\big) \tag{20}$$

$$V_P = \frac{E_P\ \eta_{max}}{\rho\ g\ H_{Pbep}} \tag{21}$$

$$V_P = \frac{\beta \cdot E_{SG}\ \eta_{max}}{\rho\ g\ H_{Pbep}} \tag{22}$$

For the operation of the PAT, as a design criterion, it was established that the pumped volume V_P is equal to the turbined volume, that is:

$$V_P(\beta) = V_{PAT} \tag{23}$$

Based on the highest energy tariff period (Figure 12) the established time for the PAT to work is $t_{PAT} = 8.4$ hours. The procedure for calculating the operational performance in turbine mode follows Equations (24) to (28).

The operating point in turbine mode is given from the turbined volume, which related to the operating time provides the PAT flow, as follows.

$$Q_{PAT}(\beta) = \frac{V_{PAT}(\beta)}{t_{PAT}} \tag{24}$$

From the PAT performance curve, with the defined flow, the head can be calculated.

$$H_{PAT} = H_T(Q_T = Q_{PAT}) \tag{25}$$

The rotation of the machine that provides the flow and head is given by the formulation of the Yang-Rossi method, together with the efficiency.

$$N_{PAT} = N_T(Q_T = Q_{PAT}\,; H_T = H_{PAT}) \tag{26}$$

$$\eta_{PAT} = f(N_{PAT}) \tag{27}$$

In this way, the energy produced in PAT mode can be calculated as follows.

$$E_{PAT} = \rho\ g\ H_{PAT}\ Q_{PAT}(\beta)\ \eta_{PAT}\ t_{PAT} \tag{28}$$

The cost of energy generated in the PAT, sent to the grid, is given by:

$$COE_{PAT}(\beta) = E_{PAT}(\beta) \cdot Tarif \tag{29}$$

Thus, Equation (17) can be rewritten to represent the design condition of the hybrid system.

$$COE_{PAT} + COE_{grid} = COE_{bal}$$

$$COE_{PAT}(\beta) + COE_{bal}(1-\beta) = COE_{bal}$$

$$COE_{PAT}(\beta) + COE_{bal}(1-\beta) - COE_{bal} = 0$$

$$COE_{PAT}(\beta) - \beta \cdot COE_{bal} = 0 \tag{30}$$

Equation (30) exactly represents the insertion condition of the pumping/generation hydraulic component without changing the balance of costs or credit and debit losses, as projected in the purely solar condition. Thus, combining Equations (14) and (30):

$$COE_{PAT}(\beta) - COE_{pump}(\beta) = 0 \quad (31)$$

With the insertion of the pumping component for the water mass balance, the same volume that is pumped is turbined at peak hours, when the energy tariff is higher, so that although there is less energy being produced, the costs are equivalent. The analysis, therefore, results in determining the value of β that represents the balance proposed by the above formulation.

3.4. Predicting the use of variable speed PATs

The solutions available in the literature for predicting PATs, analytical, numerical, and experimental, focus their efforts on finding the behavior of the machine, in general, at the best efficiency point (BEP). However, for real applications whose interest is the verification of performance outside the design point, these methods fail or diverge. It is in this sense that Rossi *et al*. [6] present an interesting approach to predict the complete curve in turbine mode, based only on the BEP in pump mode, and should be used from an appropriate approach to predict the PAT in its BEP. The authors establish a normalized mathematical relationship between the dimensionless coefficients of pressure, flow, and efficiency to trace the characteristic curves of the PAT.

The prediction of the pump behavior in turbine mode was made by combining the propositions of Yang [58] to determine the BEP in turbine mode and Rossi [6], whose formulation allows for predicting the general behavior of the PAT outside the best efficiency point. Thus, the performance curves in the reverse mode were calculated according to Equations (32), (33), and the already mentioned (1) to (5), while the pump performance and its characteristics were obtained based on the data in Table 3 and the manufacturer's information.

$$h = 1.2/\eta_p^{1.1} \quad (32)$$

$$q = 1.2/\eta_p^{0.55} \quad (33)$$

$$\psi/\psi_{BEP_t} = 0.2394R^2 + 0.769R \quad (1)$$

$$\eta/\eta_{BEP_t} = -1.98R^6 + 9.06R^5 - 13.15R^4 + 3.85R^3 + 4.56R^2 - 1.37R \quad (2)$$

$$R = \phi/\phi_{BEP_t} \quad (3)$$

$$\phi = Q/(ND^3) \quad (4)$$

$$\psi = gH/(ND)^2 \quad (5)$$

Table 3. Pump characteristics.

Model	BMI 250330 60 Hz
Impeller diameter	280 mm
Rotation	1750 rpm
Maximum efficiency	0.80
Best Efficiency Point	27.84 m
	1152 m³/h

4. APPLICATIONS

This section presents the results achieved within the research developed based on articles that were published in congresses and journals. The main article is available in full version in the Appendix of this document. One has been submitted and is in the process of being reviewed by the *Journal of Energy Storage*.

4.1. Renewable energies integration in hydropower locks

The first article, addressing the case study of the locks, entitled *"Using hydropower waterway locks for energy storage and renewable energies integration"*, published in the journal Applied Energy, the study to demonstrate the potential of using lock structures combined with energy systems has the objective to carry out an analysis of alternatives for the operation of the Tucuruí locks considering two possible scenarios: one with purely photovoltaic energy supply and the other with a hybrid system composed of solar and hydraulic sources, with pumped storage. In addition, the economic viability of each alternative and the payback time is investigated.

The project consists of an installation for power generation taking advantage of the existing structure of the Locks. The chamber, in its internal structure, has an unused aqueduct for connection between the upstream and downstream reservoirs, independent of the filling and drainage system, which can be used for the project. Figure 15 shows the existing structure and a schematic representation of the planned project.

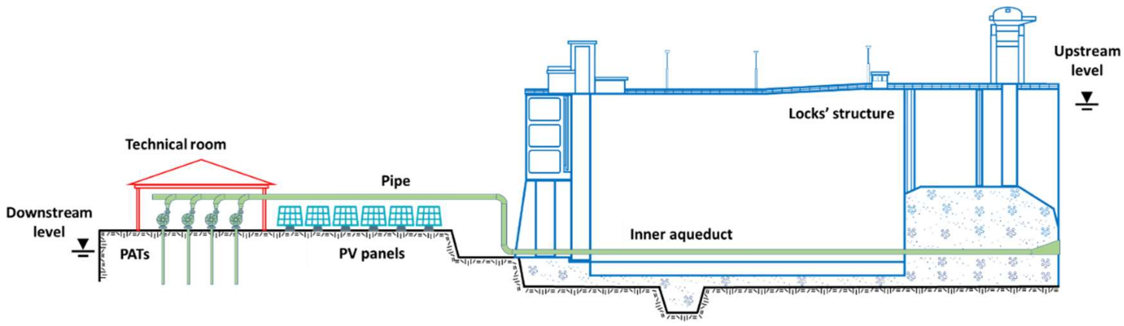


Figure 15. Schematic representation of the facility

The hybrid system evaluated in this study was designed with the objective of offering a cheaper solution with a shorter payback time [53], grid stability [89], and the possibility of quick corrections in operational quantities to respond to changes in demands and sunlight on site. The hybrid system is composed of a photovoltaic solar source and a hydraulic source using PATs, schematized in Figure 16.

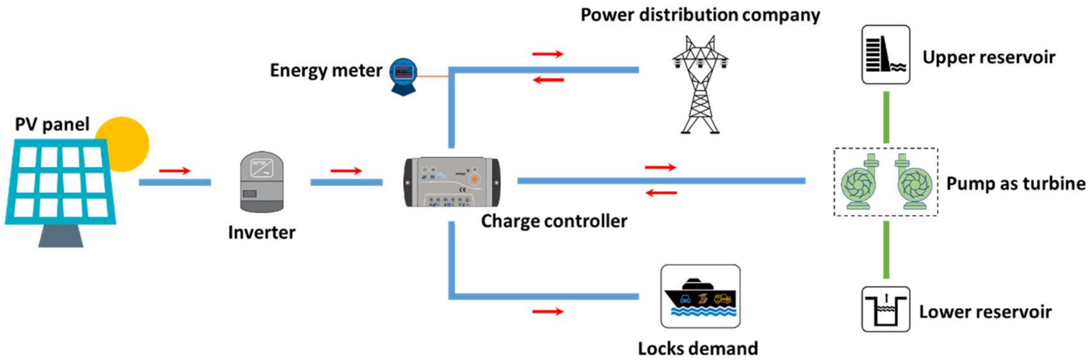
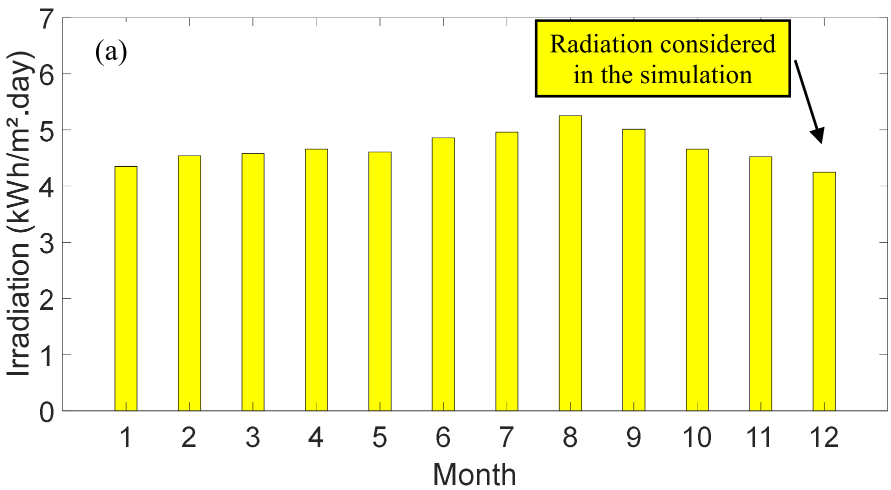


Figure 16. Schematic arrangement of the proposed hybrid system

The energy alternatives are discussed technically and economically, involving energy costs in different scenarios, operational arrangements, prediction of the behavior of pumps in turbine mode, rational use of water resources, use of the local distribution grid as an intermediate store, providing important data for the use of hydroelectric energy and providing support for energy integration around Locks.

The Tucuruí locks, shown in Figure 10, are installed in an area where the average daily solar irradiance is represented in Figure 17a. In addition, the installation is in the same structure as the existing dam and allows for the possibility of using the head for generation aiming self-consumption. Figure 17b shows the variation of the head along a hydrological cycle.



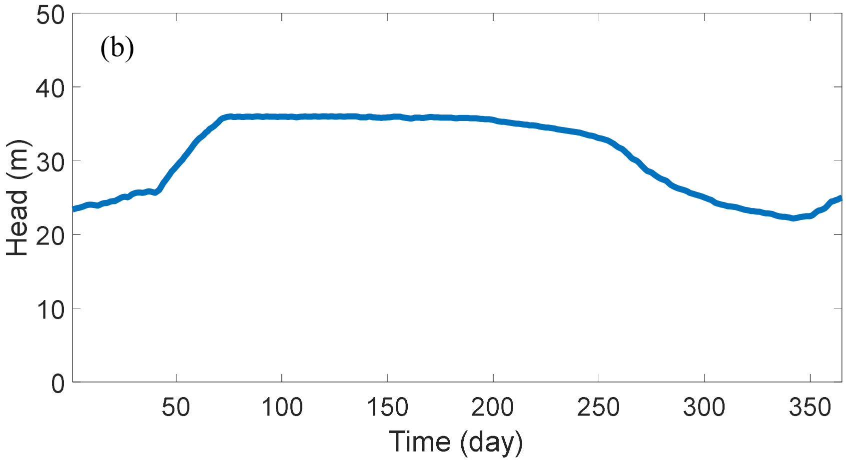


Figure 17. Availability of renewable energy on site

The purely photovoltaic system is the first energy alternative analyzed in order to meet the energy demand for the operation of the Locks. This application would use the grid as storage in the form of energy compensation, according to the rules of the National Electric Energy Agency (ANEEL). In the second case, a solar system with pumped storage is evaluated with a percentage of each source for sizing the system. The operation of the pump as a variable speed turbine is adopted, ensuring flexibility to the system. The design criterion of $\alpha = 0.5$ is adopted, which means the percentage of the demand that the photovoltaic system was designed to meet.

For the first case, a purely photovoltaic system, a power of 1,569 kW is obtained by the 4,757 photovoltaic modules, occupying an area of 9,249 m^2. Figure 18 shows the comparison between hourly demand and photovoltaic production. Based on the insolation data for the critical month (December), by the method used, solar production meets the operating demand, ensuring in the daily balance a surplus stored in the grid of about 1,500 kWh.

The demand profile was determined based on the actual measurement of the energy meters within one month of the operation of the locks. For the energy required for operation, 16 transposition maneuvers were considered, according to the project forecast as the maximum maneuver, per day. Thus, the daily demand for the operation of the locks was calculated. As each of the filling and emptying operations takes about 15 minutes, the profile of Figure 18 shows demand every half hour, with approximately 10% being set aside as minimum operating energy for lighting, office services, machinery, and other equipment. This consideration was necessary because the data for real values of demand was unavailable. For this first analysis, an assessment in global terms of feasibility is thus possible. However, for detailing at the executive project level, this load profile must be established with more precision, although the total energy of 135,090 kWh was measured in one month of operation of the facility.

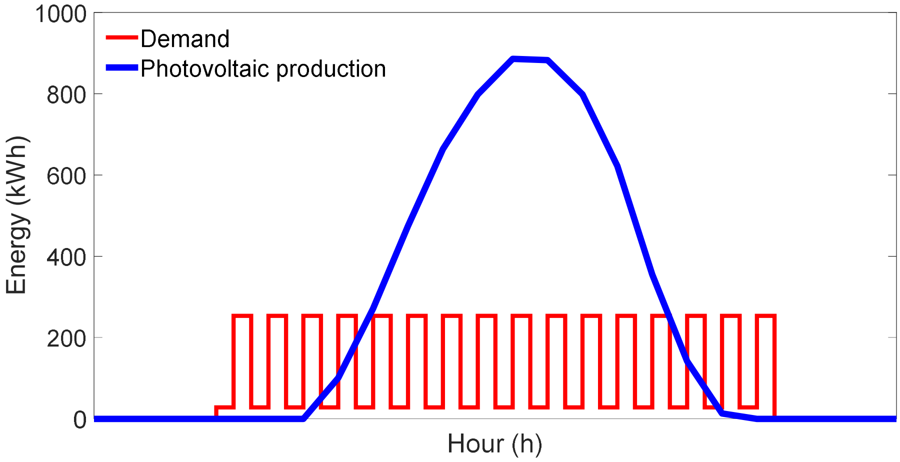


Figure 18. Hourly demand and production of the purely photovoltaic system.

Figure 20a presents the energy production by hybrid sources. In this system, the use of the α factor causes a reduction in the same proportion of occupied area, installed power, and number of panels, in relation to the purely photovoltaic alternative. The solar production presented in Figure 18 was obtained based on the irradiation data in Figure 19 for the month of December.

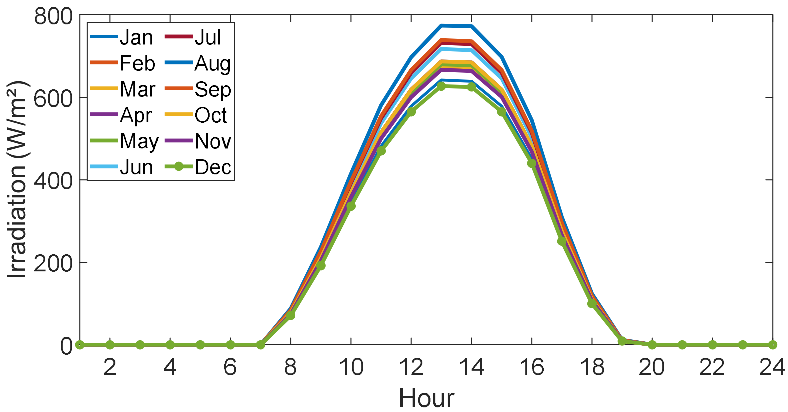


Figure 19. Average irradiation in the site.

In this arrangement, PAT guarantees the necessary complement for the supply of energy for the operation, considering the balance at each moment. It is observed that the negative energy values represent the energy consumed by the pump to store the energy.

From the analysis of Figure 20a, the PAT operation mode depends on the balance between demand and photovoltaic production at each moment. Thus, due to the intermittent variation in demand, it would be necessary to have a high number of conversions in the machines, in addition to operating under different conditions of power, rotation, etc. In this way, it is proposed to use the grid as an intermediate means of energy storage, establishing a new continuous and economical operation scheme for operation in pump mode and only one conversion to turbine mode (Figure 20b).

Conceiving the system for continuous operation in pump mode and later in turbine mode, the quantities needed at each moment are evaluated and taken to determine the operational characteristics. That is, the volumes at each instant are summed to determine the total volume in each mode. Thus, relating it to the operating time, it is possible to determine the flow, head, and rotation in each period as a pump and as a PAT.

Considering the design criterion $\alpha = 0.5$, which means the percentage the demand that the photovoltaic system was designed to meet, the solar power, number of modules, and hourly solar energy were calculated according to Equations (34) to (36).

$$P_{m2} = \alpha \cdot L_A / (H_{SP} Red_1 Red_2) \tag{34}$$

$$N_{PV2} = P_{m2} / P_{PV} \tag{35}$$

$$E_{s2} = G_{sol} N_{PV2} A_{PV} \eta_{PV} \eta_{inv} \tag{36}$$

Where P_{m2} is the photovoltaic power for the hybrid case, α is the sizing factor for the system (corresponding to 0.5), L_A is the demand considered for the solar project, N_{PV2} is the number of solar panels, P_{PV} is the power unit of each photovoltaic panel, E_{s2} is the solar energy calculated at each time of irradiation G_{sol}.

PAT energy is calculated by the difference between demand and solar production at each instant of time, according to Equation (37).

$$E_{PAT} = d_{ei} - E_{s2} \tag{37}$$

This operational configuration, however, establishes a lot of several conversions or implies a large change in speed. Since the facility has a connection to the power distribution company, it is possible to use this feature as an intermediate storage source, transferring the energy balance from an hourly basis to the daily basis.

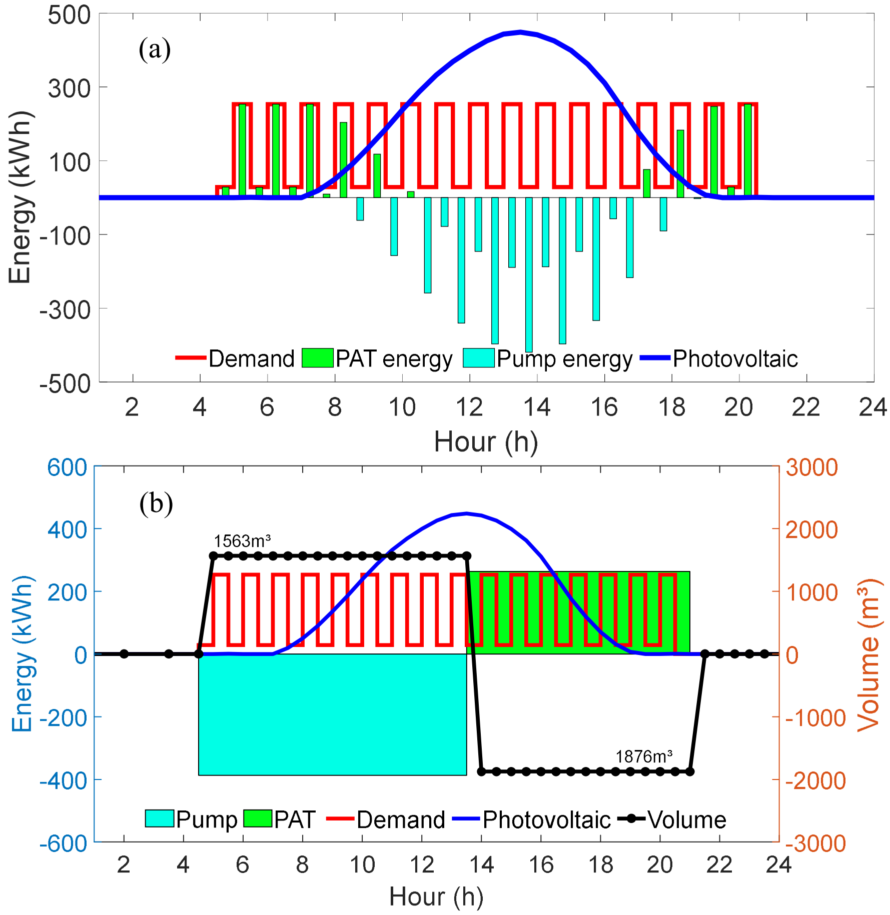


Figure 20 . Production in the hybrid system

The hybrid project aims to operate without interfering with the local hydrological dynamics, to keep the pumped and turbined volumes the same. In this sense, Figure 21 shows the use of water in each operating mode. It is possible to notice that the accumulated volume of pumped water is turbined in the sequence, after conversion to the reverse mode.

The energies in each mode were determined based on the balance of Equation (37) to dimension the total amount necessary for the operation. In this initial assessment, however, the cost balances were not evaluated in detail considering the second operating scheme with a single conversion. This includes the number of PAT/pumps needed to meet the flows and powers, operating points, efficiency etc. Thus, the operation in PAT mode, for example, in the proposed period there is a higher energy cost due to a higher tariff. This analysis opportunity is explored in detail in section 4.2, in which an optimized system considering all these costs is proposed.

The determination of volumes in pump mode and in turbine mode, flow rate and consequently the operating point for selection of suitable machine, Equation (38), which represents the energy in a hydraulic turbine, was used. For initial purposes an efficiency

η_t of 0.8 was considered. Head H is defined by the hydrological condition of the day, and its variation over a hydrological cycle is shown in Figure 17.

$$E_t = \rho g H Q_t \eta_t t_{0t} \tag{38}$$

Considering that $Q_t = V_t/t_{0t}$, the equation can be rewritten to determine the volume of water used in the production of energy E_t, as follows:

$$V_t = E_t/\rho g H \eta_t \tag{39}$$

The use of water resources in the responsible exploitation of the site was an established concept for the installation project, so that in one day of operation, the pumped volume is equal to the turbine, according to Equation (40).

$$V_t = V_b \tag{40}$$

From the equality relationship between turbine and pumped volumes, the total flow rate in pump mode was calculated considering the operating time in direct mode t_{0b}, as follows. Table 4 presents the operating values in each mode, as shown in Figure 21:

$$Q_b = \frac{V_b}{t_{0b}} \tag{41}$$

Table 4. Water use process data.

Time (h)	Mode	Flow rate (m^3/h)	Volume (m^3)
0.5	-	-	-
2.0	-	-	-
3.5	-	-	-
4.5	Pump	3127	1563
5.0	Pump	3127	1563
5.5	Pump	3127	1563
6.0	Pump	3127	1563
6.5	Pump	3127	1563
7.0	Pump	3127	1563
7.5	Pump	3127	1563

8.0	Pump	3127	1563
8.5	Pump	3127	1563
9.0	Pump	3127	1563
9.5	Pump	3127	1563
10.0	Pump	3127	1563
10.5	Pump	3127	1563
11.0	Pump	3127	1563
11.5	Pump	3127	1563
12.0	Pump	3127	1563
12.5	Pump	3127	1563
13.0	Pump	3127	1563
13.5	Pump	3127	1563
14.0	PAT	3752	1876
14.5	PAT	3752	1876
15.0	PAT	3752	1876
15.5	PAT	3752	1876
16.0	PAT	3752	1876
16.5	PAT	3752	1876
17.0	PAT	3752	1876
17.5	PAT	3752	1876
18.0	PAT	3752	1876
18.5	PAT	3752	1876
19.0	PAT	3752	1876
19.5	PAT	3752	1876
20.0	PAT	3752	1876
20.5	PAT	3752	1876
21.0	PAT	3752	1876
21.5	-	-	-
22.0	-	-	-
22.5	-	-	-
23.0	-	-	-
23.5	-	-	-
24.0	-	-	-

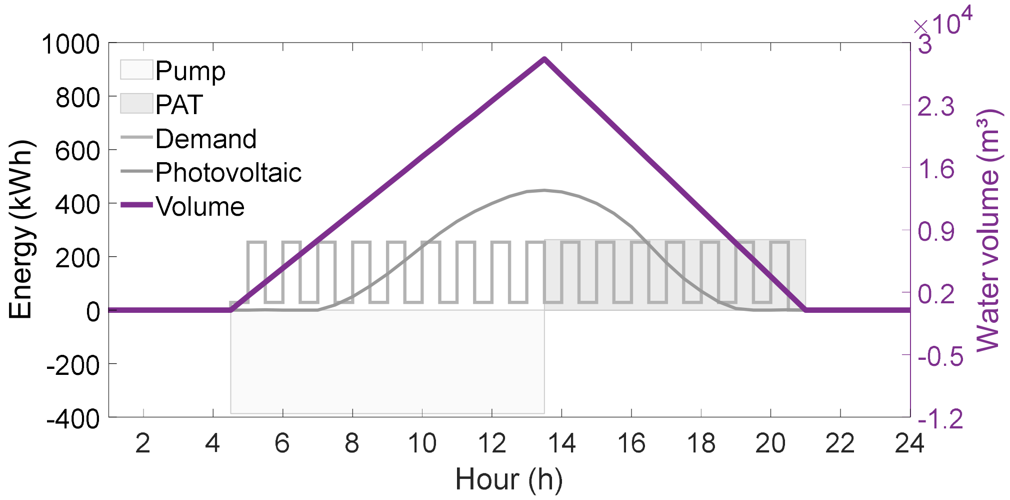


Figure 21. Use of water in the hybrid generation process.

For the evaluation of costs and payback were used the energy tariffs in Brazil which vary according to Table 5. The calculated costs for the payback evaluation for the studied alternatives took into account the hourly cost for each solution. These results were projected annually, considering the variations of the tariff for working days and weekends. The tariffs shown in Table 5 represent the values applicable by the local power distribution company and, therefore, differ from other states in the country.

Table 5. Energy tariff in the region (US$/kWh).

Tariff station	Pick time	Intermediary		Off pick time
Hour (h)	18:30 to 21:29	17:30 to 18:29	21:30 to 22:29	22:30 to 17:29
Tariff (working days)	0.34936	0.22415		0.13773
Tariff (weekend)	0.13773			

Exchange ref. 09/29/2019.

The costs of energy supplied by the grid for one day were calculated on an hourly basis for working days and weekends separately based on Equations (42) and (43). TOE represents the tariff of energy according to the data in Table 5, which follows the rule of the Brazilian National Electric Energy Agency. The cost of energy over time has been calculated by Equations (44) and (45), where t is the year.

$$COE_{wd} = \sum d_e TOE_{wd} \quad (42)$$

$$COE_{wk} = \sum d_e TOE_{wk} \tag{43}$$

$$COE_{c_{year}} = 365/7(5COE_{wd} + 2COE_{wk}) \tag{44}$$

$$COE_c = t \cdot COE_{c_{year}} \tag{45}$$

Energy costs for photovoltaic and hybrid alternatives were calculated according to Equations (46) and (47), considering capital costs plus operation and maintenance costs. It was adopted the suggestion of Jannuzzi and Melo [118] which considers the O&M costs of these installations to be 1% of the capital cost for photovoltaic systems. For the hybrid case, the estimate used was 2%.

$$COE_{PV} = C_{cap_{PV}} + t \cdot C_{O\&M_{PV}} \tag{46}$$

$$COE_{Hyb} = C_{cap_{Hyb}} + t \cdot C_{O\&M_{Hyb}} \tag{47}$$

In turn, the capital costs for solar and hybrid alternatives were determined based on Equations (48) and (49), which consider the cost of availability C_{Av}, under the rules of the Brazilian energy regulator, regarding the use of transmission system and the financial estimate for implementation of photovoltaic systems in Brazil C_{PV} of 1.8 $US\$/W_p$. For the hybrid case, the cost of acquiring the equipment C_{Aq} was added to these.

$$C_{cap_{PV}} = C_{Av} + C_{PV} P_{m1} \tag{48}$$

$$C_{cap_{Hyb}} = C_{Aq} + C_{Av} + C_{PV} P_{m2} \tag{49}$$

To determine the payback time for each alternative, Equations (45) and (48) were combined for the photovoltaic-only case and Equations (45) and (49) for the hybrid case, as follows, with the data summarized in Table 6.

$$t_{PV} = C_{cap_{PV}} / \left(COE_{c_{year}} - C_{O\&M_{PV}} \right) \tag{50}$$

$$t_{Hyb} = C_{cap_{Hyb}} / \left(COE_{c_{year}} - C_{O\&M_{Hyb}} \right) \tag{51}$$

Table 6. Parameters used in the paypack calculation.

Parameter	Symbol	Value	Unit
PV capital cost	$C_{cap_{PV}}$	2,800,000	$US\$$
PV O&M cost	$C_{O\&M_{PV}}$	28,300	$US\$/year$
Hybrid system capital cost	$C_{cap_{Hyb}}$	1,600,000	$US\$$
Hybrid system O&M cost	$C_{O\&M_{Hyb}}$	10,681	$US\$/year$
Availability cost	C_{Av}	193	$US\$/year$
PV system installation cost	C_{PV}	1,8	$US\$/W_p$
Hydraulic equipment cost	C_{Aq}	260,000	$US\$$

Figure 22a shows the comparison between the proposed solutions and the conventional case, without its generation. It is noteworthy that among the alternatives, the hybrid system has the best return (6.8 years) compared to the pure photovoltaic system (11.2 years). An additional consideration regarding the payback time concerns the influence of the powerplant adjacent to the lock. During the wet season, typically from February to May, the dam's spillway operates continuously. The configuration of the Hybrid System components is shown in Table 7.

Thus, since there is no need for pumping in this period, the amount of energy consumed in the pumping mode is deducted from the demand for calculating the hybrid system, resulting in a reduction in solar power, the number of panels. In this way, the wet period allows the hybrid installation to run constantly in turbine mode without the need for storage.

Considering this aspect, Figure 22b shows the influence of this spillway on the payback time of the proposed project. This figure describes the return on investment according to the behavior of the equipment under the following conditions: without going into operation, operating for only one month, and 2 to 4 months of opening over a year. Therefore, in the absence of storage, the proposed system presents a faster return to investor of up to 5.2 years.

Table 7. Hybrid system configuration.

Source	Power (kW)	Number of units
Photovoltaic	784	2378
Hydro	110	1

The curves presented for the payback represent, from the point of view of solar production, the average generation for a typical day, the same used for the sizing of the system. Production variations due to shade, low irradiation, rain, losses, or any other condition that interferes with the variability of generation are not considered. In this way, the project conditions are considered as a reference for analyzing the results.

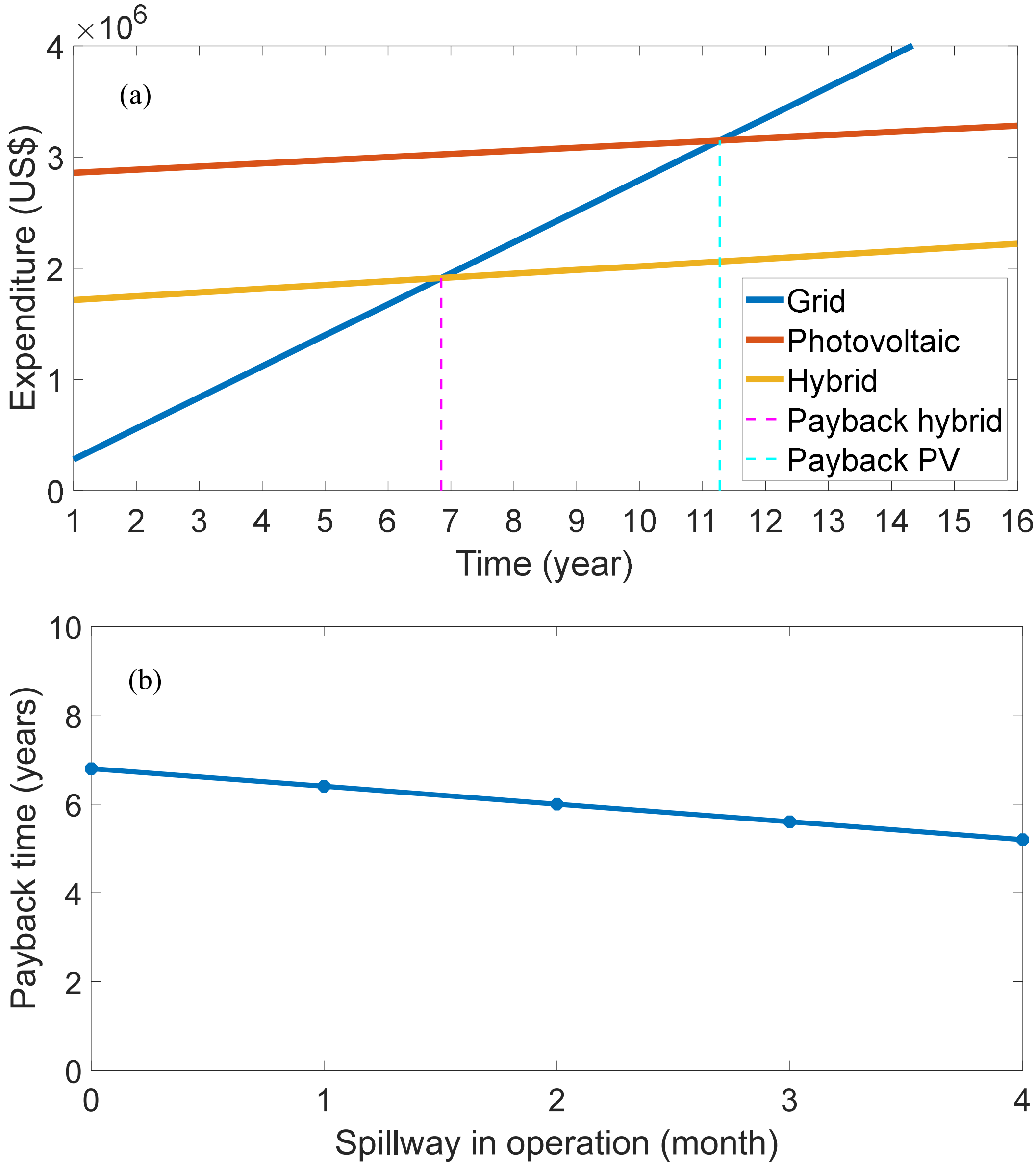


Figure 22. Payback analysis of the proposed system.

4.2. An optimized hybrid system to locks

The article entitled *"Optimization of hybrid system solar-pumped storage with pump-as-turbine using the rules of the Brazilian electric sector: case study of Tucuruí hydropower locks"* explores the improvement in the project presented in the previous section (specific objective iii).

The analysis is based on the optimization of the sizing of the hybrid system solar with pumped storage, considering the following conditions: cost balance between energy sold and purchased (in the form of credit and debit); balance between pumped and turbined volumes; lower Levelized Cost of Energy (LCOE); pump operation at lower tariff period; operation as a turbine at peak hours; use of the grid distribution and pump for storage; variable speed machine operation; efficient PAT operation; spillway influence on project payback.

The first dimensioning step (Figure 23) shows that a system with an installed solar power of 816 kW, the system achieves a balance between purchase and sale costs, setting the optimal point for dimensioning the system, within the rules of the Brazilian electricity sector. This point is important from a technical and economic point of view, given that the sale and purchase are not effectively remunerated. In this way, any surplus, whether credit or debit, represents losses.

Figure 23 shows the variation in costs and quantities of energy purchased and sold as a function of installed solar power. The equation for calculating the curves is presented in detail in section 3.2. The simulation consists of evaluating for each photovoltaic power, ranging from $0 \leq P_{PV} \leq 2000$, the energy balance of Equation (7). The purchase and sale cost curves show an inverse behavior because the less solar energy available, the greater the need for purchase. As the solar power increases, the energy to be sold also rises from a power value that supplies energy greater than the demand. The cost curves are exactly equivalent at the solar power of 816kW. It is noteworthy that the balance of cost and energy occur at different points, due to tariff differences in Brazil.

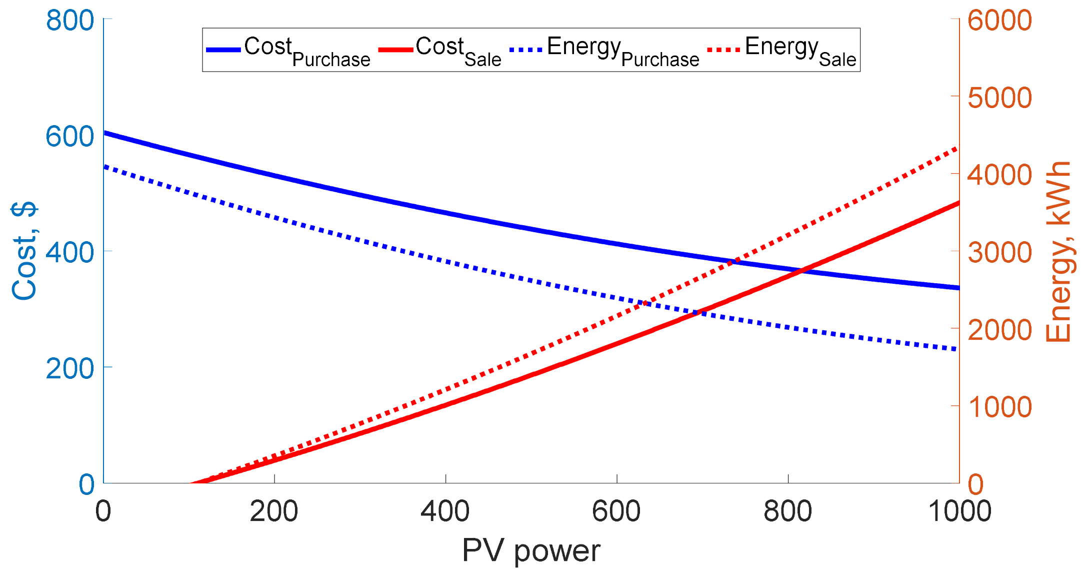


Figure 23. Purchase and sale for energy and cost in the optimum sizing.

For the design of the hydraulic part, 3 different models are analyzed, that is, with one, two and three PATs operating in parallel. In Figure 24 these configurations are evaluated, demonstrating that the three possibilities are technically feasible ($\beta_1 = 0.34$, $\beta_2 = 0.68$ and $\beta_3 = 0.99$), with emphasis on the high efficiency operating point.

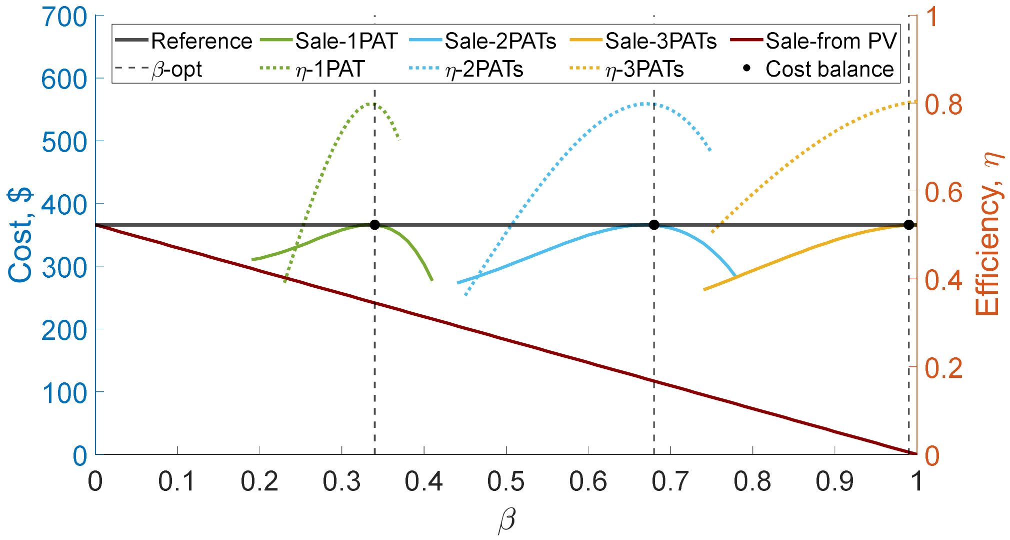


Figure 24. Sales cost with one, two and three machines as a function of β.

The options presented are evaluated economically and the results shown in Figure 25a, whose arrangement with a single pump is shown to be the lowest LCOE and, therefore, the most economically viable, even when compared to the purely photovoltaic system (Figure 25b).

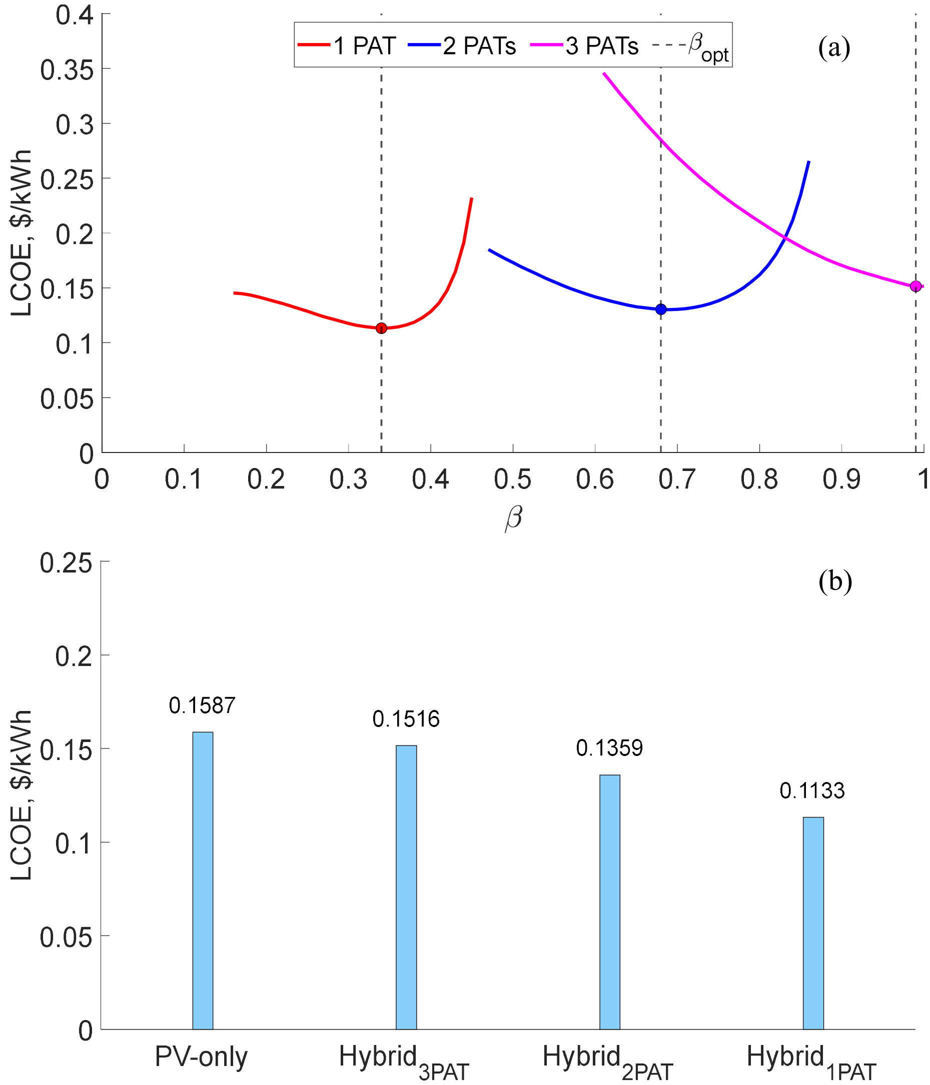


Figure 25. Cost comparison (LCOE) in the analyzed proposals.

Several proposals for hybrid systems are presented in the literature, whose energy costs are available. Awan *et al.* [72] studied different hybrid combinations with solar, wind, fuel cells, pumped storage diesel, and conventional batteries with LCOE results ranging from 0.1780 to 0.3120 $/kWh. Garrido *et al.* [119] have costs in the order of 0.44 and 0.56 $/kWh. Other systems studied provide values in the order of 0.229 [120], 0.311 to 0.467 [68], 0.524 and 0.510 [67], 0.1834 [38], 0.168 to 0.175 [39], 0.129 to 0.366 [121], 0.76 to 0.81 [69] and 0.196 to 1.32 $/kWh [75].

The costs referring to the designed system are detailed in Table 8, in which it is possible to compare the results of this work in the context of several authors who study hybrid energy systems. The values presented in the references specify only the hydraulic and photovoltaic part of the published systems, for comparison purposes

Table 8. Costs for the components of the hybrid system.

Source	Reference	Quant. Panels/PATs	Capacity	Capital cost	O&M cost	Replac. cost	Grid use	LCOE	Lifetime (years)
PV	Case study	1632	538 kW	413 $/unit 1253 $/kW	4.13 $/unit 12.5 $/kW	340 $/unit 1030 $/kW	163 $	0.113	25
	[122]	68930	13 MW	400 $/unit 2121 $/kW	4 $/unit 21,2 $/kW	340 $/unit 1802 $/kW	-	0.234	15
	[77]	27	7,67 kW	572 $/unit 2007 $/kW	1,85 $/unit 6,5 $/kW	244 $/unit 856 $/kW	-	0.334	20
	[68]	-	462 kW	- 2467 $/kW	- 1208 $/kW	- 541 $/kW	-	-	20
	[39]	17840	4370 kW	522 $/unit 2150 $/kW	2,97 $/unit 24,7 $/kW	- -	-	0.175	20
	[123]	-	154 MW	- 900 $/kW	- 21,6 $/kW	- 900 $/kW	-	0.248	25
	[75]	-	221 kW	- 896 $/kW	- 15 $/kW	- -	-	0.373	25
	[124]	-	683 kW	- 891 $/kW	- 9650 $/kW	-	-	0.460	25
Hydro	Case study	1	110 kW	1790 $/kW	17.9 $/kW	1075 $/kW	-	0.113	20
	[122]	-	5376 kW	1075 $/kW	0,10 $/kW	1075 $/kW	-	-	10
	[77]	-	-	-	-	-	-	-	-
	[68]	-	250 kW	-	-	-	-	-	-
	[39]	-	827 kWh	68 $/kWh	-	-	-	-	20
	[123]	-	71M W	700 $/kW	16,8 $/kW	700 $/kW	-	-	10
	[75]	-	11 kW	370 $/kW	-	-	-	-	60
	[124]	-	42,2 kW	1670 $/kW	1057 $/kW	-	-	-	60

Figure 26 shows the main results of the hybrid system. Figure 26a shows the energy production for the initial system, purely photovoltaic, and how the energy balance determines whether the energy goes to the grid (credit) or is consumed from the grid (debit). It is highlighted in Figure 26b only the amount of energy stored in the grid. In this quantity, the β factor is then analyzed, the result of which is shown in Figure 26c, in which the parcels that are stored in the grid and via pumping are observed, together with the energy generated via PAT at the higher tariff period. Figure 26d, finally, shows the consumption of water, in volume, during the operations as a pump and as a turbine.

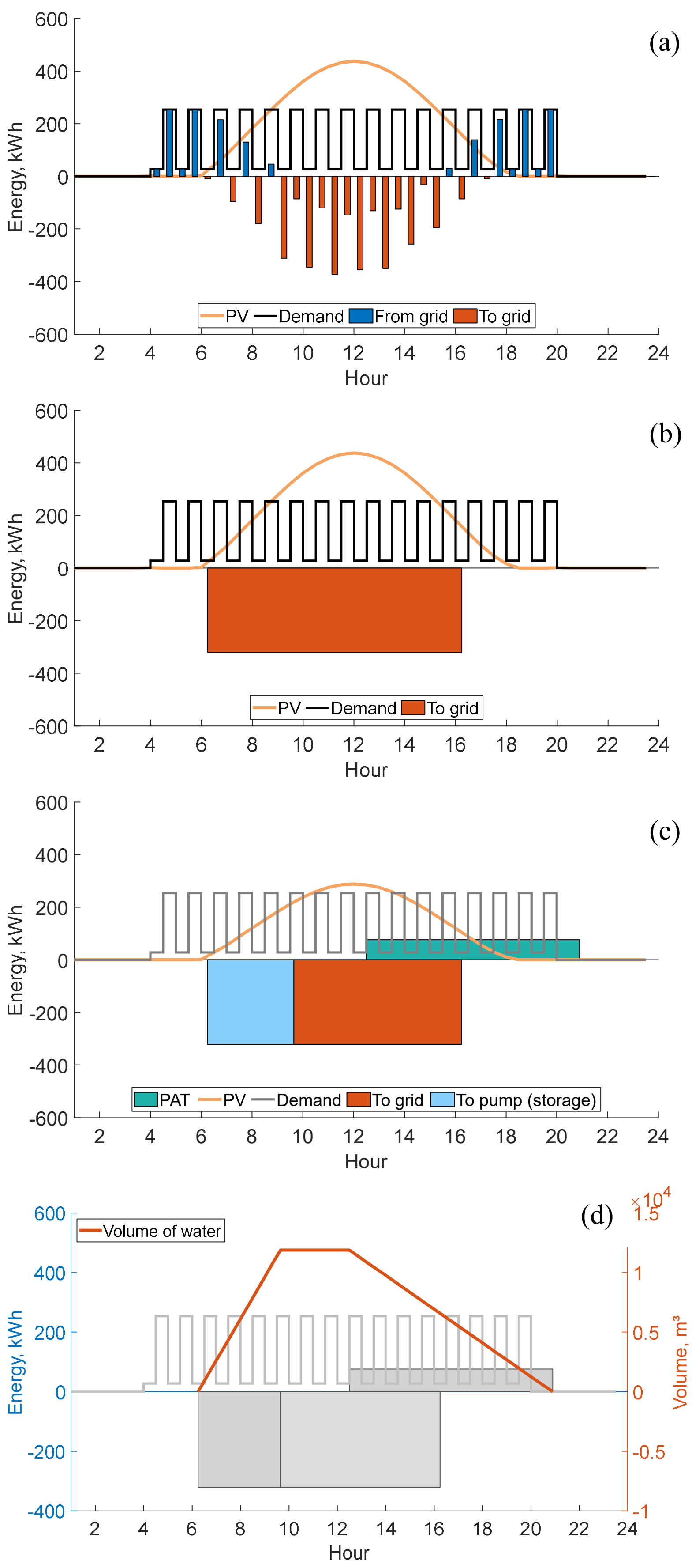


Figure 26. Features of the scaled hybrid system.

The work also showed that the hybrid renewable energy system optimized for application in the Tucuruí Locks presents interesting advantages in terms of costs, when compared to systems in the literature and the use of a volume of water in the order of 11,520 m^3 is enough to make the project technically feasible, with the same amount pumped used for the turbine. The cost balance for one day of operation is shown in Figure 27.

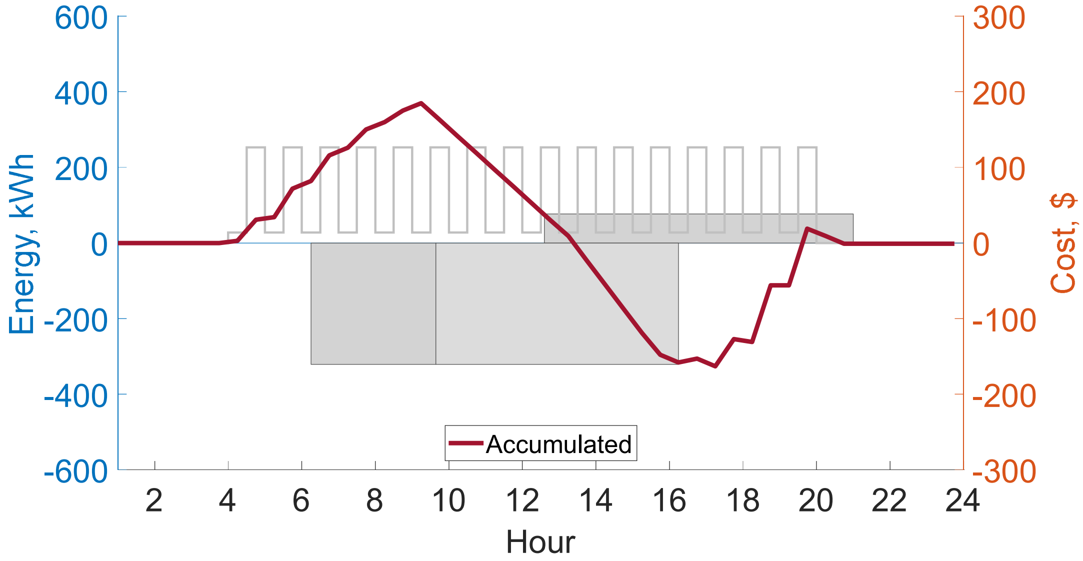


Figure 27. Accumulated cost in one day of operation.

The regulation rules of the Brazilian electricity sector can be used favorably for the project of a mini power generating plant aiming at reducing operating costs. It also showed an interesting case that demonstrated the possibility of completely replacing the photovoltaic system with a purely hydraulic one (case of $\beta = 0.99$). This situation would be the case of a pumped storage plant, whose characterization can be widely found in the literature.

Renewable energy systems are directly linked to storage technologies and based on the case study, the proposal for pumped storage has excellent prospects for use, especially due to hydraulic share in the Brazilian and global energy matrix, requiring regulation and regulatory incentives for its dissemination.

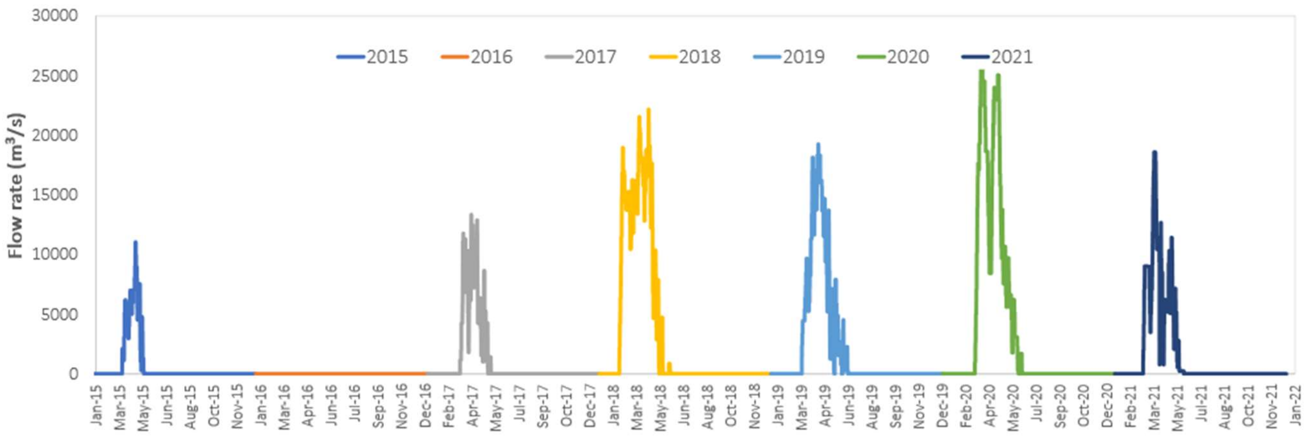


Figure 28. Spillway operation history.

Highlighting the importance of the spillway operation impact, the article *"Spillway operation effects on the feasibility of a hybrid solar pumped storage system for supplying energy to a lock"* presents, based on its operation history, shown in Figure 28, the influence on the spillway operation. optimized design payback, whose values are shown in Figure 29. The configuration of the analyzed hybrid system is shown in Table 9.

Table 9. Optimized hybrid system setup.

Source	Power (kW)	Number of units
Photovoltaic	538	1632
Hydro	110	1

The payback for a hybrid system under the conditions studied offers interesting results in the order of 3.7 years, which, compared to the studies cited in the literature, is among the most attractive cases. In the particular case of this paper, when the lock is connected by the upper reservoir to a hydroelectric plant, this payback is even shorter, reaching the value of 2.3 years.

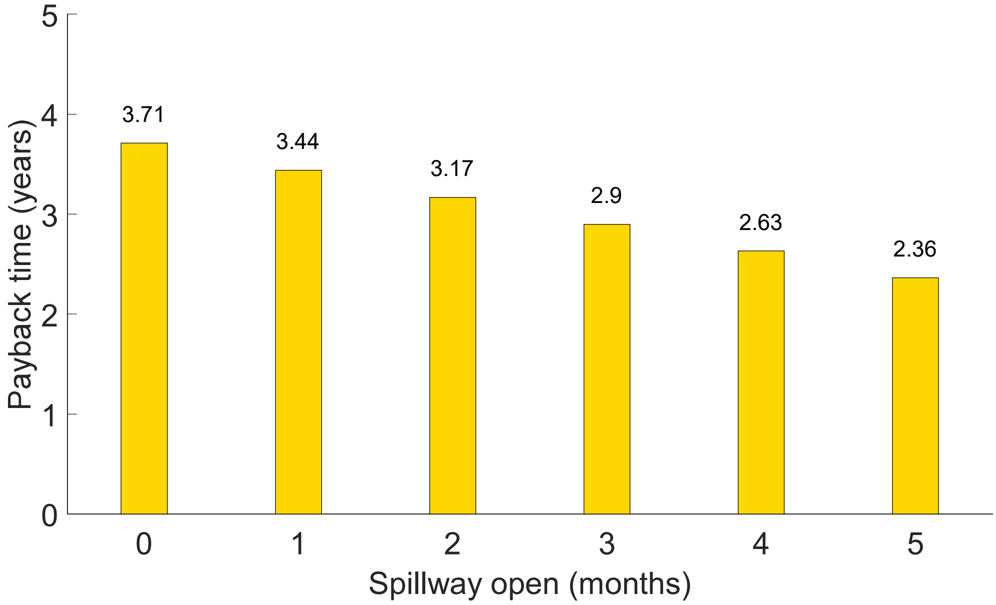


Figure 29. Influence of spillway operation on payback time for the project.

4.3. Proposal of a hybrid system to an island

The objective of this article, entitled *"Hybrid energy system with pumped hydro storage for off-grid applications - Case study of Tucuruí Lake islands"*, is to demonstrate the feasibility of a hybrid solar system with pumped storage using PATs, exploring the natural potential of the lake region of the Tucuruí hydroelectric plant, about solar irradiation and hydraulic heads, highlighting the analysis of the impact of the relationship between renewable sources on the return on investment, the volume needed for the reservoir and the initial investment.

For off-grid energy systems, as in the case, due to the variability of natural sources, the combination of sources with a suitable storage system reduces or solves the problem of intermittency and instantaneous compatibility between demand and generation [125], in addition to contributing to the decarbonization of energy systems [126]. Several studies have demonstrated the technical feasibility and/or potential use of renewable hybrid energy production systems, using solar and wind sources with pumped storage [33,34,127].

A pumped storage solar system sizing methodology [60] is used, in which the criterion is to meet 100% of the demand, using PATs with variable speed and using the same volumes of water to pump and turbine in the system operation. The project is presented on a preliminary basis. Therefore, details and operational difficulties of operating an off-grid hybrid system were not addressed. The hybrid proposal is compared with a photovoltaic system currently installed in order to analyze the feasibility and advantages of implementation, aligning sustainable thinking and respect for the environment with clean and economically viable energy alternatives for the benefit of all.

The study is motivated by the need for practical proposals for the energy issue of the place since, despite being next to the fifth largest hydroelectric plant in the world, these islands do not have electricity available on the grid. In these places, the hydraulic potential can be seen in Figure 30.

Figure 30. Variation of water level on site.

The photovoltaic system installed on the island is part of a program by the local energy distributor, with financial support from the federal government, to provide electricity to these isolated communities. The classic configuration of the system is composed of a set of 1,280 Wp photovoltaic modules, twelve 12V lead-acid batteries and

1 inverter, as shown in Figure 31. For this case, a diesel generator is still present to complement energy at certain times. In this case, the diesel generator does not automatically integrate the installed system. But it remains available for manual activation in case of need.

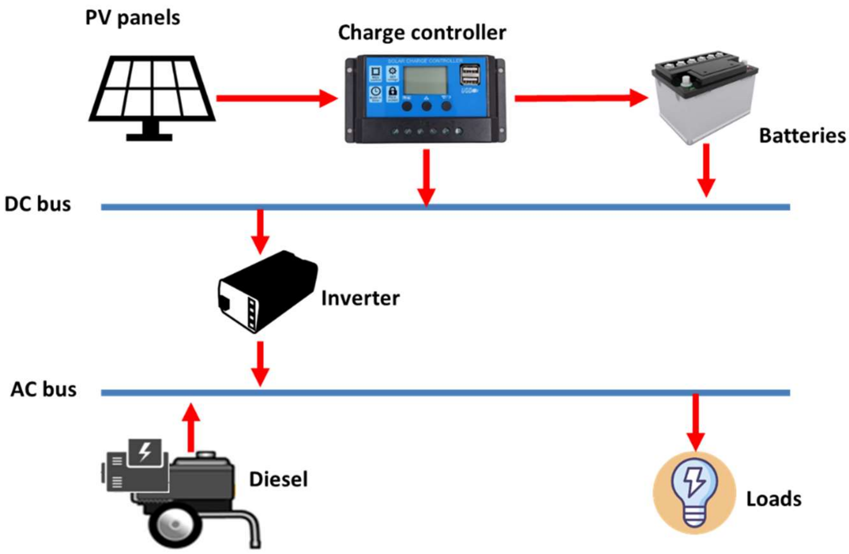


Figure 31. Photovoltaic system installed on site

The hybrid system is proposed as a solution to meet the island's total demand within the expectations related to systems of this nature, such as lower return on investment [53], grid stability [89], and the possibility of quick corrections in operational quantities to respond to changes in demand and on-site solar energy.

The hybrid system is designed with the characteristics shown in Figure 32. For the hybrid system design, it is considered as a criterion that each source meets half of the demand ($\alpha = 0.5$). In the corresponding article, this figure is shown only schematically, aiming at a general understanding of the components, without suggesting the electrical interaction between them. In the following figure, however, the configuration was adjusted aiming, with the symbolization of the AC and DC buses, to better present the interconnection of the sources from a technological point of view.

The energy demand, for sizing the power systems for the site was obtained from on-site measurements. The hourly variations in the energy, shown in Figure 33, take into account the use of some residential and other equipment due to on-site tourism such as refrigerators, stereos, lamps, television, refrigerators, etc.

The Figure 33a presents the expected energy production for the proposed hybrid case. In this system, considering a proportion imposed by the α factor of 50%, in which the photovoltaic and hydraulic components are designed to meet half of the demand, an arrangement composed of 12 photovoltaic modules (rated power 320 Wp), power of 3.7 kWp plus a pump operating as a turbine was calculated to guarantee energy complementation. The choice of factor $\alpha = 0.5$ is based on an initial estimate of the project's evaluation given its preliminary nature. As a dimensioning criterion, this proportion could be different within an evaluation to seek the optimal proportion, which for this work is beyond its objectives. In Figure 33, the negative part of energy represents consumption and the positive part represents production by PAT.

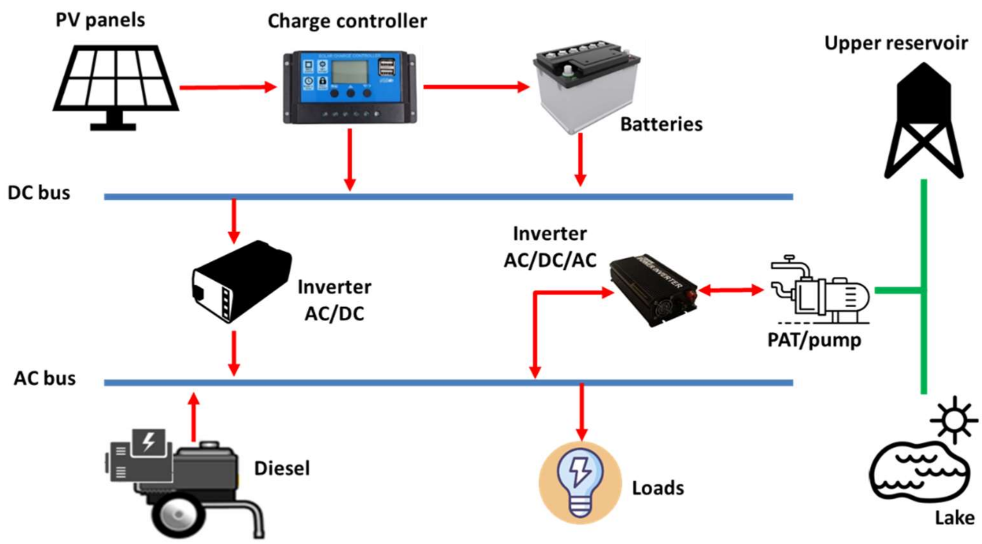


Figure 32. Hybrid system proposed.

Note also that the energy in the PAT varies from hour to hour. In this way, the variation in the operating point is ensured by the proposition of a dedicated speed control system. The use of speed controllers is also demonstrated by [128] as a better alternative when compared to other storage sources such as conventional batteries. The hybrid system proposed for the island of Lake Tucuruí was designed to take advantage of the site with natural differences and the availability of solar energy, so as not to interfere with the hydrological dynamics of the site.

With the possibility of direct and reverse operation, the amount of water used by the PAT, whose maximum volume is 129 m³, has the behavior shown in Figure 33b, with estimated costs for its construction in the order of US$ 7,752.00. It is noted that the balance between the pumped and turbined volume is guaranteed at the end of one day of operation, following the trend of sustainable development with the maintenance of the natural balance of the environment [129].

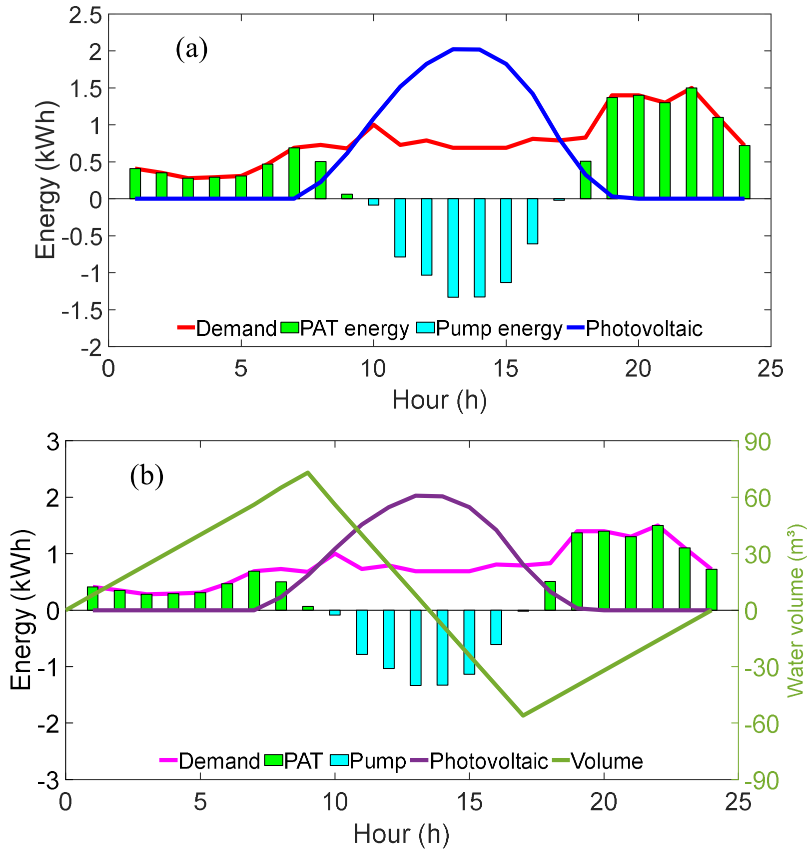


Figure 33. Forecast of proposed hybrid system operation.

Figure 34 shows the payback time for the solar-hydraulic hybrid system application compared to currently installed solar-diesel. The graph depicts the economic viability with a payback of 6.1 years when compared to the current system. This result is advantageous when compared to other systems applied in isolated islands that have a payback of 9 years [130], 8.5 [131], 9.8 [132], and up to 20 years [44].

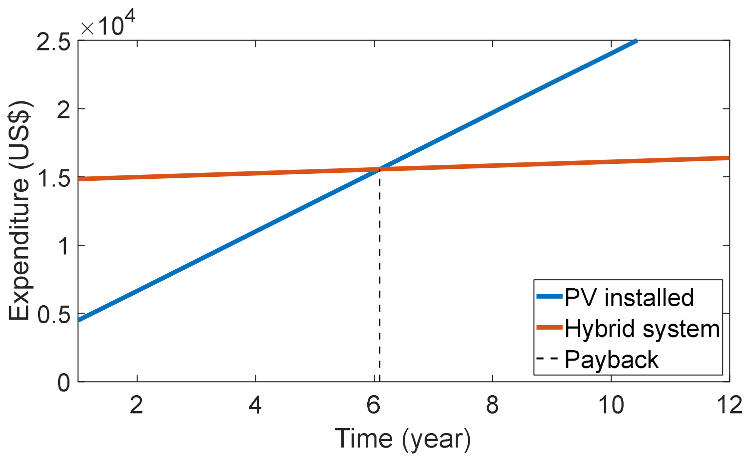


Figure 34. Payback time for the proposed project.

In this preliminary analysis, we emphasize, once again, that the technological and operational details were not explored to the point of an executive project. There is a need to consider and evaluate the possibility of a direct connection of the solar generator with the PAT/pump, to guarantee the synchronism between the sources, due to the off-grid characteristic of the system, which can also be guaranteed by the use of a grid forming inverter. The preliminary project seeks to eliminate 100% of the batteries. However, experience shows that, due to the need to stabilize the grid for coupling the generating source, a minimal number of batteries could be used. Another issue that could be analyzed, seeking operational viability, is the use of two machines exclusively for each mode: pump or turbine, thus circumventing the need for coupling the two sources to the same bus.

Another fundamental issue to be analyzed in future details of this and in off-grid projects is the overall efficiency of the system. In practice, hydraulic pumps connected to the network have an efficiency of 50 to 55%. However, when connected to photovoltaic generators, this value, due to the variability of solar production, is around 30 to 35%. Thus, considering these losses, a point of study arises aiming to increase this project's efficiency value. In a preliminary analysis, the PAT/pump system presents an efficiency of the order of 64% (considering individually that the machine has an operational efficiency of 0.8). For a system that uses common batteries with storage media, the losses are on the order of 15%, depending on the charging scheme used. This raises a study opportunity that seeks to answer the following question: considering the best efficiency, how much is it worth replacing the battery storage medium by pumping? To make the system viable, an increase in the number of photovoltaic panels could be evaluated, aiming to compensate for these hydraulic losses, given the periodic need to replace the batteries, which today represent the largest portion of the costs of an off-grid photovoltaic system.

5. CONCLUSIONS

The potential use of infrastructure related to hydroelectric plants, including the physical structure of the dam itself, locks, and islands in the upper reservoir for energy generation by hybrid solar and hydraulic renewable sources was demonstrated by the research in its broad context, within it showed results.

The feasibility analysis of taking advantage of the available solar and hydraulic potential, to meet the demand of the Tucuruí HPP Locks (specific objective i) was carried out in an initial work entitled *"Using hydropower waterway locks for energy storage and renewable energies integration"*. The alternatives studied in this work were demonstrated as viable solutions in the installation of the Tucuruí Locks. By comparing different renewable energy sources, it showed that the solar-hydraulic hybrid system with pumped storage is more economically and technically viable for this case study compared to a purely solar one.

The presence of structures for hydraulic use and the high costs for an autonomous photovoltaic installation allows for a pumped storage application. In addition to the lower initial investment for this scenario, the energy expenditure for the proposed hybrid system in relation to the costs of supply by the local concessionary leads to a shorter payback time (around -40%) due to the available head and the high costs of a purely photovoltaic plant.

With regard to the conscious use of water resources, the option for a hybrid system guarantees responsible use of the facility in relation to the environment, using water for generation and storage without additional impact on the existing hydrological dynamics.

As demonstrated, the operation of the spillway has an important influence on the results of the project studied, in terms of economic and operational aspects.

It was therefore demonstrated the potential and feasibility of using Locks for energy generation and storage when associated with the use of renewable solar and hydraulic sources, as an innovative opportunity to take advantage of the head and solar availability and provide the necessary energy for the operation of the transposition system. In addition, it offers much sought-after information on hybrid energy systems applied to locks and waterways, promoting the growing debate on energy sustainability.

From the point of view of project optimization (specific objective iii) it was shown (submitted article *Optimization of hybrid system solar-pumped storage with pump-as-turbine using the rules of the Brazilian electric sector: case study of Tucuruí hydropower* *locks*) that the hybrid renewable energy system optimized for application in the Tucuruí Locks presents interesting advantages in terms of costs, when compared to systems in the literature, in addition to the feasibility of the investment opportunity for the company that operates the plant.

An important feature from the point of view of water resource use was demonstrated as a design criterion. The use of a volume of water in the order of 11,520 m^3 is enough to make the project technically feasible, with the same amount pumped used for the turbine. This allows projects of this nature an advantage in relation to the low impact on the local hydrological cycle, therefore, environmentally responsible.

The payback for a hybrid system under the conditions studied offers interesting results in the order of 3.7 years which, compared to the studies cited in the literature, is among the most attractive cases. In this case, still applying in a lock connected to a hydroelectric plant, this payback time can be reached in up to 2.6 years.

The regulation rules of the Brazilian electricity sector can be used favorably for the project of a mini power generating plant aiming at reducing operating costs, using renewable energy, and guaranteeing the meeting of demand with an excellent return on investment. In addition, taking advantage of the opportunity existing in the locks in Brazil presents an unexplored potential that can contribute to increasing the energy supply capacity of the Brazilian energy matrix, with renewable energy.

An interesting case demonstrated the possibility of completely replacing the photovoltaic system with a purely hydraulic one (case of $\beta = 0.99$). Although it has a higher LCOE than the other cases, this means that all the energy that would be stored in the grid could be pumped and subsequently turbined, without the need for solar generation, also keeping the cost balance. This situation would be the case of a pumped storage plant, whose characterization can be widely found in the literature.

Renewable energy systems are directly linked to storage technologies and, based on the case studied, the proposal for pumped storage has excellent prospects for use, especially due to hydraulic share in the Brazilian and global energy matrix. However, the topic is still the subject of discussions, requiring regulation and regulatory incentives for its dissemination, which could have a positive impact on energy availability and the Brazilian interconnected system.

The use of pumps working as a variable speed turbine offers an excellent example of flexibility applied to hybrid energy systems, regulating the intermittence related to the variability of renewable generation, and also offering conditions to obtain greater energy efficiency in generation and storage operations.

Regarding the solar hybrid energy potential with pumped storage on the islands of Lake Tucuruí, the energy solution presented is in line with the growing search for clean, sustainable, and economic installations, respecting the specifics of each location.

This case study (*Hybrid energy system with pumped hydro storage for off-grid applications - Case study of Tucuruí Lake islands*) demonstrates the feasibility of implementing an environmentally responsible hybrid system to meet 100% of the demand, guaranteeing energy autonomy for the island, using a secure and easily accessible pumped storage technology (specific objective ii). Thus, in addition to the environmental gain, the initially higher investment is quickly compensated (6.1 years) due to the annual cost curve being influenced only by the operation and maintenance costs of the hybrid system.

6. FUTURE WORKS OPPORTUNITIES

In the context of the research, we present some suggestions of works with the possibility of future development:

- ✓ Study of an optimized hybrid system without considering the restriction imposed by the water grant, as foreseen in the Brazilian case.
- ✓ Extension of the model presented for the case of reversible turbines, including analysis of generation complementarity in small and medium-sized hydroelectric plants.
- ✓ Study of hybrid systems including other sources of generation and energy storage systems.
- ✓ In the case of a lock, the assessment of the energy use of the water discharge during the filling and draining of the lock chambers.

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8. APPENDIX

In this section, the article published is presented in full version: “Using hydropower waterway locks for energy storage and renewable energies integration”. In: Applied Energy (2020).

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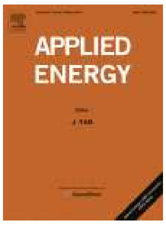

Using hydropower waterway locks for energy storage and renewable energies integration

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Using hydropower waterway locks for energy storage and renewable energies integration☆

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HIGHLIGHTS

- Use of parallel pumps as turbines for power generation and energy storage.
- Harnessing the structure of a lock for hybrid power generation.
- Use of the grid as an intermediate means of energy storage.
- Manipulation of the water without additional impact on the existing hydrology.
- Spillway at adjacent plant positively influences on payback time.

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ABSTRACT

Waterway are one of the most efficient means for transportation. It can be applied for energy storage demonstrating the potential of using these structures with renewable energy systems, here, through an analysis of energy alternatives. This paper analyzes two different solutions for energy supply, using the Locks of the Tucuruí powerplant, in Brazil. A photovoltaic power station is compared to a hybrid system composed by photovoltaic and pumped storage. The alternatives are discussed technically and economically. The energy costs of the scenarios are calculated based on the evolution of the expenses and the related payback time are found. The water resource is exploited responsibly, keeping balanced the pumped and turbined volumes of water. The grid works as an intermediate storage and allows the operations with a single pump-turbine conversion. Its location lowers down the initial investment in favor of the hybrid system as the more viable alternative. It was found that the locks could be used to handle up to 263 kW and 387 kW of electricity in turbine and pump mode, respectively. This paper gathers crucial data on the use of hydropower in waterways locks that support the integration of renewable energies surrounding the locks. In addition, the use of pumped storage plants to store energy from intermittent sources, present themselves as an innovative opportunity to, using the own head available at facility, improve the financial return of meeting the energy demand through an economically and environmentally responsible energy system, may be useful in similar facilities around the world.

1. Introduction

Waterways are the most efficient means for transportation and the only land infrastructure with the free capacity not subject to congestion problems. Navigation is the energy and carbon-efficient mode as a ship uses 1–2 times less fuel than a train and 3–5 times less fuel than a truck and can be economically competitive [1]. Additionally, waterways can be built with pumped storage plants together with intermittent energy sources, present themselves as an innovative opportunity to, using the own head available at facility, improve the financial return of meeting

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Nomenclature

A, B, C	Coefficients of the speed equation
a, b, c	Coefficients of pump equation
A_{PV}	Area of PV module
$C_{O\&M_{Hyb}}$	Operation and maintenance hybrid cost
$C_{O\&M_{PV}}$	Operation and maintenance photovoltaic cost
$C_{cap_{Hyb}}$	Hybrid capital cost
$C_{cap_{PV}}$	Photovoltaic capital cost
C_{Aq}	Cost of equipment acquisition
C_{Av}	Cost of availability
$COE_{c_{year}}$	Cost of energy per year
COE_{Hyb}	Cost of hybrid energy
COE_{PV}	Cost of photovoltaic energy
COE_c	Annual cost of energy
COE_{wd}	Cost of energy (working days)
COE_{wk}	Cost of energy (weekend)
C_{PV}	Cost of photovoltaic system
d	Demand
d_s, e_s	Coefficients of system equation
E	Energy
E_{s1}, E_{s2}	Solar energy for alternatives 1 and 2
g	Acceleration of gravity
G_{sol}	Hourly solar irradiation on the site
h_{lT}	Head losses
H	Head
H_{SP}	Peak sun-hour
L_A	Energy demand
N_1, N_2	Rotational speed at conditions (1) and (2)
N_{PV1}, N_{PV2}	Number of panels for alternatives 1 and 2
N_b	Number of pumps
p	Pressure
P_1, P_2	Power of pump at conditions (1) and (2)
P_{PV}	PV module nominal power
P_{m1}, P_{m2}	Solar power of the alternatives 1 and 2
Q	Flow rate
Red_1, Red_2	Factors of reduction 1 and 2
TOE	Tariff of energy
t	Time
t_0	Time of operation
t_{Hyb}	Hybrid system payback
t_{PV}	Photovoltaic system payback
U	Velocity
V	Volume
z	Static level
η	Efficiency
α	Demand factor
ρ	Density of water

Subscripts

PAT	Pump as turbine
$0, 1, 2$ *and* 4	Conditions
at	Current condition
t	Turbine
s	System
$máx$	Maximum
min	Minimum
b	Pump
req	Required
wd	Working days
wk	Weekend
e	Facility
i	Instant
PV	Photovoltaic
inv	Inverter

the energy demand for a solar hybrid generation system with pumped storage.

In the city of Tucuruí, Brazil, the dam of the hydropower plant on the Tocantins river creates a water height difference of 61.7 m. Two locks allow the water transport and passage of local goods in the state of Pará. The operation of these locks is under the responsibility of the National Department of Transport Infrastructure (DNIT), regardless of the adjacent hydroelectric plant.

Several studies have been conducted in regard of the environmental effects of the Tucuruí dam and its upper reservoir. Curtarelli et al. [2] investigate, by mathematical modeling, the carbon emission due to the formation of the Tucuruí reservoir. The authors demonstrate that the quantity emitted in the lake is of the order of 1.1 Tg of carbon per year, highlighting the importance of the carbon inventory in energy systems and the use of less environmental impact resources. Chen et al. [3] show the impact patterns in deforestation and forest degradation due to the construction of the aforementioned hydropower plant. The implementation of such a large infrastructure (the fifth hydropower station in the world) have affected the local biodiversity in addition to the consequences of urban development.

Today, it is important to reduce the environmental and carbon footprint of dam's appliances as the locks of the waterways. Renewable energy sources (RESs) are now considered an important and strategic way of ensuring the sustainability of projects [4,5] and the coupling with energy storage systems contributes in their optimal exploitation in terms of reliability [6,7] operations [7,8] and return of investment [9].

Further investigations on the use of RES combined with energy storage for standing alone system can be found in the literature. Ma et al. [10] study the optimization of the sizing of renewable energy system for electrification of isolated areas without access to the grid, highlighting the importance of storage for the success of the project aiming at continuity and reliability due to the intermittency of the solar source. Malheiro et al. [11] also study energy optimization and programming in stand-alone systems. Evaluating a hybrid system with solar, wind and diesel sources as a backup supply, mathematically analyzes, within a year, the hourly changes in the availability of sources and energy demand. Considering that hybrid energy systems are increasingly used in isolated or energy-deficient areas, Aziz et al. [12] demonstrate that an optimized system is more economical and reliable than a power system with a single source. Ma et al. [13] study the optimization of a hybrid solar-wind system with pumped storage to serve an isolated grid with a capacity of the order of a few hundred kW. Pali and Vadhera [14] propose a new configuration of a hybrid system with wind and hydro sources for rural and isolated areas. Connecting the wind turbines directly to the energy storage, the authors highlight the cost reduction and improvements in simplicity and reliability regardless of the wind power fluctuations. Thus, the application of hybrid systems, even considering the peculiarities of each situation, can be useful in different scenarios of energy needs [5].

Researchers put particular effort into RES solutions connected with pumped hydro energy storage (PHES), which has today the most used technology in terms of capacity worldwide. Kusakana [15] proposes an optimal energy dispatch model by using a combination of solar, wind, diesel sources and PHES in order to meet the variable demand: this modelization tackles the seasonality and the intermittency of RES, which represents a continuous challenge for energy management systems (EMS). EMS of hybrid solutions counts further complexity due to the diversity and variability of diverse sources [4,5,12–14,16,17].

Analyzing the traditional scenario of power generation, Bhattacharjee and Nayak [4] analyze the application of a solar hybrid system with pumped storage searching a viable, continuous and cost-effective solution to the problem of low water availability in power plant reservoirs, demonstrating it as a good option for restoring the reservoir's performance. Xu et al. [17] observe consistent load fluctuations due to the variability of wind and solar sources that, on a large scale, can cause stability and safety threats in the electricity network. Besides, PHES can cause instabilities due to the interaction between shaft vibration and governing strategies during the connection and disconnection of the system [17].

Morabito and Hendrick [18] study a solar, wind and PAT hybrid system connected to a smart grid in a real application. The prototype uses a speed control to guarantee the operation of the machine in the BEP according to the suitable hydrological conditions, what highlights the importance of the study in the field of hybrid systems integrated to the grid.

Another aspect of energy generation from renewable sources is the operational and storage limitations of each source. Ma and Javed [19] present an integrated design of a hybrid system with solar, wind and battery storage considering the saturation limits for each source, based on economic and technical indexes. Javed et al. [20] propose a hybrid system with stored pumping and batteries as an off-grid renewable energy system. The authors use a new operating strategy based on the maximum extraction of energy stored at the point of maximum PAT efficiency, with the battery used only to meet very low levels of load. To evaluate the performance of the system, a general indicator of storage overall performance, energy utilization ratio and storage usage factor is used. In this way, the need to know the limiting characteristics of each source proposed as a solution is highlighted.

Hybrid systems may be viable in other types of power generation. Stenzel and Linssen [21] present an application concept and a new form of pumped storage using federal waterways as a lower reservoir in Germany, identifying a potential of 400 MWh. An energy solution for the transposition system is proposed by Zhang et al. [22]. The authors present a project of potential energy exploration using the head and flow in the operations of filling and draining. The authors demonstrate viable applications that seek maximum utilization of energy availability, even in facilities or places intended for other purposes. The costs involved in the design, installation and maintenance are decisive in the adoption and determine the viability of renewable energy systems. An adequate economic approach to energy systems can be carried out considering the annual cost and the payback of the systems [23,24] or the effective cost using the net present value method [25] including availability, efficiency, installation, operation and maintenance costs.

The varied research and applications of hybrid energy systems show the feasibility of these solutions for energy supply in isolated areas, integrated into the grid, etc. However, the implementation of RES in Locks presents an interesting gap that can be investigated, with very few studies in the literature. For the Brazilian case, there are more than 20 Locks and more than a hundred other dams [26], in which the combination of head and solar radiation is very frequent, thus allowing the use of both sources for energy generation and storage. The results of which can easily be applied to hydroelectric plants and transposition systems worldwide.

In this work, in particular, the study to demonstrate the potential of using these structures with renewable energy systems focuses on performing an analysis of energy alternatives for the operation of the Tucuruí locks considering two possible scenarios: one with pure photovoltaic energy supply and the other one with a hybrid system composed of solar and hydraulic sources, with pumped hydro energy storage. Moreover, the economic feasibility of each alternative and the payback is investigated. The evaluation of the alternatives studied shows that the hybrid system with pumped storage is more economically (around 40%) and technically feasible due, mainly, to the availability of head and the high costs of a purely photovoltaic plant.

This paper is structured as follows: in Section 2 a brief description of the site, location and main characteristics of the hydrological use is presented. Availability to use potential and solar energy is shown. Section 3 contains the work approaches regarding the proposed solutions to meet the energy demand of the facility, the systems designed, the selection of machines and the calculation of PAT performance in pump mode. The methodology for calculating energy costs and payback time for each proposal analyzed is also presented. Section 4 discusses the results of the analysis from the previous section and, finally, the conclusion is presented in Section 5.

2. Characteristics of Tucuruí locks

The Tucuruí hydroelectric plant is the fifth largest in the world and has an installed capacity of 8,535 MW, distributed in 25 hydraulic generating units with 22.5, 350 and 395 MW power capacity. The turbines take advantage of a 61.7 m net head maintained by an earth and rock dam of over 11 km. Its spillway is designed for a maximum flow of 110,000 m^3/s, characterizing it as the world's largest in spillway capacity. This feature allows the possibility of exploitation of the water resource due to the water spill that occurs during some months each year.

The Tucuruí locks, showed in Fig. 1, are installed in an area where the incident solar insolation allows for a utilization of the solar resource at an average cost of 1.8 US$/Wp. The average daily solar irradiance of the selected site is depicted in Fig. 2. In addition, the installation is located in the same existing dam structure and it allows the possibility of take advantage of the head for generation aiming to self-consumption. In this context, Fig. 3 shows the variation of the head over a hydrological cycle.

The head variation is related to the natural seasonality of the Tocantins River and the power generation of the plant. The difference between the effluent and turbined flow rate gradually changes the head, causing it to vary by up to 15 m over a year. As it shares the same upper reservoir, Lock 1 is also subject to variation in the head, although the downstream level, which is independent of the powerplant's lower

Fig. 1. Overview of the Tucuruí hydropower dam and its locks.

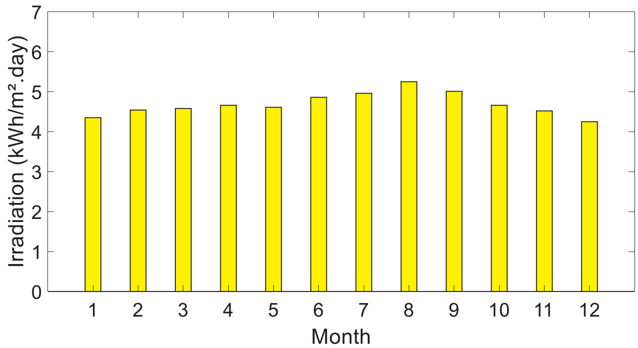

Fig. 2. Average monthly irradiation in the site.

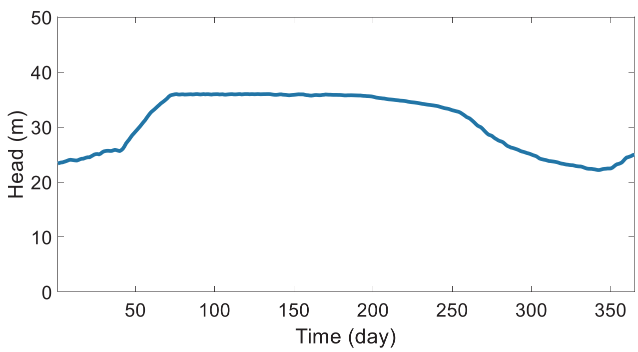

Fig. 3. Head over a year in the site.

reservoir, remains constant.

The transposition system studied is composed of two locks connected by a channel that allows trains maneuvers and crossings in navigation. Each structure is 210 m long, 33 m wide and is designed to operate independently of each other. The filling and draining operations are carried out in approximately 30 min, with capacity to handle up to 19 thousand tons of load, in trains of 200 m length, 32 m wide and 3 m draft [27].

This geographical area benefits from a good sun exposure as demonstrated by Jannuzzi and Melo [28]. Based on the experience of developed countries, the application of photovoltaic systems follows a trend established by the combination of the continuous reduction of the costs of the solar modules with the increase of the tariffs of conventional electric power [29]. The data available for solar irradiation in the Brazilian territory show an enormous potential for renewable energy production, although these values are subject to overestimation [30]. However, European countries, which receive lower solar insolation take advantages of good policies for regulating renewable energy. An analysis of hybrid systems connected to the grid is presented by Martins et al. [31] showing the feasibility and usefulness in the energy planning.

3. Analysis of energy alternatives

3.1. Demand

For the calculation of the demand profile, the following procedure was performed. The total energy consumed in the transposition operations, which includes filling and draining, and the functioning of the control system was measured directly in the energy meters of the Locks in two months. The one of greatest consumption was considered, in which the total energy for operation of the installation E_O was 135,090 kWh. From this, the daily average of 4,503 kWh was calculated. In Eq. (1), the quantity n represents the maximum number of 16 maneuvers per day, established in the design, based on which the energy required for each maneuver was calculated, within the hours of operation of the facility. Each transposition maneuver is carried out in about 30 min, for

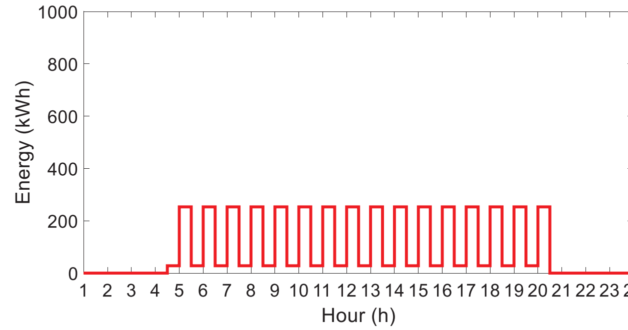

Fig. 4. Facility demand.

that reason, Fig. 4 presents the demand profile with this resolution. Alternatively, therefore, every half hour the energy consumption d_e varies from a maximum value, related to transposition, and a minimum value referring to the general operation of the plant in terms of lighting, administrative services, auxiliary machinery and equipment etc. The adoption of time interval i in Eqs. (1)–(3) establishes the amount of energy being consumed at each moment, between the maximum and minimum values. Thus, the demand at each instant d_e can be written analytically as following.

$$d_e = \left(\frac{E_o}{30n}\right) d_i \tag{1}$$

$$d_i = \begin{cases} 0,\ i < 9 \\ 0.1,\ i = 9,\ 11,\ 13\cdots \\ 0.9,\ i = 10,\ 12,\ 14\cdots \\ 0,\ i > 40 \end{cases} \tag{2}$$

$$0 \le i \le 48 \tag{3}$$

3.2. Photovoltaic-only alternative

The solar power P_{m1} for this alternative was calculated based on Eq. (4), proposed by Pinho and Galdino [32] that takes into account the lowest irradiation in year H_{SP} and energy demand L_A plus reduction factors related to dirt, permanent degradation throughout use, lower manufacturing tolerance, temperature losses and system losses including wiring, controller, diodes etc.

$$P_{m1} = max_{j=1}^{12}\left[L_A/(H_{SP} Red_1 Red_2)\right] \tag{4}$$

The solar irradiation data at the site H_{SP} were obtained from CRESESB [33] and, as shown in Fig. 5, presents in December the lowest average incidence, as considered in the P_m estimate. For the factors Red_1 and Red_2, the values of 0.75 and 0.90, respectively, were considered.

For the designed system the model cs6u-330p photovoltaic module with efficiency of 16.97% and rated power P_p of 330 W, of Canadian manufacture, was selected. Relating this to the solar power P_{m1}, the number of panels N_{PV1} required was calculated. Hourly solar energy, for

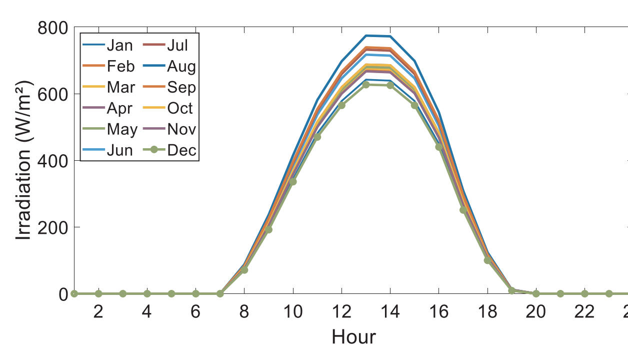

Fig. 5. Average irradiation in the site.

the purely photovoltaic case, E_{s1}, was determined by Eq. (5), which relates the performance characteristics of the photovoltaic module with the received radiation. The methodology proposed by Pinho and Galdino [32] through Eq. (5) presents an estimate for the photovoltaic project.

$$E_{s1} = G_{sol} N_{PV1} A_{PV} \eta_{PV} \eta_{inv} \tag{5}$$

The solar photovoltaic system is the first energy alternative analyzed in order to meet the energy demand for the operation of the Locks. This application would use the grid as storage in form of energy compensation, according to the rules of the National Electric Energy Agency.

3.3. Hybrid system alternative

The hybrid system has been designed with the aim of adding a cheaper solution with shorter return of investment time [34], grid stability [17] and the possibility of rapid corrections in operational quantities to respond to changing demands of the facility and solar incidence on site. A system consisting of a photovoltaic solar source and a hydraulic source using PATs was designed, shown in Fig. 6.

The power supply for the installation can come from different sources. The first option considers a 100% photovoltaic generation. The second form can be supplied directly by the grid, in which energy is generated in a conventional manner, for example, at the adjacent hydroelectric plant, through a Francis turbine. Finally, a hybrid solar-hydraulic form with a percentage of each source in the system. The appropriate choice of this factor, referred as α in Eq. (6), must be carried out through an optimization process that offers the most attractive value in terms of cost and efficiency, in different consumption and generation scenarios, such as example, that performed by Wang and Huang [35,36]. The design of the hybrid system, by font optimization, is not the scope of this work. Calculations testing different percentages were carried out, pointing the value of 50% as more attractive, although refinement is required, which will be the subject of a future work. This factor is proposed with the objective of sizing the hybrid system, considering the period of less solar and head availability. However, the generation of each source to meet the demand must be analyzed considering the specific scenarios at each moment, in view of their variation throughout the year.

The possibility of the pump operating as a turbine associated with a speed regulator guarantees the flexibility needed to meet the above-mentioned variations. PAT has its operational quantities defined by the correlation between solar energy and demand at each moment. This difference, positive or negative, is transferred to the hydraulic machine and defines its pump or turbine mode. In this model the energy, consumed or produced, is determined every half hour, as shown in Fig. 12.

Considering the design criterion $\alpha = 0.5$, which means the percentage that the demand that the photovoltaic system was designed to meet, the solar power, number of modules and hourly solar energy were calculated according to Eqs. (6)–(8). The variation at each instant of solar incidence G_{sol} is shown in Fig. 5.

Table 1
Installation characteristics.

Quantity	Symbol	Value	Unit
Maximum head	$H_{máx}$	36	m
Minimum head	H_{min}	22	m
Time in turbine mode	t_{0t}	7.5	h
Time in pump mode	t_{0b}	9	h
Pump minimum flow rate	Q_{bmin}	700.38	m^3/h
Pump maximum flow rate	$Q_{bmáx}$	1146.1	m^3/h
Number of pumps	N_b	4	–
Maximum flow rate of the facility	$Q_{máx}$	4584.4	m^3/h

$$P_{m2} = \alpha{\bullet}L_A/(H_{SP} Red_1 Red_2) \tag{6}$$

$$N_{PV2} = P_{m2}/P_{PV} \tag{7}$$

$$E_{s2} = G_{sol} N_{PV2} A_{PV} \eta_{PV} \eta_{inv} \tag{8}$$

PAT energy is calculated by the difference between demand and solar production at each instant of time, according to Eq. (9).

$$E_{PAT} = d_{ei} - E_{s2} \tag{9}$$

This difference is the energy that must be generated by PAT, whose magnitude will imply the selection of the machine according to the flow rate given by the Eq. (10), within the compatibility between the maximum $H_{máx}$ and minimum head H_{min} of the system and those established by the manufacturer. With the efficiency considered 0.8 the operational limits of the project were calculated, as shown in Table 1.

$$Q_{PAT} = \frac{E_{PAT}}{\rho g H \eta_t t_{0t}} \tag{10}$$

This operational configuration, however, establishes a lot of number of conversion or implies a large change in speed. Since the facility has a connection to the power distribution company, it is possible use this feature as an intermediate storage source, transferring the energy balance from the hourly basis to the daily basis.

3.4. Use of water resource

To determine the water volume, flow rate and consequently the operating point for selection of suitable machine, Eq. (11), which represents the energy in a hydraulic turbine, was used. For initial purposes an efficiency η_t of 0.8 was considered. Head H is defined by the hydrological condition of the day, and its variation over a hydrological cycle is shown in Fig. 3.

$$E_t = \rho g H Q_t \eta_t t_{0t} \tag{11}$$

Considering that $Q_t = V_t/t_{0t}$, the equation can be rewritten to

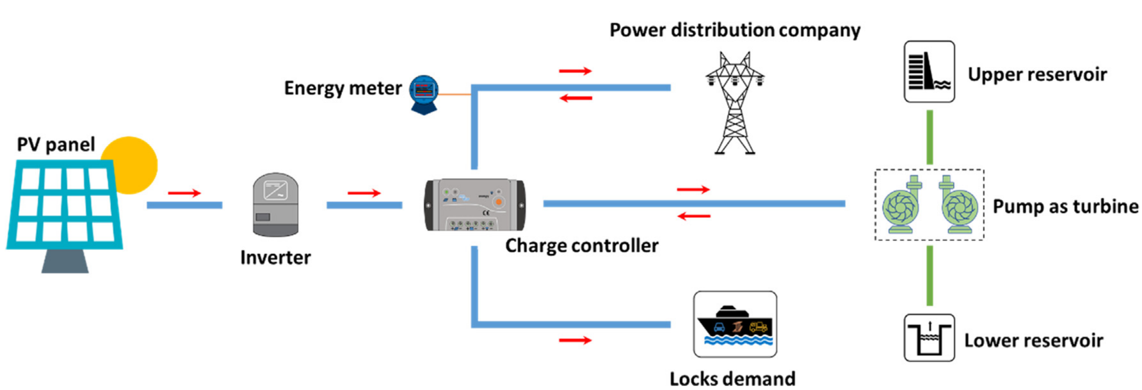

Fig. 6. Schematic arrangement of the proposed hybrid system.

determine the volume of water used in the production of energy E_t, as follows:

$$V_t = E_t/\rho g H \eta_t \tag{12}$$

The use of water resources in the responsible exploitation of the site was an established concept for the installation project, so that in one day of operation, the pumped volume is equal to the turbine, according to Eq. (13).

$$V_t = V_b \tag{13}$$

From the equality relationship between turbine and pumped volumes, the total flow rate in pump mode was calculated considering the operating time in direct mode t_{0b}, as follows:

$$Q_b = \frac{V_b}{t_{0b}} \tag{14}$$

The quantity Q_b is the total flow rate pumped by the energy E_b during an operating day. In this work, in order to research and explore the behavior of PATs operating in parallel, a number N_b of four machines was established for the composition of the operation scheme.

3.5. The selection of the machines

The pump selection process was based, a priori, on the characteristics of the installation, such as head and flow rates, as shown in the previous items. The prediction of the behavior of the pump selected to operate with turbine will be the subject of research and future articles. The proper pump was determined considering the seasonal variations of head due to Tucuruí lake level variation. Thus, two limit curves were calculated for the system, shown in Fig. 9. The minimum and maximum flow rates for the project Q_{bmin} and $Q_{bmáx}$ were calculated according to Eq. (15), for the maximum and minimum heads, respectively.

$$Q_{bmin} = \left.\frac{Q_b}{N_b}\right|_{H_{máx}} \quad \text{and} \quad Q_{bmáx} = \left.\frac{Q_b}{N_b}\right|_{H_{min}} \tag{15}$$

The operating range for a pump was calculated according to Eq. (15), which determine the operating points for commercial selection by crossing the flow rate lines with the system curves. For the case under study, the following characteristics were calculated, shown in Table 1. From the maximum head and minimum flow rate point, a model BMI 250330 1750 rpm pump manufactured by IMBIL was selected.

3.6. The facility

The project consists of a facility for energy use taking advantage of the existing structure of the Locks. The chamber, in its internal structure, has an unused aqueduct for communication between upstream and downstream levels independent of the filling and draining system, which can be utilized for the project. Fig. 7 shows the existing structure and a schematic representation of the planned project.

The system curves were calculated from Bernoulli, Eq. (16), applied between the upstream and downstream levels for loss determination and between the downstream and suction pump levels for calculating the net positive suction head for cavitation checking, both considering the dimensions and characteristics of the hydraulic system such as piping, fittings, head etc., according to Fig. 8, where all points and lines refer to the pipe and pipe fitting.

$$\frac{p_4}{\rho g} + \alpha_4\frac{U_4^2}{2g} + z_4 = \frac{p_1}{\rho g} + \alpha_1\frac{U_1^2}{2g} + z_1 + \frac{h_{lT}}{g} \tag{16}$$

3.7. Variable rotational speed

From the selected pump, the following procedure was performed to calculate the machine operating in variable rotational speed, guaranteed by a dedicated control system. Eq. (17) shows the generic form of the pump and system equations, respectively.

$$H_b = a + bQ + cQ^2 \quad \text{and} \quad H_s = d_s + e_s Q^2 \tag{17}$$

By the similarity law for pump, the quantities rotation N, flow rate Q, head H and power P are related to the form of Eq. (18), in their initial and final conditions. To change the operating point in this pumping system was chosen by shifting the pump curve, to ensure greater efficiency, compared to changing the system curve by inserting pressure losses.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2};\quad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2;\quad \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{18}$$

By combining Eqs. (17) and (18) and the operating point, the following relationship in N_2 can be found as an equation of the second degree as a function of known pump and installation characteristics.

$$\left[\frac{a}{N_1^2}\right]N_2^2 + \left[b\frac{Q_{req}}{N_1}\right]N_2 + \left[Q_{req}^2\left(c - \frac{H_{at} - H_0}{Q_{at}^2}\right) - H_0\right] = 0 \tag{19}$$

$$A = \frac{a}{N_1^2} \tag{20}$$

$$B = b\frac{Q_{req}}{N_1} \tag{21}$$

$$C = Q_{req}^2\left(c - \frac{H_{at} - H_0}{Q_{at}^2}\right) - H_0 \tag{22}$$

Therefore, having the new required flow rate Q_{req}, the new speed rotation can be determined by the solution of Eq. (19). A new pump curve at the new rotation N_2 can also be calculated from Eq. (18). Thus, from the curves of losses, selected pump, similarity law and parallel pump theory, Fig. 9 represents the operational field of the system in

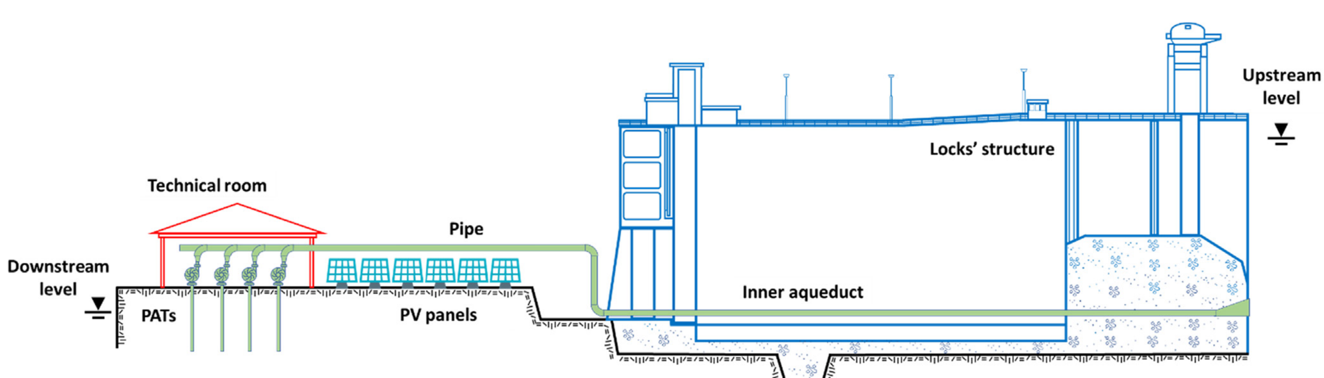

Fig. 7. Schematic representation of the installation.

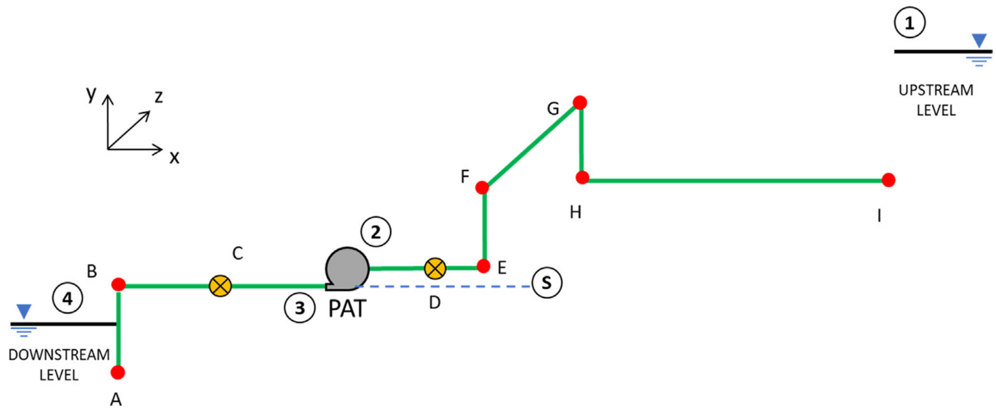

Fig. 8. Hydraulic system diagram for the pipeline.

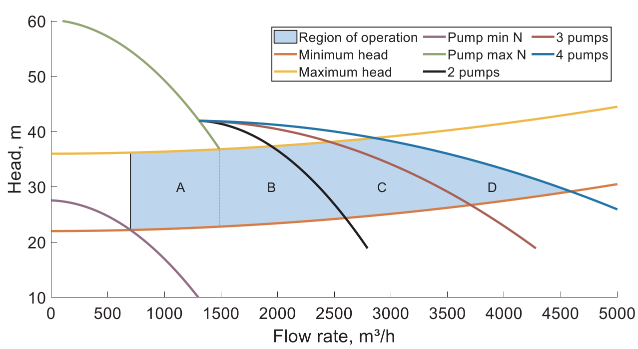

Fig. 9. Pump mode system operation prediction.

pump mode.

In the configuration shown in Fig. 9 it is possible to note that only one machine operating at variable speed associated with the others three operating at fixed rotation guarantees the pumping in the whole flow rate and head range of the installation. This chart highlights four distinct regions that represent the possible operating areas for each set of machines. In region A pumping requirements are met by a single pump operating at variable speed. In the event of increased pumping energy, the facility operates in region B with the start of one more machine at a fixed speed. As the demanded flow increases other fixed speed units come into operation in regions C and D respectively. All cases respect the limits set by the pump manufacturers.

The forecast for operating the system in reverse mode is shown in Fig. 10. Two methodologies were associated to establish the speed limits for PAT and, consequently, the region of operation. Morabito and Hendrick [18] use a statistical/empirical formulation based on subgroups defined by the diameter of the impeller that lead to better match with the experimental values of h and q [34,37]. For the project's impeller diameter of 0.282m, Eqs. (23) and (24) are valid, which depend on the specific speed of the pump N_{Sp}, in Eq. (25), and provide the best efficiency point in turbine mode.

$$h = 5.196 N_{Sp}^{-0.323} \tag{23}$$

$$q = 3.127 N_{Sp}^{-0.219} \tag{24}$$

$$N_{Sp} = N_P \sqrt{Q_P} / (H_P)^{0.75} \tag{25}$$

Rossi et al. [38] present an interesting approach to predict the behavior of a pump operating as a turbine, based on the turbine's BEP. The authors establish a normalized mathematical relationship between the non-dimensional coefficients for pressure, flow rate and efficiency to plot the characteristic curves of PAT. The curves shown in Fig. 10 were calculated by Eqs. (26)–(30). Formulation in which the characteristics of flow rate, head, speed rotation, diameter of impeller, specific speed and efficiency of the selected machine are compatible.

$$\psi/\psi_{BEP_t} = 0.2394R^2 + 0.769R \tag{26}$$

$$\eta/\eta_{BEP_t} = -1.9788R^6 + 9.0636R^5 - 13.148R^4 + 3.8527R^3 + 4.5614R^2 - 1.3769R \tag{27}$$

$$R = \phi/\phi_{BEP_t} \tag{28}$$

$$\phi = Q/(ND^3) \tag{29}$$

$$\psi = gH/(ND)^2 \tag{30}$$

The behavior described is a prediction for the variable speed PAT under three different conditions: the nominal curve and two others that represent the maximum and minimum speeds necessary to guarantee the operation within region A. Although the general theoretical prediction of the operation is shown, detailing the behavior of the machine in turbine mode including its operation in parallel and the influence of efficiency in generation will be topics addressed in a future paper.

3.8. Cost of energy

The energy tariffs in Brazil vary according to Table 2. The calculated costs for the payback evaluation for the studied alternatives, took into account the hourly cost for each solution. These results were projected annually, considering the variations of the tariff for working days and weekends. The tariffs shown in Table 2 represent the values applicable by the local power distribution company and, therefore, differ from other states in the country.

The costs of energy supplied by the grid for one day were calculated from the hourly basis for working days and weekend separately based on Eqs. (31) and (32). *TOE* represents the tariff of energy according to the data in Table 2, which follows the rule of the Brazilian National Electric Energy Agency [39,40]. The cost of energy over time has been

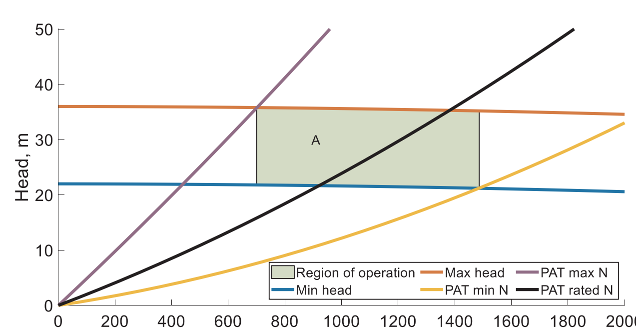

Fig. 10. Turbine mode system operation prediction.

Table 2
Energy tariff in the region (US$/kWh).

Tariff station	Pick time	Intermediary		Off pick time
Hour (h)	18:30 to 21:29	17:30 to 18:29	21:30 to 22:29	22:30 to 17:29
Tariff (working days)	0.34936	0.22415		0.13773
Tariff (weekend)	0.13773			

Exchange ref. 09/29/2019.

calculated by Eqs. (33) and (34), where t is the year.

$$COE_{wd} = \sum d_e TOE_{wd} \tag{31}$$

$$COE_{wk} = \sum d_e TOE_{wk} \tag{32}$$

$$COE_{c_{year}} = 365/7(5COE_{wd} + 2COE_{wk}) \tag{33}$$

$$COE_c = t\bullet COE_{c_{year}} \tag{34}$$

Energy costs for photovoltaic and hybrid alternatives were calculated according to Eqs. (35) and (36), considering capital costs plus operation and maintenance costs. It was adopted the suggestion of Jannuzzi and Melo [28] which considers the O&M costs of these installations to be 1% of the capital cost for photovoltaic systems. For the hybrid case the estimate used was 2%.

$$COE_{PV} = C_{cap_{PV}} + t\bullet C_{O\,\&\,MPV} \tag{35}$$

$$COE_{Hyb} = C_{cap_{Hyb}} + t\bullet C_{O\,\&\,MHyb} \tag{36}$$

In turn, the capital costs for solar and hybrid alternatives was determined based on Eqs. (37) and (38), which consider the cost of availability C_{Av}, under the rules of the Brazilian energy regulator, regarding the use of transmission system and the financial estimate for implementation of photovoltaic systems in Brazil C_{PV} of $1.8US\$/W_p$. For the hybrid case, the cost of acquiring the equipment C_{Aq} was added to these.

$$C_{cap_{PV}} = C_{Av} + C_{PV} P_{m1} \tag{37}$$

$$C_{cap_{Hyb}} = C_{Aq} + C_{Av} + C_{PV} P_{m2} \tag{38}$$

In comparison to the purely photovoltaic system, the hybrid system design incorporates hydraulic components such as the centrifugal pump, piping and accessories in the cost composition, in addition to the driver and supervision equipment. Research in the Brazilian market to prepare the project budget showed that the rate between the cost of purchasing hydraulic equipment and the total cost of the hybrid system $C_{Aq}/C_{cap_{Hyb}}$ is in the order of about 26%, although it may vary by be based on commercial estimates.

3.9. Payback time

To determine the payback time for each alternative, Eqs. (34) and (37) were combined for the photovoltaic-only case and Eqs. (34) and (38) for the hybrid case, as follows.

$$t_{PV} = C_{cap_{PV}}/(COE_{c_{year}} - C_{O\,\&\,MPV}) \tag{39}$$

$$t_{Hyb} = C_{cap_{Hyb}}/(COE_{c_{year}} - C_{O\,\&\,MHyb}) \tag{40}$$

4. Results and discussion

4.1. Photovoltaic-only alternative

For the purely photovoltaic system, the power of 1,569 kW is obtained by the 4,757 photovoltaic modules, occupying an area of 9,249 m^2. Fig. 11 shows the comparison between hourly demand and photovoltaic production. The solar energy shown was calculated according to Eq. (5). The graph, with sunshine data for the critical month (December), shows that solar production meets the demand for operation, guaranteeing in the daily balance a surplus stored in the grid of about 1,500 kWh.

4.2. Hybrid system alternative

Fig. 12 presents the energy production by the installed photovoltaic arrays and by the PAT. In this system, the use of factor α causes a reduction in the same proportion of occupied area, installed power and number of panels, in relation to the purely photovoltaic alternative. In this arrangement, the PAT guarantees the necessary complement for supplying the energy for operation, taking into account the balance at each moment, according to Eq. (9). It is observed that the negative energy values represent energy consumed by the pump for storing the energy. This chart represents a case among the possible combinations of solar irradiation and demand. Therefore, in this hybrid system, the variation of the operating point in the pump to ensure energy supply is ensured by a dedicated speed control system, the object of research and detail in future articles.

4.3. Operation scheme

From the analysis of Fig. 12 it can be observed that the mode of operation of the PAT depends on the balance between demand and photovoltaic production at each moment. Thus, due to the intermittent variation of the demand, it would be necessary to have a high number of conversions in the machines, besides operation in different conditions of power, rotation etc. To prevent the problems arising from this type of operation in mechanical and electrical equipment, the use of the grid as an intermediate means of energy storage is proposed, taking into account the energy tariffs presented in Table 2. Thus, it is possible to establish a new continuous and economical scheme for pump mode operation and only one conversion to turbine mode, as shown in Fig. 13. In this case, while the intermittent consumption of the plant is supplied by the grid, the charge controller manages consumption and production at PAT to ensure at the end of the day the balance in demand, generation and consumption.

4.4. Use of water resource

The hybrid system, proposed for installation in the Tucuruí Locks, is designed to take advantage of renewable energy, without interfering with the local hydrological dynamics, in order to maintain constant amounts of turbine and pumped water. In this sense, Fig. 14 shows the use of water in each mode of operation. It is possible to note that the cumulative volume of pumped water is turbined in the sequence, after conversion to the reverse mode. The different slopes in the volume curves reflect the operation at different flow rates, so as to ensure the equality established by Eq. (13). Based on the operation scheme shown

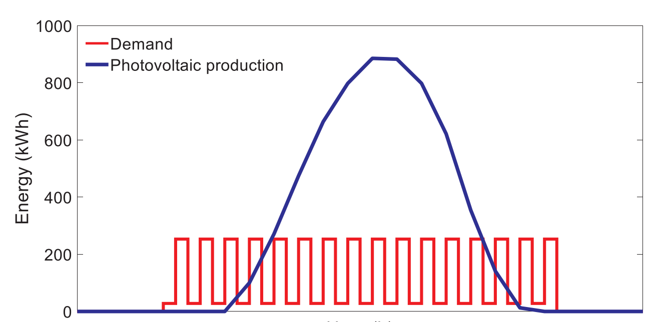

Fig. 11. Hourly demand and photovoltaic production (N_{PV1} = 4757).

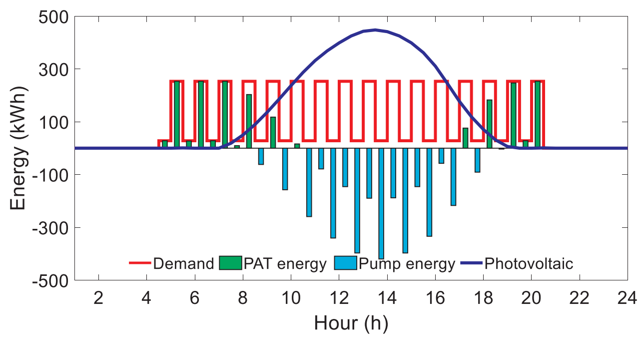

Fig. 12. Power production in the hybrid system (N_{PV2} = 2378).

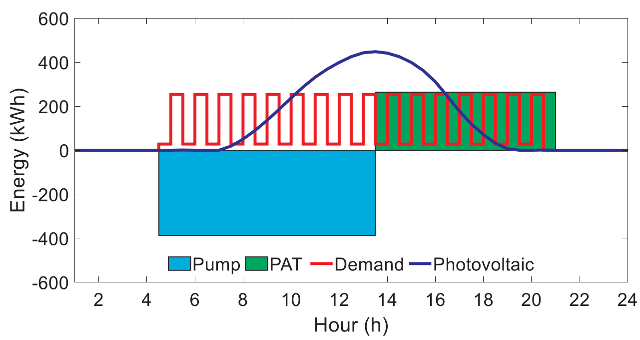

Fig. 13. Hybrid system operation scheme.

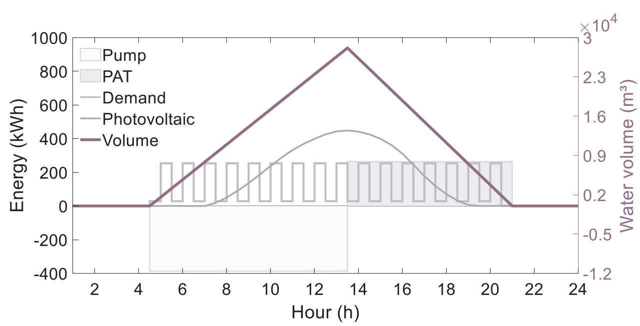

Fig. 14. Use of water in hybrid generation process.

in Fig. 13, volumes were calculated as a linear function of PAT operating time.

4.5. Energy payback time

Fig. 15 shows the comparison between the proposed solutions and the conventional case, without own generation. The curves were calculated according to Eqs. (35) and (36). It should be noted that among the alternatives the hybrid system presents better payback (6.8 years) compared to the pure photovoltaic system (11.2 years).

Photovoltaic energy solutions are widely explored in the literature, applied in several cases aiming at autonomy, respect for the environment, laws and economic viability. The payback time is one of the aspects addressed to assess the viability of a project. These values vary with the specifics of each project. In systems where photovoltaic technology is present, paybacks of 2.3 [41], 4.1 [42], 4.9 [43], 6 [44], 7.4 [45] and 9.6 years [46] are reported, noting that among several photovoltaic technologies the expected payback values are less than 10 years [46].

An additional consideration about the time to return on investment refers to the influence of the powerplant adjacent to the facility. During humid period, typically from February to May the dam spillway operates continuously.

Considering that during this season there is no need for pumping, the amount of energy consumed in the pump mode (Fig. 13) is discounted from the demand for calculation of the hybrid system, Eq. (6), resulting in a reduction in the quantities P_{m2}, N_{PV2} and E_{s2}, consequently decreasing the return on investment time shown in Eq. (40).

In this way, the humid period allows the hybrid installation a constant operation in turbine mode without the need for storage. This feature causes an important reduction in payback to 5.2 years, as can be seen in Fig. 16.

4.6. Scenarios analysis

By way of example, Fig. 17 shows a history of spillway operation over 5 years to show the variability of the operation. Its operation depends on hydrological factors subject to natural variations. In this way, in different years, the equipment can operate for up to four consecutive months or until it does not go into operation, as in 2016. Considering this aspect, Fig. 18 shows the influence of this spillway, installed in the dam adjacent to the project, with which the upper reservoir is divided, in the payback time of the proposed project. This figure describes the return on investment according to the behavior of the equipment under the following conditions: without going into operation, operating for only one month and 2 to 4 months of opening over a year. It is noted, therefore, that in the absence of storage, the proposed system presents a faster return to the investor.

The use of renewable sources in energy generation systems has the characteristic of variability that needs to be considered in different scenarios in order to make better use of the resource. Wang and Huang [35] demonstrate the importance of cooperative energy planning between different sources and their impact on total generation costs, in addition to an optimization proposal to minimize investment costs [36]. In this sense, Fig. 19 exemplifies the average daily variation in different months of irradiation at the project's site and the head profile, configuring different availability conditions.

A general overview of the system's expected production is described in Fig. 20. The graph shows the capabilities of the hybrid system in the design condition. Being sizing based on the month with the lowest irradiation and head (December), it presents additional storage capacity for the months with greater solar availability.

5. Conclusions

The installed global capacity of renewable energy grows steadily every year, and more environmentally friendly and cost-effective facilities are designed according to the specificity of the site [17,18,20].

The project for energy solution of the Lock operations studied by Zhang et al. [22] proposes the use of a hydraulic turbine with variable rotational speed for the exploitation of the fluctuating flow rate and available head. This work, in turn, explores other designing key-factors crucial for analyzing the energy options offered by solar and hydraulic

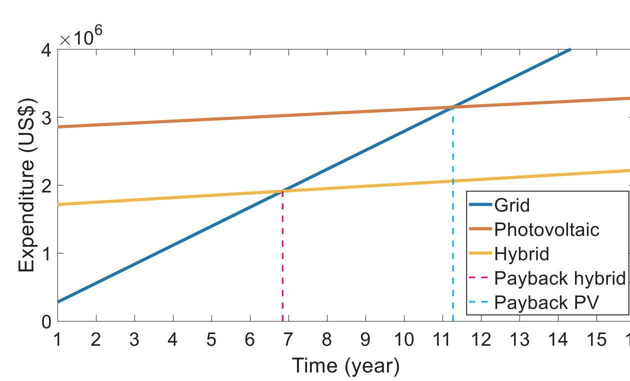

Fig. 15. Comparison of energy alternatives payback.

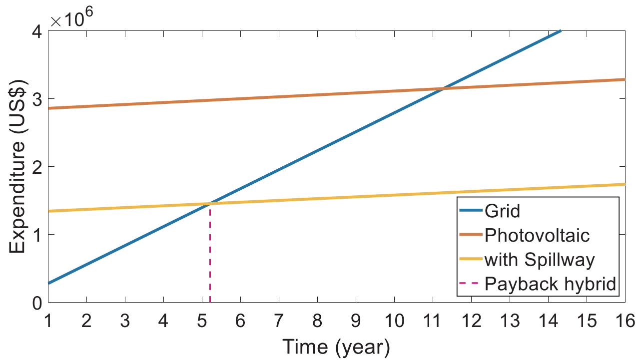

Fig. 16. Payback time considering humid period.

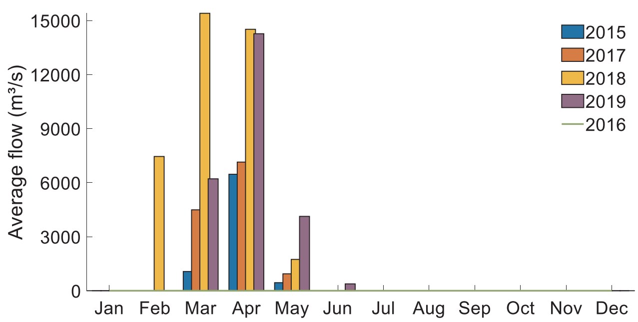

Fig. 17. Spillway operation history.

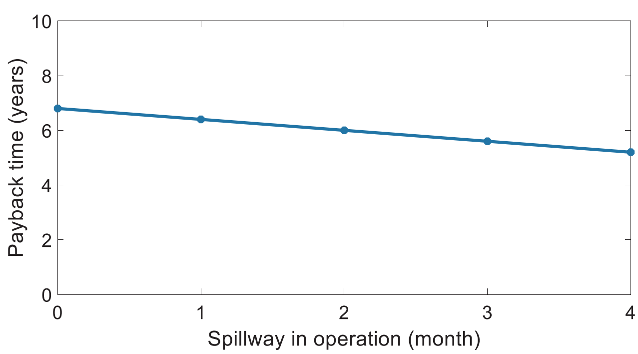

Fig. 18. Influence of adjacent spillway operation on project's payback.

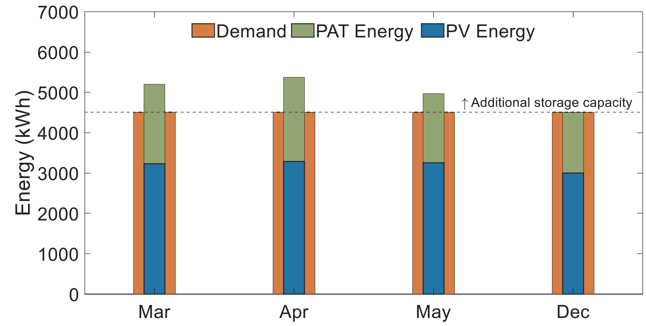

Fig. 20. Energy capacity of the hybrid system in different months.

sources. This paper provides the much-sought information regarding a hybrid energy source system to be implemented to waterways locks and dams, promoting the growing debate in energy sustainability.

The alternatives studied in this paper are presented as viable solutions at the installation at Tucuruí Locks. This work, with the objective of comparing different renewable energy sources, showed that the hybrid solar-hydraulic system with pumped storage is more economically and technically feasible for this case study.

In the specificity of this project, the grid is used as an intermediate storage and it allows the system to operate with a single pump/pump as turbine conversion, preventing excessive number of starts and stops, faults, defects and, consequently, maintenance. In this way, the balance is passed at the end of the day of operation.

The presence of the existing structures for hydrological exploitation and the high costs for a stand-alone photovoltaic installation provide the opportunity of a pumped storage application for a more efficient and cheaper energy source installation. In addition to the lower initial investment for this scenario, the energy expenditure for the hybrid system proposed compared to the utility's supply costs leads to a shorter payback time (around -40%) because of the available head and the high costs of a pure photovoltaic plant.

Another advantage also depicted by Xu et al. [17] is that the pumped storage integrated with solar source allows to a better absorption of fluctuations due to photovoltaic variability, favoring the optimal use of the sources.

Regarding a conscientious use of the water resource, the option of a hybrid system guarantees a responsible use of the installation in respect of the environment by manipulating the water for energy use without additional impact on the existing hydrological dynamics.

As shown, the operation of the spillway causes an important influence on the facility outcomes, within regards to economic and operational aspects. In the future work, this approach will be carried out

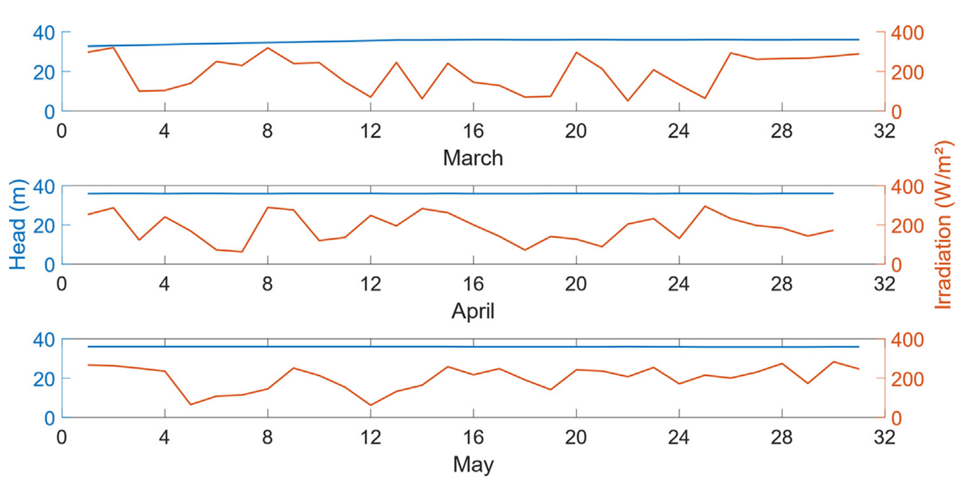

Fig. 19. Scenarios of solar availability and head for different months of the year.

based on a statistical analysis of the historical series of the spillway's opening for further investigation in the energy solution of waterways locks.

Finally, the potential of using Locks for energy generation and storage was demonstrated, when associated with the use of renewable solar and hydraulic sources, as an innovative opportunity taking advantage of the head and the solar availability, improving the financial return on meeting the energy demand for operation through an economically advantageous and environmentally responsible system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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