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SPILLWAY OPERATION EFFECTS ON THE FEASIBILITY OF A HYBRID SOLAR PUMPED STORAGE SYSTEM FOR SUPPLYING ENERGY TO A LOCK

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Abstract. Hybrid systems have been proposed around the world as alternatives to solve energy questions. The increasing insertion of renewable sources, especially photovoltaic, in the generation matrices due to the advantages such as solar availability, continuous reduction of investment costs and increasingly attractive return on investment, also brings restrictions of use, such as the issue of variability and storage to ensure energy delivery with the desirable characteristics. The objective of this work is to demonstrate, in a hybrid system proposed to meet the energy demand of a lock, its feasibility by associating solar source with pumped storage, in addition to the reduction in payback caused by the presence of the adjacent spillway with which the system shares the same upper reservoir. The system, solar with pumped storage and hydraulic generation through PATs, is designed to operate in accordance with the rules of the Brazilian electricity sector, providing for operation as pump and turbine at the lowest and highest tariff times, respectively, besides optimizing operating time, installed power, energy cost and volume of water used, in addition to payback. The main result highlighted is related to the advantages of the use of pumps and PATs associated with the photovoltaic source in the absorption of oscillations, in financial terms, considering the period of up to five months of opening of the spillway, in which for the system, there is no need of storage there is a reduction in the capital cost of the project, favoring the consequent reduction in the payback from 3.7 years to approximately 2.3 years, which makes the system even more attractive and demonstrating its feasibility. The analysis of the spillway influence in a project applied in locks can be an interesting approach to assist in the decision making regarding the adoption of a renewable energy project, in view of the important implications for the company that operates the installation.

Keywords: Renewable hybrid system, pumped storage, pump as turbine, payback, spillway

1. INTRODUCTION

Sustainable energy systems play a key role in harmonizing world development in environmental and economic terms. Although the world has seen rapid growth in this regard, particularly in recent decades, with penetration levels of renewable energy sources reaching double-digit percentages of electricity supply in many nations, many other countries and other sectors such as transport are still in an incipient level in terms of renewable energy use (Østergaard et al., 2020).

The mitigation of climate change is one of the greatest challenges of modern society and is closely linked to the question of the future of energy systems. Among the most important are those that can increase energy efficiency and the use of renewable energies (Potrč et al., 2021), whereas, although the use of traditional fossil fuels leads to economic growth, the excessive use of non-renewable resources emits a large amount of CO₂ into the environment, contributing to the increase in the greenhouse effect (Shahbaz et al., 2020).

Due to its intermittent characteristic, renewable energies present incompatibility with the requested demand, leading to difficulties in supply. Therefore, the integration of energy sources must consider, among other factors, the question of complementarity through hybrid systems and the implementation of forms of energy storage (Jurasz et al., 2020).

In the case studied in this paper, 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. (Andrade Furtado et al., 2020) The locks are facilities associated with the construction of hydroelectric plants and, therefore, divide the results between the benefits and impacts caused by

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

The objective of this work is to demonstrate, in a hybrid system proposed to meet the energy demand of a lock, its feasibility by associating solar source with pumped storage, in addition to the reduction in payback caused by the presence of the adjacent spillway with which the system shares the same upper reservoir.

From an optimized hybrid system, composed of a solar source with pumped storage, proposed to meet the energy requirements of operation of the Tucuruí Locks, the energy costs for different proposals are evaluated. Three solutions and their respective energy costs are presented. The first refers to the supply of energy by the local concessionaire, that is, without any Renewable Energy System (RES) used. The second is the proposal of an optimized purely photovoltaic system and, finally, the costs using the proposed hybrid system are presented.

In this last proposition, there is an evaluation of the spillway influence on the payback time, since with the plant's spillway open, there is no need to operate the system in pump mode, for storage. This is addressed in the form of a reduction in the need for solar production, as the system operates continuously in turbine mode, reducing capital cost.

In this way, a significant improvement is observed in the results regarding the payback of the hybrid system, which reduces from 3.7 to 2.3 years, depending on the operation time of the spillway, which historically operated in some years for five months, while in another, opening did not take place.

The analysis of the spillway influence in a project applied in locks can be an interesting approach to assist in the decision making regarding the adoption of a renewable energy project, in view of the important implications for the company that operates the installation.

The results achieved can be used for feasibility studies in other existing locks in Brazil, which total approximately one hundred throughout the Brazilian territory, with transposition systems of this nature. These projects, together, can represent blocks of energy inserted in the electrical system and can be redirected to other investments and applications.

2. CASE STUDY

Waterways are the most efficient means of transport, with the infrastructure free from congestion problems. In addition, waterways can also be built with pumped storage plants as a means of storing energy from renewable sources (Andrade Furtado et al., 2020). In the context of the opportunity to explore lock waterways for energy generation and storage, this work details the approach taken in the design of a solar energy system with pumped storage applied to the Tucuruí transposition system (Figure 1).

An energy generation and storage system that couples photovoltaic generation with a pump operating as a turbine (PAT) is proposed in order to take advantage of the existing head in the Lock and the solar availability on site (Figure 2). The studied lock, because it is connected to the hydroelectric plant, shares the same upper reservoir and, therefore, in a pumped storage system, the spillway influences the operation and feasibility of the project.



Figure 1. Overview of the Tucuruí site (a) and locks (b) (DNIT, 2018)

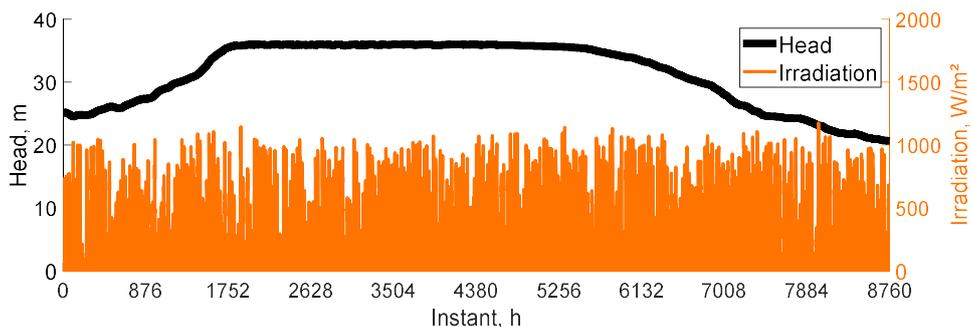


Figure 2. Available head and solar irradiation on site

2.1 The designed hybrid system

The designed project is schematically shown in Figure 3. It consists of a solar source with storage pumped by PATs. The hybrid system takes advantages of the existing head in the lock structure itself, which has the possibility of interconnecting the upstream reservoir with the lower one, allowing the PAT to operate in turbine or pump mode. The system's solar source consists of 1,632 panels with a rated power of 538 kW and the hydraulic component of 1 pump with a nominal power of 110 kW. The system is interconnected to the local distribution grid, which allows operation within the rules of the Brazilian electricity sector, using the grid as a store of energy in terms of credit and debit, according to the tariff posts. A charge controller is inserted to manage the generated/consumed energy to inject it into the grid or send it to the facility's system to meet the operation energy demand or turn on the PAT in direct mode in the pump storage function.

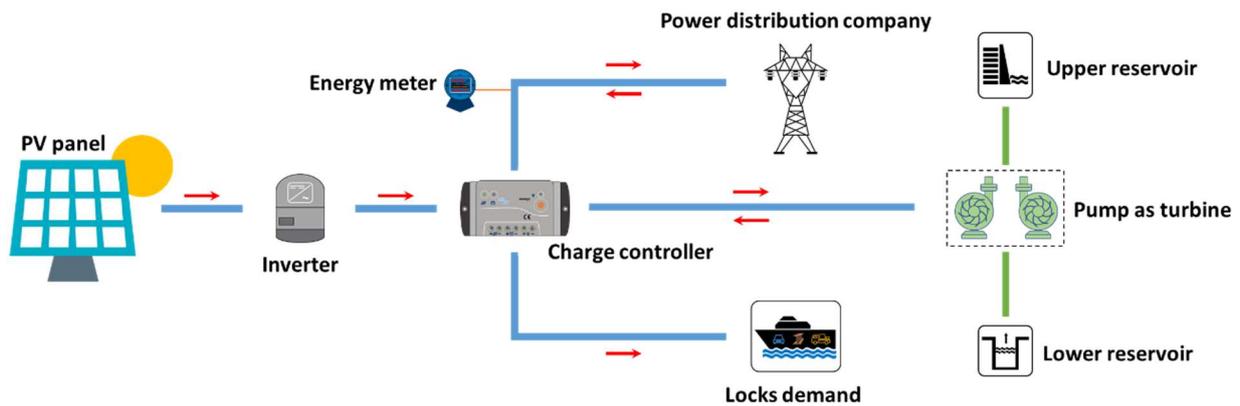


Figure 3. Schematic arrangement of the proposed hybrid system.

In this way, the system is able to direct the generated/consumed energy according to the best condition in order to optimize energy costs. Figure 4 shows the system configuration in the optimal condition, describing the operating time in turbine mode (green), in pump mode (blue) and the energy stored in the grid in the form of credit (red), using the Brazilian distributed energy generation regulation. This energy balance originates from the difference between the solar energy produced in the panels and the instantaneous demand. The staggered demand profile is given by the energy used in each vessel transposition operation during a day.

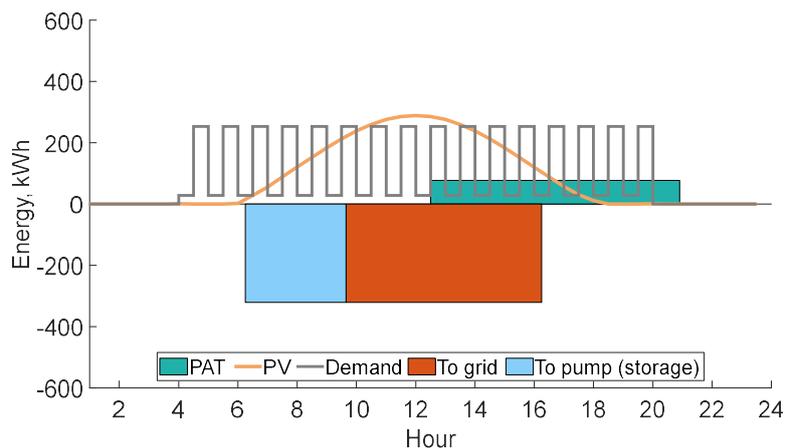


Figure 4. Configuration of energy production of the hybrid system.

This balance of energy costs in the system is detailed in Figure 5a, whose purchase and sale costs are also shown cumulatively over a typical day of operation. From Figure 4, the energy for pump mode operation comes from the purchase from the grid (debit), which is why the cost line increases until the moment the energy starts to be sold to the grid (credit). Within the energy balance at each moment, therefore, the cost line varies, increasing and decreasing, until reaching zero, evidencing that there are no financial losses for the projected system, since, according to the rules of the electricity sector in Brazil, these costs are not effectively addressed financially.

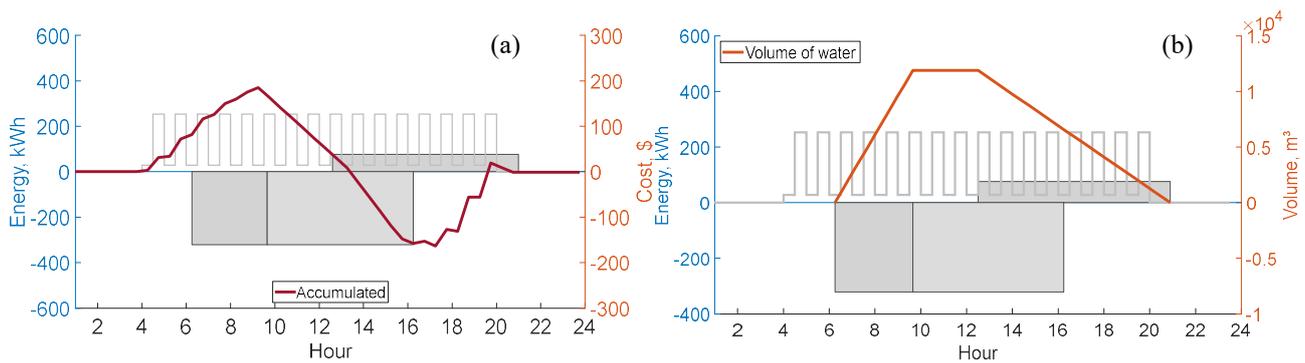


Figure 5. Balance of purchase and sale cost with the system (a) and water use (b).

Figure 5b presents the water balance between the two reservoirs. The null net value of the water balance was established as a design criterion. Thus, the volume of water used for pumping must be equal to the volume turbined at the end of the day of operation. This criterion, in the designed model, considers regulatory aspects of water use and aims at minimum impacts, since there is no interference in the local hydrological cycle. For this system, the operating dynamics requires a volume of 11,520 m³ for its operation. Even if for the case studied, due to their characteristics, the upper and lower reservoirs can be considered of infinite volume. For other applications, this criterion can be used to size the reservoirs or even evaluate the daily impacts on the level variation.

2.2 Spillway of the Tucuruí Hydropower Plant

The project at its installation site has the characteristic of being directly connected to the adjacent hydroelectric plant and, therefore, to its spillway. The Tucuruí Hydropower Plant spillway has a nominal capacity of 110,000 m³/s, used to control the reservoir level and plan the plant's energy production. As they are usually found, to guarantee the navigability of the waterway, which is interrupted with the construction of the dam, the Locks share the same upper reservoir, and in some cases even the lower one. The spillway overview is shown in Figure 6.



Figure 6. Spillway of the Tucuruí hydroelectric plant.

Its operation is based on the flow of water inflowing to the plant. Aiming to control the water level upstream, in the periods of greater affluence, which happens in the Amazon region, in the first semester of each year, the operation of the spillway begins. Its operation, therefore, varies according to the need to drain the water that reaches the dam.

Figure 7 shows a history of 7 years of operation in which it is possible to notice that the adjusted flow in the spillway varies each year, in direct relation to the rainfall along the Tocantins River. It is possible to note that the hydroelectric plant operated with the spillway open over these years with operating times of 4 (2015, 2017, 2020, 2021), 5 months (2018, 2019), in addition to a year in which the spillway did not operate (2016).

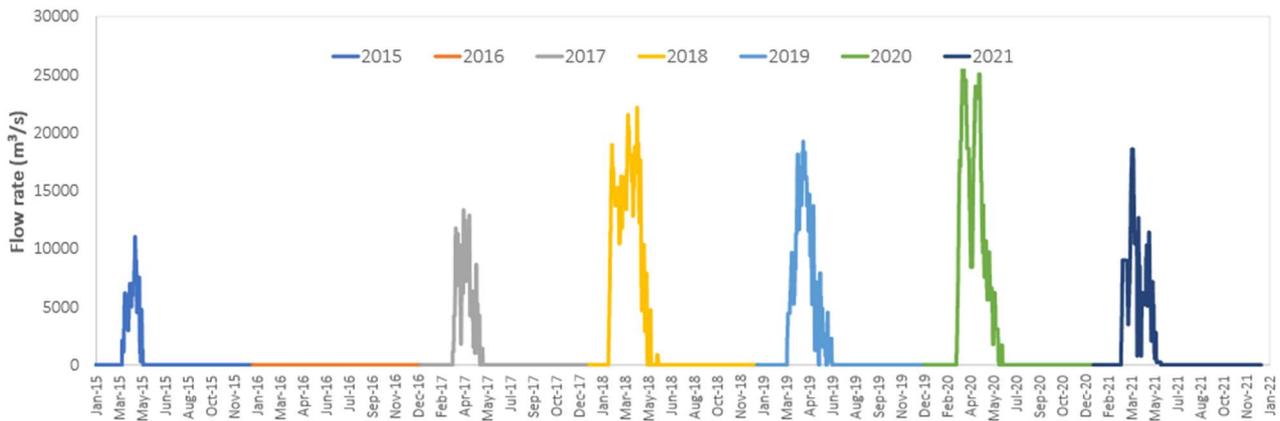


Figure 7. Spillway operation history.

In this way, because this spillway operation affects the storage function of the designed hybrid system, since there is no need for pumping when the spillway is open, its influence analyzed in the time of return on investment (payback). The design of the analysis consists of considering that during its opening, the PAT operates continuously in turbine mode. Thus, this equivalent amount of energy is discounted from the photovoltaic energy, thus affecting the capital cost.

3. RESULTS

Figure 8 shows the comparison between the return times considering different solutions for the supply of energy for the operation of the Locks. The blue line shows the electricity costs in case no renewable energy system (RES) is used, which is equivalent to supply by the local concessionaire. The red line is the costs using a purely photovoltaic system. The yellow line refers to the proposed hybrid system and, finally, the purple line also represents the costs of the hybrid system, however, considering that the plant's spillway operates during the average time of four months during a year. For each case, the payback refers to the time in which the cost lines cross the line for referenced to without RES, which characterizes that at this point the expenses are equivalent. Each proposal presented has a higher financial expenditure, at the beginning, which is related to the capital cost. For a purely photovoltaic system the payback time is 4.8 years. Using the hybrid system this time reduces to 3.7 years. Still considering the operational influence of the spillway, this time can be improved reaching the value of 2.3 years.

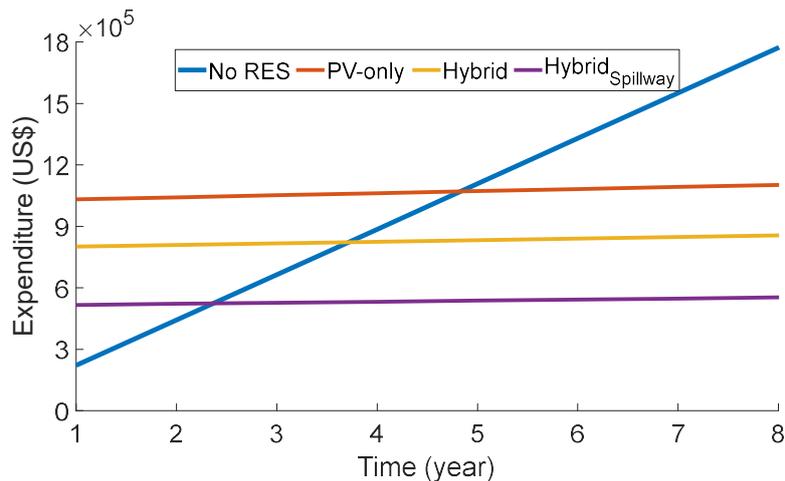


Figure 8. Payback for the alternatives.

Considering that the operating conditions of the spillway over the years, in terms of flow and opening time, are dependent on meteorological conditions, Figure 9 shows, within the range presented in the historical series, as the time, in months of operation, is affect project payback. Therefore, with the implementation of the project, if the spillway operated for five months or even closed, the payback of the project would be within the range of 3.71 to 2.36 years. This is a very interesting results when compared to other energy projects available in the literature, that point to a payback of 8 (Rodrigues et al., 2020), 12 to 14.7 (Tahani et al., 2015), 5.73 to 13.29 (Awan et al., 2019), 6.49 to 11.23 (Jung et al., 2019), 8.1 to 12.5 (Simão & Ramos, 2020) and in the range of 0.4 to 3.2 years (Mousavi et al., 2020).

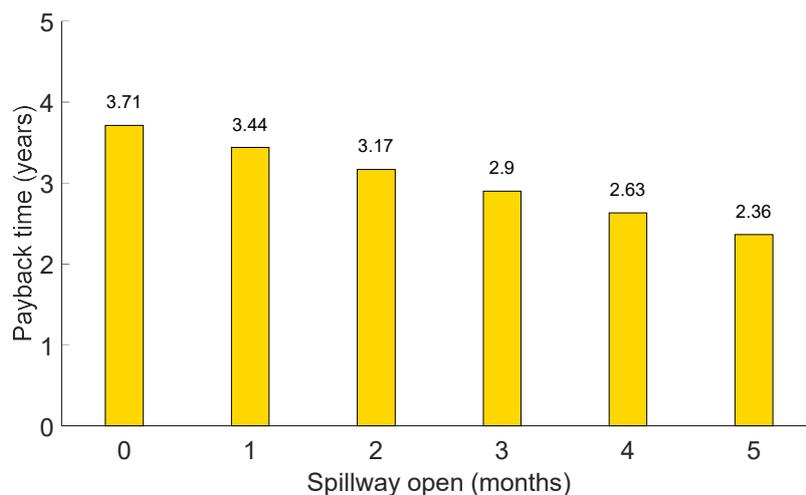


Figure 9. Influence of spillway operation on payback time for the project.

4. CONCLUSIONS

The use of the solar and hydraulic availability of the site was studied as a good opportunity for this project, considering the costs of electric energy for operation, the existence of ready civil structures and low need for investment for adaptations.

Renewable energy systems are directly linked to storage technologies and, based on the case studied, the pumped storage proposal presents excellent prospects for use, mainly due to the hydraulic participation in the Brazilian and world energy matrix. However, the topic is still the subject of discussions, requiring regulation and regulatory incentives for its dissemination, which can positively impact the availability of energy and the Brazilian interconnected system.

The results achieved can be used for feasibility studies in other existing locks in Brazil, which total approximately one hundred throughout the Brazilian territory, with transposition systems of this nature. These projects, together, can represent blocks of energy inserted in the electrical system and can be redirected to other investments and applications.

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. 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.

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