International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0932

ENERGY ALTERNATIVES FOR THE OPERATION OF TUCURUÍ LOCKS

Gilton Carlos de A. Furtado[1], André Luiz A. Mesquita[2], Alessandro Morabito[3], Patrick Hendrick[4]

1 Postgraduate Program in Natural Resources Eng. of the Amazon, UFPA, Brazil. giltoncar@gmail.com (Corresponding Author)
2 Amazon Development Center in Engineering, UFPA, Brazil. andream@ufpa.br
3 Aero-Thermo-Mechanics Dept., Université Libre de Bruxelles (ULB), Brussels, Belgium. alessandro.morabito@ulb.ac.be
4 Aero-Thermo-Mechanics Dept., Université Libre de Bruxelles (ULB), Brussels, Belgium. patrick.hendrick@ulb.ac.be

ABSTRACT

The objective of this work is to analyze two different solutions to the energy demand of the Tucuruí Locks. A photovoltaic power station is compared to a hybrid power generation system composed by photovoltaic and small hydraulic turbine, with pumped storage. The alternatives are discussed technically and economically: the annual energy costs of the scenarios are calculated based on the evolution of the expenses and the related energy payback time are found. The water resource is exploited responsibly, keeping balanced the volume of water in pumping and generating mode. The grid works as an intermediate storage and allows the operations with a single Pump As Turbine (PAT). The installation site is adjacent to the boat-lift structure of the Tucuruí dam. Its specific location lowers down the initial investment in favor of the hybrid system as the more viable alternative to the considered conditions.

Keywords: Hybrid system, Tucuruí Locks, Photovoltaic energy, Pump As Turbine (PAT), Renewable Energy Sources (RES).

NONMENCLATURE

Symbols	
E_h	Hydraulic energy (kWh)
ρ	Specific mass (kg/m³)
g	Gravity (m/s²)
H	Net head (m)
Q	Flow rate (m³/s)
η_t	Turbine efficiency
t_o	Time of operation (h)

1. INTRODUCTION

The Tucuruí locks were designed to ensure navigation on the Tocantins river. In its design concept, electric power must be supplied by the local power distribution company in accordance with the rules of quality, availability and prices established for the Brazilian electricity sector. Thus, the operational cost is directly affected by the electric energy consumed to drive motors, hydraulic pumps, solenoid valves, drainage system, control panels, monitoring centers etc.

Renewable energy is now considered an important and strategic way of ensuring the sustainability of projects and contributing to the balance of CO_2 emissions in the world. The use of different renewable energy sources with some storage systems strategies is object of study and available in the literature. For example, an optimal energy dispatch model is proposed by [1] using a combination of solar, wind and diesel sources with pumped storage to meet the variable demand, taking into account the seasonality and intermittency of natural sources.

Renewable energy systems integrated to power systems is studied by [2], who observes that due to variability of wind and solar sources, large scale systems can cause stability and safety threats in the grid and, in addition, pumped storage systems can cause instabilities due to interaction between shaft vibration and governing strategies, during the connection and disconnection of the system. A model that considers these hydraulic forces is proposed showing the feasibility of adopting a pumped storage system to a hybrid system under steady and fault scenarios.

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

An energy solution for locks is proposed by [3]. The authors present a project of potential energy exploration using the head and flow in the operations of filling and draining. Here, a mathematical model is applied to simulate the energy flow in the grid during the system operation regimes.

The motivation of this study is related to the operational energy needs of the locks with the opportunity to take advantage of available renewable natural sources, with direct effects on the company's financial economy.

This paper has the objective of 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 investment in each alternative and the payback is further investigated.

The evaluation of the alternatives studied shows that the hybrid system with pumped storage is more economically and technically feasible due, mainly, to the availability of head and the high costs of a purely photovoltaic plant.

2. CHARACTERISTICS OF TUCURUÍ LOCKS

The Tucuruí locks, showed in Fig 1, are installed in an area whose incident insolation allows potential utilization of the solar resource. 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, Figure 3 shows the variation of the head over a hydrological cycle.

Fig 1 Overview in the Tucuruí facilities.

The transposition system studied is composed of two locks connected by a channel that allows trains maneuvers and crossings in navigation. Each structure is 210m long, 33m wide and is designed to operate independently of each other. The filling and draining operations are carried out in approximately 30 minutes,

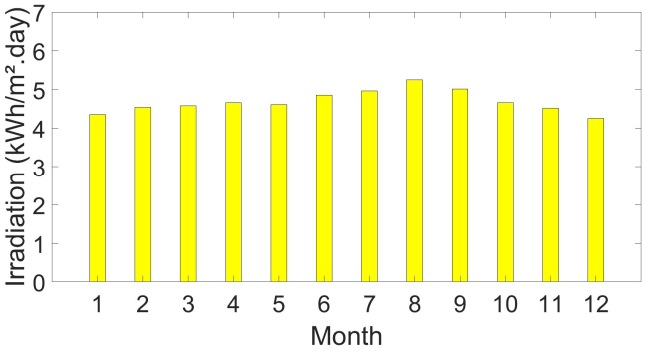

Fig 2 Solar irradiance on site.

with capacity to handle up to 19 thousand tons of load, in trains of 200m length, 32m wide and 3m draft [4].

This geographical area benefits from a good sun exposure as demonstrated by [5]. 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 [6].

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 [7]. 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 [8] showing the feasibility and usefulness in the energy planning.

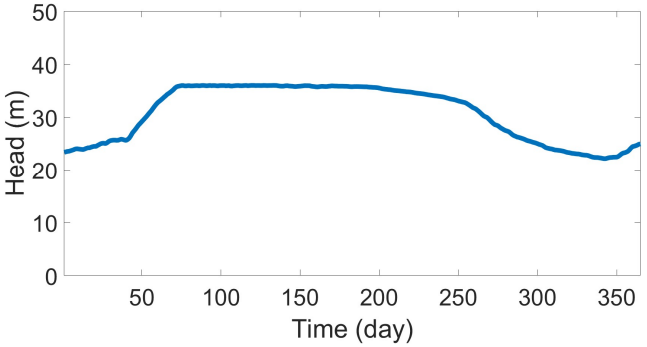

Fig 3 Variation of head on site.

3. ANALYSIS OF ENERGY ALTERNATIVES

3.1 Photovoltaic system

The site selected for the photovoltaic power station is located on the side of Lock 1. The total area estimated for installation is 8082m², considering 3929 Canadian photovoltaic modules, model cs6u-330p, with efficiency of 16.97% and nominal maximum power of 330W. The

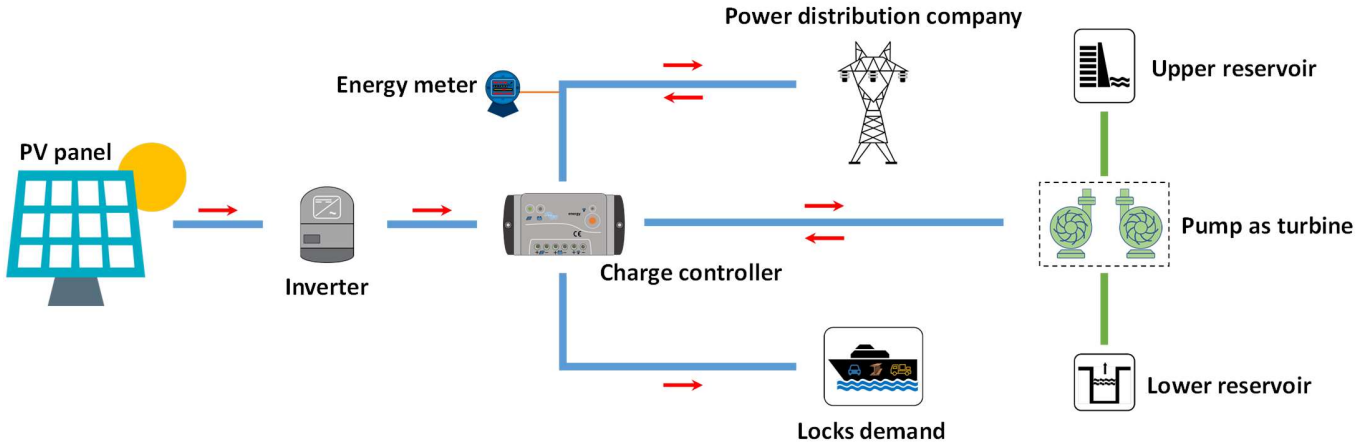

Fig 4 Schematic arrangement of the hybrid system proposed.

installed solar power of 1296.7 kW was calculated using the minimum irradiance method as the design criterion, according to [9]. The hourly demand presented as a reference is calculated based on the actual measurement of the busiest period of the Locks during the year counting 16 transposition maneuvers per day.

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.

3.2 Hybrid system

The hybrid power generation system analyzed in the second energy alternative is showed by the scheme in Fig. 4. In this case, the solar source is calculated by the same methodology proposed in section 3.1. It aims to meet half of the energy demand and it to load the pumped storage system in addition to connecting to the

$$E_h = \rho g H Q \eta_t t_o \qquad (1)$$

grid as backup. A Pump as Turbine (PAT) is selected for hydroelectricity generation (Eq. 1) to fulfill the hourly demand, as a function of solar production.

3.3 Cost of Energy

In the analysis of energy costs in the proposed alternatives, an estimated Brazilian installation of 7.50 R$/Wp was considered for photovoltaic systems, in addition to the cost of availability [10] and cost of maintenance estimated at 1 and 2% of the total cost of installation for each case.

Considering the variation of the energy tariff at the installation site, presented in Tab 1, with the time and days of consumption [11], the generation costs on an annual basis were calculated for three cases: operation with power supply by the power distribution company, by a purely photovoltaic and by a hybrid system.

Tab 1 Tariff of energy in the region (R$/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	1,45334	0,93247		0,57295

(1 US$=R$4.02. Ref. 05/27/2019)

4. RESULTS AND DISCUSSION

4.1 Photovoltaic-only alternative

For the purely photovoltaic system, the power of 1569 kW is obtained by the 4757 photovoltaic modules, occupying an area of 9249 m².

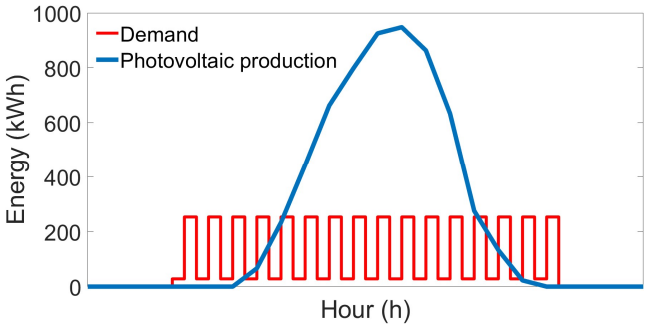

Fig 5 Daily photovoltaic production.

Figure 5 shows the comparison between hourly demand and photovoltaic production. 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 1500 kWh.

4.2 Hybrid system alternative

Figure 6 presents the energy production by the installed photovoltaic arrays and by the PAT. In this

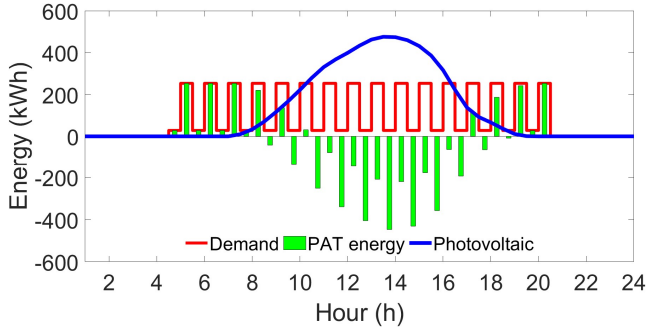

Fig 6 Hybrid system daily production.

system, 50% of the demand was considered for the solar source, reducing in the same proportion the occupied area, installed power and the number of panels.

In this arrangement, the PAT guarantees the necessary complement for supplying the energy for operation. It is observed that the negative energy values represent energy consumed by the pump for storing the energy. The variation of the load would be hourly guaranteed by a dedicated control system.

4.3 *Operation scheme*

From the analysis of figure 6 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 and rotation etc.

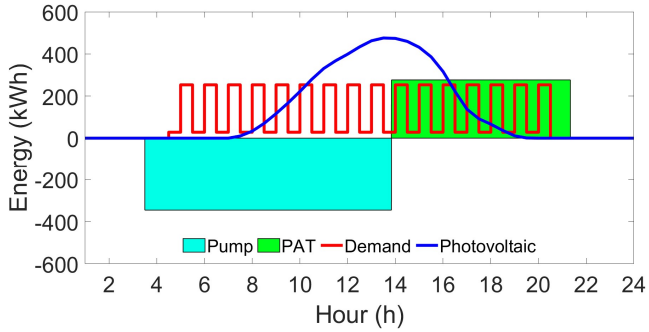

Fig 7 Operational scheme proposed.

Using the grid as an intermediate storage and taking into account the energy tariffs, as presented on Tab. 1, it is possible continuous and economical operation in pump mode and only a single conversion to the turbine mode, as shown on figure 7.

While the intermittent internal consumption is supplied through the grid, the charge controller manages the production/consumption in the PAT, so as to ensure at the end the equality in the balance between demand and generation.

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.

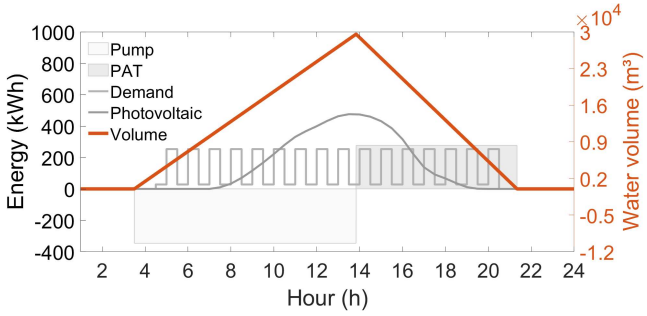

Fig 8 Use of water resource.

Figure 8 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 volume within the time set for each mode.

4.5 *Energy Payback time*

Figure 9 shows the comparison between the proposed solutions and the conventional case, without own generation.

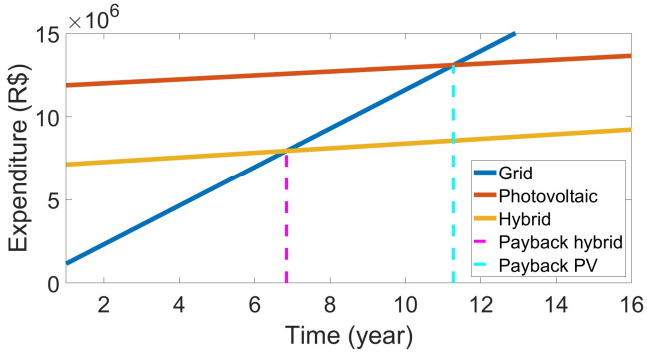

Fig 9 Comparison of energy alternatives payback.

The curves present the energy cost for each case, considering the investments in installation and costs with operation and maintenance.

It should be noted that among the alternatives the hybrid system presents better payback (6.8 years) compared to the pure photovoltaic system (11.3 years).

However, in this study the influence of the power plant spill way operation is not yet considered. In the humid period, typically between February and May, the use of the water resource is possible without needs of the pumping mode to water storage, allowing the continuous PAT operation. This fact will generate an important reduction of the payback value (to 5.1 years), according to figure 10.

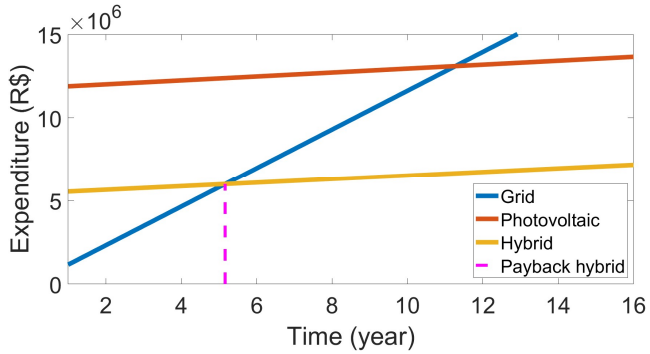

Fig 10 Payback time considering humid period.

5. CONCLUSIONS

The installed global capacity of renewable energy grows incessantly every year and more environmentally friendly and cost-effective facilities are designed according to the specificity of the site.

The project for energy solution of the Lock operations studied by [4] proposes the use of a hydraulic turbine with variable rotational speed for the exploitation of the fluctuating flow rate and available head.

Other designing key-factors are explored in this work, analyzing energy options offered by solar and hydraulic sources.

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/PAT 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 return on investment time.

Another advantage also depicted by [2] 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 in this paper, the operation of the spillway causes important influence on the facility, with regard to economic and operational aspects. In the future work, this approach will be carried out based on statistical analysis of the historical series of the spillway's opening.

ACKNOWLEDGEMENT

Authors wish to acknowledge the assistance from National Department of Transport Infrastructure (DNIT), Carlos Gil of Eletronorte for data and site visits and Propesp/UFPA for all support in this project.

REFERENCE

[1] Kusakana K. Optimal scheduling for distributed hybrid system with pumped hydro storage. Energy Conversion and Management. 2016; 111. 253-260.

[2] Xu B, Chen D, Venkateshkumar M, Xiao Y, Yue Y, Xing Y, Li P. Modeling a pumped storage hydropower integrated to a hybrid power system with solar-wind power and its stability analysis. Applied Energy. 2019; 248. 446-462.

[3] Zhang J, Tounzi A, Leontidis V, Dazin A, Libaux A. Canal Lock Variable Speed Hydropower Turbine Energy Conversion System. 12th EVER. 2017.

[4] National Department of Transport Infrastructure. Tucuruí Locks-PA. Brasília, DF, 2011 (in portuguese).

[5] Jannuzzi GM, Melo CA. Grid-connected photovoltaic in Brazil: Policies and potential impacts for 2030. Energy for Sustainable Development. 2013; 17. 40-46.

[6] Rüther R, Zilles R. Making the case for grid-connected photovoltaics in Brazil. Energy Policy. 2011; 39. 1027-1030.
[7] Martins FR, E.B. Pereira, S.A.B. Silva, S.L. Abreu, Sergio Colle. Solar energy scenarios in Brazil, Part one: Resource assessment. Energy Policy. 2008; 36. 2853-2864.
[8] Martins FR, Rüther R, Pereira EB, Abreu SL. Solar energy scenarios in Brazil. Part two: Photovoltaics applications. Energy Policy. 2008; 36. 2865-2877.
[9] Pinho JT, Galdino MA. Engineering Manual for Photovoltaic Systems. 2014, p.309 (in portuguese).
[10] National Electric Energy Agency. Normative Resolution 414, September 9, 2010 (in portuguese).
[11] National Electric Energy Agency. Normative Resolution 2433, August 7, 2018 (in portuguese).