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HYBRID RENEWABLE ENERGY GENERATION: SOLAR PHOTOVOLTAIC AND STORAGE BY REVERSIBLE PLANT

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Abstract: *This article is the result of a mathematical modeling experiment to insert parameters in the input equations of each system: pumped-storage hydropower plants (PSHP) and solar photovoltaic. The output represents functions regarding the time of production of these sources. When in generation mode, the turbines of the PSHP pour water from a reservoir located at a high altitude, to the lower reservoir, downstream in a river. When in pumping mode, in the need to store energy for later use, which usually happens in times in which the demand for energy is high; energy is consumed from the electrical network to re-establish the volume of water in the upper reservoir, that will act comparatively with charging a battery. It is concluded that this hybrid system can offer stability in demand management and flexibility of operating modes to respond to the intermittency of energy from other sources, as is the case of photovoltaic energy.*

Keywords: *Pumped-storage hydropower plants; Photovoltaics; Renewable energy.*

1. INTRODUCTION

Many countries find dependence on fossil fuel in the generation of electric energy, contributing to the increase of the greenhouse effect and several environmental problems. Studies and discussion of the possibility of renewable energy production using more than one primary source, the hybrid plants, are growing. Different combinations of sources and technologies have been proposed by project developers and equipment manufacturers, some of which have already been tested on a smaller scale (EPE, 2018).

Among the technologies available for storing energy on a large scale, energy storage in Reversible Hydroelectric Plants (UHER) is the most widely adopted. The large amount of potential energy that can be stored in hydraulic reservoirs, the energy conversion efficiency of the entire cycle, the cost per unit of energy and the flexibility provided by these plants

to the Transmission System Operator (OST) in the operation of short term makes UHER the most attractive option for large-scale energy storage (Pérez-Díaz. et al.. 2015).

Photovoltaic solar energy is a promising type of renewable energy because it uses the sun as a means of generating electricity. It works by the photovoltaic principle. where the radiation that falls on the modules is converted into electrical current. thus generating energy (Ribeiro. 2016).

According to Petrakopoulou. F.. Robinson. A.. & Loizidou. M. (2016) in their simulation and evaluation confirmed that. in order for a renewable plant to offer stability and safe energy generation. more than one renewable technology must be combined.

According to the study by Ma. T.. Yang. H.. Lu. L.. & Peng. J. (2014) who proposed a hybrid plant with renewable sources. using as a base a reversible hydroelectric plant (UHER) with participation of solar energy and wind. The results reveal that the photovoltaic panel has a relatively larger share of energy production than that of wind turbines. the solar energy resource combines better with the load pattern.

The duration curve for loading and unloading energy. which can be used to calculate the overall energy efficiency of the energy storage subsystem. was discussed. The study also indicates that using a small battery bank to cover the peak load could greatly reduce the upper reservoir and improve the reliability of the power supply. This article demonstrates that technically the renewable energy system based on (UHER) is an ideal solution for 100% energy autonomy in remote communities. Using the three technologies in a complementary way. the hybrid system could generate and store electricity at low cost and with minimal complexity.

In this study. we consider a synthetic case of a reversible hydroelectric and photovoltaic solar plant where both systems are connected to the centralized electric power network that is located in the northwest of Portugal. where a simulation is made to see its behavior both in generation and energy storage. he physical model. mathematical model and operation principle of this system are presented.

2. METHODOLOGY

2.1 Characterization of Frades II Plant

The following Tab. 1 shows the main characteristics of the Frades II Reversible Plant. located in Portugal. Fig. 1 illustrates the topographic view and the location.

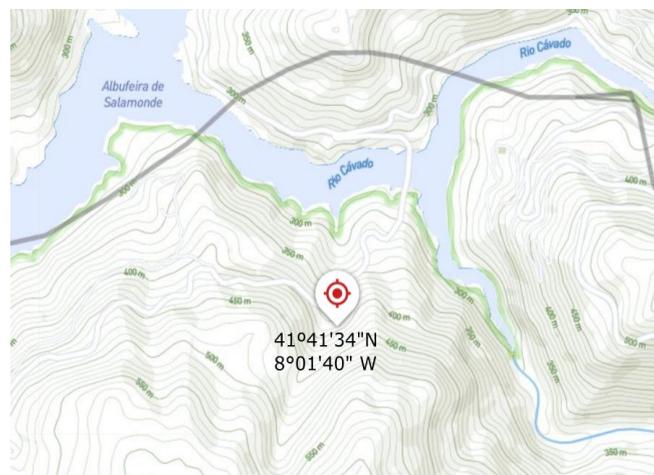


Figure 1. Coordinates of Usina de Frades II on topographic map (available at globalsolaratlas.info)

Table 1. Main characteristics of the Friar II URH (Mcpar & Hedaidi, 2020)

URH Friars II features:	
Water abstraction	Cávado River
Turbine-Pump	2 Francis variable speed turbo pumps
Rated power	Total of 780 MW (two of 390MW)
Maximum flow	Turbine Mode: 200 m ³ / s
	Pumping Mode: 160 m ³ / s
Height difference between upper and lower reservoirs	Fall - 420 m
Submergence	60m
Maximum Efficiency	85%
Coordinates	41 ° 41'34"N. 8 ° 1'40"W

2.2 Physical scheme and operating principle

The electricity grid will be responsible for the exchange of energy in the system. the plant works in power generation mode to meet the consumption needs together with the photovoltaic matrix and works in turbine mode to store energy in periods of low demand.

As shown in Fig. 2. the system involved in this study is equipped with a power generator (PV matrix). an energy storage system (storage water by pumping). the electricity grid and a control station.

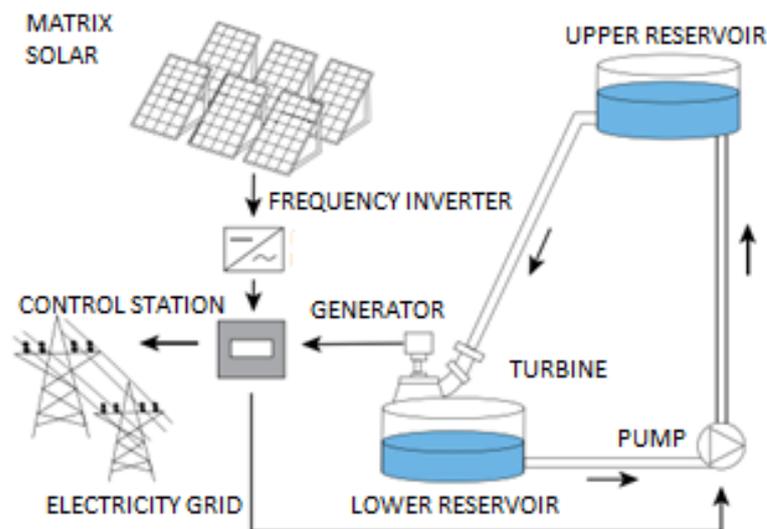


Figure 2. Hybrid solar system with pumping storage system

2.3 Mathematical modeling and simulation

Pumping Mode: Using the it is possible to estimate the power used to pump water from the lower reservoir by the pumps. The power supply is supplied directly by the solar matrix and/or the grid (Ma et al.. 2015)

$$P_b(t) = \frac{\rho g H \cdot Q_b(t)}{\eta_b} \quad (1)$$

Where $P_b(t)$ is the power in the turbine mode. from the generator to the pump (W). $Q_b(t)$ is the pumping rate and can be compared to the battery charging rate; H is the height of fall (m); g is the acceleration due to gravity (9.8 m / s^2); ρ is the density of the water (1000 kg / m^3); η_b is the overall pumping efficiency. Still. they are fixed parameters: $\rho \cdot g \cdot H \cdot \eta_b$; $P_b(t)$ and $Q_b(t)$ are functions in relation to time.

Generator Mode: In the case of energy deficits. water is removed from the upper reservoir to operate the hydroelectric turbines. Using a. it is estimated that the power released from the turbine / generator unit (Ma et al.. 2015)

$$P_t(t) = \eta_t \rho g H \cdot Q_t(t) \quad (2)$$

Where η_t is the overall efficiency of the turbine / generator unit; $Q_t(t)$ is the volumetric flow of water entering the turbine (m^3 / s); $\rho \cdot g \cdot H \cdot \eta_t$ they are fixed parameters; $P_t(t)$ and $Q_t(t)$ are functions in relation to time. According to the manufacturer VOITH (2014). the efficiency of the Francis turbine pump at its best point of operation is about 85%. According to technical information from EDP. the company responsible for the Frades II Hydroelectric Power Plant. the installed capacity for the plant is 736MW and an average annual productivity of 1441 GWh.

2.4 Load demand profile

The daily average of energy production at the plant is a relationship between its generation and its pumping. To illustrate the load demand profile. and compare them to the pump pumping profiles. turbine generation and solar photovoltaic generation profiles. let's consider a real scenario in order to create a very reasonable profile for energy consumption electrical. This profile is illustrated in the following graphic: According to the website of the Information Center of Portugal (REN. 2020). the energy flow profiles in Portugal are presented as follows in Fig. 3 (analyzed date: 05/07/2020).

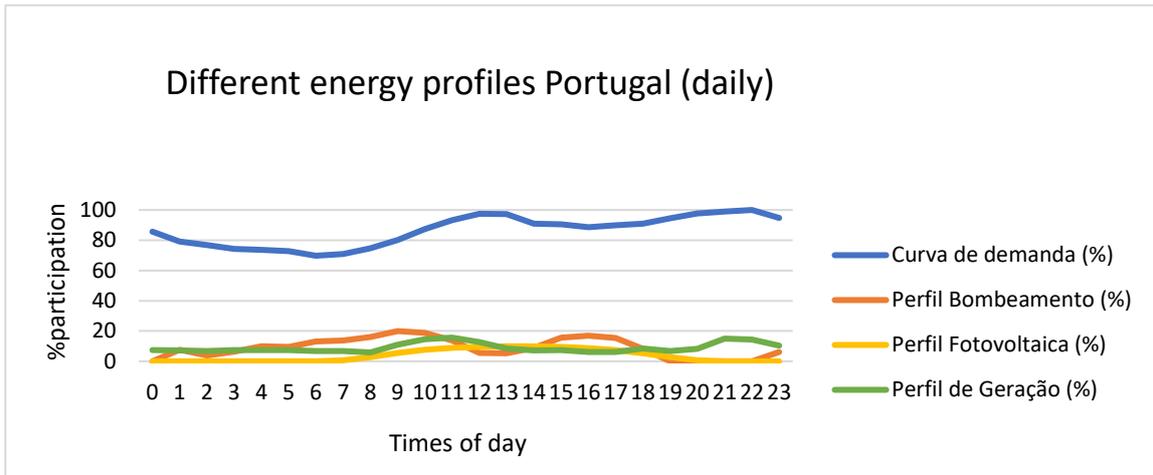


Figure 3. Daily demand curves in Portugal (REN. 2020)

2.5 Solar energy resource

The meteorological data in this region were collected by Global Solar Atlas (2020) at the coordinates 41 ° 41'34"N. 8 ° 1'40"W. which includes solar radiation at room temperature. The distribution of solar radiation taken as a basis the daily average for the month of June is shown in Fig 4.

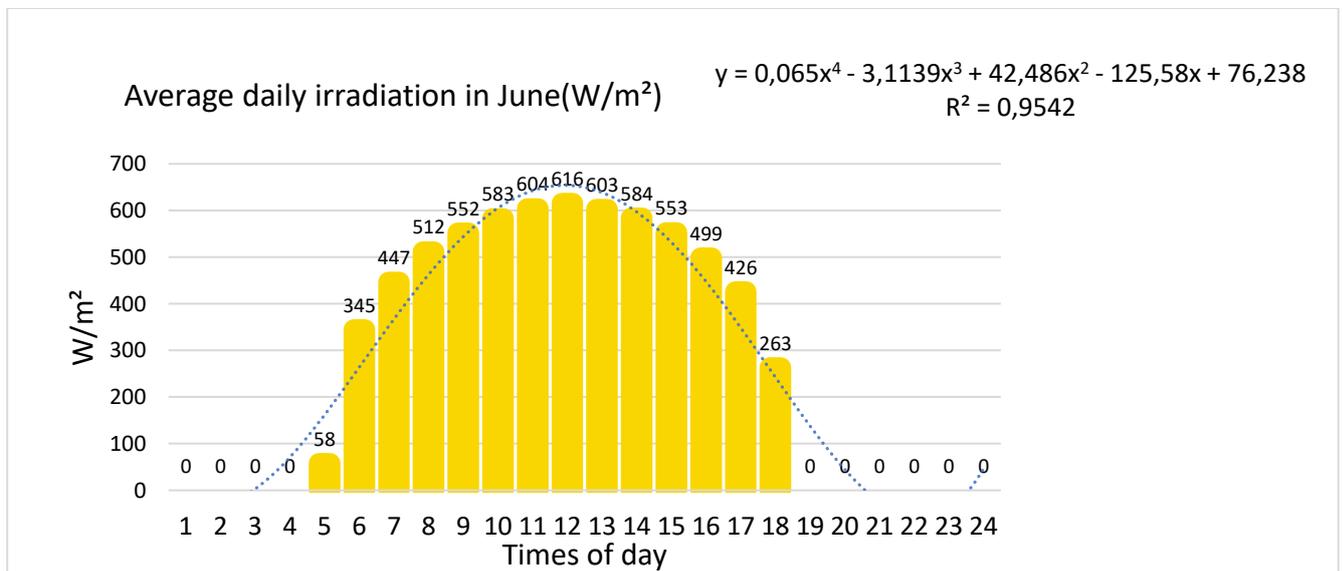


Figure 4. Average daily irradiation

2.6 Number of photovoltaic modules

Using the specifications of the Canadian Solar CS1U-400MS PV panel and the profile for solar irradiation based on the daily average for the month of June; also taking 2.061m² of module area and efficiency $\eta = 19.4\%$ and still admitting that the module offers acceptable efficiency behavior over the entire irradiation range and does not offer temperature sensitivity. we can expect that the module will produce energy at the output of a unit as illustrated in Fig 5.

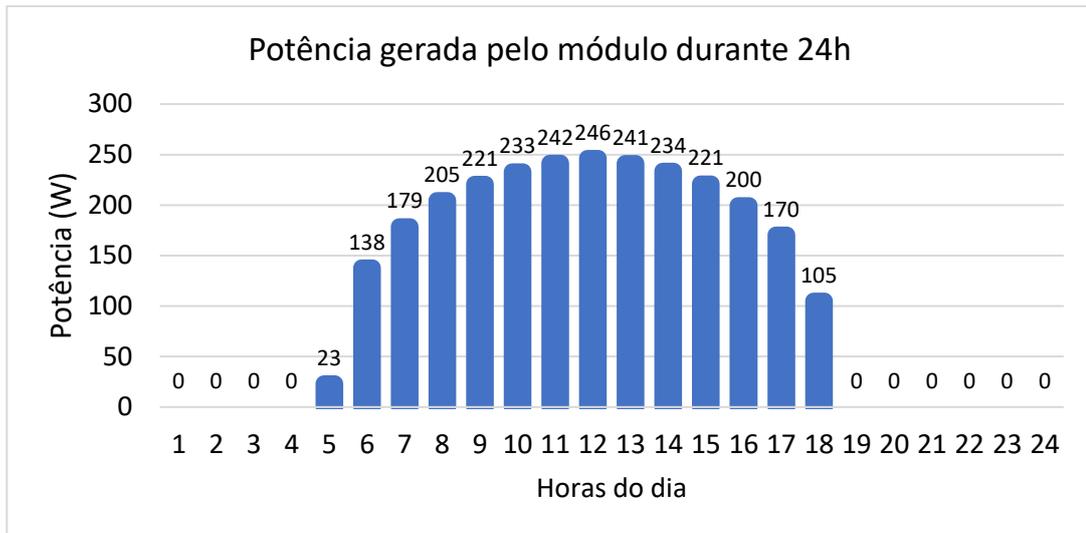


Figure 5. Power generated by the module

Given equation 3 and 4 to calculate the photovoltaic energy during the day:

$$E = \sum_{t=0}^{24} (P_t + P_{t+1} + \dots + P_{24}) \tag{3}$$

$$E = 2658 Wh \tag{4}$$

So, this is the amount of energy produced by a module during a day of operation. For the creation of the photovoltaic system, related to the generation of electricity from solar energy incident on the site, 4000 monocrystalline silicon photovoltaic modules were used, totaling 1.6MW of installed capacity.

It was observed that an amount of energy equivalent to 10632MW was produced on a given day of operation. The area occupied by the modules: $2.061m^2 \times 4000 = 8244 m^2$

3. RESULTS

3.1 Flow chart of the energy route

the flow and generation of energy with the electricity grid demanding both the generation and the use of energy for pumping are presented in Fig 6.

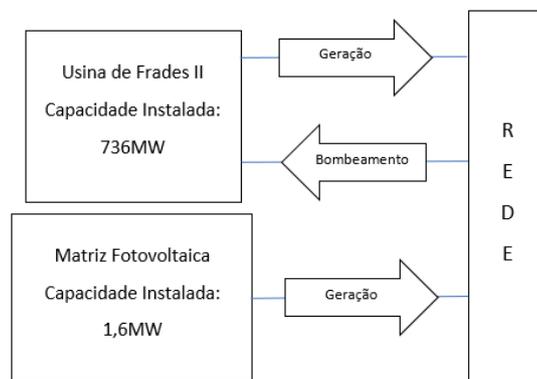


Figure 6. Energy route

3.2 Reversible Plant Generation and Pumping

Based on the generation and pumping profiles in fig. 3 about daily demand, the results follow in Tab 2 and total resulting energy in Tab 3.

Table 2. Generation and Pumping profile

Hour	Frades II Generation (MW)	Frades II Pumping (MW)	Variation (MW)
0	214.274	0	214.274
1	204.958	-205.765	-0.807
2	195.642	-102.390	93.252
3	214.274	-173.768	40.506
4	214.274	-271.727	-57.453
5	214.274	-261.390	-47.116
6	195.642	-359.842	-164.200
7	195.642	-374.610	-178.968
8	167.693	-436.634	-268.942
9	316.753	-544.439	-227.686
10	419.232	-510.473	-91.241
11	447.181	-373.625	73.556
12	363.334	-150.139	213.195
13	242.223	-147.186	95.037
14	204.958	-243.669	-38.711
15	214.274	-424.328	-210.054
16	177.009	-461.247	-284.238
17	177.009	-418.421	-241.412
18	242.223	-226.440	15.783
19	195.642	0	195.642
20	232.907	0	232.907
21	428.548	0	428.548
22	409.916	0	409.916
23	298.120	164.907	133.213

Table 3. Total Resulting Energy

	Resulting Energy
Generation Mode	6186 MWh
Pumping Mode	5851 MWh
Variation	335 MWh

with these results from the table we can then demonstrate the results in the graphs in Fig. 6 below.

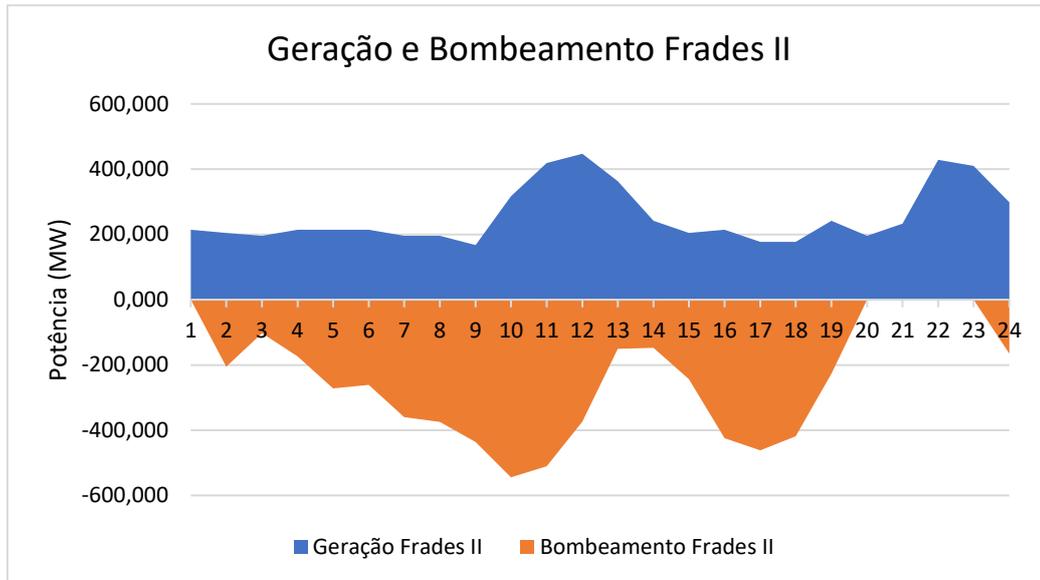


Figure 7. Generation and pumping

3.3 Ending Balance

The final energy balance of the system comprises the Reversible Plant + Photovoltaic Matrix configuration, which includes the part of total generation and pumping. The latter constitutes a negative flow in the energy balance because energy is consumed from the grid.

Table 4. Ending Balance Frades II

Hour	Frades II Generation (MW)	Generation Photovoltaic matrix - 4000 modules (MW)	Frades II Generation + Photovoltaic Matrix (MW)	Frades II Pumping (MW)	Total Variation (MW)
0	214.274	0	214.274	0	214.2741
1	204.958	0	204.958	-205.765	-0.80677
2	195.642	0	195.642	-102.390	93.25153
3	214.274	0	214.274	-173.768	40.50639
4	214.274	0.0928	214.367	-271.727	-57.3605
5	214.274	0.552	214.826	-261.390	-46.5639
6	195.642	0.7152	196.357	-359.842	-163.485
7	195.642	0.8192	196.461	-374.610	-178.149
8	167.693	0.8832	168.576	-436.634	-268.058
9	316.753	0.9328	317.686	-544.439	-226.754
10	419.232	0.9664	420.198	-510.473	-90.2751
11	447.181	0.9856	448.166	-373.625	74.54113
12	363.334	0.9648	364.299	-150.139	214.1599
13	242.223	0.9344	243.157	-147.186	95.97161
14	204.958	0.8848	205.843	-243.669	-37.826
15	214.274	0.7984	215.072	-424.328	-209.255
16	177.009	0.6816	177.691	-461.247	-283.557

17	177.009	0.4208	177.430	-418.421	-240.991
18	242.223	0	242.223	-226.440	15.78338
19	195.642	0	195.642	0	195.6416
20	232.907	0	232.907	0	232.9066
21	428.548	0	428.548	0	428.5482
22	409.916	0	409.916	0	409.9157
23	298.120	0	298.120	-164.907	133.2134
Average:					
	257.75	0.443	258.193	-243.792	14.401

Table 5. Total ending balance resulting

	Resulting Energy
Generation + Photovoltaic Mode	6196.632 MWh
Pumping Mode	5851 MWh
Variation	345.632 MWh

Finally, below in Fig. 8 we have the participation in percentage of the hybrid system modeled in this study:

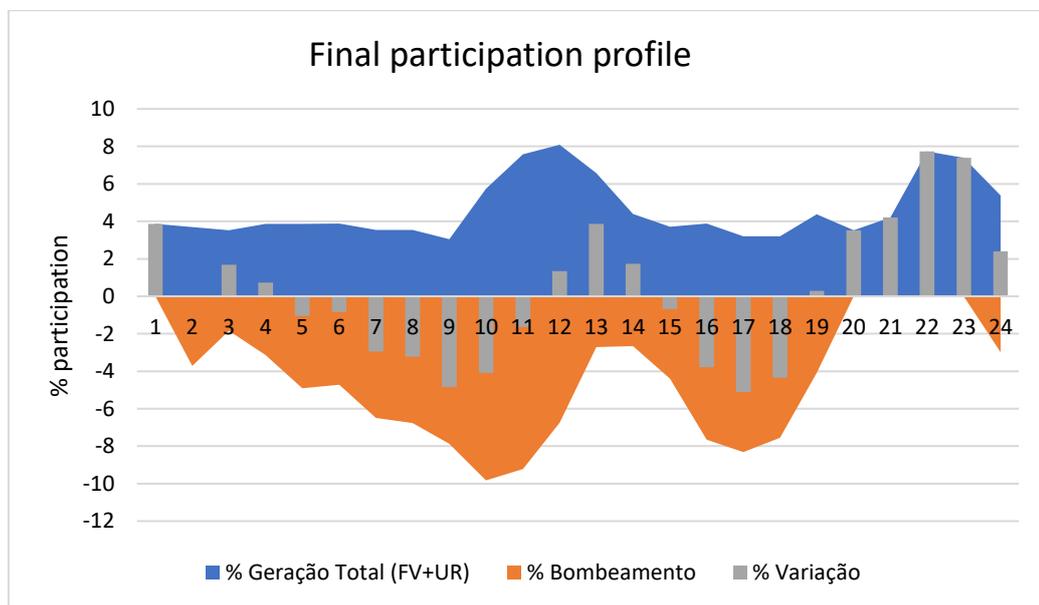


Figure 8. Final participation profile

4. CONCLUSIONS

The electricity grid be responsible for the energy exchange in the system. The parameter that shows the current energy flow during an operating day that is exchanged is represented by the variation values, which is nothing more than

the energy balance made between the generation mode of the turbines plus the photovoltaic matrix (positive flow) and discounted from the amount of energy required to pump water to the upper reservoir (negative flow).

Reversible plants work in power generation mode to fulfill the role of meeting consumption needs during peak periods and work in pumping mode to store energy in periods of low demand.

The photovoltaic matrix, alone, shows little influence on the energy generation curve compared to the Frades II Plant, participating in only a fraction of what is produced in the turbines.

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