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Hybrid electrical energy generation from hydropower, solar photovoltaic and hydrogen

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ABSTRACT

The global concern to reduce greenhouse gas emissions and increase the use of renewable sources has led Brazil to stand out as a promising nation in this context, with a large portion of its energy capacity coming from renewable sources. However, renewable sources have the disadvantage of intermittency and seasonality, which has prompted the search for solutions to these challenges. This study assesses the feasibility of integrating hydro and solar power with a Hydrogen-based Electrical Energy Storage System (H_2EESS) at the Serra da Mesa hydroelectric Brazilian power plant. Hydrogen would be produced through water electrolysis, taking advantage of the available excess renewable energy, and subsequently converted back into electricity through fuel cells. The integration of hydro and solar power with H_2EESS resulted in an increase of 11.10 % in the energy produced compared to conventional hydroelectric generation, with 36.06 % of this increase coming from H_2EESS. Additionally, there was a 9.71 % increase in the utilization of substation capacity. These results highlight the feasibility and benefits of integrating hydro and solar power with H_2EESS. This approach allows for maximizing renewable energy generation, reducing greenhouse gas emissions, and better utilizing available resources without the need for significant infrastructure investments.

1. Introduction

The influence of the global energy sector on greenhouse gas emissions (GHG) has been the subject of international studies and efforts. The Paris Agreement, signed during the United Nations Conference on Climate Change (COP21) in 2015, established the goal of limiting the global temperature increase to within 2 °C by reducing GHG emissions. It is noteworthy that approximately 65 % of emissions originate from the energy sector and countries agreed to strive for the neutralization of these emissions by 2050 [1].

An effective solution to this issue, without compromising the existing energy demand, lies in the expansion of renewable sources. According to a study by the International Energy Agency [2], the utilization of renewable sources contributes to a reduction of 35 % in GHG emissions. In this context, Brazil emerges as a promising nation. Its electrical matrix consists of diverse sources of energy generation, including both renewable and non-renewable sources. As per the Synthesis Report of the National Energy Balance 2021 – base year 2020 [3], renewable sources account for approximately 85 % of the country's installed capacity, with solar and wind sources experiencing a respective increase of 32.9 % and 11.4 % in their installed capacities between 2020 and 2021.

The intermittency and seasonality of renewable sources such as solar and wind energy pose significant disadvantages for their efficient utilization. The availability of sunlight and wind varies according to the region and time of year, thereby affecting energy generation [4–7]. To address this challenge, a possible solution is the integration photovoltaic (PV) solar generation with hydroelectric generation, which utilizes water reservoirs to store energy in hydroelectric power plants (HPP),

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provides a more consistent production, even during periods of low solar irradiation or wind intensity. Conversely, PV solar generation offers low generation costs and reduced emissions of polluting gases [8–10].

Currently, the most widely used technology for energy storage is electrochemical accumulators, such as batteries. However, these batteries require high maintenance, have a reduced cyclic lifespan, and pose environmental hazards associated with the use of lead and sulfuric acid [11,12].

It is expected that the demand for energy storage technology will increase in the upcoming years, particularly with the growing integration of renewable sources into the energy matrix. An emerging alternative is the utilization of Hydrogen-based Electrical Energy Storage Systems (H_2EESS) [13–17]. Hydrogen, generated through electrolysis, is considered a primary form of clean hydrogen production as it does not emit polluting gases during the production process. H_2EESS can harness surplus renewable energy to produce hydrogen via water electrolysis. This gas can be converted back into electricity when needed, through fuel cells, which are devices capable of cleanly and efficiently transforming hydrogen into electrical energy [18–22].

Simultaneously, hydrogen possesses a substantial potential for energy security, owing to the possibility of its acquisition from various sources, enabling the prioritization of each country's local resources, thereby reducing or avoiding energy imports and dependence on fossil fuels. Speaking specifically of Brazil, which possesses abundant renewable natural resources and an energy matrix with a significant contribution from renewable sources, the integration of hydrogen utilization technologies into the energy matrix will facilitate a more efficient utilization of these energy sources, consequently bolstering our nation's energy security [23,24].

From this perspective, this study examines the potential of hydro-solar integration and the utilization of hydrogen-based energy storage at the Serra da Mesa HPP. The analysis encompasses the energy aspects and the collaborative operation of these systems, emphasizing the elevated potential of hydrogen storage to optimize the utilization of natural resources and enhance the operational efficiency of HPP, without necessitating additional investments in infrastructure. In this way, the analyses presented in this work lead to an important collaboration in order to enhance the use of hydrogen as an energy vector in the current energy transition scenario.

2. Method and materials

With the intention of evaluating the potential for hydro-solar integration and the use of stored hydrogen for the generation of electrical energy in a HPP, the proposed methodology is: a) analyze historical electric generation data from the Serra da Mesa HPP; b) quantify the need for photovoltaic solar generation on the surface of the water reservoir of the Serra da Mesa HPP; c) examine the possible generation of electrical energy through fuel cells (FC) powered by hydrogen originating from the use of renewable energy; d) analyze the integration capacity of the solar energy generation system through hydrogen storage using the existing infrastructure of the hydroelectric plant's energy substation.

The complete system scheme is presented in Fig. 1, and each subsystem is described and characterized below in the paper. The analysis proposals in this work contemplate an energy flow that originates from solar radiation captured by a photovoltaic solar plant (PVSP) floating above the water reservoir of an HPP. This electrical energy is used by an electrolyzer to generate green hydrogen through a physical-chemical process with water, which is stored in a specific tank. Finally, through a fuel cell, the stored hydrogen is used to produce electrical energy to be sent to the power plant substation, already integrated into the power grid. The complete system is presented in Fig. 1, and each subsystem is described and characterized throughout this paper.

2.1. Photovoltaic solar energy

Photovoltaic solar energy is a method of generating electricity by converting solar energy through photovoltaic cells. This technology harnesses the photovoltaic effect, discovered by the French physicist Alexandre-Edmond Becquerel in 1839. Solar panels are comprised of modules containing these cells, which are responsible for converting sunlight into electrical energy [25,26].

There are two main types of PV systems: off-grid and on-grid. The off-grid system, also known as an Isolated Photovoltaic System or Stand-alone Generation, operates independently without a connection to the electrical grid and is commonly used in remote areas. These systems utilize batteries to store the energy produced by the solar panels during periods of low or no generation and, is this way, it provides a more affordable solution for distant communities, proving to be economically viable compared to the installation of conventional electrical infrastructure, such as gasoline or diesel generators [26].

On the other hand, the on-grid system, also referred to as a Grid-Connected Photovoltaic System or Distributed Generation, is connected to the conventional electrical grid provided by local utilities. The electricity generated by the solar panels can be used as a supplement or replacement for the conventional energy available in the grid [27].

2.2. Hydrogen technology

Hydrogen plays a significant role as an energy carrier, with various positive outcomes in terms of energy efficiency, such as decarbonizing productive sectors, integrating large amounts of variable renewable energy, and enabling the dissociation between energy generation and consumption through the production of transportable hydrogen [28]. Although hydrogen is abundant worldwide, its extraction, on the other hand, is not commonplace, as this element, according to [13], is chemically active and readily combines with other compounds, such as oxygen, forming water and carbon. Approximately 96 % of all hydrogen produced globally is derived from methane in fossil fuels [29].

In recent years, several studies have been carried out aimed at different technologies for the production, storage, transport and reconversion of hydrogen into energy. In terms of environmental impact, the best alternative is the production of hydrogen from renewable energies

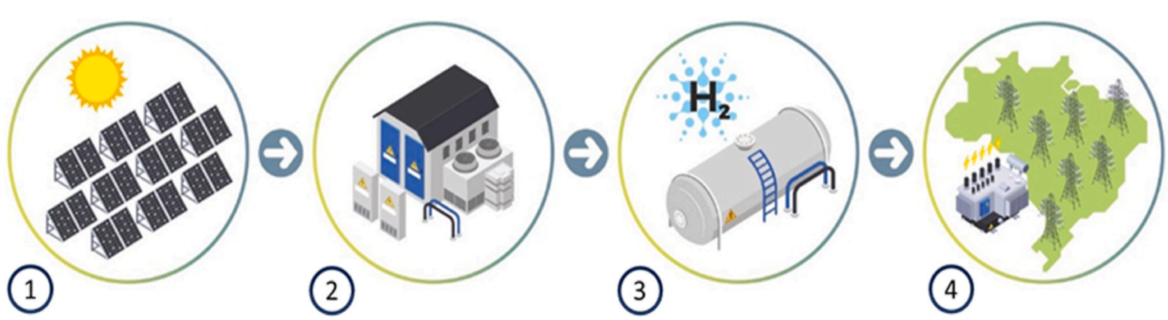

Fig. 1. Proposed components of the system: 1) PVSP; 2) Electrolyzer; 3) Hydrogen storage; 4) Fuel cell system.

[30], as is the case of solar photovoltaics studied by [31–47] with promising results. The use of photocatalysis using solar energy has also been studied by [48,49] pointing out a great potential for the use of this method. Another method concerns concentrated solar energy [50], with a great chance of applicability in steam plants using this technology. Other studies using wind energy point to a great potential for the production of green hydrogen in Australian territories [34], Colombia [39], Egypt [47], Paraguay [42] and Brazil [40,51].

In accordance with [30], the cleanest way to produce hydrogen, known as green hydrogen, is through water electrolysis coupled with renewable energy sources. In 2020, only 0.03 % of all hydrogen produced globally came from electrolysis [52]. The number is still low due to the high costs involved in the process. However, advancements in renewable energy research have significantly reduced its costs. Another factor that influenced this reduction was the conflict between Russia and Ukraine. Due to the conflict, a study by [53] indicates an increase in the production costs of natural gas that supplies Europe, intensifying research on green hydrogen and making its costs comparable to that of gray hydrogen (cheaper but highly polluting) as early as 2024.

Electrolysis is a process that involves splitting water molecules into hydrogen and oxygen by applying an electrical potential. Two electrodes are immersed in an aqueous solution (electrolyte), which increases the availability of ions in the water. The water molecule is divided, producing oxygen at the anode and hydrogen at the cathode, as shown in Fig. 2. Currently, the most widely used electrolyzer in the market is the polymer electrolyte membrane (PEM) electrolyzer, with a solid conductor made of a proton-exchange membrane [54]. This electrolyzer exhibits an efficiency ranging from 65 % to 78 %, and the investment cost for this technology varies between $500/kW and $3800/kW, primarily due to the platinum catalyst used [2].

After its production, hydrogen needs to be stored so that it can be transported or stockpiled. The so-called Hydrogen-based Electrical Energy Storage Systems (H_2EESS) act in the long-term storage of large energy blocks without significant losses in the process. The excess energy generated from renewable sources and stored in H_2EESS can be used for the production of H_2, and this gas is reconverted into electrical energy through a FC.

Once produced through electrolysis and stored in the gaseous form, hydrogen can be reconverted into energy through a reverse process of electrolysis, which occurs in FC [55]. In the general operating principle, as shown in Fig. 3, hydrogen is fed into the anode of the FC, where it is split into protons and electrons by a catalyst. The membrane allows only protons to pass through, while electrons are forced to follow an external circuit, creating an electric current. Oxygen from the ambient air is supplied to the fuel cell at the cathode. Oxygen, electrons from the external circuit, and protons combine to form water and heat [55].

In addition to the storage of hydrogen in the gaseous state, several studies have been carried out with a focus on storage in other states [56], developed a study about storage in liquid organic hydrogen carriers,

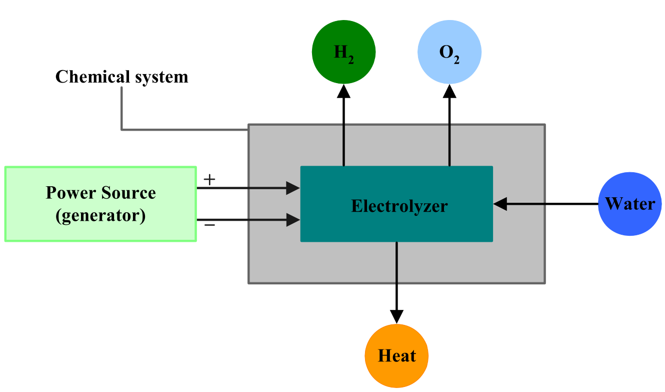

Fig. 2. Water electrolysis process.

using ammonia, concluded that this way is an attractive alternative to compression or liquefaction at low temperatures. In a study carried out by [31] concluded that magnesium represents a reliable source of stored energy that could be exported by air, sea or other means of transportation to remote locations for power-generation.

Green hydrogen is a promising alternative for decarbonizing various sectors of the planet [57]. The Siemens Energy, for example, is working on projects for the production and storage of green hydrogen for the natural gas industry. The company is building a green hydrogen pilot plant in the United Kingdom, which will use electrolysis to produce renewable hydrogen from renewable energy sources. The produced hydrogen will then be used to blend with natural gas, reducing greenhouse gas emissions in the production and distribution of natural gas [58].

Another application of green hydrogen in decarbonizing the planet is in fertilizer production. Fertilizer production is responsible for about 2 % of global greenhouse gas emissions, and most fertilizers are produced from hydrogen obtained from fossil fuels. Siemens Energy is working on a project with Yara, a global leader in fertilizer production, to produce green ammonia using renewable hydrogen. The project involves the construction of a pilot plant in Norway that will use electrolysis to produce green hydrogen from renewable energy, reducing greenhouse gas emissions in fertilizer production [58].

3. Application case of the methodology

3.1. Definition of the case study

The case study of this paper is the Serra da Mesa HPP, situated in the Upper Tocantins Basin in Goiás (GO), which occupies a prominent position along the main course of the Tocantins River within the municipality of Minaçu (GO), approximately 1.790 km from its estuary. The Serra da Mesa reservoir is Brazil's largest water body, boasting a voluminous capacity of 54.4 billion m^3 and encompassing an expansive area of 1784 km^2. It has three vertical-axis Francis turbines generating units and a total power capacity of 1275 MW [60]. The Reservoir Monitoring System of the National Water Agency (SAR/ANA) highlights significant storage variability within the Serra da Mesa reservoir over the past twenty-five years. This change in storage is a result of the seasonal and inter annual variation on precipitation and the demand for electricity in the country, as exemplified in Fig. 4 [61]. Considering the historical averages of monthly hydroelectric power between 2018 and 2022, the Serra da Mesa HPP has an average monthly power of 344.98 MW_{avg} [61], as shown in Table 1. According to Table 1, over the past five years, the average electrical power generated in the Serra da Mesa HPP amounted to 344.98 MW_{avg}, which corresponds to a 27.05 % capacity factor (total capacity 1275 MW). This gives a lot of flexibility for the plant to operate in combination with PVSP and hydrogen storage.

3.2. Photovoltaic solar plant

For the purpose of electricity generation from photovoltaic solar energy, it is essential to beforehand ascertain the solar radiation at the installation site of the PV panels. Hence, the initial stage of this study involves collecting solarimetric data from the HPP, as well as studying the variation of solar irradiance throughout the day at the location.

With these established data, it becomes feasible to perform the sizing of the PVSP to be installed at the site, considering the maximum daily photovoltaic generation and the total number of PV panels required – encompassing the total installed capacity and the area they will occupy.

3.2.1. Solarimetric data

This stage involves estimating the generation throughout a typical day, considering the distribution of solar irradiation in each hour of the day. To do so, the SunData software provided by [27] was utilized. This software provides monthly average solar irradiation data at any location

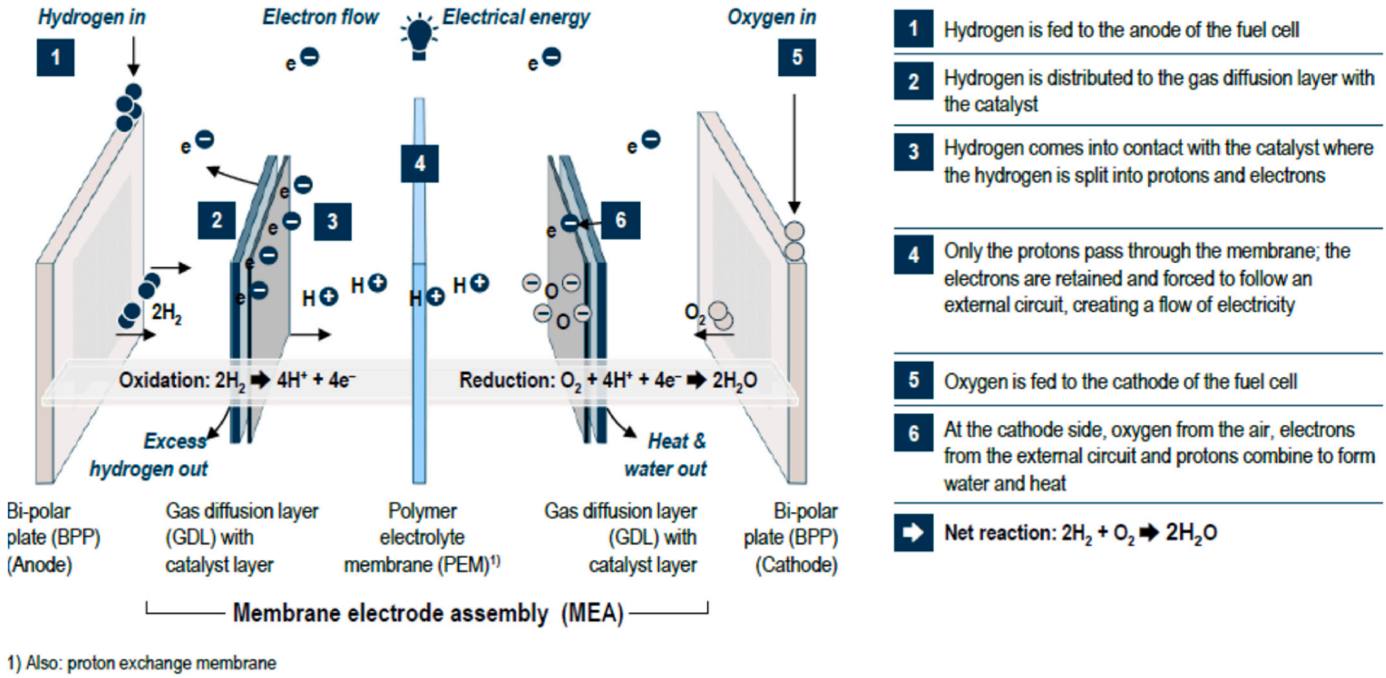

Fig. 3. Fuel cell operation diagram [59].

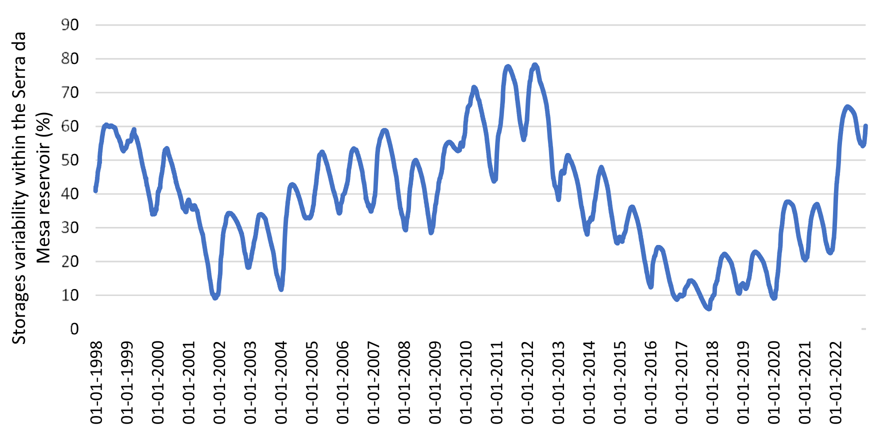

Fig. 4. Historical storage records (in percentage) at Serra da Mesa, from 1998 to 2022 [61].

Table 1
Monthly averages between 2018 and 2022 for the hydrological and electric power generation data of the Serra da Mesa HPP [61].

Month	Quota (m)	Influx (m^3/s)	Outflow (m^3/s)	Turbined Flow (m^3/s)	Effective Volume (%)	Average Power (MW_{avg})
Jan	430.35	890.44	379.33	379.33	18.93	310.57
Feb	432.29	1262.81	269.55	269.55	22.70	224.61
Mar	435.36	1171.16	178.06	178.06	28.73	153.53
Apr	437.91	777.62	117.43	117.43	33.90	106.41
May	439.24	371.78	146.28	146.28	36.73	134.43
Jun	439.30	234.61	347.49	347.49	36.83	321.54
Jul	438.79	149.35	365.03	365.03	35.75	335.86
Aug	438.06	91.74	423.02	423.02	34.18	387.16
Sep	436.69	61.21	649.17	649.17	31.19	593.36
Oct	434.91	140.98	686.41	686.41	27.65	601.95
Nov	433.60	415.52	647.08	647.08	25.31	558.45
Dec	433.63	862.94	474.47	474.47	25.54	411.90
Average	**435.86**	**532.17**	**390.52**	**390.52**	**29.82**	**344.98**

in the country, based on the geographic coordinates of the study site. Thus, Table 2 presents the average irradiation values throughout the year at the Serra da Mesa HPP. Assuming a tilted plane with the same angle as the latitude of the measurement location (17°N), it is observed that the average irradiation is 5.41 kWh.m^{-2}.day^{-1}.

Table 2
Monthly averages of irradiation in kWh.m^{-2}.day^{-1} at the Serra da Mesa HPP [27].

Inclination	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.
17°N	**4.96**	**5.23**	**5.16**	**5.49**	**5.63**	**5.52**	**5.89**	**6.23**	**5.82**	**5.38**	**4.76**	**4.91**	**5.41**

3.2.2. Typical solar day

Due to the variation in solar photovoltaic generation throughout the day, it is necessary for system sizing to understand the amount of solar energy that can be produced in each hour of the day, characterizing the typical solar day. Therefore, considering a clear sky day, the fractions of average solar irradiation for the Serra da Mesa reservoir are represented in Fig. 5, using [62].

3.2.3. Dimensioning

In this study, a continuous hydraulic generation throughout the day was taken into consideration, so that any variations or excess in power dispatch would be absorbed by the H_2EESS, and photovoltaic solar generation occurred on a typical sunny day. With this in mind, the calculations described below [62].

a) Maximum Photovoltaic Generation

Max PVSP Gen. = Max Cap. Sub. - Hydro Gen. (MWh) (1)

Where *Max PVSP Gen.* refers to the maximum solar photovoltaic generation that occurs at 12:00 p.m., expressed in (MWh); *Max Cap. Sub.* refers to the maximum capacity of the substation to inject energy, as granted by [3], measured in (MWh); and *Hydro Gen.* represents the hydroelectric generation at 12:00 p.m., expressed in (MWh).

b) Daily Photovoltaic Generation

Daily PVSP Gen. = (Max PVSP Gen.) / (% of Irradiation at 12:00 p.m.) (MWh) (2)

Where *Daily PVSP Gen.* represents the total energy produced by the PV plant during the day, expressed in (MWh); and *% of Irradiation at 12:00* p.m. refers to the percentage of the total irradiation that occurs at 12:00 p.m.

c) Number of photovoltaic panels

Number of PVSP Panels = (Daily PVSP Gen.) / (Average Daily Irradiation × PVSP Panel Power × PR) (3)

Where, *Number of PVSP Panels* refers to the quantity of modules necessary to produce the complementary energy to the hydraulic one, originating from the solar source; *Average Daily Irradiation* corresponds to the annual average irradiation incident over the course of a day, given in (kWh.m^{-2}.day^{-1}); *PVSP Panel Power* pertains to the electrical power of each selected photovoltaic panel, measured in (kWp), and PR refers to Performance Ratio of the PVSP, considering electrical losses. For this paper, the PR was considered to be 80 % [9,25,26].

d) Installed Power

Installed PVSP Power = Number of PVSP Panels × PVSP Panel Power (MWp) (4)

Where *Installed PVSP Power* indicates the total installed power of the PVSP plant, measured in (MWp).

e) Solar Photovoltaic Plant Area

PVSP Plant Area = Number of PVSP Panels × PVSP Panel Area × (1 +% Allowance) (km^2) (5)

Where PVSP *Panel Area* corresponds to the area of an PVSP panel, given in (m^2); *(1 +% Allowance)* includes the allowance for spacing between the PVSP panels and the floaters.

3.3. Parameters for sizing the H_2EESS

To assess how H_2EESS can harness the excess PV energy generation, similar systems studied by [62] were associated with the hybrid project in question. This is due to the fact that the established configurations in the case studies can generate energy surpluses that would be lost if not stored. The following criteria were adopted to determine the equipment capacities of the storage system: a) The average excess electrical power generated by the PVSP corresponds to the maximum hydrogen production capacity through the electrolysis process at noon, namely the electrolyzer power; b) The H_2EESS will revert the stored energy to distribute electricity to the grid during moments when there is no energy

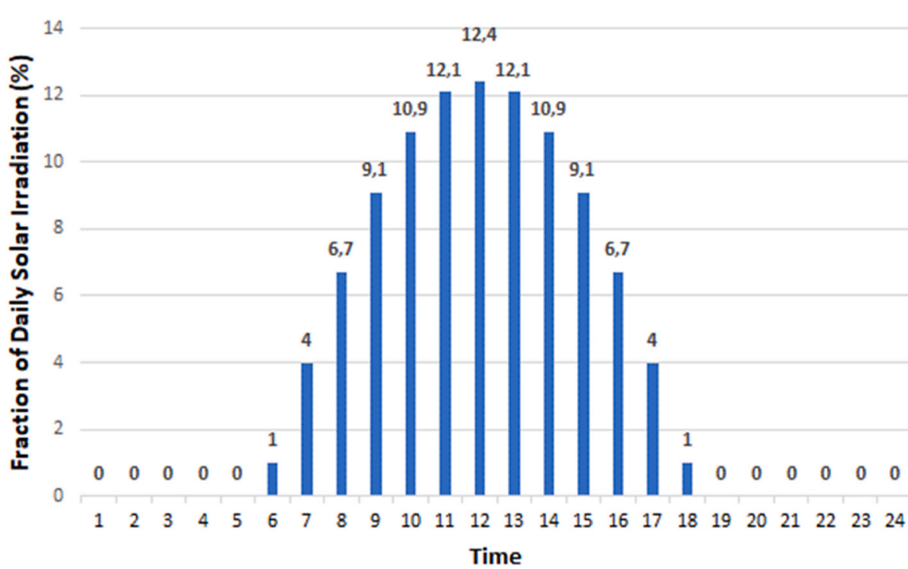

Fig. 5. Fractions of average hourly solar irradiation for the Serra da Mesa reservoir [62].

production from the PVSP; c) The specific consumption of the electrolyzer and the specific production of the grid are the same as those observed in the equipment of the projects evaluated by [62]. Table 3 presents the values to be used for calculating the sizing of the PVSP and the operation and sizing of the H_2EESS, composed by electrolyzers and fuel cells.

4. Results and discussion

4.1. Case study 1

This case study 1 presents an analysis of the average hydraulic power generation between the years 2018 and 2022 at the Serra da Mesa HPP, with a capacity of 344.98 MW_{avg}, as recorded by ONS data (2023). In order to expand the system, a photovoltaic solar plant with a capacity of 1732.94 MWp was added to the HPP. At noon, the energy generation from the PVSP complements the generation from the HPP by injecting 930.02 MW (*Max PVSP Gen.)* of power into the electrical grid. This action allows the total power capacity granted to the power plant during the operation period to reach the maximum capacity of 1275 MW *(Max Cap. Sub)*.

A summarized representation of the PVSP sizing is presented in Table 4. The results presented are associated with the average irradiation corresponding to the 17° N orientation, as indicated in Table 1 and inserted at Table 4.

Table 5 illustrates the simultaneous operation of the photovoltaic solar plant and the hydraulic generation over a 24-h period. It is observed that all the electric energy generated by the PVSP plant was directly injected into the electrical grid, resulting in a 90.58 % increase in generation and a daily addition of 7500.16 MWh to the grid. By combining the hydraulic generation with the solar generation, the total average power injected into the electrical grid amounts to 657.49 MW_{avg}, corresponding to an increase in the maximum utilization capacity of the substation from 27.06 % to 51.57 %. The analysis of Fig. 6 unveils that the PVSP achieved a peak power production of 930.02 MW at noon, thereby reaching the maximum capacity of the substation when combined with the energy generated by the HPP - 344.98 MW. However, on 50 % of the days, the hydroelectric production will surpass the average of 344.98 MW, resulting in a surplus of photovoltaic energy generation.

Table 3
Parameters used for the sizing of the PVSP and the H_2EESS.

Item		Parameters	Values
PVSP		Area	1784 km^2
		% Irradiation at 12:00 p.m.	12.4 %
		PR	80 %
		PVSP Panel Model	*Halfcell Osda Solar* ODA550-36V-MHD
		PVSP Panel Power	550 W_p
		PVSP Panel Area	3.15m^2
		% Allowance (Maintenance)	50 %
H_2EESS	Electrolyzer [63]	Manufacturer/ country	Hytron/Brasil
		Model	HT-40PEM
		Technology	PEM
		Power consumption	116 kW
		H_2 production	20 Nm^3/h
		Specific consumption	5.72 kWh/Nm3
	Fuel cell [64]	Manufacturer/ country	Hydrogenics/Canadá
		Model	HyPM-R100
		Technology	PEM
		H2 consumption	70 Nm^3/h
		Generated power	100 kW
		Specific production	1.43 kWh/Nm3

Table 4
Characteristics of PVSP sizing – case study 1.

Item	Values
Hydropower Generation Power *(Hydro Gen.)*	344.98 MW_{avg}
Maximum Photovoltaic Generation *(Max PVSP Gen.)*	930.02 MW
% Irradiation at 12:00 p.m.	12.4 %
Daily Photovoltaic Generation *(Daily PVSP Gen.)*	7500.16 MWh
Average Daily Irradiation	5.41 $kWh.m^{-2}.day^{-1}$
Number of PVSP Panels (millions)	3.15
Installed PVSP Power	1732.94 MW_p
PVSP Plant Area	14.88 km^2
% HPP Occupancy	0.83 %

Table 5
Hydroelectric and solar generation throughout the day at the Serra da Mesa HPP (average hydroelectric generation power) – Case Study 1.

Time	Fraction (%)	PVSP Power (MW)	HPP Power (MW)	PVSP Grid Power (MW)	Power Injected into the Grid (MW)
1	0	0	344.98	0	344.98
2	0	0	344.98	0	344.98
3	0	0	344.98	0	344.98
4	0	0	344.98	0	344.98
5	0	0	344.98	0	344.98
6	1	75.00	344.98	75.00	419.98
7	4	300.01	344.98	300.01	644.99
8	6.7	502.51	344.98	502.51	847.49
9	9.1	682.51	344.98	682.51	1027.49
10	10.9	817.52	344.98	817.52	1162.50
11	12.1	907.52	344.98	907.52	1252.50
12	12.4	930.02	344.98	930.02	1275.00
13	12.1	907.52	344.98	907.52	1252.50
14	10.9	817.52	344.98	817.52	1162.50
15	9.1	682.51	344.98	682.51	1027.49
16	6.7	502.51	344.98	502.51	847.49
17	4	300.01	344.98	300.01	644.99
18	1	75.00	344.98	75.00	419.98
19	0	0	344.98	0	344.98
20	0	0	344.98	0	344.98
21	0	0	344.98	0	344.98
22	0	0	344.98	0	344.98
23	0	0	344.98	0	344.98
24	0	0	344.98	0	344.98
Total		**7500.16**	**8279.52**	**7500.16**	**15,779.68**
% of TPC of the HPP		**24.51 %**	**27.06 %**	**24.51 %**	**51.57 %**
				Total Average Power	**657.49 (190.58 %)**

4.2. Case study 2

In order to quantify the surplus power generated by the photovoltaic solar plant, a comparative analysis was conducted between its operation and the maximum power output of the hydroelectric generation (Case 2). By examining the daily energy generation between 2018 and 2022, the maximum recorded hydroelectric energy generation was 27 GWh, as depicted in Fig. 7 [65]. According to Fig. 8 [65], this value corresponds to 87.5 % (1116 MW_{avg}) of the total power capacity (TPC) of the HPP (1275 MW), indicating the potential for increased production without altering the infrastructure of the hydroelectric facility. For this purpose, data from the PVSP with a capacity of 1732.94 MWp and the maximum power of the HPP of 1116 MW were collected, as shown in Table 6.

Based on the conducted assessment, it was determined that the average power produced by the PVSP in Case 2, considering the maximum power of hydro generation, amounts to 312.51 MW_{avg}, with 74.68 % of this value being surplus. Therefore, the power injected into the grid from the PVSP plant corresponds to 79.13 MW_{avg}, which represents a 7.08 % increase in the total production of the hybrid arrangement. However, there are 233.38 MW_{avg} that are not utilized. It

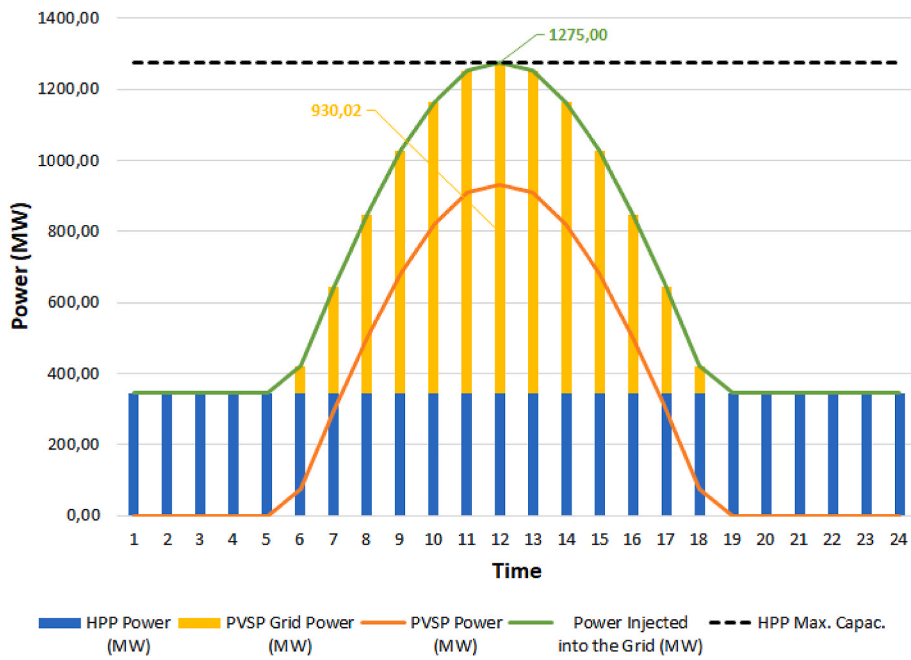

Fig. 6. Average daily operation of the Serra da Mesa HPP (average hydroelectric generation power, PVSP plant 1386.35 MWp).

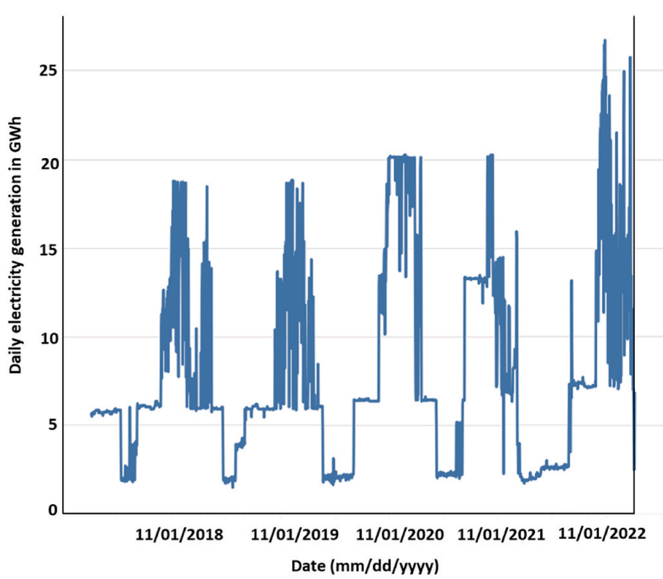

Fig. 7. Daily electricity generation (GWh) at the Serra da Mesa HPP between 2018 and 2022 [65].

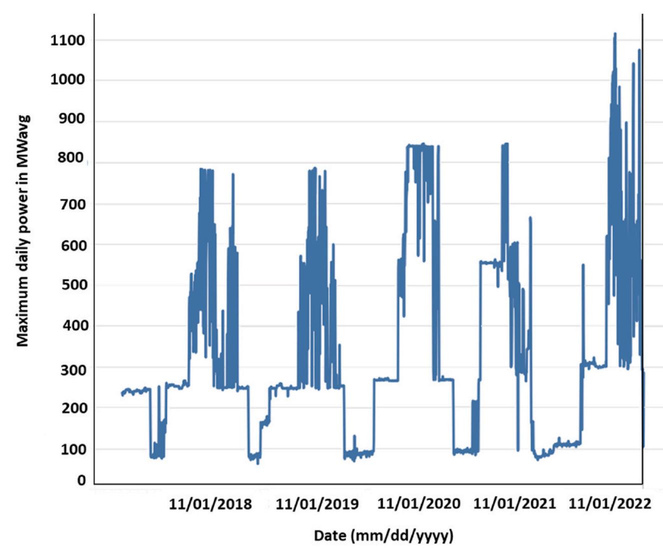

Fig. 8. Maximum daily power (in MW_{avg}) at the Serra da Mesa HPP between 2018 and 2022 [65].

was found that the hydro-solar association enabled the utilization of infrastructure equivalent to 93.74 %, representing a 6.21 % increase compared to the HPP.

The analysis of the PV plant's operational behavior throughout the day, as depicted in Fig. 9, highlights the occurrence of excess photovoltaic generation between 7:00 a.m. and 5:00 p.m., with a peak power of 771.02 MW. The excess energy generated corresponds to the amount of energy produced by the plant that exceeds the substation's transmission capacity. Furthermore, it is observed that the increase in hydraulic power contributes to the increase in surplus photovoltaic generation.

4.3. Case study 3

The fraction representing the surplus corresponds to 19.53 % of the total generated by the combined hydro-solar system. Under these circumstances, the implementation of solutions aimed at electrical energy storage, particularly those utilizing hydrogen as a means of energy transmission, could enable the capture of portions of the surplus energy derived from the photovoltaic source. According to the sizing parameters of the H_2EESS defined in section 3.3, the total of 5601.16 MW of surplus energy generated over an 11-h period (hydro plus solar generation and considering the TPP of the HPP equal to 1275 MW), amounts the limit to 509.20 MW at peak hours (7 h). This value represents the amount of energy required to produce hydrogen at noon and, therefore, must be taken into account in determining the necessary electrolyzer and hydrogen storage system capacities. Table 7 presents the description of the operation of the PVSP with an average capacity of 1732.94 MWp, along with the maximum power of the hydraulic generation (1116 MW), where a H_2EESS is employed to harness the surplus electrical energy from photovoltaic generation during the solar light interval.

Table 6
Hydroelectric and solar generation throughout the day at the Serra da Mesa HPP (maximum hydroelectric generation power) – Case Study 2.

Time	Fraction (%)	PVSP Power (MW)	HPP Power (MW)	PVSP Grid Power (MW)	Surplus (MW)	Power Injected into the Grid (MW)
1	0	0	1116.00	0	0	1116.00
2	0	0	1116.00	0	0	1116.00
3	0	0	1116.00	0	0	1116.00
4	0	0	1116.00	0	0	1116.00
5	0	0	1116.00	0	0	1116.00
6	1	75.00	1116.00	75.00	0	1191.00
7	4	300.01	1116.00	159.00	141.01	1275.00
8	6.7	502.51	1116.00	159.00	343.51	1275.00
9	9.1	682.51	1116.00	159.00	523.51	1275.00
10	10.9	817.52	1116.00	159.00	658.52	1275.00
11	12.1	907.52	1116.00	159.00	748.52	1275.00
12	12.4	930.02	1116.00	159.00	771.02	1275.00
13	12.1	907.52	1116.00	159.00	748.52	1275.00
14	10.9	817.52	1116.00	159.00	658.52	1275.00
15	9.1	682.51	1116.00	159.00	523.51	1275.00
16	6.7	502.51	1116.00	159.00	343.51	1275.00
17	4	300.01	1116.00	159.00	141.01	1275.00
18	1	75.00	1116.00	75.00	0	1191.00
19	0	0	1116.00	0	0	1116.00
20	0	0	1116.00	0	0	1116.00
21	0	0	1116.00	0	0	1116.00
22	0	0	1116.00	0	0	1116.00
23	0	0	1116.00	0	0	1116.00
24	0	0	1116.00	0	0	1116.00
Total		**7500.16**	**26,784.00**	**1899.00**	**5601.16**	**28,683.00**
% of TPC of the HPP		**24.51 %**	**87.53 %**	**6.21 %**	**18.30 %**	**93.74 %**
Average		**312.51**		**79.13**		

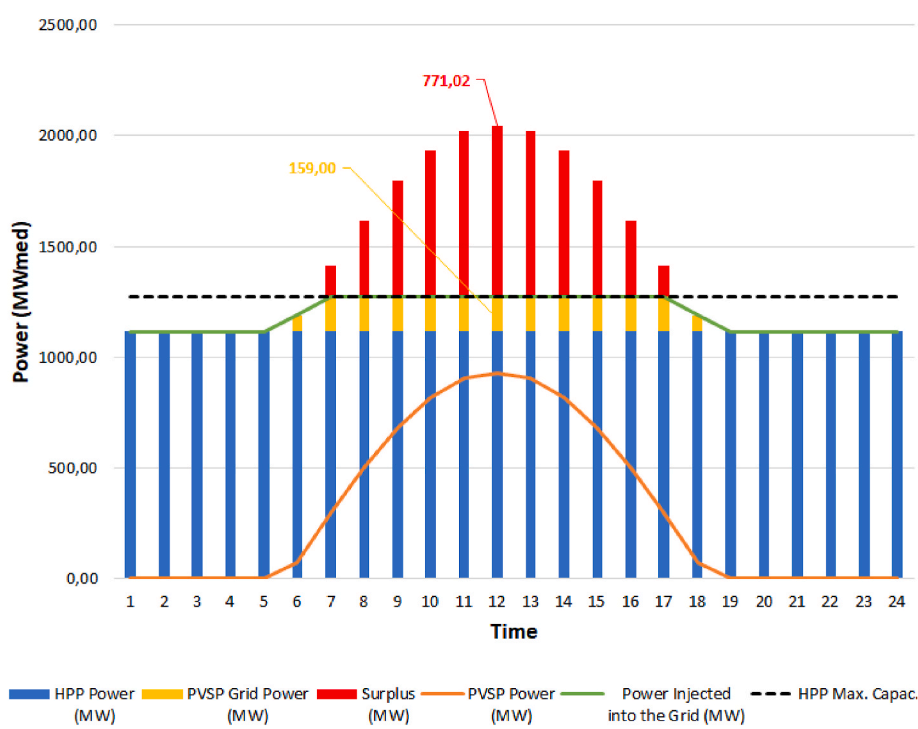

Fig. 9. Average daily operation of the Serra da Mesa HPP (maximum power of hydraulic generation, PVSP plant 1732.94 MWp).

Based on Tables 7 and it is observed that the H_2EESS stored an excess amount of 5601.16 MW (in 11 h), of which 1071 MW were subsequently utilized in the power grid, with an approximate efficiency of 23 % (1,071MW/4533.41 MW), resulting in an increase of 2970 MW per day (1899 MW of PVSP grid and 1071 MW from the FC), equivalent to a 11.10 % increase and in relation to the overall hydro-solar system, the H_2EESS contributed to a 3.5 % increase in total electricity production. To transmit the maximum amount of electrical energy generated by the HPP, it is necessary to allocate 87.53 % of the substation's capacity. However, when the PVSP plant is combined with the H_2EESS, the average power supplied is equivalent to 1239.75 MW_{avg}, corresponding to a utilization of 97.24 % of the substation's capacity. It is important to highlight that, in the absence of the H_2EESS, the substation utilization is 93.74 % (Table 6). From Tables 7 and it is possible produce Fig. 10, where it is possible to observe the respective contribution of each component regarding the total energy production. It was determined that hydroelectric generation, photovoltaic solar energy, and fuel cells account for 87.53 %, 6.21 %, and 3.5 % respectively, of the utilization of

Table 7
Hydroelectric and solar power generation supplemented by H_2EESS throughout the day at the maximum capacity of the Serra da Mesa HPP – Case Study 3.

Time	Fraction (%)	PVSP Power (MW)	HPP Power (MW)	PVSP Grid Power (MW)	Surplus (MW)	Electrolysis (MW)	H_2 Production (10^3 Nm^3)	Fuel Cell (MW)	Power Injected into the Grid (MW)
1	0	0	1116.00	0	0	0	0	82.38	1198.4
2	0	0	1116.00	0	0	0	0	82.38	1198.4
3	0	0	1116.00	0	0	0	0	82.38	1198.4
4	0	0	1116.00	0	0	0	0	82.38	1198.4
5	0	0	1116.00	0	0	0	0	82.38	1198.4
6	1	75.00	1116.00	75.00	0	0	0	82.38	1273.4
7	4	300.01	1116.00	159.00	141.01	−141.01	24.32	0	1275.0
8	6.7	502.51	1116.00	159.00	343.51	−343.51	59.26	0	1275.0
9	9.1	682.51	1116.00	159.00	523.51	−509.20	87.84	0	1275.0
10	10.9	817.52	1116.00	159.00	658.52	−509.20	87.84	0	1275.0
11	12.1	907.52	1116.00	159.00	748.52	−509.20	87.84	0	1275.0
12	12.4	930.02	1116.00	159.00	771.02	−509.20	87.84	0	1275.0
13	12.1	907.52	1116.00	159.00	748.52	−509.20	87.84	0	1275.0
14	10.9	817.52	1116.00	159.00	658.52	−509.20	87.84	0	1275.0
15	9.1	682.51	1116.00	159.00	523.51	−509.20	87.84	0	1275.0
16	6.7	502.51	1116.00	159.00	343.51	−343.51	59.26	0	1275.0
17	4	300.01	1116.00	159.00	141.01	−141.01	24.32	0	1275.0
18	1	75.00	1116.00	75.00	0	0	0	82.38	1273.4
19	0	0	1116.00	0	0	0	0	82.38	1198.4
20	0	0	1116.00	0	0	0	0	82.38	1198.4
21	0	0	1116.00	0	0	0	0	82.38	1198.4
22	0	0	1116.00	0	0	0	0	82.38	1198.4
23	0	0	1116.00	0	0	0	0	82.38	1198.4
24	0	0	1116.00	0	0	0	0	82.38	1198.4
Total		**7500.16**	**26,784.00**	**1899.00**	**5601.16**	**−4533.41**	**782.01**	**1071.00**	**29,754.00**
% of TPC of the HPP		**24,51 %**	**87.53 %**	**6.21 %**	**18.30 %**	**−14.82 %**		**3.5 %**	**97.24 %**
							Total Average Power	**44.63**	**1239.75**

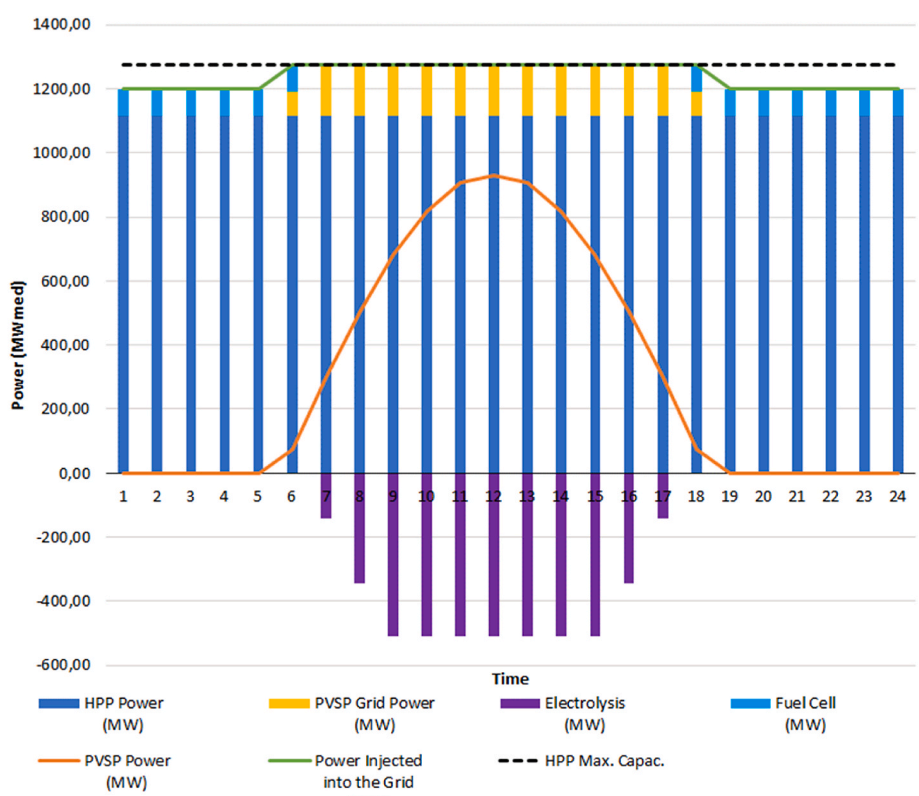

Fig. 10. Average daily operation of the Serra da Mesa HPP (maximum power of hydraulic generation, PVSP plant 1732.94 MWp) assisted by a H_2EESS – Case 3.

the substation's capacity. When combined, these values amount to a total utilization of 97.24 % of the available infrastructure.

5. Conclusions

The primary aim of this paper was to address the design of integrating photovoltaic solar systems with hydropower plants, working in a hybrid manner, through the utilization of hydrogen-based electrical energy storage systems. In this context, it was assumed as a premise that no expansions would be carried out on the existing electrical infrastructure. Thus, the following conclusions have been observed: (a) The obtained results indicate that the integration of hydro-solar systems with hydrogen-based energy storage applied at the Serra da Mesa HPP is capable of augmenting energy production by 2.97 GWh during periods of peak energy availability, representing an 11.10 % increase in the maximum generation capacity of the plant. These findings suggest that the utilization of H_2EESS holds promise as a solution to optimize the generation of electric power in hydroelectric plants, thus contributing to the expansion of a renewable and sustainable energy matrix; (b) The analyses conducted have revealed that the required areas for the installation of PVSP correspond to a negligible fraction of the evaluated reservoir, amounting to merely 0.83 % of the total area. It is worth highlighting the extensive expanse above the water surface that can be utilized for the expansion of PVSP, demonstrating a high potential for development in this technology; (c) The H_2EESS enabled the recovery of a significant surplus, equivalent to 44.63 MW_{avg}, which represents 3.5 % % of the HPP's maximum production. In this context, the implementation of H_2EESS assumes relevant roles, as it becomes possible to harness the excess energy generated by the PVSP during periods of peak PV production and enhance the energy supply during non-PV generation periods, thus optimizing the utilization of the HPP's infrastructure. Lastly, it is essential to mention that there are some relevant aspects that have not been addressed in this study and could be the subject of investigation in future works. Firstly, it would be intriguing to conduct a comparative analysis from an economic and financial perspective on the feasibility of operating PVSPs as hybrid power plants assisted by an H_2EESS. Secondly, a study could be carried out to compare the technical and economic viability of implementing energy storage systems with the expansion of infrastructure, such as the installation of power substations and transmission lines, for instance.

Declaration of Competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

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