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Assessment of Photovoltaic-Hydraulic Hybridisation for Firm Power Supply

Juan A. Tejero-Gómez[1], Ángel A. Bayod-Rújula[1], Natalia Naval[1]
[1] Department of Electrical Engineering

E.I.N.A., Universidad de Zaragoza
C/ María de Luna 3 – Zaragoza, 50018 (Spain). jatejero@unizar.es & aabayod@unizar.es

Abstract. The fight against climate change requires replacing fossil fuels with clean, low-emission energy sources. Photovoltaic technology has established itself as the most developed option among renewable energies; however, its intermittent and uncertain nature requires support systems to ensure supply stability. This paper presents simulations developed in MATLAB for the sizing of a hybrid system consisting of long-term hydraulic storage and photovoltaic generation with the capacity to provide a firm supply. The study addresses a configuration that has been little explored due to its limited current economic viability. The availability of suitable sites for hydraulic storage suggests that this could be a viable solution. The methodology is based on mathematical models integrated into an algorithm that represents the dynamic behaviour of the system, considering solar irradiance and temperature profiles. Through hourly simulations, the interaction between renewable generation and pumped storage is analysed in order to guarantee a stable supply under constant dispatch instructions at daily intervals. This study highlights the potential of converting solar photovoltaic energy into a dispatchable source, thus contributing to the transition to a cleaner and more reliable energy system.

Key words. Solar Photovoltaic, Pumped Hydro Storage, Renewable Energy Integration, Firm Power Supply, Optimal sizing.

1. Introduction

There is scientific consensus that in order to tackle the current energy crisis and climate change [1], it is essential to accelerate the integration of renewable energies. Furthermore, the decarbonisation of the electricity system is central to the roadmaps towards net zero emissions [2]. In this context, the drastic reduction in the cost of solar photovoltaic technology [3] has consolidated it as a highly competitive alternative to fossil fuel-based technologies. It is estimated that by 2030, global installed solar photovoltaic capacity could exceed 7 TW [4], with an annual rate of close to 1 TW [4], a scale unprecedented to date. Likewise, in the coming years, solar photovoltaics will account for around 80% of the global increase in renewable capacity [5].
However, the intermittent, random and variable nature of solar radiation makes it difficult to integrate solar photovoltaic energy into the electricity system and poses challenges in ensuring its stability. Pumped hydroelectric storage systems are a mature and widely implemented technology. They are characterised by their high efficiency, reliability and long service life exceeding 50 years [6]. They provide large-scale energy storage, making them a flexible and dispatchable solution capable of mitigating the intermittency inherent in solar photovoltaic generation when both technologies are combined to supply energy.
The integration of photovoltaic plants with hydroelectric storage systems has received considerable attention in recent scientific literature; examples include [7–9]. The inherent regulation capacity of pumped-storage power systems makes it possible to effectively offset the variability characteristic of photovoltaic generation. Furthermore, using the reservoirs themselves as a platform for floating photovoltaic installations maximises the use of available space, reducing the need for additional land and minimising the impacts associated with land use.
In this context, the optimal sizing of the storage volume is a critical design parameter, the correct determination of which influences both the system's energy performance and the viability of the infrastructure.
This paper analyses the integration of solar photovoltaic generation with pumped storage systems, with the aim of converting intrinsically variable photovoltaic production into a firm and constant supply, capable of providing robustness and stability to the electricity grid.

2. Methodology

Figure 1 illustrates the schematic of the proposed hybrid system, comprising a photovoltaic plant and a pumped-storage hydropower facility. The PV plant injects energy into the grid to meet the required constant power demand. Any surplus solar generation is utilised to pump water into the upper reservoir. Conversely, when PV production is insufficient to satisfy the grid power setpoint, the system operates in generating mode, dispatching the stored water to cover the energy deficit. The proposed model assumes full operational availability of the system, neglecting downtime associated with preventive or corrective maintenance in both the PV plant and the pumped-storage system. While this limitation represents an idealisation of the physical system, it simultaneously constitutes a methodological strength. By eliminating the stochastic variability inherent in maintenance events, the analysis focuses exclusively on average meteorological variables, ensuring the reproducibility of the results across different geographical or climatic scenarios. The hybridization of utility-scale solar photovoltaic plants with hydroelectric storage systems presents a significant operational limitation due to its strong dependence on local hydrological availability. Specifically, this approach is highly vulnerable to prolonged droughts, which can substantially reduce the active storage volume of the reservoirs and, consequently, the system's energy backup capacity. Furthermore, the exploitation of water resources for energy generation must be integrated into a multi-purpose water management framework, where it competes with priority demands such as agricultural irrigation, municipal water supply, and the maintenance of environmental flows.

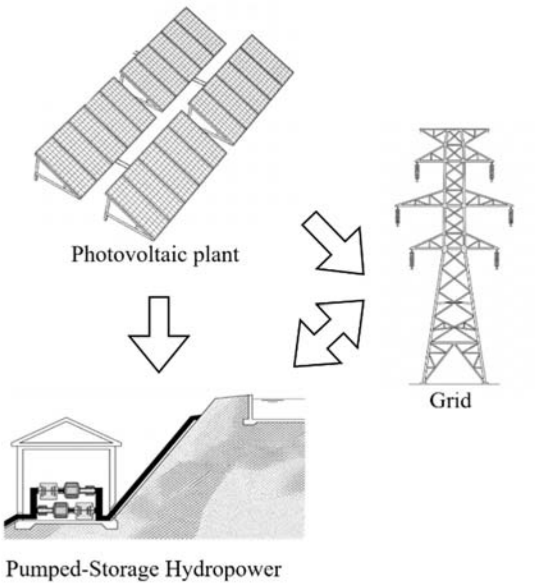

Fig. 1. Schematic diagram of the hybrid photovoltaic-pumped storage hydropower (PV-PSH) system.

Figure 2 shows the basic operating strategy based on an energy balance for a representative day. In this balance, PV represents the photovoltaic energy produced, TURB the energy produced by the turbine, PV-GRID the fraction of photovoltaic energy injected directly into the grid to meet the constant power requirement, and PV-PUMP the surplus photovoltaic production used for pumping to the upper reservoir. In this way, the sum of PV-GRID and TURB guarantees a firm and constant power supply 24 hours a day. The energy behaviour of the proposed system is modelled and analysed using simulation in Matlab R2023a [10]. Using hourly intervals and the variables defined in Table I, a long-term simulation is performed from 1 January 2010 to 31 December 2020, encompassing a complete 11-year solar cycle. To guarantee the robustness of the findings, this methodology processes extensive volumes of data to extract underlying patterns and mitigate the influence of specific outliers. The hourly data on solar irradiance on the plane of the photovoltaic module and ambient temperature are obtained from the PVGIS-SARAH2 database [11], taking a location in Zaragoza (Spain) as the geographical reference.

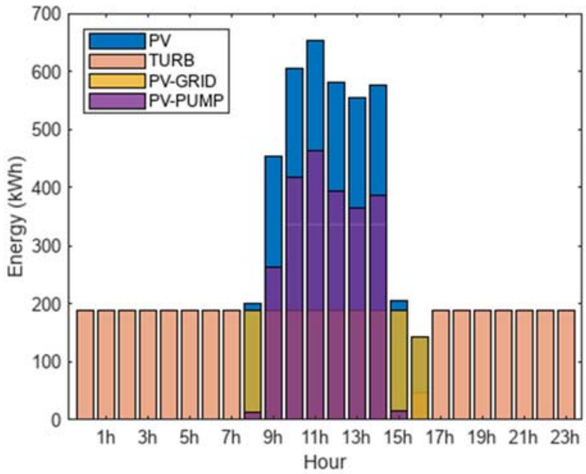

Fig. 2. Hourly energy balance in the system.

Based on these variables, Equations (1) are applied at hourly intervals to estimate the photovoltaic energy produced. Where T_C is the cell temperature, T_A is the ambient temperature, G_M is the irradiance, NOCT is the panel operating temperature, E_{PV} is the photovoltaic production, P_N is the nominal power of the panel, γ is the temperature coefficient, and G_{STC} are the ideal irradiance conditions.

$$\begin{aligned} T_C &= T_A + G_M \cdot \left(\frac{\text{NOCT} - 20}{800}\right) \\ E_{PV} &= P_N \cdot G_M \cdot \left(\frac{1 + \gamma \cdot (T_C - 25)}{G_{STC}}\right) \end{aligned} \quad (1)$$

When photovoltaic production is lower than the power setpoint, all the energy generated is fed into the electricity grid. Conversely, when production exceeds this setpoint, the surplus energy is used to power the pump to the upper reservoir. Any deficit in photovoltaic generation with respect to the power setpoint is compensated by the hydroelectric power station turbine. The flow rate required for energy generation in the turbine is calculated using Equation (2), where E_{TURB} is the energy to be generated by the turbine, g is gravity, H is the height of the reservoir, H_{LOSS} is the losses associated with conduction (2 m), and η_G is the generator efficiency (0.85) [12].

$$Q_{TURB} = \frac{E_{TURB}}{g \cdot (H - H_{LOSS}) \cdot \eta_G} \cdot \frac{1\,m^3}{1000\,l} \cdot \frac{3600\,s}{1\,h} \quad (2)$$

The flow rate to be pumped to the upper reservoir due to surplus photovoltaic production is calculated using Equation (3), where $E_{PV\text{-}PUMP}$ is the energy required to raise the flow rate and η_M is the pumping efficiency. Energy variables represent hourly energy, or in other words, hourly power.

$$Q_{PUMP} = \frac{E_{PV-PUMP}}{g \cdot (H - H_{LOSS}) \cdot \eta_M} \cdot \frac{1\,m^3}{1000\,l} \cdot \frac{3600\,s}{1\,h} \quad (3)$$

Flow deficits due to the upper reservoir being empty and insufficient photovoltaic production are accounted for using the E_{DEF} variable. Energy that could not be stored in the upper reservoir because it was full and there was surplus photovoltaic production is accounted for using the E_{EXC} variable. Therefore, the strategy that aims to cover photovoltaic deficits and surpluses with respect to the setpoint is analysed using the indicators associated with these two variables. At all times, priority is given to dispatching photovoltaic production to the grid, rather than pumping it.

Table I. - Variables

COL.	PARAMETER	DESCRIPTION	UNIT
1	Hour	Time of day	h
2	Day	Day of month	
3	Month	Month of year	
4	Year	Year	
5	G_M	Irradiance	
6	T_A	Ambient temperature	º C
7	T_C	PV cell temperature	º C
8	E_{PV}	PV energy produced	kWh
9	E_{SUPPLY}	Constant power supply	kWh
10	$E_{PV-GRID}$	PV energy supply	kWh
11	$E_{PV-PUMP}$	Surplus PV for pumping	kWh
12	E_{TURB}	Energy to turbine	kWh
13	Q_{TURB}	Flow rate to turbine	$m^3 \cdot h^{-1}$
14	Q_{PUMP}	Flow rate to be pumped	$m^3 \cdot h^{-1}$
15	V_{UP}	Available capacity	m^3
16	V_{DEF}	Total flow deficit	m^3
17	V_{SUR}	Total flow surplus	m^3
18	$E_{/TURB}$	Energy not turbined (empty)	kWh
19	$E_{/PUMP}$	Energy not pumped (full)	kWh

3. Results

In the case of a 1 MW photovoltaic plant and a long-term simulation of 11 years, various model runs are performed using simulation. Considering an upper reservoir capacity of 6 hm^3 (equivalent to 6 x 10^6 m^3), Figure 3 shows the temporal evolution of its reservoir water volume, with a maximum value of 5.9 hm^3 reached in 2016 and a minimum of 1.29 hm^3 recorded in 2014. Recurring seasonal patterns associated with variations in photovoltaic production are identified. This scenario confirms the feasibility of supplying a constant level of power from renewable sources, backed up by pumped hydroelectric technology. Throughout the period, there are no energy deficits or surpluses.

The enlargement included in Figure 4 allows us to observe in detail the seasonal pattern corresponding to one year. The annual reservoir volume profile exhibits a cyclic pattern driven by solar radiation seasonality. A significant depletion phase occurs between winter and early spring, with storage falling to a minimum of 1.45 x 10^6 m^3.

Subsequent to this point, the reservoir undergoes a quasi-linear recovery phase, peaking at 5.15 x 10^6 m^3 by late October. The consistency between the year-end and initial January levels suggests that the proposed operational strategy maintains a stable long-term hydrologic balance.

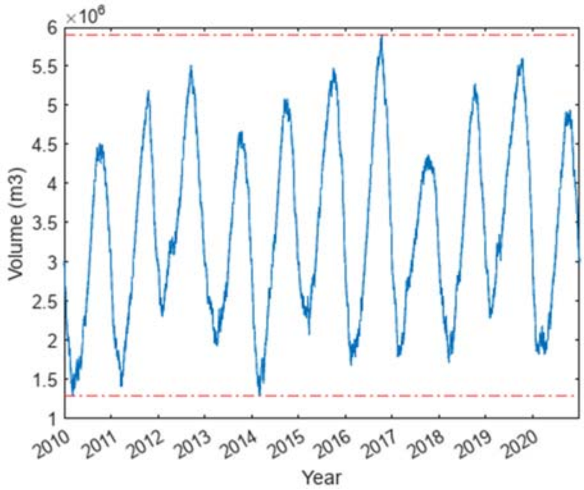

Fig. 3. Stored water volume for a full simulation.

Figure 5 shows the average monthly photovoltaic energy production. Generation peaks in July and August, exceeding 230 kWh / month. In winter, December and January record the lowest values, below 150 kWh / month.

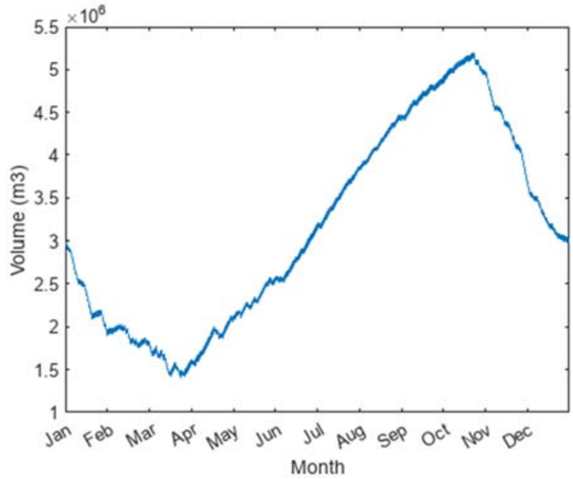

Fig. 4. Volume in the reservoir within the area of interest.

This seasonal variation is directly linked to the number of hours of sunshine and the levels of incident irradiance. This seasonal pattern determines the charging and discharging dynamics observed in the system volume in Figure 4. The system operates as a seasonal storage system: the energy surpluses generated in summer offset the winter production shortfall.

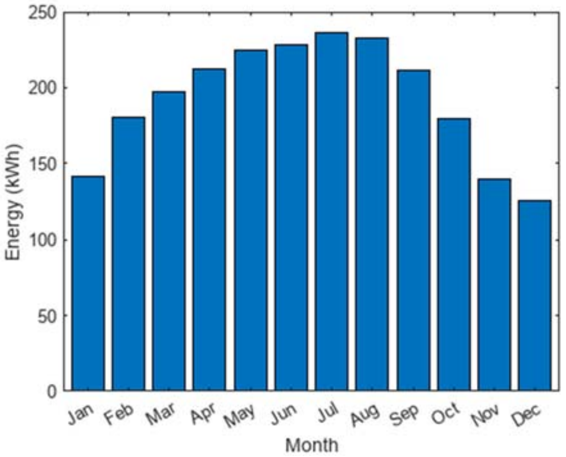

Fig. 5. Average photovoltaic production.

An operating regime has been identified that is capable of converting all photovoltaic output into firm and constant power, ensuring strict compliance with the setpoint. However, the required storage capacity may prove technically unfeasible due to its excessive size. Given this limitation, 600 simulations were carried out, increasing the storage capacity up to a limit of 6 hm^3. The purpose of this analysis is to determine the optimal storage capacity by evaluating the correlation between the surplus energy that the system cannot store (EXCESS) and the net energy that is actually supplied to the electricity grid (SUPPLY).
Figure 6 shows the sensitivity of both variables to variations in reservoir volume. In this graph, the x-axis represents storage capacity in m^3, whilst the y-axis quantifies the energy supplied by the system and the excess energy. The results reveal asymptotic behaviour in Figure 6. The SUPPLY variable shows logarithmic growth and the EXCESS variable a reciprocal reduction. Both curves reach a state of saturation where a marginal increase in storage capacity does not result in a significant improvement in either energy variable.

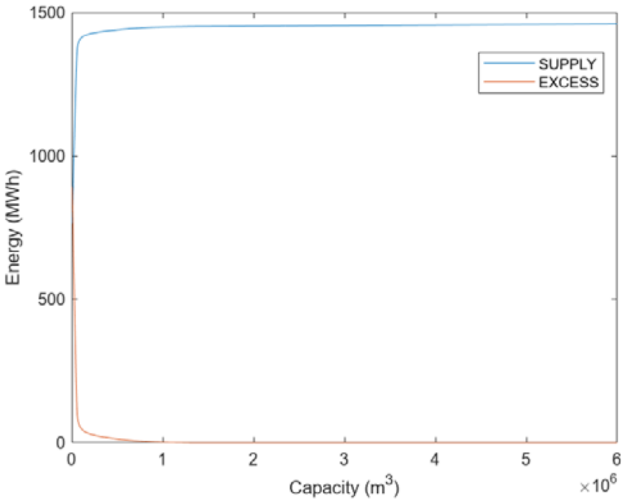

Fig. 6. Average annual energy supplied by the system (SUPPLY) and system surpluses (EXCESS) based on reservoir capacity.

Figure 7 details the saturation zone of the energy variables shown in Figure 6, identifying a reservoir volume of 60,000 m^3 as the operational limit point. In the range from 0 to 60,000 m^3, the system exhibits significant performance improvements. Beyond this threshold, the energy supplied to the electrical grid stabilizes with minor variations above 1,400 MWh, while non-storable energy surpluses decrease to below 80 MWh, also with negligible fluctuation.
These results indicate that the initially proposed volume of 6 hm^3 is excessive. Sizing the reservoir at the inflection point of the curve prevents infrastructure oversizing, as capacities exceeding 60,000 m^3 yield no significant operational benefit.

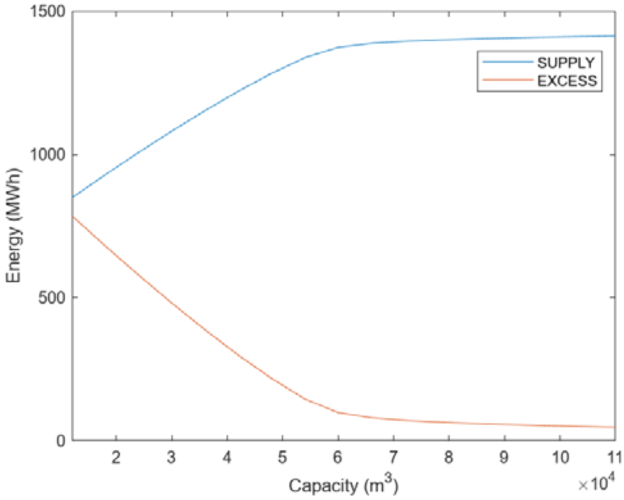

Fig. 7. Enlarged view of Figure 6, focusing on the initial saturation zone.

The results demonstrate the reliability of the proposed hybrid system. Pumped-storage hydropower effectively compensates for the inherent intermittency of photovoltaic generation, ensuring a firm power supply.

4. Conclusion

The results obtained demonstrate that hybridising photovoltaic generation with pumped hydro storage is a complementary and effective solution for transforming an intrinsically variable renewable source into a steady and constant power supply, achieving an ambitious goal with no margin for operational error. Through long-term analysis, a reservoir size capable of guaranteeing such continuous supply has been identified, confirming the technical feasibility of the proposed approach. The system utilises all photovoltaic output over the 11-year simulation period. The storage capacity required to ensure both the absence of an energy deficit and the disposal of surpluses is determined, based on a constant annual output power target. An optimal capacity has been determined for the reservoir. This volume does not guarantee the full supply of the required baseload power. However, adopting this capacity prevents the infrastructure from being unnecessarily oversized.
As future lines of research, we plan to evaluate power settings defined in shorter time periods, with the aim of reducing the size of the storage required and optimising the overall design of the system.
The reliable and efficient integration of non-dispatchable renewable generation sources constitutes one of the most prominent challenges in current energy systems literature. Although this study has focused on pumped-storage hydropower as the primary backup mechanism, the hourly

fluctuations in solar generation can induce excessive cycling, leading to significant mechanical fatigue in the pumping equipment. Consequently, the integration and optimal sizing of Battery Energy Storage Systems is proposed as a future line of research. This hybridization would enable a more stable operation of the hydropower plant by reducing the frequency of start-ups and shut-downs. Furthermore, since the dynamic response of the hydraulic system may be too slow to handle abrupt transients in the grid, a detailed analysis of these combined control strategies is imperative.

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