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# Energy arbitrage in PV-PHS systems

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**Abstract.** In this paper, we use MHOGA software for the evaluation of adding pumped hydro storage (PHS) for energy arbitrage in utility-scale PV generating systems. PHS is used for electricity price arbitrage, pumping water from the lower reservoir to the upper reservoir with the PV generation during hours of low electricity price and generating electricity by means of the stored water with the turbine during hours of high price (during these hours the PV generator also injects its production to the grid). The control strategy creates setpoints for the use of the pump and the turbine, trying to obtain the maximum benefits from the electricity sold to the grid, maximizing the net present value (NPV). An example of application is shown, obtaining conclusions about the economical viability of the PV-PHS system compared to the PV-only system: in the case studied in this work, it is not worth to add PHS to the PV system.

**Key words.** PHS, PV, utility-scale, price arbitrage, SPOT price.

## 1. Introduction

Renewable generators sell electricity to the AC grid in the long term market through a power purchase agreement (PPA) or in the daily / intraday market establishing the marginal cost of electricity (SPOT price, representing the cost of supplying an additional MWh to the grid) [1].

Energy storage can bring energy arbitrage and ancillary services. In renewable generation systems, PHS can avoid their unbalances (which cause unpredictable deviations from the predicted production) [2] and in some cases the increase in benefits due to price arbitrage can compensate its investment cost. PHS benefits for renewable power are: curtailment reduction, frequency regulation, fast and flexible ramping, black start and capacity firming [3].

Depending on the SPOT prices and PHS CAPEX and OPEX costs, energy arbitrage with PHS could be profitable. In this paper we evaluate and optimize a utility-scale PV-PHS system, considering the 2021 SPOT prices in Spain and assuming an increase of 1% annual in these prices during the 25 years of the system lifetime.

## 2. System description

The PV-PHS system consist of a PV generator (with its own inverter), a reversible pump-turbine or two different machines and upper and lower reservoirs (Fig. 1, where only upper reservoir is shown). The lower reservoir could also be a river or the sea.

The benefits are obtained by selling electricity to the AC grid. PV-only systems inject all the electricity to the AC grid at the time when it is being generated, but PV-PHS system can store electricity by pumping water or generating electricity by the hydro turbine (using the stored water), depending on the electricity price: during hours with low electricity prices pump stores water in the upper reservoir with the PV generation and during hours with high electricity prices hydro turbine generates electricity and injects it to the grid, maximizing benefits (energy arbitrage). Also, when PV power is higher than the maximum power that can be injected to the AC grid, pump uses the surplus power to store water.

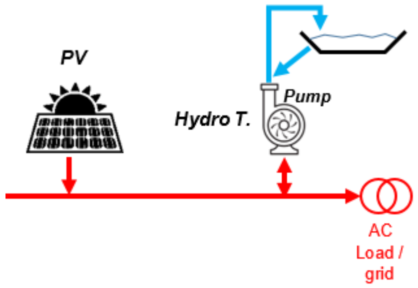

Fig. 1. PV-PHS system (it can be a reversible pump-turbine machine or two different machines) (MHOGA software [4]).

In this case, the maximum allowed power to be injected to the grid is Pmax_grid = 3 MW. Considering the Spanish SPOT prices of 2021, the optimal PV-only system consists of a PV generator of 6 MWdc with an inverter of 4.8 MWac.

In this work we will evaluate the economical viability of adding PHS storage (PV-PHS system), optimizing the control strategy setpoints for the use of the pump and the turbine, trying to obtain the maximum benefits.

The simulation and optimization of the system will be performed by MHOGA software (MegaWatt Hybrid Optimization by Genetic Algorithms) [4]. This software can simulate and optimize off-grid or grid-connected renewable systems (PV, wind and/or hydro), with or without storage (batteries, PHS and/or hydrogen), with or without fossil fuel generator. Energy arbitrage optimization and other advances features are included in the software.

### *A. Location and irradiation*

The system will be located in Huesca province, near the Pyrenees mountains, in Spain (latitude 42.53º N, longitude 0.32º W). The irradiation and temperature hourly data during one year can be directly downloaded by the software from different databases. In this case we will use the PVGIS [5] database, downloading hourly data for the year 2020, PV slope 35º, azimuth 0º (south faced), Fig. 2 and 3.

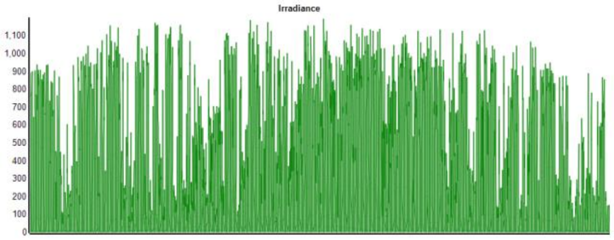

Fig. 2. Hourly Irradiance (W/m$^2$), PVGIS, year 2020, slope 35º, azimuth 0º

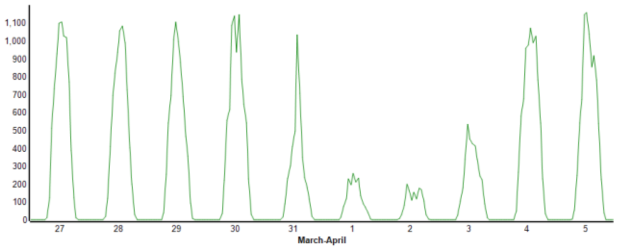

Fig. 3. Hourly Irradiance (W/m$^2$), PVGIS, 10 days of March-April 2020, slope 35º, azimuth 0º

### *B. Costs and sell electricity price*

The total investment cost (CAPEX) of a PHS plant depends on many factors, from a low estimate for USA of 2,500 €/kW (for 9 h power plant duration) to the high estimate of 3,500 €/kW (for 18 h power plant duration), assuming 1€=1$ conversion [6]; however IRENA [3], for all the world, considers CAPEX from 617 to 2,465 €/kW; in Ref. [7] the value of 1,000 €/kW was used for the base case, which consist of 80 MW turbine, 70 MW pump and water reservoir of 560 MWh (that is, 7 h of full capacity operation in the generation mode). In this work we will consider PHS of different duration, from 3h to 20 h, with CAPEX from 1,000 to 1,500 €/kW. Regarding PHS OPEX costs, they are around 30.4 €/kW/yr [6], that is, around 2% of the CAPEX, value which will be used in our work. The PHS lifetime considered will be 25 years.

Regarding PV generator, CAPEX cost (included its own inverter) considered is 0.8 €/Wac (now it is even lower in Spain) and OPEX annual cost is 1% of CAPEX.

Financial costs considered are the following: nominal discount rate 7%, general inflation rate 2%, installation and other costs 25% of CAPEX.

The electricity SPOT price of 2021 in Spain (Spanish electricity system operator [9]) has been considered for the selling electricity price, Fig. 4. A 1% annual increase will be considered during the 25 years of the system lifetime.

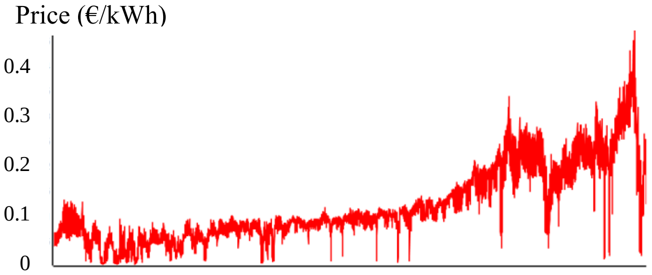

Fig. 4. SPOT price (€/kWh), Spain, year 2021

### *C. Components characteristics*

In our case, the maximum power that can be injected in the HV AC grid will be limited to 3 MWac.

First we have optimized the PV-only system, considering PV generators from 1 to 10 MWdc (the AC power, that is, the output of the inverter is multiplied by 0.8) in 1 MW steps, including MPPT but no sun tracking system in this case (fixed slope of 35º, south). NOCT is 43º and power temperature coefficient -0.4%/ºC. PV lifetime is expected to be the same as the system lifetime (25 years). PV inverter efficiency is considered variable with output power, with a maximum of 97% (Fig. 5) [10].

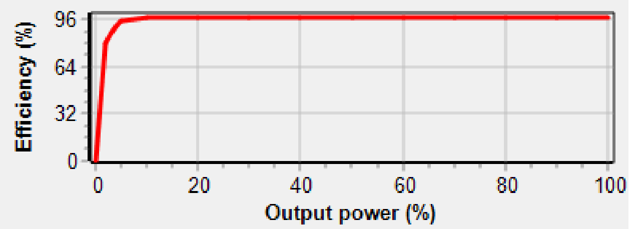

Fig. 5. Inverter efficiency (%) vs output power/rated power (%)

The optimal PV-only system consists of a PV generator of 6 MWdc with its inverter of 4.8 MWac.

In the optimization section we will consider this optimal PV system to which we will add PHS, considering 6 different possibilities, from 0.5 to 3 MW (2 to 12 m$^3$/s max. flow) reversible pump/turbines, in steps of 0.5 MW (costs from 1,500 €/kW to 1,000 €/kW in steps of 100 €/kW), with a reservoir of 130 dam$^3$ (net volume) and an available head of 30 m. Friction losses will be considered as constant value of 4%. When the upper reservoir is full, water stored energy (MWh) will be E = 10.2 MWh, obtained by equation (1):

$$E = V \cdot \rho \cdot g \cdot H / 3600 / 1000 \qquad (1)$$

Where V is the water volume (130 dam$^3$), ρ is the water density (1,000 m$^3$/kg), g is the gravitational acceleration (9.81 m/s$^2$) and H the available head minus losses (30·0.96 = 28.8 m).

Therefore, the storage energy duration when hydro turbine works at full power will be between 10.2 MWh / 0.5 MW = 20.4 h and 10.2 MWh / 3 MW = 3.4 h, depending on the PHS rated power.

Hydro turbine mechanical efficiency considered is shown in Fig. 6, this efficiency will be multiplied by the multiplier gearbox efficiency (98%), by the generator efficiency (95%) and by the transformer efficiency (98%).

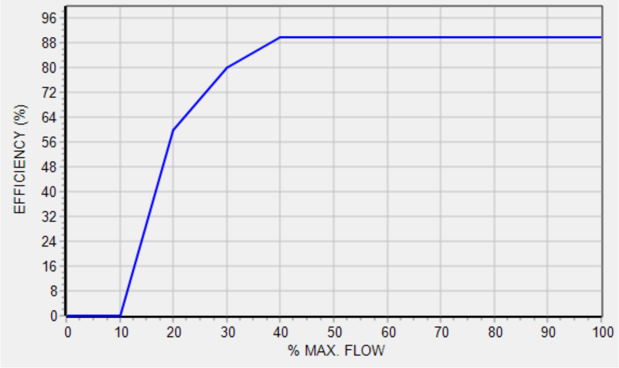

Fig. 6. Hydro turbine efficiency (%) vs. maximum flow (%).

In the pump mode, the machine efficiency considered is 90%.

## 2. PHS management strategy for price arbitrage

The management of the PHS uses 3 variables, this kind of management was previously used in a previous publication for battery storage [11]:

- X1: it is the minimum difference between the maximum and minimum price of each day such so that it can be profitable to use PHS. If a given day the difference between the minimum price and the maximum price is less than X1, it is not worth using PHS, so pump/turbine won't be used that day. If this difference is greater than X1, PHS can be used that day.
- X2: it is the percentage of the difference between the maximum and minimum price of the day that is added to the minimum price so that in the hours whose price falls within that range the pump is used to store water in the upper reservoir, using the renewable power.
- X3: it is the percentage of the difference between the maximum and minimum price of the day that is subtracted from the maximum price so that in the hours whose price falls within that range the turbine is used to generate power and sell it to the AC grid.

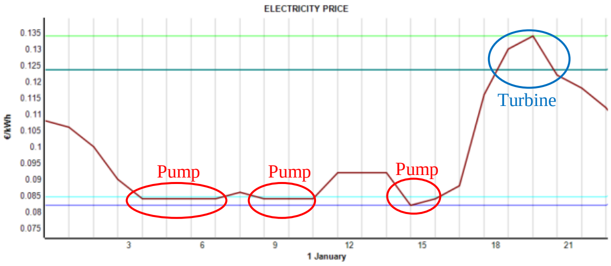

Fig.7. PHS management for a specific day with X1 = 0.06 €/kWh, X2 =5%, X3 = 20%.

As an illustrative example, Fig. 7 shows the hourly price of a specific day with X1=0.06 €/kWh, X2 = 5% and X3 = 20%.

X1 value is for the first year of the simulation, next years (up to the system lifetime) X1 will be increased in the same 1% annual as the SPOT electricity price.

In this work the strategy will be optimized to maximize benefits from selling electricity to the grid.

Also, pump is used whenever the PV output power is higher than the maximum allowed to inject to the AC grid (Pmax_grid = 3 MWac), with the surplus power that cannot be injected to the grid.

## 3. System optimization

The optimal PV-only system of 6 MWdc (4.8 MWac) has a net present value (NPV) of 4,01 €, accounting all the incomes for the energy selling and costs (including CAPEX, OPEX for the different years, components replacement during the system lifetime and residual value of the components at the end of the system lifetime), converting all the incomes and costs to the initial time of the inversion.

Now we will optimize the PV-PHS system, considering the same 6 MWdc (4.8 MWac) PV generator and 5 cases of PHS, from 0.5 to 3 MW in steps of 0.5 MW, with the characteristics shown in section 2.C. For each combination of PHS, the software evaluates 10 cases for each control variable, therefore it evaluates $10^3$ = 1000 different cases of PHS management.

After evaluating all the combinations, they are sorted from best to worst NPV. Also other economical parameters are calculated, as internal rate of return (IRR), capacity factor, levelized cost of energy (LCOE), etc.

## 4. Results

The optimal configurations (system with maximum NPV) obtained for the PV-only system and for the PV-PHS systems are shown in Table I.

In both cases the optimal system includes a PV generator of 6 MW. The optimal PV-PHS includes a pump/turbine of 1 MW (with the 10.2 MWh water reservoir), therefore the storage duration is of 10.2 h (considering efficiencies it is reduced to 10.2·90%·98%·95%·98% = 8.37 h).

We can see that the NPV of the PV-PHS is lower than the PV-only, therefore, it is not economically viable to add PHS in the conditions of this case. Also, the investment cost in PV-PHS is higher, with lower IRR and higher LCOE.

PV-PHS capacity factor (defined as annual energy sold to the grid divided the maximum power allowed to inject to the grid x 8760 h) is higher than PV-only one, as more energy is injected to the grid during the year.

Table I. – Optimal configurations for PV-only and PV-PHS systems

| | PV-only | PV-PHS |
|---|---|---|
| **PV (MW)** | 6 | 6 |
| **PHS (MW)** | 0 | 0.5 |
| **PHS management strategy: X1 (€/kWh), X2(%), X3(%)** | - | 0.003 €/kWh, 0%, 100% |
| NPV (M€) | 4.01 | 3.55 |
| Investment cost (M€) | 6 | 6.94 |
| IRR (%) | 13.4 | 12 |
| Capacity factor (%) (defined as Sell energy divided Pmax_grid·8760) | 29.9 | 31.6 |
| LCOE (€/kWh) | 0.060 | 0.066 |
| PV generation (GWh/yr) | 9.59 | 9.559 |
| Pump energy (GWh/yr) | - | 0.663 |
| Hydro turb. energy (GWh/yr) | - | 0.459 |
| Pumping hours per year | - | 1,468 |
| Turbine running hours per year | - | 1,157 |
| Sell energy (GWh/yr) | 7.86 | 8.32 |
| Sell incomes, 1st year (M€) | 0.83 | 0.88 |
| Sell incomes, NPV (M€) | 10.69 | 11.38 |
| PV costs, NPC (M€) | 5.48 | 5.48 |
| PHS costs, NPC (M€) | - | 0.96 |

Each system is simulated during a whole year, but, in order to show the performance of the system, in Fig. 8 we can see the simulation of 3 consecutive days for the optimal combination of PV-PHS.

The three days the difference between the maximum and minimum electricity price of the day is higher than X1 = 0.036 €/kWh, therefore the PHS is ready to work these days. In the upper chart of Fig. 8 we see the electricity price, the lower limit to discharge (that is, to use the turbine, turquoise line, X3=100% under the maximum of the day, that is, all the day the priority is to use the turbine) and the higher limit to charge (that is, to use the pump, X2=0%, in this case this means that the priority is never to pump, pump only works when there is surplus energy that cannot be sold to the AC grid).

The first day during the night the upper reservoir is at 0, therefore during the hours when strategy implies using the turbine in the night, it cannot work (no water in the upper reservoir). During the day, in the midday, there are several hours when PV output is higher than the maximum that can be injected to the grid, therefore the surplus power is used to pump water (dark blue line). The thin blue line shows the water energy in the upper reservoir (right axis). As the priority during all the day is to use the turbine, the first hour with no surplus power the turbine runs (thick blue line), injecting electricity to the grid. It continues until there is no net water in the upper reservoir.

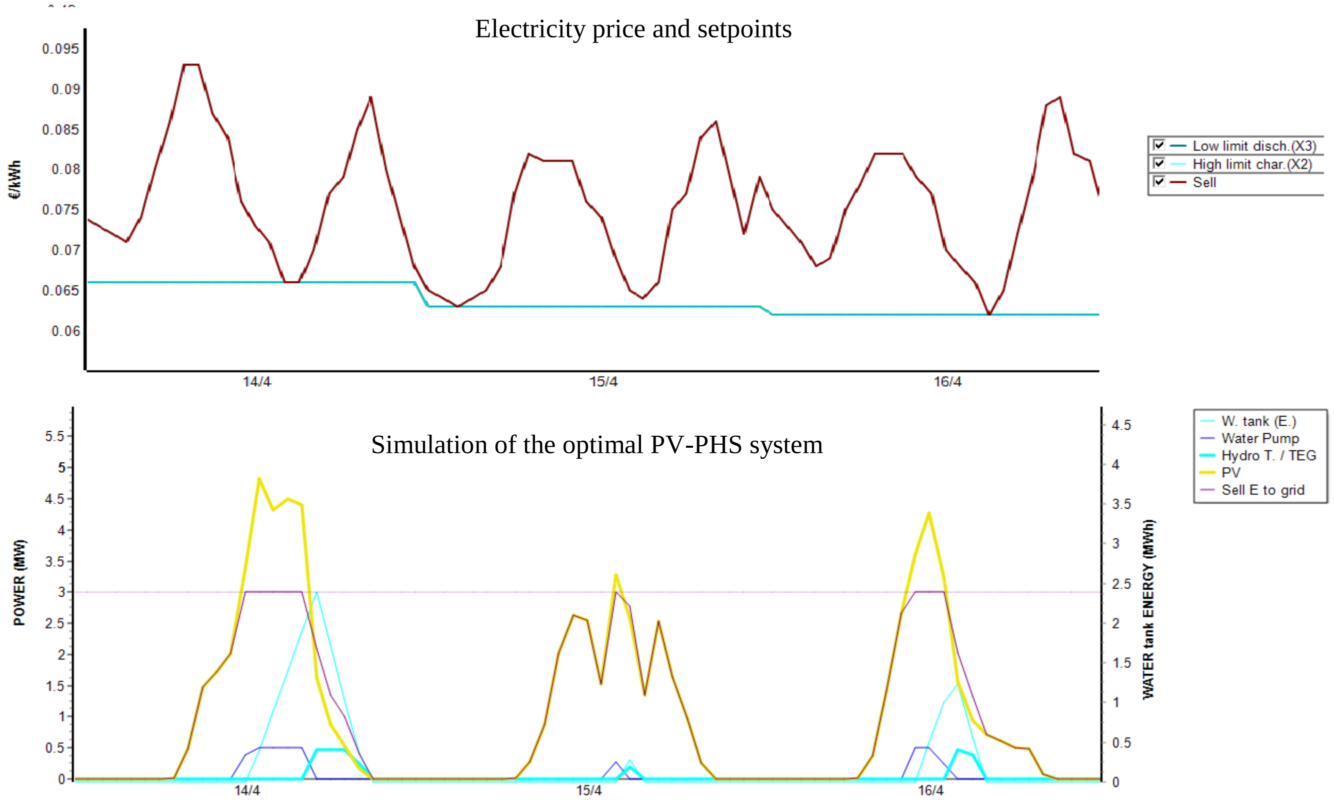

Fig. 8. Electricity price with the setpoint limts for the PHS management (up) and simulation of the optimal PV-PHS system for three consecutive days (14th to 16th April).

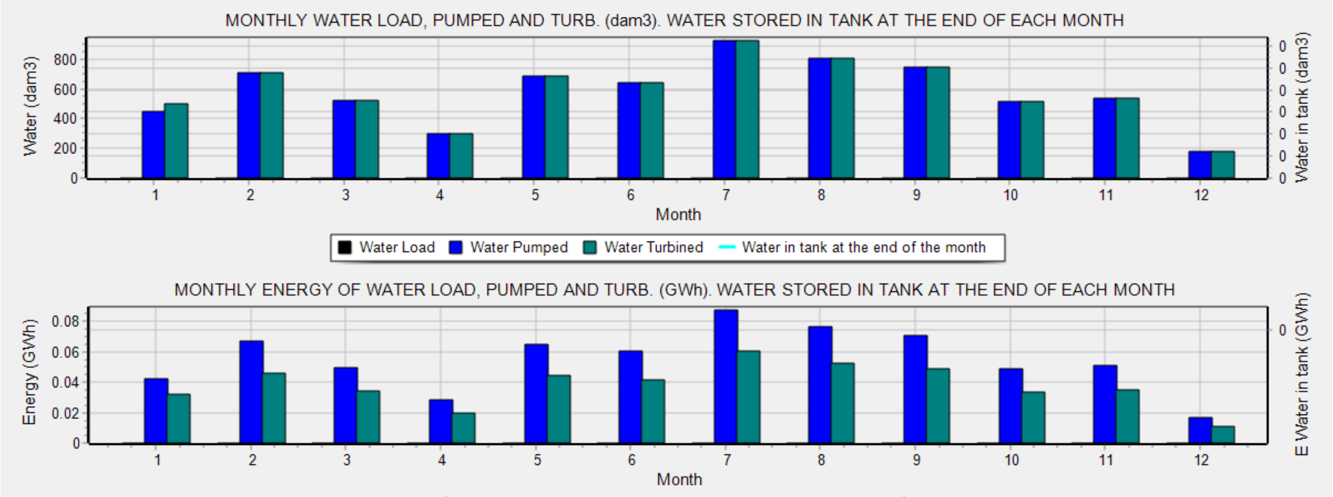

Fig. 9. Monthly values of water pumped (dark blue) and water turbined (green) referred to left axis; water stored in the upper reservoir (light blue line) referred to right axis is not shown as at the end of every month it is in 0 (upper reservoir empty). Upper chart water in dam$^3$, lower chart energy in GWh.

Fig. 9 shows the monthly values of water pumped, turbined and stored in the optimal PV-PHS system. Water stored at the end of each month is 0 (reservoir empty), as everyday at midnight the reservoir has been fully discharged. Fig. 10 shows the hourly water pumped / turbined and the water stored in the upper reservoir. The upper reservoir capacity is 130 dam$^3$, but at the beginning of the simulation (first hour of the year) the reservoir capacity is 50 dam$^3$, we can see that due to the optimal management, the reservoir is never full, the maximum (except for the first hour of the year) is about 40 dam$^3$.

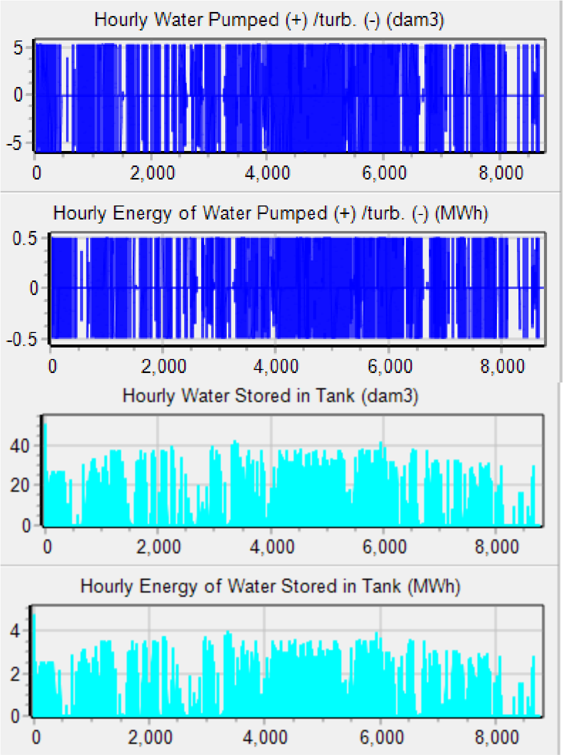

Fig. 10. Hourly water pumped (+) / turbined (-) (dark blue) and water stored in the upper reservoir (light blue), in dam$^3$ and MWh. Stored energy in this graph is considered as the energy needed to store the water in the upper reservoir, considering the pump efficiency of 90%.

## 5. Conclusion

In this paper, we have used MHOGA software for the optimization of a PV-PHS system, using the PHS for energy arbitrage to maximize the benefits. The PV-only system is compared to the optimal PV-PHS, evaluating different options for PHS, from 3 to 20 h storage duration and optimizing the PHS size and its management strategy in order to maximize NPV. In the case evaluated, considering SPOT electricity prices of 2021 with expected annual increase of 1% and PHS cost of 1,400 €/kW (for the case of 1 MW, 10.2 h storage duration, which was obtained the optimal one), the PV-PHS system is not economically viable compared to the PV-only, as its NPV is lower than the NPV of the PV-only system. Also PV-PHS has higher LCOE and lower IRR. However, the capacity factor of the PV-PHS system is higher than PV-only system. The optimal management of the PV-PHS system is obtained by using energy arbitrage, pumping water to the upper reservoir when electricity price is low (using the PV generation) and generating electricity by means of the turbine and injecting it to the grid when price is high. The management strategy has been optimized using three setpoint variables.

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