Hybrid energy solution with pumped-storage: modelling, sensitivity analyses and case study

Gonçalo Santos Cerejo Amaro

goncalo.cerejo.amaro@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

The high intermittence of renewable energy sources conditions the production of electricity, which remains highly dependent on fossil fuels. Since there is complementarity between renewable energy sources, their joint integration could be a good solution to reduce this dependency. Together with this, a pumped-storage system capable of generating hydro reserves can coexist to supply the surplus demand.

In the present dissertation, two models were developed: one about turbomachine's costs and another to study the potential of a hybrid energy solution with a pumped-storage system. Through this last model, the combined production of hydro and wind, hydro and solar, and the combination of the three as well were analysed. The developed models propose two operating options for storage: i) pumping and hydroelectric generation due to the difference between the demand and the energy supplied; ii) pumping and hydroelectric generation as function of the tri-hour tariff of the energy consumption applied in Portugal. Different solutions were analysed, according to the demand and installed power, for different heads and storage volumes, assuming three conventional turbines and a pump as turbine, for which an economic analysis was developed.

Finally, a pre-design of a hybrid energy solution with a sea water pumped-storage system was carried out, as a possible model to apply in the Portuguese coast. For the established demand, the solution adopted allows a total energy satisfaction of 81 %, being 30 % supplied by hydroelectric storage.

Key-words

Renewable energy; hybrid energy solution; pumped-storage.

1. Introduction

Nowadays, the question of social, economic and environmental sustainability is already in developed countries concerns. There is an objective to improve the management of available natural resources so that the needs of the current population are guaranteed, without compromising the needs of future generations. This vision extends to the energy sector too. Instead of the exploitation of fossil fuels, renewable energy sources should be a primary solution to produce electricity. In addition to fossil fuels becoming increasingly scarce, their use is responsible for a large part of gas emissions of greenhouse effect to the atmosphere, contributing to a poor-quality environment.

The reason why renewable energy does not correspond to a higher percentage of total consumption is because these sources have a high temporal variability, since they depend on climatic conditions. This intermittence generates a considerable difference between supply and energy demand over time, occurring periods in which the supply is higher, and therefore there is energy that is not properly used, and periods where the supply is less, forcing the use of fossil fuels to guarantee the energy consumption.

Rather than increasing the installed renewable energy power, it is important to make a more efficient management of these resources by looking for solutions that are aimed to backup production failures due to their intermittency. The joint production of renewable energy sources, such as hydro, wind and solar, could be a very effective solution to overcome this problem, since these sources complement each other. To a hybrid energy solution of this kind, a system with pumped-storage can be added, taking advantage of the wind and solar energy that is not consumed (when the consumption is lower than the supply), to create hydro reserves that later will be used in hydroelectric energy production to satisfy the peak demand.

2. Renewable energy and pumped-storage

Europe has been made a huge investment in renewables in this early century. Data released by the Environment Energy Agency (EEA 2017) show that since 2005, the share of renewable energy sources in final energy consumption has increased by an average of 6.7% per year (having slowed slightly in the last 2). The EU goal is to reach the target of 20% of renewable energy use by 2020. By 2016 the share is estimated to have been 16.9%, so it is within the expected. Of the 28-member states, Sweden is arguably the most prominent (with a 54% share), followed by Finland and Latvia (40% and 38%, respectively). Portugal appears in this study in seventh place (28%), contributing positively to this European average. The same study also highlight that Portugal was one of the 9 EU countries that registered significant reductions in emissions of greenhouse gases (more than 10% from 2005 to 2015). In fact, the Portuguese territory has huge potential for energy production from renewable energy sources, such as hydro, wind, bioenergy, and solar. However, 2017 brought a setback, since it was marked by the presence of extreme drought conditions, which reflected in hydroelectric production, which decreased to just 1/3 of the 2016 production. Consequently, only 44.3% (22 956 GWh) of the total electricity consumption in Portugal (51 839 GWh), came from renewable sources. In the opposite direction was the fuel fossil energy that complemented with 31 567 GWh. This reversal resulted in an increase in carbon dioxide emissions of more than 25% over the previous year, which accounted for approximately 15 x 10^6 $tonCO_2$ (APREN 2017). The electric energy sale price has also increased, since it is lower the greater the representativeness of renewable production.

Although there is often insufficient renewable production to ensure consumption, an in many other times there is surplus. To avoid waste, this surplus energy can be exported through a good connection to the electrical grid, or it can be stored, to be used in periods of greater demand. There are several ways to store energy, but it is difficult to do it on a large scale. Pumped-storage is, to date, the most economical and efficient technology. It is still under construction the largest hydropower complex ever built in Portugal. Composed by three dams (Alto Tâmega, Daivões e Gouvães), this complex will have a total installed generation capacity of 1158 MW, able of producing more than 1760 GWh per year, equivalent to 6% of the electricity consumption in Portugal (Iberdrola 2017). It will be equipped with a pumping system that connects it to the Daivões reservoir (Figure 1), capable of moving volumes between one reservoir to another whenever necessary, and it will be the first, in a national context, to store surplus energy from wind production. There are also complementarity between solar and hydro power. Still in test phase, there is a floating photovoltaic solar power plant in Alto do Rabagão reservoir (Figure 2). This is a pilot project in Europe, which has 840 photovoltaic (PV) panels in an area of 2500 m^2, corresponding to 0.2 MW of installed capacity, which could generate 300 MWh per year (EDP 2017).

In addition to allowing the integration of other renewable energies, such as solar and wind (overcoming their intermittent production), pumped-storage has another important advantage: it does not depend on the rainfall or the available upstream flows, and thus, the proper use of hydro power is more efficient. Among other issues, the biggest disadvantage is that it requires the construction of two reservoirs, so a high initial investment will be necessary. However, this can be avoided by using the sea as the bottom reservoir. The proof that this can be done is the Okinawa Yanbaru Seawater Pumped-Storage Power Station, in Japan (Figure 3). The use of the sea water will require the choice of specific materials and a more demanding maintenance of the structural components, due to corrosion issue, but equivalent to desalination plant. Nevertheless there are already technologies able to overcome this situation, such as self-priming paints that can protect pipelines and turbomachines (Montemor 2018).

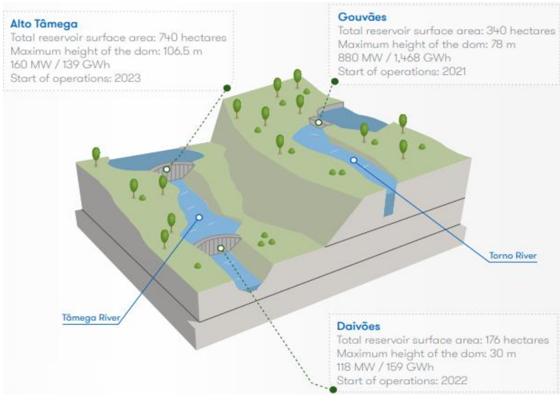

Figure 1 – Tâmega hydropower complex (Iberdrola 2017)

Figure 2 – Floating photovoltaic solar power plant in Alto do Rabagão reservoir

Figure 3 – Okinawa Yanbaru seawater pumped-storage power station

3. Developed models

In this chapter, two different models were developed: one about turbomachines' costs and other about the potential of a hybrid energy solution with pumped-storage.

3.1. Turbomachines' cost model

For this model, 4 different turbomachines' types were considered: Pelton, Francis, Kaplan and PAT (Pump as Turbine). The first tree are well known conventional turbines with an efficiency higher than 85% (Ramos 2000) and the last one can't go further than 70% (Carravetta et al., 2018). Nevertheless, these turbomachines are very effective for low powers and can be very useful in a pumped-storage system, since they can operate in both ways, and are more economic than turbines (so it can be easily used more than one unit, without having prohibitive costs).

Turbines' cost can be estimated based on Table 1:

Table 1 – Turbines' cost (Ogayar et al., 2009)

Turbine	Cost (€)
Kaplan	$31\,196 * P^{0.41662} * H^{-0.113901}$
Francis	$25\,698 * P^{0.439865} * H^{-0.127243}$
Pelton	$17\,693 * P^{0.635275} * H^{-0.281735}$

Since there are few studies about PAT's cost, a more detailed analysis was developed. Vilanova has elaborate a formulation about PAT's cost, for installed power (P) up to 100 kW, since they vary in a different way for higher power's values (Vilanova, 2007). He states that there is no direct relationship between power and PAT's cost, and the head (H) has a major influence on this matter. Hence 4 equations as function of installed power (one for each head's range) are suggested:

$$\text{C (€)} = -0.02P^2 + 143.0P + 1\,655.7;\ 0 < H_u \leq 30 \quad (1)$$

$$\text{C (€)} = -0.10P^2 + 152.9P + 1\,641.9;\ 30 < H_u \leq 50 \quad (2)$$

$$\text{C (€)} = -0.04P^2 + 134.8P + 1\,732.6;\ 50 < H_u \leq 75 \quad (3)$$

$$\text{C (€)} = -0.05P^2 + 144.5P + 1\,647.8;\ 75 < H_u \leq 100 \quad (4)$$

Recent studies (Novara et al. 2018) show a cost comparison of 4 different PAT options: radial pump with 1, 2, or 3 pairs of magnetic poles (pp) and vertical multi-stage pump with 1 pair of magnetic poles:

$$\text{C(€)} = 11\,589.32Q\sqrt{H_u} + 1\,389.79\ ;\ radial\ pp{=}1 \quad (5)$$

$$\text{C(€)} = 12\,864.77Q\sqrt{H_u} + 1\,281.25;\ radial\ pp{=}2 \quad (6)$$

$$\text{C(€)} = 15\,484.97Q\sqrt{H_u} + 1\,172.72;\ radial\ pp{=}3 \quad (7)$$

$$\text{C(€)} = 24\,928.61Q\sqrt{H_u} + 1\,177.98;\ vertical\ pp{=}1 \quad (8)$$

The radial ones have similar cost and are less expensive than the vertical multistage pump. This is due to the fact that the vertical pumps have higher efficiencies for a wider flow range.

To cover higher installed power (up to 1000 kW), a new generalized equation was proposed:

$$\text{C (€)} = 150P + 2\,084 \quad (9)$$

The Figure 4 shows the PAT's unit cost, and in Figure 5 is presented the unit cost for the 4 types of turbomachines considered in this developed model. The PAT's cost varies between 2200 and 150 €/kW for power values from 1 kW to 1 MW. For higher powers, it is assumed that cost remain constant and equal to 150 €/kW. It also can be concluded that PAT's unit cost can be 5 times lower than conventional turbines.

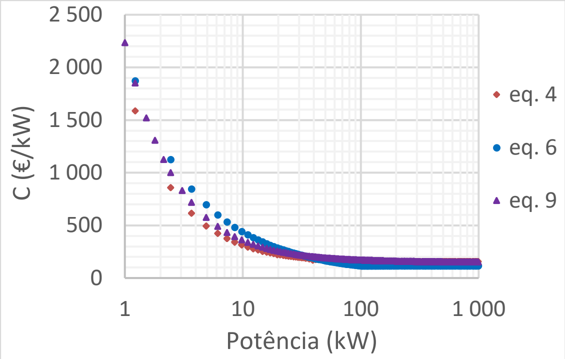

Figure 4 – PAT's unit cost

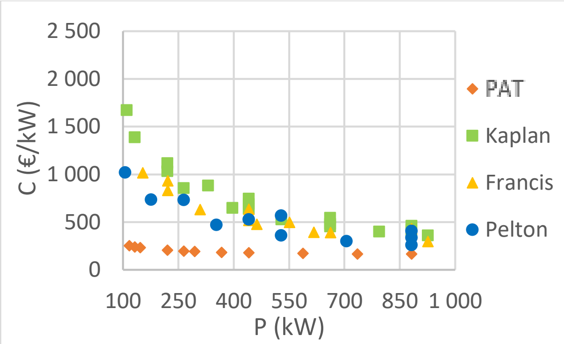

Figure 5 – Turbomachines' unit cost

3.2. Hybrid solution with pumped-storage modelling

To study the operation of a pumped-storage system combined with wind and/or solar energy production, was developed a computational model that verifies the capacity of the upper reservoir to bridge the gap between the energy's offer/demand and production or storage depending on whether there is lack or excess of energy production by the considered renewable sources considered. The model was developed for 1-year time series, with hourly variations of the demand and wind and/or solar data series. Up next is shown the input and output data, the two different options adopted for the pump-storage systems operation, and the 4 types of turbomachines, and respectively restrictions:

I. Input:

- ρ water density
- g gravity acceleration
- H_0 net head
- H_t total elevation
- η_t turbine efficiency
- η_p pump efficiency
- Q_t^{Min}/Q_t^{Max} minimum turbined flow fraction allowed
- Q_p^{Min}/Q_p^{Max} minimum pumped flow fraction allowed
- $D_{adim}^{(i)}$ adimensional demand at hour "i"
- D_p peak demand
- $P_{w/s.adim}^{(i)}$ adimensional wind/solar energy at hour "I"
- $P_{w/s}^{Inst}$ wind/solar power installed
- $P_{w/s}^{Efet}$ wind/solar effective power
- $Rest_{grid}$ grid restriction
- V_{Res}^{Max} maximum reservoir's volume
- V_{Res}^{Min} minimum reservoir's volume

II. Output:

- $D^{(i)}$ demand at hour "i"
- $E_{w/s}^{(i)}$ wind/solar energy at hour "i"
- $\Delta_E^{(i)}$ difference between wind/solar energy and demand t hour "i"
- $E_h^{(i)}$ hydro energy at hour "I"
- $E_p^{(i)}$ pump energy at hour "i"
- E_h^{Max} maximum hydro energy
- E_p^{Max} maximum pump energy
- $V_{res}^{(i)}$ reservoir's volume at hour "i"
- $V_p^{(i)}$ pumped volume at hour "i"
- $V_t^{(i)}$ turbined volume at hour "i"
- V_p^{Max} maximum pumped volume
- V_t^{Max} maximum turbined volume
- Q_p^{Max} maximum pumped flow
- Q_t^{Max} minimum turbined flow

III. Pumped-storage system's operating options:

i. Pumping and hydro generation as function of the difference between energy offer and demand:
   - If $\Delta_E^{(i)} < 0 \rightarrow E_h^{(i)} = -\Delta_E^{(i)}\ e\ E_p^{(i)} = 0$;
   - If $\Delta_E^{(i)} > 0 \rightarrow E_h^{(i)} = 0\ e\ E_p^{(i)} = \Delta_E^{(i)}$.

ii. Pumping and hydro generation as a function of the tri-hour tariff of the energy consumption applied in Portugal:
   - Pumping when the energy price is low (between 0 an 7h);
   - Hydro generation in remaining hours.

For these two options the system as to calculate and verify this:

- $P_{w/s}^{Efet} = P_{w/s}^{Inst} * Rest_{red}$
- $E_{w/s}^{(i)} = E_{w/s.adim}^{(i)} * P_{w/s}^{Efet}$
- $D^{(i)} = D_{adim}^{(i)} * D_p$
- $\Delta_E^{(i)} = E_{w/s}^{(i)} - D^{(i)}$
- $V_{res}^{Min} = 0.15 * V_{res}^{Max}$

- $V_{res}^{(i)} = V_{res}^{(i-1)} + V_p^{(i)} - V_t^{(i)}$
- $If\ V_{res}^{(i)} \geq V_{res}^{Max} \rightarrow V_p^{(i)} = 0$

  $else\ \ V_p^{(i)} = \dfrac{E_p^{(i)} * \eta_p}{\rho * g * H_t} * 3600$
- $If\ V_{res}^{(i)} \leq V_{res}^{Min} \rightarrow V_t^{(i)} = 0$

  $else\ \ V_t^{(i)} = \dfrac{E_h^{(i)}}{\rho * g * H_0 * \eta_t} * 3600$
- $V_p^{(i)} \geq \frac{Q_p^{Min}}{Q_p^{Max}} * V_p^{Max}$
- $V_t^{(i)} \geq \frac{Q_t^{Min}}{Q_t^{Max}} * V_t^{Max}$

IV. Turbomachine's conditions:

With this model and based on Table 2the design project of a pumped-storage can be developed.

Table 2 – Turbomachines' conditions

Turbomachine	$\frac{Q_t^{Mín}}{Q_t^{Máx}}$	η_t	$\frac{Q_b^{Mín}}{Q_b^{Máx}}$	η_p
Kaplan	0.2	0.8	0.5	0.7
Pelton	0.2	0.9	0.5	0.7
Francis	0.4	0.8	0.5	0.7
PAT	0.7	0.5	0.5	0.7

By specifying a head and a maximum volume for the upper reservoir, for a peak demand and a wind/solar power installed:

- $E_h^{Max}\ and\ E_p^{Max} \rightarrow Turbomachine(s)$
- $V_t^{Max}\ e\ V_p^{Max} \xrightarrow{Q=V/3600} Q_t^{Max} e\ Q_p^{Max} \xrightarrow{D=2*\sqrt{\frac{Q}{U\pi}}} D$

4. Hybrid solution with pumped-storage analyses

Using the previous developed models, deeply extended sensitivity analyses of the hybrid solution with pumped-storage performance were carried out. As a basis for comparison, Tables 3 and 4 shows the fulfilled demand and the energy that is not consumed, for wind and solar production, respectively, without a pumped-storage system. Then, for each turbomachine, different heads and stored volumes were analysed, for an energy power installed equals to the double or the triple of the peak demand. Firstly, it was carried out a separately analysis of the combination of wind + hydro (Figure 6) and solar + hydro (Figure 7), for each pumped-storage system operating option (i and ii). Later, it was analysed the integration of the tree sources (i.e., hydro + wind + solar), for different combinations of wind and solar power installed (in MW), for a unitary peak demand (D_p=1 MW), a head of 200 m and a storage volume of 100 000 m^3.

It is easily observed that the use of wind or solar energy as only source of electricity supply may not be sufficient to fulfil the demand. Comparing wind and solar, the first one can meet higher demand fulfilment, and this value will be greater as the relationship between installed power and peak demand increases. The production of solar energy, although more predictable, presents lower values of demand's fulfilment, not varying much with the installed power. Since photovoltaic production has zero values on many occasions (during night). When there is no pumped-storage system capable of bridging the flaws of these two intermittent sources, much of the wind and solar energy generated is not consumed locally and must be exported to not be wasted. With a pumped-storage system, a larger share of wind and photovoltaic energy is used to fulfil the demand, reducing the need of fossil fuels and the consequent emissions of greenhouse gases. The analysis of solutions with a pumped-storage system concludes that the ones with Pelton or Francis are more effective. In fact, based on economic analysis, Francis turbines are more suitable for these types of project since it can be used in a reversible way (i.e., it can be used as a pump), dismissing the use of a pump for the flow reverse purpose. PAT also can work in both ways, although it presents poor demand's fulfilment. Nevertheless, its consideration could be very useful, since they are economic, and then, the number of units in the system can be easily increased, covering a wider range of flow, allowing more demand to be fulfilled. The results show that with just one more PAT unit in the system, it can duplicate the demand fulfilment.

Table 3 – Wind exploitation without pumped-storage

P^{inst}	Wind energy	
	Fulfilled Demand	**Not cons. energy**
$=D_p$	41 %	3 %
$=2xD_p$	64 %	24 %
$=3xD_p$	75 %	41 %
$=5xD_p$	85 %	60 %

Table 4 – Solar exploitation without pumped storage

P^{inst}	Solar energy	
	Fulfilled Demand	**Not cons. energy**
$=D_p$	31%	5%
$=2xD_p$	41%	37%
$=3xD_p$	44%	55%
$=5xD_p$	48%	71%

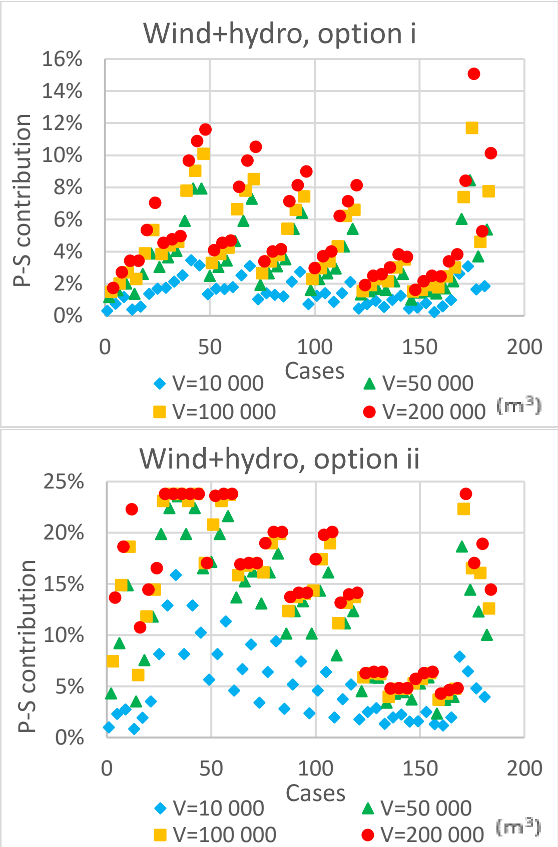

Figure 6 – Pumped-storage contribution to the wind exploitation

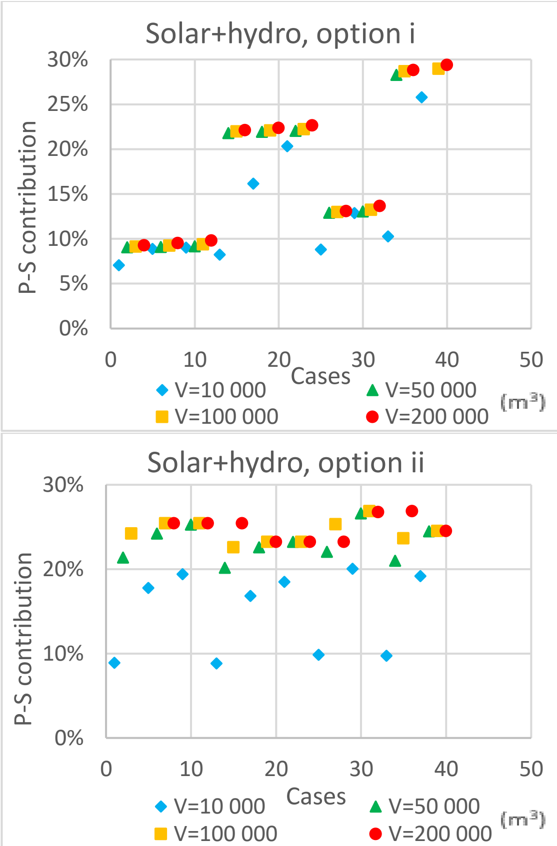

Figure 7 – Pumped-storage contribution to the solar exploitation

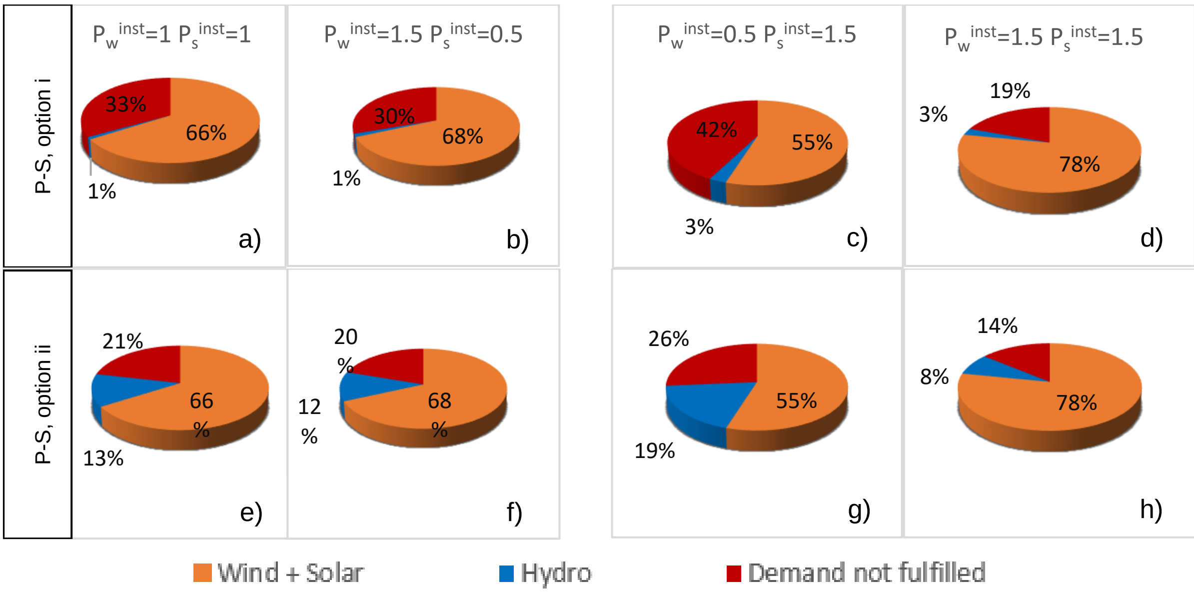

Figure 8 – Contribution of the different energy sources to demand fulfilment (D_p=1 MW)

Comparing the two operating options (option i - pumping due to excess wind / solar production, option ii - pumping according to the electric energy price tariff) in most situations, option ii fulfils more demand.
The joint action of wind and solar energy production presents good results of demand's fulfilment. Since the installed wind and solar power values tested were not much higher than the peak demand, there was no surplus, so the operating option i presented a reduced fraction of demand fulfilment by hydropower. Operating option ii presented again better results, proving the solutions that exhibit the highest installed wind power share satisfy a higher percentage of consumption.

5. Case study – Hybrid solution with sea water pumped-storage pre-design

5.1. General considerations

In this chapter proceeded to the design of a hybrid solution with sea water pumped-storage. Projects as these do not need a construction of a lower reservoir since the water intake is made directly by the sea. Although, it needs to design an upper reservoir. This must be near sea and relatively high to get a maximum power profit, and to reduce pipeline costs. It should find a place with a natural depression to reduce the excavation works and must be larger than deeper to have less water stratification, and consequently less problems with the eutrophication.
For this case study, it was considered a single conduit, for both pumping and generation, with a hydropower plant with one single Francis turbine, that can operate in reversible mode too (as pump). This project also integrates the combined production of wind and solar energy, and so, it is needed to find a place for them as well. Since solar power needs a large area, it was opted to take place the photovoltaic solar panels on the upper reservoir's water surface, within a floating platform. This way not only it can save outside space, but also can help refrigerate the panels system, promoting better efficiencies for production. Wind power must be located nearby on a higher place to obtain higher wind velocities.

5.2. Location

The location chosen for the case study was the Sintra region, since it is a coastal zone that has some high plateaus of considerable altitude. The upper reservoir will take place at the geographical coordinates of 38 ° 47'4 "N (latitude) and 9 ° 29'26" W (longitude). This site shows a good relation between distance to the coast and altitude (450/140=3.2) and has enough space with a generous maximum width (about 240 m), without houses nearby (see Figure 9).

Figure 9 – Upper reservoir location

The PV panels will be on upper reservoir's water surface, on a floating platform of 7 500 m^2 (2520 PV panels) with a total production capacity of 0.6 MWh. The wind farm will be located adjacent to the interior, at an altitude of 400 m, and it will be constituted by 3 wind turbines with 150 m height, spaced 250 m apart and with a total installed capacity of 6 MW (2 MW for each module).

5.3. Pre-Design

5.3.1. Upper reservoir

It was opted to design a hexagonal shape for the upper reservoir surrounded by a 2 m crest around, made with excavation remain material, and it will have a maximum depth of 20 m. With hexagonal side of 110 m, it will have a total area of 31 437 m^2. Admitting a maximum and minimum height of 18 and 3 m, respectively, it was counted a total admissible volume for generation of 343 219 m^3. With this value, a fixed head of 140 m, and with the use of the developed model for pumped-storage, it was calculated the project flow – 4.11 and 2.49 m^3/s, for generation and pumping, respectively.
To prevent the water to drain out of the reservoir, it was considered a rubber sheet EPDM (Ethylene-Propylene-Diene), 10 mm thick, which exhibits excellent chemical properties and weather resistance (for temperatures between -40 and 125 °C).

5.3.2. Hydraulic circuit

It was considered a single circuit for both generation and pumping action. Admitting a maximum flow velocity of 2 m/s, and a project flow of 4.11 m^3/s, the minimum diameter for the tunnel is 1.62 m. Therefore, a diameter of 1.7 m was chosen. It will be in natural excavation tunnel, not only due to its dimensions but also to allow the hydropower plant to be protected underground. It was considered a geotextile coating on the deteriorated parts of the tunnel, to minimize the

head losses. The length of the penstock and tailrace tunnels are 218 and 340 m, respectively.
It was calculated the singular and friction head losses for both generation and pumping. The net head and the total elevation head are 136.00 and 143.56 m, respectively.

5.3.3. Hydropower plant

It was designed a single unit for both generation and pumping. The Francis turbine can do this job, and is suitable for a net head of 136 m and a project flow of 4.11 m^3/s. It was calculated the group parameters – turbine power (P), rotational speed (N), specific speed (n_s) and number of pair of poles (n_{pp}) shown in Table 5.

Table 5 – Group parameters

n_{pp}	N (r.p.m)	n_s (r.p.m)	P (kW)
3	1 000	153	5 053

The powerhouse is installed at level –11.5 m. The Francis has the suction head required since it is under the outlet level (that is the sea level), and therefore cavitation problems are avoided.

5.3.4. Coast protection

One of main issues of sea water pumped-storage is the water intake from the sea. The waves that arrive to the coast line can cause several damages to the hydraulic circuit (inclusively the powerhouse, if it is near the coast), or even to the cliffs nearby. For the water intake, it must have a sufficient length to reach the bathymetry of -15 to -20 m, where the sea cannot induce tensions to the structure (fluid structure interactions), and there is no risk of enter any residual or sea debris to the hydraulic circuit (Katsaprakakis et al. 2013). For this case study, the bathymetry of -20 it is placed at 580 m from the coast (920 m from the powerhouse), and therefore, it was not chosen this option for the intake/outlet. The alternative is to build a breakwater, with rocks or precast concrete modules, capable of sustain the impact of the waves, dissipating their energy, and protecting the inside reservoir. With this option the tunnel excavation or the cliff destruction are also protected.
To allow the operation of the bottom water intake, the water needs to percolate trough the breakwater, between the voids. Hence, the levels, inside and outside, are the same. Precast concrete modules with a tetrapod shape were chosen. These modules are very effective in energy wave dissipation and have 50 % of porosity.
To calculate the mass of the block, it was considered that the breakwater will take place at 35 m from the coast, where the significant head (H_s) is 6.3 m. The design values of tetrapod – mass (M), nominal diameter (D_n), height (h), volume (V) and thickness of the layer (e_c) – are shown in Table 6.

Table 6 – Design values for tetrapod model

M (ton)	D_n (m)	h (m)	V (m^3)	e_c (m)
23.02	2.12	3.25	9.59	4.22

To allow the water percolation, the breakwater design includes a core with tetrapod blocks. These ones could be bigger (40 ton with 2.55 and 3.9 m of diameter and height, respectively). Hence, the breakwater's height is 7 m.

5.3.5. Transients

The transient regime is associated to pressure and velocity variations, when fast, can lead to very high instantaneous pressures, which propagate along the hydraulic circuit. These pressure variations may be caused by variations in the valve manoeuvres or due to shutdown/start-up of a turbomachine (Ramos 2000).This case study has frequent stops/starts, and therefore, the study of pressure variations is of utmost importance for the design.
Firstly, it was determined the wave speed (1462 m/s), and then 4 different times (2 fast and 2 slow manoeuvres) were defined.
It was estimated the pressure variations along the hydraulic circuit, and the variations along time at the valve immediately upstream the turbine, as function of the time closure/stop, for both generation and pumping. This calculation was done with a hydraulic simulator model (*Hammer*) and the results were compared with theoretical formulations by Joukowski and Michaud, for fast and slow manoeuvres, respectively.
At last, it was defined the minimum time closure of the valve, to avoid cavitation in the system. It was the pumping mode that conditioned this time (63 s), due to have higher pressures than in the turbine mode. Figure 10 shows the pressure variation along the hydraulic circuit, for this

minimum time of 63 s, to avoid cavitation occurrence.

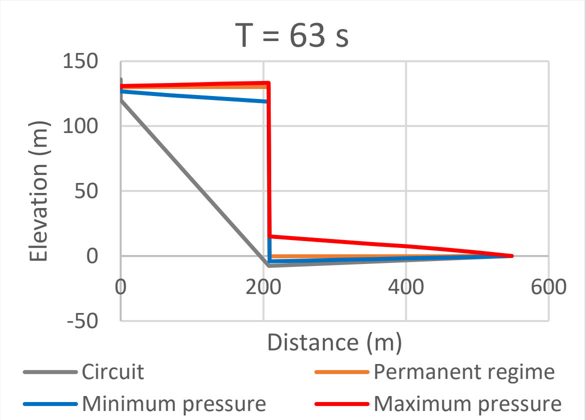

Figure 10 – Pressure variation along the circuit

5.4. Energetic System Performance

This item highlights the most relevant aspects regarding the energy contribution.

The results show that this solution, when pumping is done in the lower electric demand period, can fulfil 81% of total annual demand (assuming for the case study a peak demand of 5 MW).

This result corresponds to a total renewable energy production of 22.96 GWh per year, and by replacing fossil fuel energy production, it is possible to avoid the emissions of 8 956 tonCO2 per year (390 tonCO2/GW). The total pumping energy consumption was 11.05 GWh per year. The annual profit from the purchase and sale of energy was 1 719 101 €. It is estimated that the total cost of the project is 6 670 120 €, so that the return on investment can be reached after 3.9 years.

A hybrid energy solution of wind and solar energy, with the installed capacity of 6 and 0.6 MW, respectively, would ensure a 51% satisfaction of the annual demand. With the introduction of pumped-storage, with an installed power of 5 077 kW, the demand satisfaction is increased by 30%, and only 6% of the energy produced by wind + solar is not consumed locally (although it can be exported).

Figures 11 and 12 show the energy contribution of the three renewable sources, for a typical day of winter and summer, respectively. The results show the great influence of hydropower in total production, demonstrating the enormous potential of pumped-storage as a support solution to bridge the failure of intermittent renewable energies. Most of winter days, have a surplus of wind power at the beginning of the day, so it can be useful to reduce energy costs for pumping scheduled in the morning, (so it was considered this option). Although it was considered a relatively small installed solar power (1/10 of the wind), this source could be useful on summer days, especially in the middle of the day, when the wind slows down and solar radiation increases.

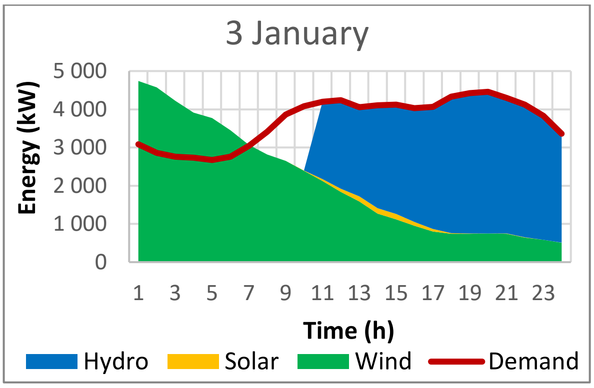

Figure 11 – Energy contribution on a winter day

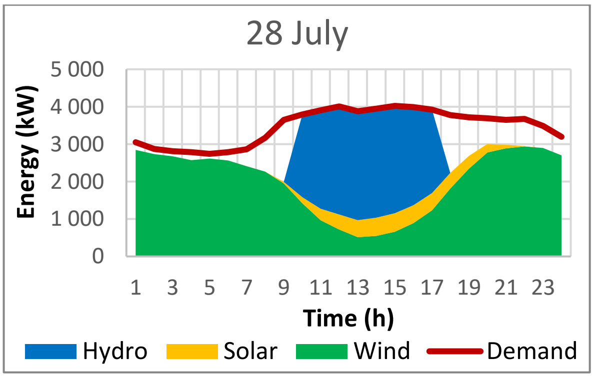

Figure 12 – Energy contribution on a summer day

6. Conclusions

Different combinations of the three renewable energy sources used (i.e., hydropower with pumped storage, wind and solar) were analysed, and for the considered solutions with an energy storage system, it was necessary to carry out sensitivity analyses. Based on different values of peak demand and wind power, were analysed the satisfied demand and wind and/or solar energy that is not consumed, varying the head and the storage volume. To cover several heads/hydro solutions, 4 types of different turbomachines - Pelton, Francis, Kaplan and pump as turbine (PAT) were studied. Francis has proved to be the most suitable for this kind of projects since it can work as a pump and has a good cost-benefit ratio.

A PAT guarantees lower consumption satisfaction, although it is a good economic option, since it may be possible to choose more than one unit, to allow the use of a wider flow range with good performance. Comparing the two operating options, the first one, although it presented better results in terms of surplus use, felt short of expectations in consumption satisfaction. The second option revealed better fulfilled demand results, since it is not dependent on the excess wind and/or solar production. As the pumping system works in the early hours of the day (0-7h), the upper reservoir has enough volume to fill intermittent renewable energy production failures during the remaining period.

In the developed sensitivity analyses, the real contribution of each energy source, exclusive or combined production solutions, with or without storage were analysed, considering one or another operating option. The results demonstrate that solar energy as the only source of production is not very effective, since there are periods of the day when the generation non-exist (i.e. at night). Therefore, a pumped-storage system is very effective in guaranteeing the satisfaction of the consumption in these periods. Wind energy turns out to be more effective. The increase of its installed power translates into a significant production improvement, which allows a greater demand fulfilment, but also a greater surplus. So, it is wise to introduce a storage system able to take advantage of the energy not consumed. The joint production of wind and solar energy has good results, since there is a high annual complementarity, with wind being more effective in winter, and solar in the summer. The integration of the three sources simultaneously allows to reach levels of fulfilled demand of the order of 75 to 90%.

A hybrid energy solution with seawater pumped-storage was design. With this solution adopted for the bottom reservoir, the costs to build it is avoided, although has costs for coastal protection and maintenance based on recent into new technologies to be applied in systems using seawater (i.e., desalination and energy production solutions). The project of a hybrid solution with installed capacity of 5, 6 and 0.6 MW for hydro, wind and solar, respectively, was able to provide 81% of the total annual consumption, assuming a peak consumption of 5 MW. The energy system performance was verified, which proved the high complementarity of solar and wind energy, not only annually, but also throughout the day, and the solar revealed a production surplus during the morning on most days. This surplus was used for pumped-storage, which contributed 30% of the total production, evidencing the great influence in reducing the dependence on the use of fossil fuels.

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