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Pumps as turbines for pumped hydro energy storage systems - A small-size case study

Fabio Licheri*, Mario Petrollese, Daniele Cocco, Francesco Cambuli
Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Italy
E-mail: `fabio.licheri@unica.it`

Abstract. Pumped Hydro Energy Storage (PHES) technology has been used since early 1890s and is, nowadays, a consolidated and commercially mature technology. PHES systems allow energy to be stored by pumping water from a lower- to a higher-level reservoir. Subsequently, this energy can be released through a turbine placed in a penstock, which connects the two reservoirs, to produce energy. Although these plants have historically been employed at large power scales (in the order of hundreds of MW), in recent years, micro- and small-scale plants are becoming more interesting, due to their possibility of being integrated with renewable energy systems (RES) used in autonomous island grids. Capital costs associated with hydraulic machines used in PHES systems represent the most critical economic factor, which can be mitigated by using commercial centrifugal pumps in reverse mode (Pumps as Turbines, PATs) in place of small hydro turbines. These expected economic benefits must be weighed in each specific case study, with some drawbacks related to the use of PATs, mainly associated to a lower round-trip efficiency with respect to specifically designed pumps and turbines.

In this work, a small-scale PHES plant has been studied coupled to an existent photovoltaic system for the integration in the electric grid of a small island in Southern Italy. Two different PHES outlines have been compared based on techno-economic considerations. The former is a typical PHES system composed of both pumps and a turbine, while the latter uses only an array of parallel pumps which work also in reverse mode. The analysis demonstrates the feasibility of integrating a photovoltaic and PHES plant, which results in a lower cost of electricity production, while PHES performance in the PAT-based outline results penalized by the lower efficiency of PATs with respect to the hydraulic turbine.

Acronyms

BEP	Best Efficiency Point
LCOS	Levelized Cost Of Storage
O&M	Operation and Maintenance
PAT	Pump As Turbine
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
RES	Renewable Energy Systems

Dimensional properties

E	energy
H	head
n	rotational speed
P	power
Q	flow rate
V	reservoir volume

Non-dimensional properties

C_H	head conversion factor
C_Q	flow rate conversion factor
η	overall efficiency

Subscripts and superscripts

N	nominal
P	pump
RT	round-trip
sur	surplus
T	turbine, pump in reverse mode
$user$	user

1. Introduction

Renewable energy production is expected to sensibly increase in the next years [1] driven by ambitious development programs [2] of emissions reduction and by energy crisis and climate changes. This growth of renewable capacity is led for approximately the 90% by solar photovoltaic (PV) and wind installations [1] which represent already the largest installed renewable energy capacities. The intrinsic variability of these two energy sources and their rapid diffusion is pointing out the need for storage systems capable to increment the flexibility of coupled renewable energy sources.

Pumped Hydro Energy Storage (PHES) systems represent a consolidate and commercially mature [3, 4] technology with the highest flexibility and storage capabilities [5] among all the available storage technologies. Such systems store potential energy by pumping water from a lower to an upper reservoir (charge-phase) using the surplus electricity available during off-peak periods. Then, water is released through a hydraulic turbine to produce energy (discharge-phase) during high power demand periods. The fast response of PHES plants to switch from charge- to discharge-phase give them a good ability to track and adapt to load changes [6].

Plant flexibility coupled to the predictable energy utilization and system reliability make PHES one of the most cost-effective storage technologies also in small- and micro-scale plants [7]. On the other hand, economic analyses have pointed out the relevance of electro-mechanical equipment costs (turbine, alternator and generator) for small-size hydro power plants [8, 9], amounting around the 30-40% of the total investment. Pump as turbines (PATs) have been considered as a reliable solution to reduce the cost of the hydraulic turbine [10] by substituting the latter with a commercial pump running in reverse mode. The use of PATs eliminates design costs while reducing maintenance costs due to the large availability of spare parts [8]. Some authors have investigated the possibility to use PATs for micro- off-grid installations in remote areas [11, 12], showing their economical advantages of installation with respect to conventional hydraulic turbines, in particular for low installed power [13]. Only few PATs installations have been actually deployed, such as the 3 kW installation in Mae Wei village, Thailand [14], the 45 kW plant of Fazenda Boa Esperança, Brazil [15] and the 50 kW Ambootia Micro Hydro Project in India [16]. Morabito et al. [17, 18] have investigated different case studies of micro-PHES plants considering their actual performance in a real-life micro-energy grid. They prove the techno-economic feasibility of PATs installation in micro-PHES, showing the benefits of rotational speed regulation to mitigate efficiency losses in off-design condition [17]. Another interesting micro-PHES solution has been proposed by Barbarelli et al. [19] and consists in recovering energy from rainwater, using an underground tank coupled to a PAT.

The present work analyses a case study where a small-PHES is coupled to an existent solar photovoltaic (PV) system, to be installed in a small island in Southern Italy. Sea water is pumped to an existing higher-level basin located near the coast, and subsequently returned to the sea in the discharge phase. The configuration of the plant has been evaluated by comparing a standard PHES, composed of separate pumps and turbines, and a PAT-based solution. Hydraulic machines were selected following general design rules and using literature models to predict commercial pump performance in reverse mode. The operation of a number of parallel pumps/PATs has been controlled by introducing a control strategy in which only one of the simultaneously operating pumps is controlled in its rotational speed. Techno-economic metrics have been used to evaluate the feasibility of PATs for the proposed case study. Particular attention has been oriented to the evaluation of the capability of the PHES to increase the self-consumption rate of the PV plant, while costs associated to the installation of the different set of machines have been used to compare the two plant solutions.

In the second Section of this manuscript, the case-study is presented, followed by the definition of methodologies and machine selection. In this part, end user energy demand and PV energy production are defined, and suitable machines are selected for the proposed PHES configurations.

PAT performance and the control strategies adopted for all the machines are also described in Section 3. Results are presented and discussed in Section 4 and some conclusions are drawn in the last part.

2. The case study

The case study concerns the possibility to use an artificial basin, with a capacity of about 25000 m^3 (see Fig. 1), located near the coast on a small island in the south-western sea of Sardinia. Currently, this small water distribution plant is in disuse and the conversion into a PHES plant is considered in this analysis.

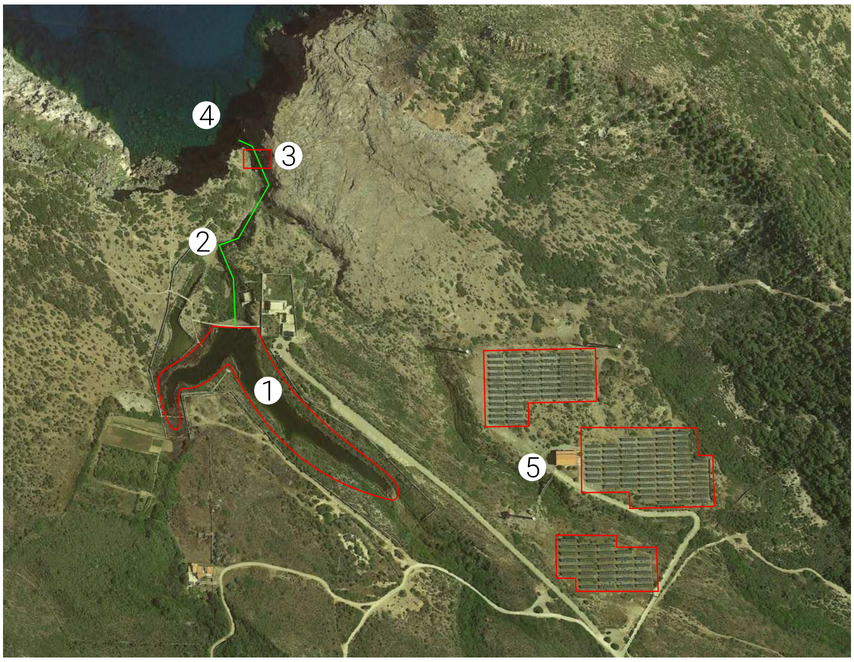


Figure 1. View of the case study installation: 1. Basin (upper reservoir); 2. Pipeline; 3. Technical room; 4. Sea (lower reservoir); 5. PV plant.

The basin has an altitude of 50 m above the sea level and is linked to the sea, which will act as the lower reservoir, by a penstock 140 m long. Indeed, the PHES plant will operate mainly with sea water, except from a small quantity of rainwater which the basin collects. The green line in Fig. 1 shows the path of the penstock, which is placed along a natural canyon that slopes down from the basin altitude (50 m) to the sea. Hydraulic machines will be located in a hidden area of the path, near the coast, with a maximum altitude of 2 meters above the sea level.

The site main characteristics used for the selection of the hydraulic machines (turbine and pumps) are listed in Tab. 1. A preliminary evaluation based on the basin capacity and on the existing penstock was conducted to define the nominal value of the flow rate used for the machine selection.

A photovoltaic system with a nominal power of 999 kW is located near the basin. It consists of 4500 photovoltaic modules, with a reference peak power of 225 W each, and a conversion efficiency, under standard test conditions, of 13.6%. The PV arrays have a surface orientation of 30° tilt toward South direction. Currently, the energy produced by this plant is sold to the network, but the direct supply of residential users located near the plant is being evaluated, through the establishment of an energy community. The techno-economic feasibility of including

Table 1. Main site parameters.

nominal net head, H_N	50 m
nominal flow rate, Q_N	600 l/s
penstock length	140 m
upper reservoir volume, V	25000 m^3

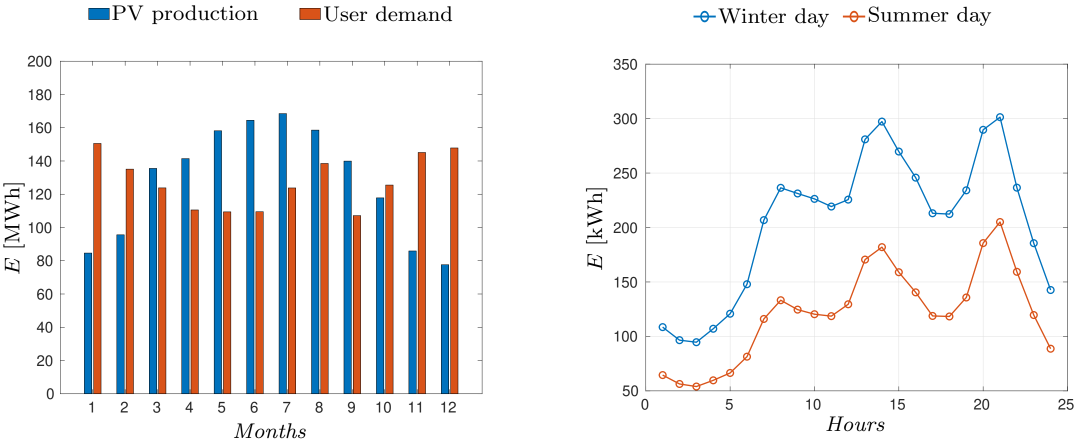
the PHES plant in this community and the optimal configuration of the system are the main goals of this study.

3. Energy profiles and machines configuration

In this section, the method followed for the selection and the design of the PHES plant as well as the control strategy adopted for the integration of the storage plant with the PV system are introduced.

3.1. PV and user energy profiles

Daily and yearly power production profiles have been reconstructed for a site in the South-West of Sardinia, close to the place of the case study. The Meteonorm software [20] has been used to simulate a typical year in terms of global solar irradiance on the modules and ambient temperature. Based on the characteristics of the installed PV panels, the operating cell temperature of the PV module and, subsequently, the actual PV efficiency have been evaluated according to the method proposed by Duffie et al. [21]. The power output of the PV plant has been calculated on a hourly basis as a function of the global solar irradiation available on the surface of the PV array and the corresponding conversion efficiency, the inverter efficiency and a derating factor assumed equal to 0.9 for taking into account other secondary losses (wiring losses, shading, soiling of the modules and aging). Based on the proposed model, the expected annual PV production is about 1.50 GWh/year. The PV monthly energy production profile is reported in Fig. 2 (a).

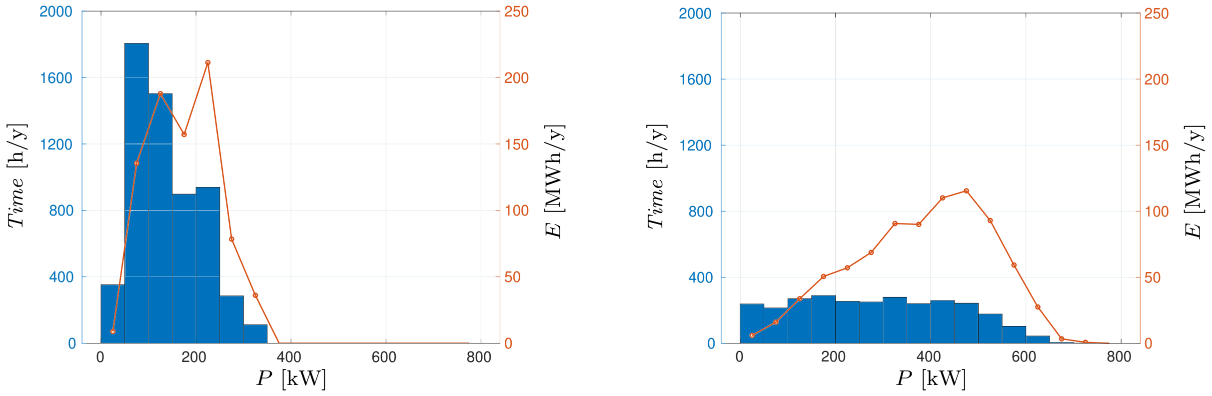


(a) Monthly energy profiles.

(b) Daily user demand.

Figure 2. Energy profiles of the PV plant and user demand.

The user demand profile has been evaluated based on a reference profile [22] available for a small village in Sardinia (Italy). The monthly load profile is shown in Fig. 2 (a), while Fig.2 (b) shows the daily energy profiles representative of a winter and a summer day. The proposed user demand is representative of a small village of about 600 inhabitants, and it has been scaled from the known profile proportionally to the photovoltaic plant capacity, to better highlight the effect of the coupling of the PV and PHES plants coherently with the aims of the present work. However, although the annual PV energy production is equal to that requested by the user, significant mismatches between supply and demand of electrical energy occur during the year, see Fig. 2 (a), and the PHES plant should be optimally designed to face this issue. Deficit and energy surplus are shown in Figs. 3 (a) and (b), respectively.



(a) Energy deficit. (b) Energy surplus.

Figure 3. Deficit of production from the PV to the user and surplus of production.

As shown in Fig. 3 (a), since the deficit of energy mainly occurs during night-time, when the energy demand is low, the range of variability of the energy deficit is limited and hardly exceeds 300 kW. Consequently, a turbine able to operate in a power range of 200-250 kW should satisfy more than 90% of the overall energy deficit. Conversely, the energy surplus is flattened in a larger period, as shown in Fig. 3 (b), as it is more influenced by fluctuations in the PV production. The wider range of variability (up to 600 kW) therefore demands a flexible pump selection able to absorb the available energy surplus with reasonable conversion efficiencies.

3.2. Machines selection

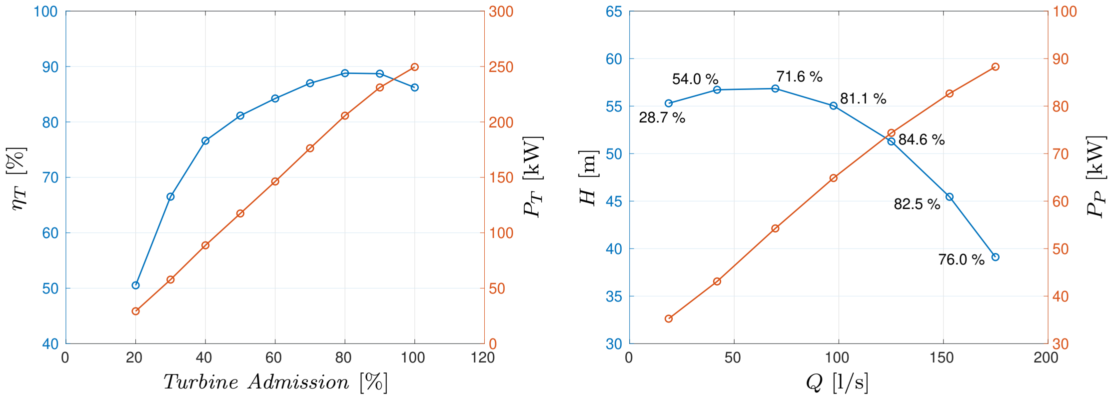
The different PHES plant configurations evaluated will be denoted as “conventional”, the one composed by a hydraulic turbine and an array of pumps, and “PAT-based”, the solution made of only an array of pumps working in direct and reverse mode.

The reference speed of the machines has been chosen equal to 1500 RPM, both for the turbine and the pumps. The same reference rotational speed (1500 RPM) has been chosen for the PATs, for both direct and reverse operating mode. The actual rotational speeds have been corrected, observing that in pump mode the motor rotates at a slightly lower speed than the synchronous speed (around 1450 RPM) while, in turbine mode, the opposite happens and the generator rotates at about 1550 RPM.

The characteristic of the circuit has been defined introducing head losses associated to circuit elements, such as curves and valves, and to the actual penstock size, which has a nominal diameter of 250 mm.

3.3. Conventional configuration

Based on the nominal parameters of Tab. 1, the “site” specific speed has been calculated, resulting in the choice of a Francis turbine. A nominal power of 250 kW was chosen, given the results of the previous analysis on the expected operating range of the turbine. The Francis turbine performance, defined based on the available literature data, are reported in Fig. 4, at different values of turbine admission.



(a) Francis turbine. (b) Pump.

Figure 4. Turbine and pumps performance. Efficiencies are reported as percentages.

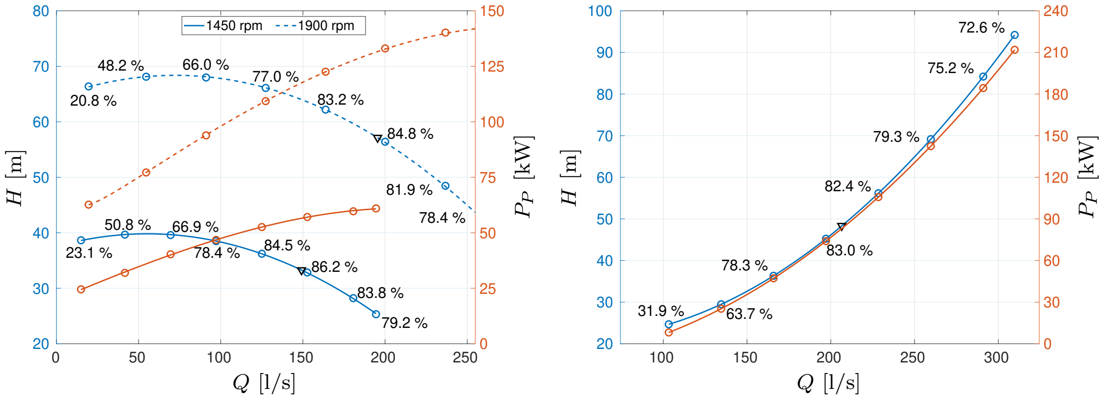
An array of 4 equal pumps was considered for the conventional configuration. The pump has been selected from the available commercial catalogs of centrifugal machines, by matching the site characteristic with the pump performance curve near the pump Best Efficiency Point (BEP) of operation. The resulting machine is characterized by a DN200 discharge port diameter, and an impeller diameter of 400 mm. The performance curves of the pump, as reported in the commercial catalogs, are shown in Fig. 4 (b).

3.4. PAT-based configuration

In this configuration, an array of pumps which operates both in direct and reverse mode is considered. In order to correctly select the optimal commercial pump to operate as PAT, most of the procedures available in literature [19, 23] suggest to assume the site nominal characteristics as the reference values for the pump operation in reverse mode. Thus, by means of simple empirical correlations, the BEP of the pump operating in reverse mode can be related to that of the pump operating in direct mode, and a suitable commercial machine can be selected in the catalogs.

As for the conventional PHES configuration, an array of 4 equal centrifugal pumps has been considered in order to match the site characteristic. The preliminary calculation of the flow rate and head conversion factors, C_Q and C_H respectively, and the use of the correlations provides in [19], led to the selection of a pump with a DN150 discharge diameter and an impeller diameter of 315 mm. Its characteristics in pump mode are shown in Fig. 5 (a).

PAT performance have been calculated following the model introduced in [19], where a simple polynomial correlation is proposed to define the characteristic of the pump operating in reverse mode, without the knowledge of any machine geometric parameter. A correlation for the PAT efficiency is also presented, based on an intense experimental activity on a relevant number of pumps. Despite the relatively high uncertainty of the method in estimating the PAT performance (between -5% and +7% for the efficiency), the simplicity of the model makes it very attractive. The correlations proposed in [19] for the pump are based on the specific speed parameter, both



(a) Pump in direct mode.

(b) Pump in reverse mode.

Figure 5. Pump performance both in direct and reverse mode. Efficiencies are reported as percentages.

in direct and in reverse mode. The value of this parameter for the chosen pump respects the range where the validity of this correlation has been verified. The resulting PAT performance are reported in Fig. 5 (b).

Since the PAT satisfies the required flow rate in BEP conditions, due to the variation of the BEP (black triangles in Figs. 5) for direct and reverse pump operation, the selected pump curve does not match the circuit characteristic for the same volume flow. Hence, a different pump rotational speed (1900 RPM) has been considered, and the performance have been calculated using the standard machine affinity laws [24]. The pump efficiency has also been scaled in order to take into account Reynolds' number effects, accordingly to the standard methodology found in [25]. Figure 5 (a) also reports the pump performance for the corrected pump speed.

3.5. Plant control strategy

The goal of the plant control strategy was to maximize energy absorption from the PV plant and provide energy to the user when the PV plant is not active. In order to modulate energy absorption and production of the PHES plant to follow profiles of Figs. 3 (a) and (b), a control strategy of the hydraulic machines has been defined.

The Francis turbine has been controlled only by regulating the flow admission, as its efficiency remains still high in a wide range of flow rates, as shown in Fig. 4 (a).

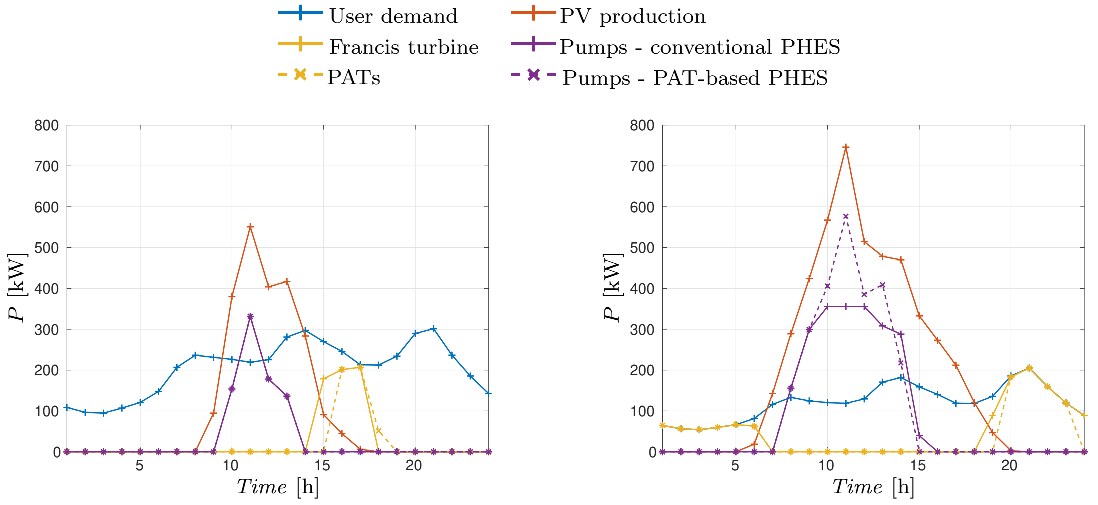
Energy consumption in pump mode has been regulated by an on/off control strategy considering each pump operating at its nominal point. The number of pumps active in parallel is selected to best fit the energy surplus, resulting in a discrete regulation. In order to mitigate this effect, an inverter has been introduced to control the pump rotational speed. Only one of the active pumps is controlled by the inverter, while the other active machines operates at their BEP.

The same hybrid strategy of control has been also used for the PAT-based plant configuration. In this case, the inverter regulates the rotational speed of a pump when it operates both in direct and reverse mode, as the PAT does not have any system for regulating the flow rate. As already mentioned, the nominal rotational speed of the pump in direct mode is different from the one in reverse mode, so that a gear system has been considered to vary the nominal rotational speed from direct to reverse modes.

Finally, the upper reservoir volume balance has been introduced in the control strategy, to stop the pumps operation when the upper reservoir reaches its maximum capacity, and the turbine/PATs operation when the basin is empty.

4. Results and discussion

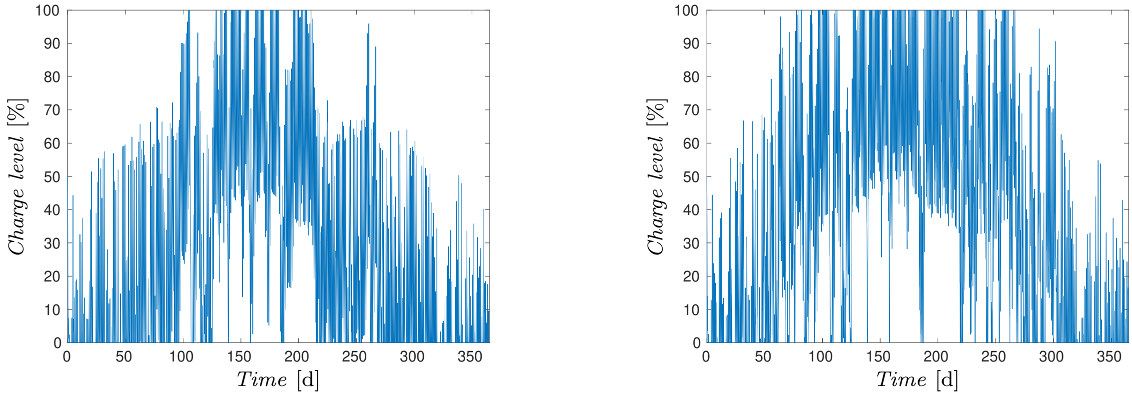
The typical power profiles from the PHES and PV plants during a winter day, Fig. 6 (a) and a summer day, Fig. 6 (b), are here presented for both the conventional and PAT-based plant solutions.



(a) Winter day. (b) Summer day.

Figure 6. Power profile during typical days for both the two plant configurations.

These profiles are useful to rapidly evaluate the percentage of power demanded by the user that is provided by the PV or the PHES plant and, more in general, the self-sufficiency rate of the considered energy community. It should be noted that the peak of energy consumption from pumps coincides with the peak of production from the PV plant, while the maximum turbine production happens when the PV plant is not working. The higher PV production during summer periods allows to store more energy with pumps, hence the energy demand when the PV plant is not working is better satisfied by the PHES plant, both with the Francis turbine and PATs. The upper reservoir charge level during a year is shown in Fig. 7.



(a) Conventional PHES. (b) PAT-based PHES.

Figure 7. Charge level of the upper reservoir.

Both the two configurations show higher levels of charge of the upper reservoir during the summer days, accordingly to the highest production of the PV plant. A higher charge level of the basin for the PAT-based PHES configuration has been also observed, due to the lower flow rate elaborated by PATs with respect to the Francis turbine. In order to better understand how hydraulic machine operate, Fig. 8 shows the number of hours of operation of both pumps and turbines for the two PHES configurations.

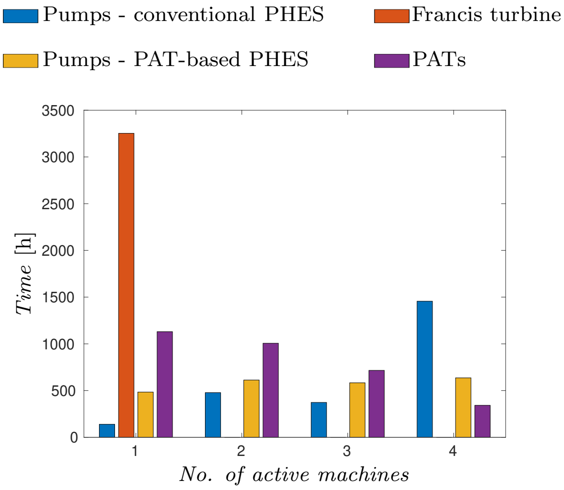


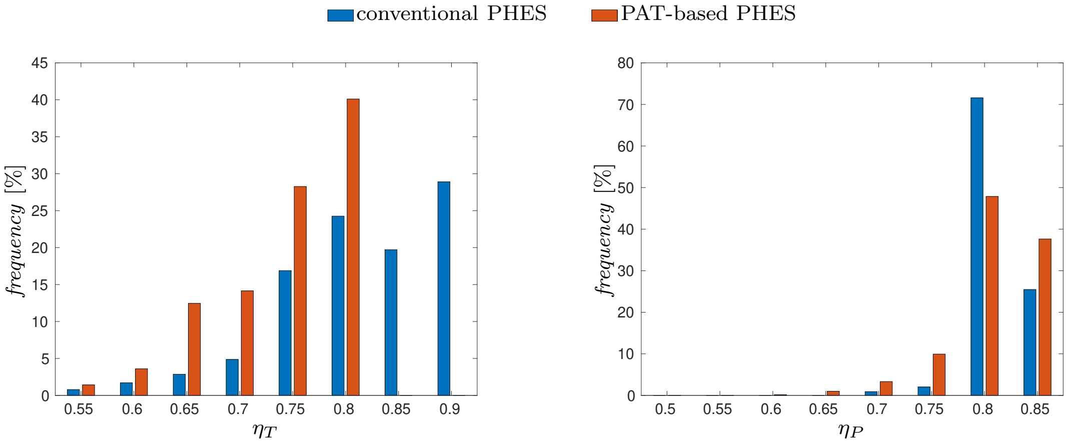
Figure 8. Histogram of machines operating time based on the number of simultaneously working ones.

This representation clearly shows that in the PAT-based PHES configuration pumps are asked to operate simultaneously more often in direct mode operation rather than in reverse mode, due to the largest flow rate elaborated when they work as PATs. A similar trend can be observed for the pumps in the conventional PHES configuration. The cumulative sum of hours of operation shows that the Francis turbine works 3253 hours per year, a time of operation larger than the one of PATs (3194 hours per year). This means a larger flow rate elaborated, which requires a larger operation time of the pumps, 2446 hours per years versus 2316 hours per year of the PAT-based configuration. The frequency distribution of the actual machines' efficiency is shown in Figs. 9 (a) and (b) for the turbine/PAT mode and for the pumps, respectively.

Figures 9 (a) and (b) highlight that PATs and pumps operate more often at the best efficiency point, thanks to the control strategy approach which approximates power profiles by selecting the number of machines which operate simultaneously. In fact, only one machine operates in off-design condition, while remaining machines operate at their BEPs. Nevertheless, the rotational speed control allows to preserve high pumps efficiencies, accordingly to what observed for micro-PHES in [17]. The Francis turbine, that is controlled by regulating the flow admission, operates more frequently in off-design conditions, as shown in Fig. 9 (a), although efficiency values are often higher than PATs ones.

In order to obtain an overall balance of the energy fluxes, Fig. 10 (a) shows how the energy demanded by the user is satisfied by the PV-PHES systems. In Fig. 10 (b), is shown how the surplus of energy from the PV is used.

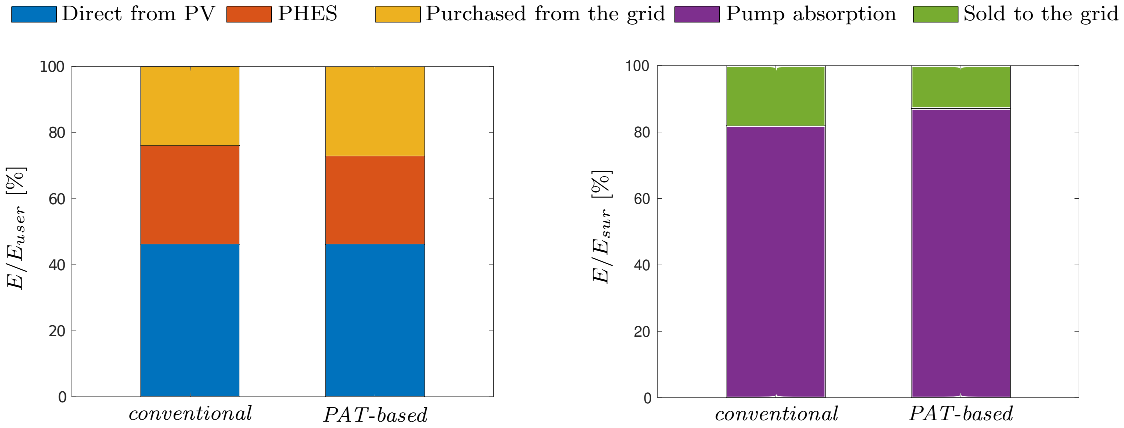
Without the PHES plant, only the 46.2% of the energy demanded by the user, E_{user}, can be directly satisfied by the PV plant, due to the characteristic intermittent production and seasonal variation of the solar source. By introducing the PHES plant, the self-sufficiency rate (that is the share of annual energy demand satisfied by the PV-PHES systems) sensibly increases to the 76.1% for the conventional PHES configuration and the 72.9% for the PAT-based one. The



(a) Turbine/PATs efficiency.

(b) Pumps efficiency.

Figure 9. Frequency distribution of machines' efficiencies both in turbine and pump modes.



(a) User energy consumption.

(b) PV surplus of energy utilization.

Figure 10. Annual flux of energy.

remaining energy not provided by PV and PHES plants needs to be purchased by the grid. On the other hand, the surplus of energy from the PV plant, E_{sur}, which can not be directly used by the user, is stored for most of the 80% by pumping the water to the upper reservoir, while the remaining amount of E_{sur} can be sold to the grid. These results demonstrate that the storage capacity of the upper reservoir is well-balanced for the analyzed application and a further increase in the storage capacity should results in a marginal improvement of the system performance.

The ratio between the energy produced in turbine mode and consumed by the pumps represents the *round-trip* efficiency of the PHES. As expected it is higher for the conventional PHES plant, 67.8%, while the PAT-based solution reaches only the 57.0% of efficiency mainly due to the lower PAT efficiency with respect to the Francis turbine.

4.1. Preliminary economic analysis

Finally, an economic comparison of the two PHES configurations has been conducted based on the Levelized Cost of Storage ($LCOS$), which si defined as the ratio between the annual costs (mainly depreciation costs and O&M costs) of the solution proposed and the yearly energy delivered by the storage system (i.e. the energy produced by the turbine). Only the costs of the hydraulic machines have been considered for the economic comparison, as penstock and civil buildings already exists, and they are reported in Tab. 2.

Table 2. Main costs estimated for the two PHES configurations.

Conventional PHES		PAT-based PHES	
turbine and generator [9]	180.0 [k€]	-	-
butterfly valve	15.0 [k€]	butterfly valve	15.0 [k€]
hydraulic power unit	12.5 [k€]	accessories	20.0 [k€]
pump array	110.0 [k€]	pump array	120.0 [k€]
frequency drive	45.0 [k€]	frequency drive	45.0 [k€]
others	24.5 [k€]	others	24.5 [k€]
Total amount	**310.0** [k€]	**198.5** [k€]	

The lifetime span of both the two configuration has been assumed equal to 25 years, significantly shorter than typical values suggested in literature [3, 7, 5] for PHES plants due to the presence of the inverter. Yearly operation and maintenance costs (O&M) have been assumed equal to 3% [26] and 2.5% of the capital cost for the conventional and PAT-based PHES solutions, respectively, in order to consider the lower maintenance due to the absence of the turbine in the PAT-based configuration. The yearly discount rate has been assumed equal to 8%. The calculations lead to a $LCOS$ of 84.10 €/MWh for the conventional configuration and 57.80 €/MWh for the PAT-based one. These results, although based on a preliminary estimation referred to available commercial price lists, highlight the relative importance of the turbine cost on a such small PHES plant. Moreover, the lower utilization factor in turbine mode, i.e. the limited hours of operation of both turbine and PATs during an year, does not reward the higher efficiency of a proper designed turbine.

A closing remark should be considered, which follow the $LCOS$ calculation here proposed. The effect of the PAT efficiency uncertainties sensibly affects the evaluation of this economic metrics, as the $LCOS$ is calculated based on the energy production. As already pointed out, the model proposed by [19] shows relatively large uncertainties on the estimation of pump efficiency in reverse mode. A sensitive analysis has been conducted to evaluate the effect of efficiency variation on plant $LCOS$ and *round-trip* efficiency, η_{RT}, and the main results are shown in Fig. 11.

These results show that using a value of the PAT efficiency lower than that given by [19], increases the $LCOS$ value of the plant and reduces the *round-trip* efficiency η_{RT}. Nevertheless, for the present case study, the economic indicators still suggest that PAT-based configuration should be preferred with respect to the conventional PHES, due to the limited number of annual operating hours of the Francis turbine and to the high cost of this machine.

5. Conclusions

This work presents a preliminary evaluation of the effect of including a small-size PHES as a storage system to increase the flexibility operation of an existing PV plant. In this analysis, the PHES system is designed to meet the energy demand of a local community in a small island in South Sardinia (Italy). Two different options for the PHES hydraulic machines are analyzed: a traditional system composed of separated pumps and turbines and a system configuration in which pumps operate in direct and reverse mode (PAT).

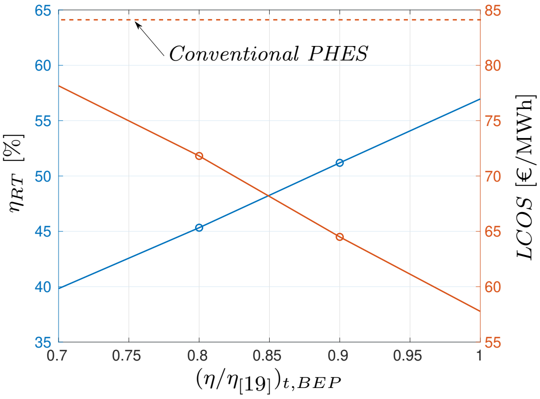


Figure 11. Effect of PAT efficiency on plant techno-economic performance.

The PAT characteristic have been evaluated using simple correlations available in literature, and the hydraulic machines have been selected based on available commercial catalogs. A hybrid control strategy of the PHES has been applied in order to best match the energy production profile of the PV plant and the user energy demand.

The technical analysis shows better performance indicators for the conventional PHES configuration, which presents higher *round-trip* efficiency values, self-consumption rate and a larger number of equivalent hours of annual turbine operation. Nevertheless, the highest capital cost of the conventional configuration lead to a higher $LCOS$ mainly due to the extra cost of the Francis turbine. In this analysis, the operation and maintenance costs are considered lower for the PAT solution, due to the absence of a separated turbine, and to lower cost and easier supply of maintenance spare parts. The other main costs are considered unchanged between the two solutions.

It is worth to note that the features of the case studied penalize the cost of the Francis turbine in the evaluation of the $LCOS$, due to the small size of the plant and the low annual operating time of the turbine. Nevertheless, these results, although obtained with a preliminary analysis, suggest the possibility to use PATs for small-size PHES plant with relatively high performance and lower capital cost of installation, coherently to what found in literature.

Acknowledgments

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