

Turning a small hydropower plant into a small pumped-storage power plant in an energy community: economic opportunities and technical threats

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1. Introduction

The importance of large pumped storage power plants (PSPPs) has grown in recent years in the debate within the energy sector, mainly because of the increasing share in the European and worldwide energy mix of the intermittent and non-programmable Renewable Energy Sources (RES). That is why the development of new large pumping plants has regained momentum almost everywhere, as has the technical-economic analysis aimed at evaluating the transformation of large hydroelectric production plants into large PSPPs.

Minor attention had and has the same transformation for small hydroelectric plants (SHPs) with an installed capacity less than 10 MW.

Thanks to the EU (and worldwide as well) legislation on Energy Communities, the above said transformation could in principle makes sense, thanks to the well known flexibility, reliability and programmability of the PSPPs, whatever their size is, being the said three virtues highly valuable in an Energy Community.

In this framework, the paper is aimed to describe the technical-economical model implemented to support the decision of turning a SHPP into a PSPP.

The paper shows also the results of applying the general model to a real case study: an existing SHPP with an installed power of 1.8 MW, located in an alpine district in Northern Italy.

The outcomes of the application to a real case allowed for highlighting which are the most important technical issues connected to the transformation and in which extent the economic opportunities given by the legal framework of the Energy Communities can cover the additional costs for it.

2. Available data

2.1 Plant features

Due to confidentiality issues, it is not possible to provide the location of the plant or mention the operator; therefore, generic names will be employed to refer to existing elements.

The scheme of the plants is quite simple, as it basically consists of a cascade of two simple high-head hydropower plants. The scheme is represented in Fig. 1. The main parameters of the plant are summarized in Table 1.

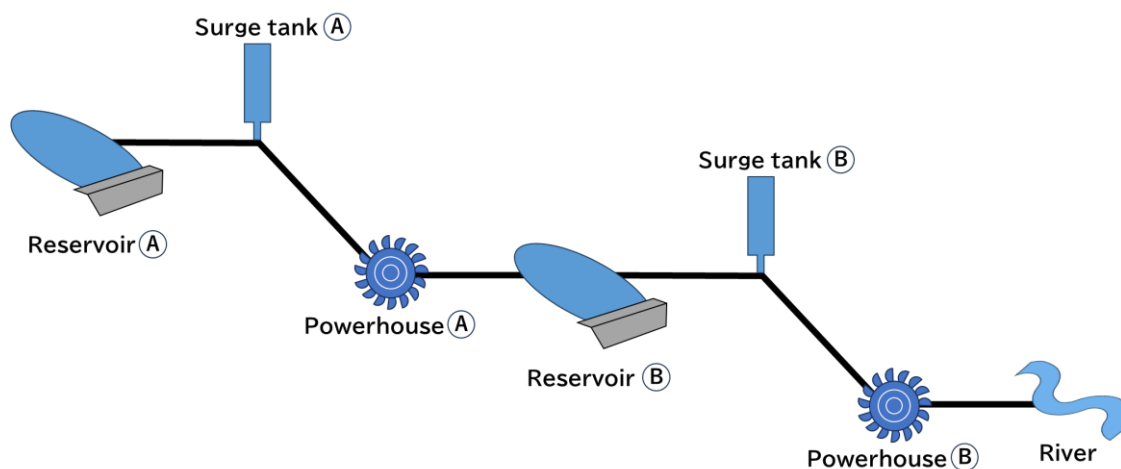


Fig. 1. Plant scheme

Reservoir A		Reservoir B	
Active storage capacity	830,000 m ³	Active storage capacity	34,600 m ³
Maximum water level variation	25.30 m	Maximum water level variation	6.50 m
Powerhouse A		Powerhouse B	
Turbine type	1 x Pelton	Turbine type	2 x Pelton
Turbine rated power	1,900 kW	Turbine rated power	2 x 2,800 kW
Turbine rated flow	750 l/s	Turbine rated flow	2 x 625 l/s

Table 1. Main parameters of the plant

2.2 Plant data

The available data provided by the operator are the following:

- Reservoirs:
 - o Correlations between water level and water surface, and between water level and storage volume
 - o Spillways geometry
 - o Water level measurements on an hourly scale from 01/01/2017 to 31/12/2021
- Waterways:
 - o Geometry and materials
- Powerhouses:
 - o Production measurements on an hourly scale from 01/01/2017 to 31/12/2021
 - o Hydroelectric units efficiency

By knowing the spillways geometries and the water level measurements, it was possible to estimate the spilled discharges during the considered period (2017-2021). Volume released through the bottom outlet is negligible due to the fact that it was only opened during supervisory visits to check its functioning.

By knowing the production measurements, the units efficiency and the waterways characteristics, it was possible to estimate the discharge that from the reservoir flows into the waterways and reaches the turbines, double checking the values of the measurements coming from the acoustic devices.

2.3 Energy prices

Energy sales and purchase prices are available on an hourly scale from GME (*Gestore dei Mercati Energetici SpA*), the manager of the Italian Energy Market. The price is defined as PUN (*Prezzo Unico Nazionale* = National Unique Price).

3. General considerations

According to the current electric energy market rules, pumped storage plants with and installed power < 10 MW cannot access to the capacity market or the ancillary service market: thus, the profits of these plants come only from the price variation throughout the day.

Two useful parameters that can help to better understand when the pumping operation is convenient are the following:

$$C_{E,t} \left[\frac{\text{kWh}}{\text{m}^3} \right] = \frac{\eta_t \cdot \gamma \cdot H_{n,t}}{3600} = \frac{\eta_t \cdot \gamma \cdot (H_g - \Delta H_t)}{3600}$$

$$C_{E,p} \left[\frac{\text{kWh}}{\text{m}^3} \right] = \frac{\gamma \cdot H_{n,p}}{\eta_p \cdot 3600} = \frac{\gamma \cdot (H_g + \Delta H_p)}{\eta_p \cdot 3600}$$

where:

- $C_{E,t}$ [kWh/m³] = Generation energy coefficient: the energy that is produced when a cubic a meter of water is turbined
- $C_{E,p}$ [kWh/m³] = Pumping energy coefficient; the energy that is absorbed when a cubic meter of water is pumped
- γ [kN/m³]: water specific weight
- η_t [-]: turbine efficiency
- η_p [-]: pump efficiency
- H_g [m]: gross head
- ΔH_t [m]: head losses in turbine mode
- ΔH_p [m]: head losses in pumping mode

The ratio between these two coefficients represents the overall efficiency of the pumped storage plant:

$$\eta_{global} = \frac{C_{E,t}}{C_{E,p}} = \eta_{global} \cdot \eta_{global} \cdot \frac{(H_g - \Delta H_t)}{(H_g + \Delta H_p)}$$

For definition, this parameter can only be < 1 , since it is the product of three parameters each of which is < 1 . The functioning of the pure pumped storage plant¹ is convenient only when the ratio between the purchase price of energy and the selling price is higher than η_{global} . This is a fast and simple method to evaluate how often (how many days in a year) the operation of the pumped storage system is convenient (i.e. the revenues coming from the generating phase are higher than the costs of the pumping phase, regardless of the investment costs of the pumping system).

Considering the data provided by the plant operator, a hypothetical pumped storage plant between Reservoir A and Reservoir B would have an overall efficiency equal to $\eta_{global} = 0.612$ (assuming a discharge in pumping mode equal or less than the existing turbine rated flow).

By analysing the prices data for the period 2017-2021 (the same period in which the plant data are available), it is possible to calculate how many days during the year the pumped storage plant would be convenient, in function of the number of consecutive hours of operation in pumping mode. Results are shown in Fig. 2.

As expected, as the number of consecutive hours of pumping increases, the number of useful days steadily decreases, as the consecutive hours of pumping are by definition the ones with the lowest prices: when more consecutive hours are taken into account, the average price of the energy in pumping mode increases, and consequently the cost of the pumping mode increases.

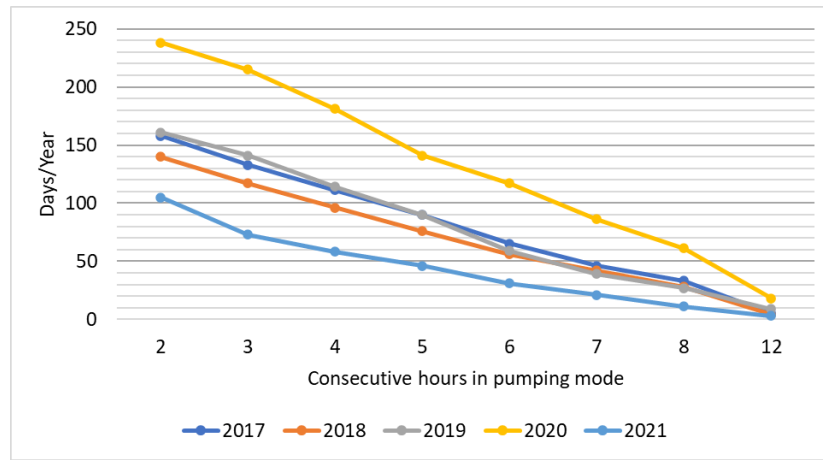


Fig. 2. Number of convenient days for the pumped storage plant in function of the consecutive hours in pumping mode and the year considered

4. Analysed scenarios

4.1 Scenario 1: Pure pumped storage between Reservoir A and Reservoir B

4.1.1 Assumptions

This first scenario is intended to simulate a pure pumped storage system between Reservoir A and Reservoir B with the following operating scheme:

- all the water that naturally is stored in the Reservoir B is pumped daily into the Reservoir A (only if there is enough capacity in the Reservoir A, in order to avoid the activation of the surface spillway); this operating mode occurs during the hours associated with the lowest consecutive prices of energy
- all the water daily pumped in the Reservoir A is then turbinated in the Powerhouse A and in the Powerhouse B, in the same day; this operation occurs during the hours associated with the highest consecutive prices of energy
- the abovementioned operating scheme is performed only in the days in which the operation is convenient (i.e. the revenues coming from the generating phase are higher than the costs of the pumping phase)

The following parameters of the pumping system are preliminarily assumed:

- Rated flow: 0,500 m³/s
- Rated head: 300 m
- Efficiency: 76 %
- Rated power: ~ 2000 kW

¹ A pure pumped storage plant (or “closed-loop pumped storage plant”) can be defined as pumped storage plant in which the natural flows of the upper basin can be considered negligible.

A rated flow lower than the rated flow of the turbine was set in order to avoid any adaptation interventions related to the existing waterways.

The consecutive duration of the pumping phase is assumed to be 4 hours, therefore the volume transferred from Reservoir B to Reservoir A is equal 7200 m³; the same volume is then transferred again to Reservoir B in three consecutive hours of generation mode (since the turbine rated flow of Powerhouse A is 750 l/s).

The costs associated with this modification of the powerhouse are roughly estimated as follows:

- Supply and installation of the pump and electrical accessories	2.5	M€
- Civil works:	0.8	M€
- Engineering:	0.3	M€
- Contingencies:	0.3	M€
- <u>TOTAL:</u>	<u>3.9</u>	<u>M€</u>

4.1.2 Results

Table 2 shows the results of Scenario 1 in terms of annual revenues under different assumptions. The second column reports the results that would have been obtained if the plant had been operated according to this scenario with actual energy prices. In the right-hand columns, on the other hand, the revenues have been evaluated if the purchase price of the energy absorbed during the pumping phase had been a percentage of the actual price (thus simulating a sort of incentive or a hypothetical decrease of the energy price).

Year	<i>Hypothetical pumping price / Actual pumping price</i>				
	100%	75%	50%	25%	0%
2017	8,800 €	20,200 €	32,000 €	43,900 €	55,800 €
2018	8,200 €	19,300 €	30,800 €	42,400 €	54,000 €
2019	6,700 €	17,700 €	29,000 €	40,200 €	51,500 €
2020	11,500 €	23,600 €	36,000 €	48,500 €	61,000 €
2021	8,200 €	28,500 €	49,600 €	70,800 €	92,000 €
<i>Average</i>	8,700 €	21,800 €	35,500 €	49,200 €	62,800 €

Table 2. Scenario 1: Annual revenues from energy sales under various hypothesis of pumped energy price vs. actual price

It is of interest to know the Net Present Value (NPV) associated with this scenario: this value represents how much the investment is profitable. The investment is profitable if NPV>0.

In order to estimate the NPV, the following assumptions are made:

- Time period	30	years
- Discount rate	2/10	%
- Inflation rate	not relevant (it impacts on both revenues and costs)	
- O&M costs	20,000	€/year
- Tax rate	0	(not taken into consideration)

According to the abovementioned revenues and assumptions, the NPV was calculated under different assumptions of the discount rate (the parameter subject to the greatest uncertainty) and different pumping energy prices as done before. Results are shown in Table 3.

		<i>Hypothetical pumping price / Actual pumping price</i>				
		100%	75%	50%	25%	0%
Average revenues		8,700 €	21,800 €	35,500 €	49,200 €	62,800 €
Discount rate	10%	-4,007,000 €	-3,883,000 €	-3,754,000 €	-3,625,000 €	-3,497,000 €
	8%	-4,027,000 €	-3,880,000 €	-3,726,000 €	-3,571,000 €	-3,418,000 €
	6%	-4,056,000 €	-3,875,000 €	-3,687,000 €	-3,498,000 €	-3,311,000 €
	4%	-4,095,000 €	-3,869,000 €	-3,632,000 €	-3,395,000 €	-3,160,000 €
	2%	-4,153,000 €	-3,860,000 €	-3,553,000 €	-3,246,000 €	-2,941,000 €

Table 3. Scenario 1: NPV under various hypothesis of discount rate and pumped energy price versus actual price

4.1.3 Remarks

- As pumping at real prices (100% column in Table 2) generates very modest revenues in absolute terms due to the fact that during the year there few hours in which it is profitable to use the pumping system, revenues would be so small that they would not be able to even cover ordinary operating and maintenance costs.
- As the cost of pumping decreases, annual net revenues increase. If the price of pumped energy were zero for the entire year (column 0% in Table 2), annual revenues would become attractive.
- The NPV at real prices (100% column in Table 3) would be negative for all the discount rate considered, meaning that the investment in the pumping system is not convenient.
- As the cost of pumping decreases, NPV increase, as expected. However, in the most optimistic case (2% discount rate), the NPV would still be negative. Therefore, this scenario is undoubtedly not convenient.

4.2 Scenario 2: Mixed pumped storage between Reservoir A and Reservoir B

4.2.1 Assumptions

This second scenario is intended to simulate a mixed pumped storage system between Reservoir A and Reservoir B with the following operating mode:

- the flow rates reaching Reservoir B are pumped to Reservoir A by varying the maximum number of pumping hours (only if there is enough capacity in the Reservoir A, in order to avoid the activation of the surface spillway); this operating mode occurs during the hours associated with the lowest consecutive prices of energy
- all the water pumped in the Reservoir A and the water that naturally reaches Reservoir A is then turbinated in the Powerhouse A and in the Powerhouse B; this operation occurs during the hours associated with the highest consecutive prices of energy
- should the volumes of water entering Reservoir A be sufficient to turbine for more than 24 hours minus the pumping hours, then no pumping is carried out
- the abovementioned operating scheme is performed only in the days in which the operation is convenient (i.e. the revenues coming from the generating phase are higher than the costs of the pumping phase).

From the point of view of plant modifications and pump characteristics, this scenario involves the same actions as the Scenario 1. Thus, the costs associated with this modification of the powerhouse are the same of the Scenario 1: 3.9 M€.

4.2.2 Results

Table 4 shows the results of Scenario 2 in terms of annual revenues under different assumptions, in an analogous way as for Scenario 1.

Year	Hypothetical pumping price / Actual pumping price				
	100%	75%	50%	25%	0%
2017	10,000	17,000	25,000	33,000	49,000
2018	7,000	13,000	19,000	26,000	34,000
2019	6,000	10,000	15,000	19,000	29,000
2020	10,000	15,000	20,000	26,000	38,000
2021	12,000	23,000	34,000	46,000	67,000
Average	9,000	15,000	22,000	29,000	42,000

Table 4. Scenario 2: Annual revenues from energy sales under various hypothesis of pumped energy price vs. actual price

According to the abovementioned revenues and the same assumptions regarding the NPV for Scenario 1 (§ 4.1.2), the NPV was calculated under different assumptions of the discount rate (the parameter subject to the greatest uncertainty) and different pumping energy prices as done before. Results are shown in Table 5.

		<i>Hypothetical pumping price / Actual pumping price</i>				
		<i>100%</i>	<i>75%</i>	<i>50%</i>	<i>25%</i>	<i>0%</i>
Average revenues		9,000 €	15,000 €	22,000 €	29,000 €	42,000 €
Discount rate	<i>10%</i>	-4,004,000 €	-3,947,000 €	-3,881,000 €	-3,815,000 €	-3,693,000 €
	<i>8%</i>	-4,024,000 €	-3,956,000 €	-3,877,000 €	-3,799,000 €	-3,652,000 €
	<i>6%</i>	-4,051,000 €	-3,969,000 €	-3,872,000 €	-3,776,000 €	-3,597,000 €
	<i>4%</i>	-4,090,000 €	-3,986,000 €	-3,865,000 €	-3,744,000 €	-3,520,000 €
	<i>2%</i>	-4,146,000 €	-4,012,000 €	-3,855,000 €	-3,698,000 €	-3,407,000 €

Table 5. Scenario 2: NPV under various hypothesis of discount rate and pumped energy price versus actual price

4.2.3 Remarks

- Results show a behaviour similar to Scenario 1 (the lower the cost of pumping, the higher the annual net revenues and the NPV).
- Annual net revenues and NPV are smaller than the results of Scenario 1. Thus, this scenario is even less convenient than the Scenario 1.

4.3 Scenario 3: Pure pumped storage between Reservoir B and a new reservoir downstream of the Powerhouse B

4.3.1 Assumptions

This third scenario is intended to simulate a pure pumped storage system between Reservoir B and a new reservoir realized downstream of the Powerhouse B. Regarding to this new reservoir (defined as “Reservoir C”), due to the morphological and environmental context of the portion of river in which the tailrace of the Powerhouse B is located, it is not considered feasible to create a reservoir in the riverbed, therefore the new reservoir should be created outside the riverbed, or as an underground basin (realized as a tunnel).

The active storage capacity of this new reservoir was set equal to 18.000 m³; the sizing was based on the following assumptions:

- the active storage capacity should be less than the active storage capacity of the Reservoir 2 (34600 m³)
- the rated flow of the pump should be less than the rated flow of the Powerhouse B (1.25 m³/s) in order to avoid any adaptation interventions related to the existing waterways
- the consecutive hours of operation in pumping mode should be equal or less to 4 hours (otherwise the average price of the energy in pumping mode would become too high and the system would be less convenient)
- $1.25 \text{ m}^3/\text{s} \cdot 4 \text{ h} \cdot 3600 \text{ s/h} = 18,000 \text{ m}^3$

The operating mode is the following:

- all the volume of Reservoir C (18,000 m³) is pumped daily to Reservoir B (only if there is enough capacity in the Reservoir B, in order to avoid the activation of the surface spillway); the pumping operation occurs during the hours associated with the lowest consecutive prices of energy
- all the water daily pumped in the Reservoir B is then turbinated in the Powerhouse B in the same day; this operation occurs during the hours associated with the highest consecutive prices of energy
- the abovementioned operating scheme is performed only in the days in which the operation is convenient (i.e. the revenues coming from the generating phase are higher than the costs of the pumping phase).

The costs associated with this modification of the powerhouse are roughly estimated as follows:

- New reservoir
 - o Civil works 4.1 M€
 - o Engineering: 0.4 M€
 - o Contingencies: 0.4 M€
- Pumping system
 - o Supply and installation of the pump and electrical accessories 6.2 M€
 - o Civil works: 0.8 M€
 - o Engineering: 0.7 M€
 - o Contingencies: 0.7 M€
- **TOTAL:** **13.3 M€**

4.3.2 Results

Table 6 shows the results of Scenario 3 in terms of annual revenues under different assumptions, in an analogous way as for Scenario 1 and Scenario 2.

Year	<i>Hypothetical pumping price / Actual pumping price</i>				
	<i>100%</i>	<i>75%</i>	<i>50%</i>	<i>25%</i>	<i>0%</i>
2017	55,000 €	163,000 €	313,000 €	464,000 €	615,000 €
2018	47,000 €	143,000 €	312,000 €	486,000 €	660,000 €
2019	38,000 €	134,000 €	278,000 €	422,000 €	566,000 €
2020	66,000 €	147,000 €	246,000 €	345,000 €	444,000 €
2021	41,000 €	244,000 €	606,000 €	972,000 €	1,338,000 €
Average	49,000 €	166,000 €	351,000 €	538,000 €	725,000 €

Table 6. Scenario 3: Annual revenues from energy sales under various hypothesis of pumped energy price vs. actual price

According to the abovementioned revenues and the same assumptions regarding the NPV for Scenario 1 (§ 4.1.2) with only difference that O&M costs are assumed equal to 30,000 € (bigger than the 20,000 € assumed for Scenario 1 and 2, due to the higher complexity of this Scenario 3), the NPV was calculated under different assumptions of the discount rate (the parameter subject to the greatest uncertainty) and different pumping energy prices as done before. Results are shown in Table 7.

		<i>Hypothetical pumping price / Actual pumping price</i>				
		<i>100%</i>	<i>75%</i>	<i>50%</i>	<i>25%</i>	<i>0%</i>
Average revenues		49,000 €	166,000 €	351,000 €	538,000 €	725,000 €
Discount rate	<i>10%</i>	-13,121,000 €	-12,018,000 €	-10,274,000 €	-8,511,000 €	-6,748,000 €
	<i>8%</i>	-13,086,000 €	-11,769,000 €	-9,686,000 €	-7,581,000 €	-5,476,000 €
	<i>6%</i>	-13,038,000 €	-11,428,000 €	-8,881,000 €	-6,307,000 €	-3,733,000 €
	<i>4%</i>	-12,971,000 €	-10,948,000 €	-7,749,000 €	-4,516,000 €	-1,282,000 €
	<i>2%</i>	-12,874,000 €	-10,254,000 €	-6,111,000 €	-1,923,000 €	2,266,000 €

Table 7. Scenario 3: NPV under various hypothesis of discount rate and pumped energy price versus actual price

4.3.3 Remarks

- Results show similar behaviour to Scenario 1 and Scenario 2 (the lower the cost of pumping, the higher the annual net revenues and the NPV).
- NPV is positive just in the case of zero cost for the energy required during the pumping phase, and for low discount rates (2 %).

5. Conclusions

The transformation of a small hydropower plant (SHPP) into a small pumped-storage power plant (PSPP) offers both economic opportunities and technical challenges, especially within the framework of energy communities. The study analysed three scenarios, considering different operational setups and economic conditions. The first two scenarios, involving pumped storage between Reservoir A and Reservoir B, showed limited profitability, with small revenues and negative Net Present Values (NPV) when using real market prices for energy. Even under the most optimistic conditions, the expected revenues could not justify the investment costs, highlighting the economic infeasibility of these configurations. Scenario 3, which proposed the construction of a new reservoir downstream of Powerhouse B, offered better financial outcomes, but the NPV was positive only under the most optimistic hypotheses (zero cost assumed for pumping energy, and low discount rate for NPV).

Turning the analysed SHPP into a small pumped-storage power plant (PSPP) would therefore not be convenient. The model developed for the analysis performed in this study can be replicated for other SHPP to investigate the profitability of converting other small hydropower plant into small pumped-storage power plant. At the current energy prices, one of the possible ways to improve the economic performance of the conversion could be connected with the supply of ancillary services at MV or LV level within Energy Communities, in the same way the bigger plants do at HV grid. The technical challenges of this type of operation could be the subject for further research in the near future. In Table 8 the price of ancillary services (k€/MW/year) to get NPV=0 is shown. Regardless of the scenario and the discount rate, the value is anyway extremely high, if compared with typical values of this price for large PSPPs, but the issue is worth additional investigation.

		Scenario 1	Scenario 2	Scenario 3
Discount rate	10%	224	224	249
	8%	188	188	208
	6%	155	155	169
	4%	125	124	134
	2%	98	97	103

Table 8. Price of ancillary services (k€/MW/year) to get NPV=0

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