

Leveraging the competitive advantages of endof-life underground coal mines to maximise the creation of green and quality jobs

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Deliverable 2.4

Deploying unconventional pumped hydro





Green JOBS

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Deliverable 2.4 | Page 2 / 39



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Deliverable 2.4 | Page 3 / 39



Table of contents

EX	ECUTIVE SUMMARY	7
<u>1</u>	INTRODUCTION	8
<u>2</u>	STATE OF THE ART OF "TECHNOLOGY"	9
2.1	ENERGY STORAGE SYSTEMS (ESS)	9
2.1		9 11
2.3		16
<u>3</u>	IDENTIFICATION OF BEST TECHNOLOGY FOR MINING AREAS OPERATIONAL	
RE	QUIREMENTS OF THE SELECTED TECHNOLOGY	19
3.1	BEST TECHNOLOGY FOR MINING AREAS	19
3.2	OPERATIONAL REQUIREMENTS OF THE SELECTED TECHNOLOGY	20
<u>4</u>	FEATURES OF THE IMPLEMENTATION OF "TECHNOLOGY" IN A MINING AREA	25
<u>5</u>	DEMOSITE INSTALLATION. MAIN FINANCIAL/SOCIAL/TECHNICAL CHARACTERISTICS	28
5.1	TECHNICAL CHARACTERISTICS	28
5.2	2 CAPITAL EXPENSE (CAPEX)	29
5.3	OPERATING EXPENSES (OPEX) AND PERFORMANCE METRICS	31
5.4	DEMOSITE JOB CREATION POTENTIAL	32
<u>6</u>	BEST PRACTICES	33
<u>7</u>	CONCLUSIONS & LESSONS LEARNT	35
<u>8</u>	GLOSSARY	36
RE	FERENCES	37





List of Figures

Figure 2-1. Annual capacity additions of solar PV, wind and other renewables, main and
accelerated cases, 2020-2026 (International Energy Agency, 2022)
Figure 2-2. Top-ten countries share of total installed renewable capacity, historical and
main case forecast, 1991-2026 (International Energy Agency, 2022)
Figure 2-3. Solar irradiation data (SolarGIS, 2021)10
Figure 2-4. Day ahead price and demand in the Iberian Market. Instantaneous power
generation by technologies (OMIE, 2023)12
Figure 2-5. Hourly generation patterns of the main emissions-free technologies in the
Iberian market (OMIE 2023) 12
Figure 2-6. Generation and prices on Sunday March 26 (OMIE, 2023)
Figure 2-7. Interconnection capacity and impact on European prices on March 26 of 2023
(adapted from Red Eléctrica and euenergy.live, 2023)14
Figure 2-8. Simplified diagram of an alternative embodiment of the unconventional
pumped hydro storage system (WO 2019/202456 A1, 24 October 2019)
Figure 3-1. US patent 11365713B2 21
Figure 3-2. China patent CN 112119213 B 22
Figure 4-1. Layout of the Nicolasa-Llosorio project
Figure 4-2. "La Catedral" area in 7 th level in San Nicolás mine, left, and close view of the
puddingstone formation, right (HUNOSA, 2023)
Figure 4-3. Apparent viscosity curves (Rubio Hernández, F.J., 2023)
Figure 4-4. Grid map of NW of Spain and offshore wind demarcation (adapted from Red
Eléctrica, 2023)
Figure 5-1. Cost of E&M equipment and installed power capacity in powerhouses for 81
hydro power plants in America, Asia, Europe and Africa (Alvarado-Ancieta, 2012) 30





List of Tables

Table 2-1. Prices of energy in France, Germany and Benelux on March 26, 2023 (NORD
POOL data, 2023)
Table 3-1. Main energy storage technologies 19
Table 5-1. Income from unconventional pumped hydro per day with 80% pumping
efficiency and 90% turbine efficiency 29
Table 5-2. Two thousand twenty-one capital price for Pumped Storage Hydropower
(PSH), 100 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ =
0.93 €
Table 5-3. Two thousand twenty-one capital price for Pumped Storage Hydropower
(PSH), 100 MW, 10 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ =
0.93 €
Table 5-4. Two thousand twenty-one operating costs for Pumped Storage Hydropower
(PSH), 100 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ =
0.93 €
Table 5-5. Two thousand twenty-one operating costs for Pumped Storage Hydropower
(PSH), 100 MW, 10 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ =
0.93 €





Executive Summary

In this deliverable, the deployment of unconventional pumped hydro is studied.

First, the minor role played by hydropower in energy generation expansion is highlighted, together with its essential role as an energy storage system, as it can be dispatched when prices are high and, where possible, operated in pumping mode when prices are low. It is an excellent opportunity for Spain, which is on the verge of becoming the first developed industrial country to have a power system dominated by photovoltaic, and to a lesser extent, other non-dispatchable technologies with zero variable cost, something that starts to be shown in its prices.

Second, unconventional pumped hydro storage characteristics are presented according to patent nº WO 2019/202456 A1 (2019) that is the property of one of GreenJOBS partners: Magellan & Barents, S.L.: Upper and lower reservoirs within mining embodiments; penstock portions; high-density fluid to be used based on slurry mixtures; surfactants that should be added to prevent freezing of the slurry; etc.

Third, the features of implementing unconventional pumped hydro storage in a mining area are pointed out using the example of the Nicolasa mine in Asturias, Spain. Conditions appear extremely attractive for a first-of-a-kind project: Lithology and topography are favourable. A massive formation of quarzitic puddingstone with high strength and low permeability runs for 800 meters along an escarpment. On the other hand, the mining infrastructure allows inspection of the cavern and even rock removal for additional capacity, with existing conveyor belts in working condition. Dense fluid materials are available and can be sourced nearby as the suitability of materials from a nearby coal-washing installation was validated.

Fourth, financial and technical characteristics of a demosite installation of 80 MW – 320 MWh in Nicolasa mine are estimated: capital expense (CAPEX), operating expenses (OPEX) and performance metrics such as Round Trip Efficiency (RTE), Depth of Discharge (DOD) and calendar life.

Finally, this technology's impact on employment or job creation potential is estimated based on a comparison to that of photovoltaic, as the job generation foreseen for newly installed hydropower capacity in the world does not allow to achieve reasonable figures.





1 Introduction

This task, named Energy strengthening technologies, led by M&B, will select the most widespread and reliable units on the market for the deployment of energy-strengthening technologies (unconventional pumped hydro and batteries) according to the project's needs.

Technical specifications, cost data, and operational constraints will be analysed. A detailed assessment of their job creation potential per MWh-MW of installed storage capacity for commissioning and operation will be developed.

The data to be analysed will be the same as in the case of energy-harnessing technologies (when applicable), complemented/substituted with the following additional data:

- Roundtrip efficiency in %. There is an important caveat here, as turbine efficiency is much more important than pump efficiency because purchased pumping power is four times cheaper than sold turbine power.
- Storage capacity in MWh and charge/discharge capacity in MW.
- Fixed relation between charge/discharge capacity and storage capacity in MW per MWh.
- Response time in minutes/seconds.
- The investment cost for storage in € per MW/MWh ratio.
- Loss of stored energy from storage over time per unit per hour. This is irrelevant for pumped hydro projects, either conventional or unconventional.

This task is subdivided into two subtasks:

- Deploying unconventional pumped hydro
- Deploying Batteries

This subtask, the subject of this study, concerns deploying unconventional pumped hydro, led by M&B, which holds the patent disclosing an unconventional pumped hydro energy storage system using high-density fluids.



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2 State of the art of "technology"

2.1 Energy storage systems (ESS)

Energy storage has become a critical part of the energy transition because photovoltaics and onshore wind power are achieving cost leadership among all power generation technologies, whether clean or dirty, and they are already supplying most of the capacity additions in the world at large, about 300 GW per year from 2020 to 2026, as can be seen in Figure 2-1 and Figure 2-2 from the International Energy Agency (IEA).

Hydropower plays a minor role in power generation expansion, but it is critical in energy storage.

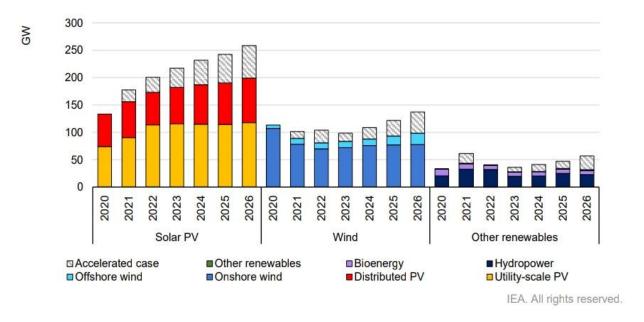


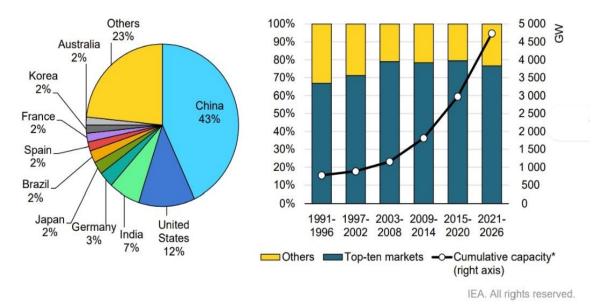
Figure 2-1. Annual capacity additions of solar PV, wind and other renewables, main and accelerated cases, 2020-2026 (International Energy Agency, 2022)

This is the case in the main countries, led by China, the US and India. The European Union is also a major player, with Germany, Spain, France and Italy in the top spots.

Iberia has the best solar resource in Europe because of its southern latitude, large land mass of 583,000 km² and high elevation inland plateau, which is sheltered from clouds, has 600 to 1000 meters less atmospheric cover than sea level, and includes large unproductive areas with low population density, as can be seen in Figure 2-3.



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* Cumulative capacity = installed renewable capacity at the end of each five-year period.

Figure 2-2. Top-ten countries share of total installed renewable capacity, historical and main case forecast, 1991-2026 (International Energy Agency, 2022)

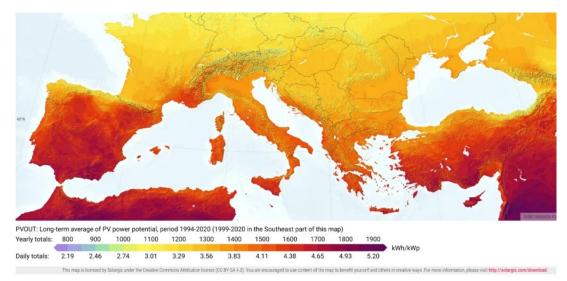


Figure 2-3. Solar irradiation data (SolarGIS, 2021)

As wind power, and especially photovoltaic, become dominant, their daily generation patterns induce volatile prices, with a prolonged valley at daylight hours (which happen to be peak hours for power demand), and two price peaks before sunrise and after sunset, when PV capacity falls sharply (somewhat paradoxically, both price spikes usually take place when demand is at a minimum).





2.2 Spanish electricity market

OMIE is the designated electricity market operator (NEMO, according to European terminology) for the management of the daily and intraday electricity market in the Iberian Peninsula. The company actively participates in the coupling of the wholesale electricity markets in the EU, together with all the designated NEMOs in each Member State.

Europe has established a regulatory framework for the European electricity sector until 2030 based on cross-border marginal energy markets. Under this regulation, OMIE manages the daily and intraday wholesale electricity market (intraday and continuous intraday auctions) for Spain and Portugal.

The data from OMIE show prices in Spain for a sunny day in winter. At the end of 2022 there were just about 20 GW of PV, but an additional 25 GW were approved in January and will be online in 2 or 3 years. That is, more than double the capacity and the production will reach the market, ensuring frequent very low prices from 10:00 to 19:00.

After the sunset, however, PV production vanishes, and it must be swiftly replaced (

Figure 2-4. Day ahead price and demand in the Iberian Market. Instantaneous power generation by technologies (OMIE, 2023)

). That is the reason for the price spikes at dawn and dusk, combined cycle gas turbines burning natural gas typically sets the price then.

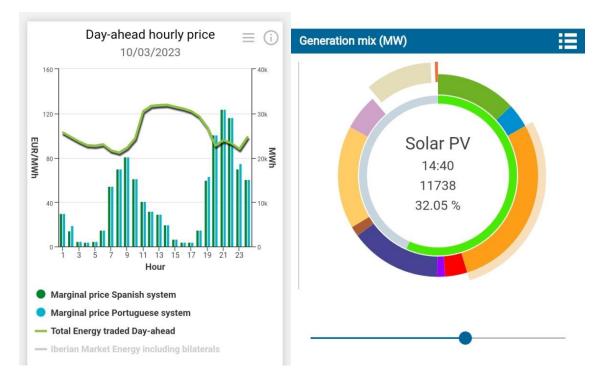






Figure 2-4. Day ahead price and demand in the Iberian Market. Instantaneous power generation by technologies (OMIE, 2023)

The Spanish electricity market is in transition, in the opening stages of a new paradigm of extremely clean, competitive, and abundant energy. It serves as a harbinger for other sunny markets, where the majority of the world's population lives.

The singular feature about the Iberian market is the abrupt, disruptive entry of Solar PV, which quite reliably supplies close to 30% of demand during the midday hours -when demand peaks- at the lowest cost in the system but goes offline every evening even more reliably.

Spain is on the verge of becoming the first developed, industrial country to have a power system dominated by photovoltaic, and to a lesser extent, other non-dispatchable technologies with zero variable cost, and that starts to show in its prices.

The low costs, as shown in Figure 2-5, of Solar PV and wind are not reflected in power prices because the marginalistic pricing system only takes into account the last, highest bid energy that goes into the market, which is still gas on most the days. But that is set to change. Together with nuclear power, which contributes some 20% day and night, and wind, which most of the time produces 30% or more, that adds up to around 80% of supply at nearly zero variable cost, and with almost no greenhouse gas emissions.

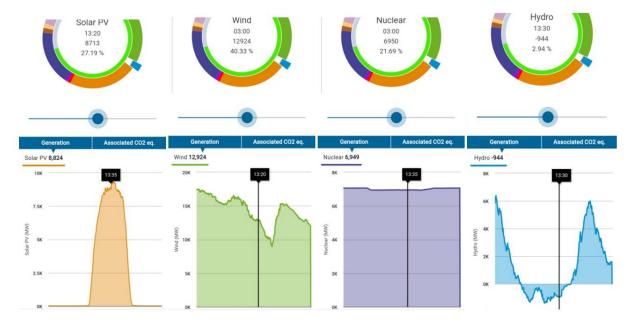


Figure 2-5. Hourly generation patterns of the main emissions-free technologies in the Iberian market (OMIE 2023).

Hydro power is a special case, because as it can be dispatched, it is operated opportunistically when prices are high and, where possible, in pumping mode when





prices are low. At present, that translates into very low prices for power when the weather is sunny and there is a bit of wind. But Solar PV is very competitive, and capacity will double in just a few semesters because once you have the permits, installation can be carried out in several months.

Solar PV offers landowners rental fees that are higher than the agricultural yields in dry lands, so it is easier to get local support. Some of the capacity will be for self-consumption, which will reduce grid demand by several GW every day.

The end result will be that soon there will be no room for expensive gas, and low prices will become ever more prevalent in daylight hours, even in winter, ensuring attractive conditions for energy storage.

At dawn and dusk, photovoltaic generation ramps from zero to 8 GW in just two hours, but that rate will naturally double with double capacity, to 8 GW in just one hour. High Solar PV production will bite into the early morning and late afternoon price spikes.

Wind is still the leading generating technology (it will be overtaken by PV soon), nuclear is virtually flat at some 7 GW, and hydropower plays a crucial balancing role, ramping in the opposite direction of Solar PV. The coming challenge is to swiftly replace Solar PV at dusk, at a ramp rate approaching 10 GW/h. That is a task for storage together with hydro conventional hydro.

We can see what happens when there is oversupply of renewable energy by checking days when demand is lower than usual. Sunday March 26, a day in early spring with reduced demand, allows us a glimpse into the future, as you can see in Figure 2-6.

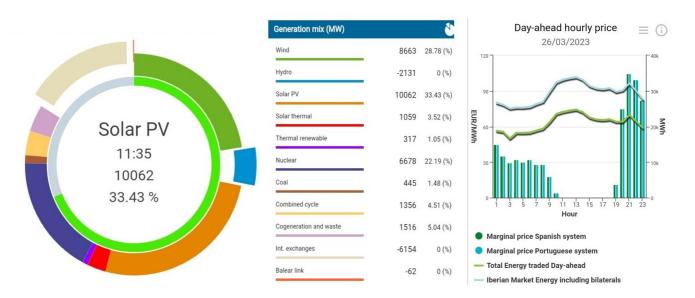


Figure 2-6. Generation and prices on Sunday March 26 (OMIE, 2023)





On a typical Sunday, demand is about 20% less than on a labour day. On March 26 of 2023, Solar PV got a bit of help from wind and prices crashed to zero for 8 consecutive hours, not at night during low demand hours, but throughout the morning and afternoon.

Hydro was in pumping mode from 01:00 AM to 7 PM. Up to 6 GW were exported (at French or Moroccan prices, but not higher than those at the evening peak in Iberia). At 8 PM the sun set and prices boomed, to an average of roughly €80/MWh.

Prices in markets connected by international cables tend to converge, and that is indeed the case between Portugal and Spain, because interconnectors allow 4200 MW of power to flow from Spain into Portugal, which is almost 50% of peak load in Portugal. That is how Portugal and Spain shared record average low prices in Europe on March 26 of 2023 (Figure 2-7).

Electrical exchange capacity (MW) in March 2023 between Spain and its neighbours

Conection	Minimum	Maximum
France - Spain	1900	2900
Spain - France	800	2100
Portugal - Spain	3200	4600
Spain - Portugal	2100	4000
Morocco - Spain	600	600
Spain - Morocco	900	900



Figure 2-7. Interconnection capacity and impact on European prices on March 26 of 2023 (adapted from Red Eléctrica and euenergy.live, 2023)

On the contrary, prices in France were more than double, because the export capacity from Spain into France is just 2100 MW, a small fraction of the French peak load of 80 GW. The Bay of Biscay interconnection will add 2000 MW, but not before 2026, and by that time Spain will have more than 20 GW of additional Solar PV capacity, so the price differential between both markets will not be diluted but strengthened.

Spanish Solar PV can depress prices in Portugal, but that is of course not realistic in the very large, interconnected markets of France, Benelux and Germany, which are in fact one single electricity market, as can be seen in Nord Pool price data. Even massive





exports of power from Iberia would not be enough to significantly lower their prices, the disparity in market size is just too large. The role Spain and Portugal can play is attracting power intensive industries, avoiding their flight to the USA or other low power price markets. As can be seen in Table 2-1, but they never went to zero. No other market in Europe behaved like the Iberian market.

HOURS 26/03/2023	FR	DE-LU	NL
00 - 01	63,84	39,66	94,57
01 - 02	53,53	39,23	80,00
02 - 03	-	-	. –
03 - 04	55,86	40,12	84,90
04 - 05	52,55	40,88	73,62
05 - 06	49,63	41,42	73,65
06 - 07	63,49	63,49	63,49
07 - 08	73,09	73,09	73,09
08 - 09	71,55	77,24	78,35
09 - 10	79,86	79,60	84,69
10 - 11	79,51	78,58	88,70
11 - 12	67,31	76,00	84,90
12 - 13	40,00	61,89	74,90
13 - 14	43,77	55,44	61,67
14 - 15	50,62	50,46	50,46
15 - 16	46,06	46,02	45,57
16 - 17	48,35	48,35	48,35
17 - 18	77,09	77,09	77,09
18 - 19	106,65	106,65	106,65
19 - 20	117,86	117,86	117,86
20 - 21	112,59	112,59	112,59
21 - 22	104,63	104,63	104,63
22 - 23	99,42	99,42	99,42
23 - 00	94,64	94,64	94,64

Table 2-1. Prices of energy in France, Germany and Benelux on March 26, 2023 (NORD POOLdata, 2023)

Iberia is of course a peninsula, electrical cables through the Pyrenees or the Bay of Biscay are much more difficult to build and costly than the flat land links between France, Germany and Benelux.

They were meant to import cheap nuclear power from France into Spain, but the French nuclear fleet is ageing and not so reliable, and nuclear power, even from already depreciated plants, is not competitive with photovoltaics.





2.3 Unconventional pumped hydro storage characteristics

Renewable energies, such as those harnessed from the sun, wind and water, are popular forms of energy to generate electricity, since they have minimal impact on our environment. For example, renewable energy does not pollute the environment, such as CO_2 emissions.

Although renewable energy has advantages, there are also disadvantages. For example, renewable energy is highly dependent on nature, which is undependable or unreliable at best. Solar power requires sunlight, which can be affected by clouds; wind power relies on the wind, which can come and go; water power relies on water, which relies on limited number of water ways and has numerous challenges. These unreliability or inconsistencies of renewable energy contribute to imbalances in supply and demand. Such imbalances cause huge swings in energy pricing.

Conventional pumped hydro energy relies on water flowing down from an upper reservoir to a lower reservoir through a penstock. The water then turns a turbine to generate electricity which is sent to the grid. To recharge the upper reservoir, water is pumped up the penstock. Pumped hydro energy storage, since it has, besides a turbine, a pump to recharge the system, provides controllability and reliability. This stabilises the imbalances of supply and demand which are inherent in traditional renewable energy sources.

Furthermore, an important consideration for conventional hydro power energy systems and pumped hydro storage is the footprint required by the reservoirs.

Unconventional pumped hydro storage is directed to a small footprint pumped hydro energy storage system and method with high power output.

Embodiments generally relate to an unconventional pumped hydro storage system and application of the pumped hydro storage system. The system has a smaller footprint and higher energy density than conventional pumped hydro power energy systems.

The system uses a high-density fluid, and allows for different configurations where upper and lower reservoirs may be at the same elevation. Hydraulic pumps and turbines may be placed higher than the lower reservoir, for example, on the surface above an underground mine.

In particular, an embodiment relates to a pumped hydro storage system which includes a first reservoir and a second reservoir which is disposed below the first reservoir. The system also includes a turbine unit. The turbine unit includes a first turbine unit flow port and a second turbine unit flow port.



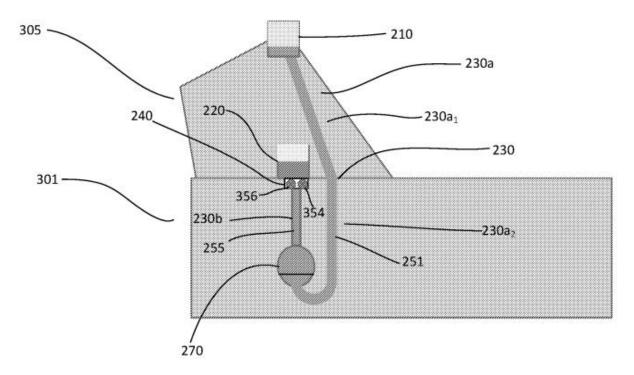


A penstock is provided which is in fluid communication with the first and the second reservoirs. The penstock includes a first portion which is coupled to the first reservoir and the first turbine unit flow port and a second portion which is coupled to the second reservoir and the second turbine unit flow port.

The turbine unit is disposed proximate to the second reservoir. A slurry circulates through the system. The slurry is a high-density fluid which has a density greater than water. The slurry flows through the turbine in a first or forward direction from the first reservoir to the second reservoir to cause the turbine unit to generate energy.

In the recharge mode, the slurry flows through the turbine unit in the second or reverse direction from the second reservoir to the first reservoir to recharge the system. The high-density slurry increases power output of the system as compared to systems using water.

Figure 2-8 shows a simplified diagram of an alternative exemplary embodiment of the unconventional pumped hydro storage system. The present pumped hydro energy storage system produces higher energy output per volume than conventional pumped hydro energy storage systems. In some embodiments, the pumped hydro energy system, unlike conventional pumped hydro energy storage systems, can be implemented on flat land or even topography (WO 2019/202456 A1, 24 October 2019).









As shown in Figure 2-8, the pumped hydro energy system includes an upper reservoir 210 and a lower reservoir 220. In this embodiment, the upper reservoir is disposed above the lower reservoir. The difference in elevation or height of the two reservoirs may be referred to as the head.

A penstock is coupled to the upper reservoir and the lower reservoir. The penstock may be a pipe, channel or other types of conduits, which provides fluid communication between the upper and lower reservoir via the upper and lower reservoir ports. In one embodiment, a turbine unit 240 is disposed proximate to the lower reservoir port.

The turbine unit is a reversible turbine. For example, the turbine is a Francis turbine which serves as a power generator when rotated in a first direction and a pump when rotated in a second direction. Other types of turbines or turbine unit configurations may also be useful.

For example, the turbine unit may include a separate turbine for generating power and a pump for recharging the system. Providing a separate turbine and pump may be particularly useful for high pressure applications. For example, a Francis turbine can only operate at 70 BAR. The use of separate turbine and pump configuration can operate beyond 70 BAR.

In operation, fluid contained in the upper reservoir flows through the penstock to the lower reservoir by gravity. This can be referred to as the discharging state of the system. As fluid flows through the penstock into the lower reservoir, it turns the Francis turbine in a first direction to generate electricity.

The electricity can be transmitted by transmission lines. For example, in times of energy demand, fluid is flowed from the upper reservoir to the lower reservoir to generate electricity. The turbine can be rotated in the second direction, pumping fluid in the lower reservoir up towards the upper reservoir.

Alternatively, a pump is used to pump fluid up towards the upper reservoir. This can be referred to as the charging or recharging state of the system. The system may be recharged in times of low energy demand or when the upper reservoir is empty or near empty.

The system may be designed with the desired parameters to generate the desired amount of electricity and when the system needs to be recharged. For example, the flow rate of the fluid, which is determined by the size of the penstock, the head which is determined by the height between the upper and lower reservoirs, and volume of the reservoirs can be configured to determine the power output and recharge time of the system. The flow rate and head determine the power output and the volume of the reservoirs determines the time between recharging.





3 Identification of best technology for mining areas. Operational requirements of the selected technology

3.1 Best technology for mining areas

First, we compare the main energy storage technologies. We intend to store clean energy, so it is very important that the storage system is also environmentally benign (Table 3-1).

Technology	Cost	Efficiency	Lifetime (cycles)	Environmental Impact
H ₂	High	25%	?	?
Li-ion	High	70%	4.000	High
Pumped Hydro (conventional)	Very Low	80%	100K+	High
Unconventional Pumped Hydro, M&B	Low or Very Low ¹	80%	100K+	Low

Table 3-1. Main energy storage technologies

¹ It is very competitive when dumpsite materials can be used in an existing cavern.

Because hydropower is a mature technology that has been providing dispatchable power since the very beginning of the electric era, it is the preferred solution for large scale energy storage, with more than 90% of existing capacity, and it will most likely remain at the top, at least where topographic conditions are good.

Conventional pumped hydro requires dams and reservoirs which take away land for people and wildlife, so there are a number of initiatives that can be considered unconventional pumped hydro, besides Magellan & Barents:

a) **Hydrostor:** This Canadian company uses water in a surface reservoir to compress air in an underground installation. It is already building commercial projects. Using a dense fluid would allow two or three times the power and energy storage capacity they are achieving with water. <u>https://www.hydrostor.ca/</u>





- b) **Pyhäsalmi:** The Pyhäsalmi energy storage project it is a 75 MW/530 MWh project in a mine about 1450 meters deep. It got EUR 26.3 million from the Government of Finland in 2022. The Pyhäsalmi project is very interesting for us because it is developing high head hydropower equipment very similar to our needs, with a great opportunity to share development and production costs. https://www.epv.fi/en/project/a-pump-storage-station-for-pyhasalmi-mine/
- c) Rheenergise: RheEnergy use a dense fluid, which is very likely made from magnetite fines and water. Density is 2.5, which in our opinion can be easily achieved. The company claims as their main advantage the reduction in tank or reservoir volume and associated civil works. <u>https://www.rheenergise.com/</u>
- d) **Shell International:** Shell prepared and patented a project in The Netherlands, EP0191516A1, but the project was cancelled after the 1986 Chernobyl NPP accident. As it could not use any escarpments, it needed two underground reservoirs for dense fluid. <u>https://patents.google.com/patent/US4691524</u>

Together, these projects point to a diverse, disruptive, but rather mature technological field, which is attracting investment multimillion Euro investments in several countries. Typically for any R+D ecosystem, M&B's technology acts as a force multiplier for some of those projects, and in turn benefits from specific developments by others.

M&B has been awarded US patent 11365713B2 (Figure 3-1) and China patent CN 112119213 B (Figure 3-2). Australian, European, Japanese, Mexican and South Korean patents are pending.

3.2 Operational requirements of the selected technology

The system includes an upper reservoir 210 (Figure 2-8) located close to the top of a mountain, creating an elevation difference between a lower reservoir 220 located at the base of the mountain, for example, within the mine. Other locations of the reservoirs may also be useful. The location may take advantage of the terrain and/or existing structures, such as tunnels and shafts.

Although the system is implanted in an existing mine, implementing the system in other locations which take advantage of the natural terrain, such as salt domes or strata, may also be useful.

The upper reservoir is configured to be in fluid communication with the lower reservoir via a penstock 230. A cavity tank 270 is disposed within the penstock below the lower reservoir. The penstock includes first and second penstock portions 230a and 230b.





(12) United States Patent Bustamante

(54) PUMPED HYDRO ENERGY STORAGE SYSTEM AND METHOD

- (71) Applicant: Magellan & Barents, S.L., Oviedo (ES)
- (72) Inventor: Ciriaco P Bustamante, Oviedo (ES)
- (73) Assignee: MAGELLAN & BARENTS, S.L., Oviedo (ES)
- (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.
- (21) Appl. No.: 17/068,801
- (22) PCT Filed: Apr. 13, 2019
- (86) PCT No.: PCT/IB2019/053055 § 371 (c)(1),
 - (2) Date: Oct. 12, 2020
- (87) PCT Pub. No.: WO2019/202456PCT Pub. Date: Oct. 24, 2019
- (65) Prior Publication Data

US 2021/0363959 A1 Nov. 25, 2021

Related U.S. Application Data

(60) Provisional application No. 62/747,678, filed on Oct. 19, 2018, provisional application No. 62/680,597, filed on Jun. 5, 2018, provisional application No. 62/672,566, filed on May 16, 2018, provisional application No. 62/657,941, filed on Apr. 16, 2018.

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- (51) Int. Cl. F03B 13/06
- F03B 13/06 F03B 3/10

(10) Patent No.: US 11,365,713 B2 (45) Date of Patent: Jun. 21, 2022

(52) U.S. Cl.

- (58) Field of Classification Search CPC F03B 13/06; F03B 3/103; F05B 2210/13; F05B 2210/20; F05B 2280/5008 See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS

4,691,524 A 9/1987 Holscher

FOREIGN PATENT DOCUMENTS

EP	0191516 A1	8/1986
GB	2511285 A	9/2014
WO	9219864 A1	11/1992
WO	2015118527 A1	8/2015

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(57) ABSTRACT

A pumped hydro energy storage system and method are disclosed. The system employs a high-density fluid, such as a slurry, to improve power output. In some cases, the fluid is a binary fluid system, with a high-density fluid and a lower-density fluid, such as water. The lower-density fluid flows through the turbine unit of the system, avoiding the need to modify the system to handle the high-density fluid, while achieving improved power output. The system can be configured with one atmospheric reservoir for a higherdensity fluid and another one for a lighter-density fluid. Each of them is connected to a pressurized cavity which is filled with the higher-density or lighter-density fluid. The atmospheric tanks may be at the same elevation, or the tank with high density fluid might be higher for increased energy output. For example, the system may be placed on a topographical elevation.

20 Claims, 8 Drawing Sheets

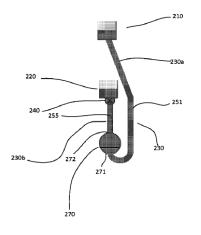
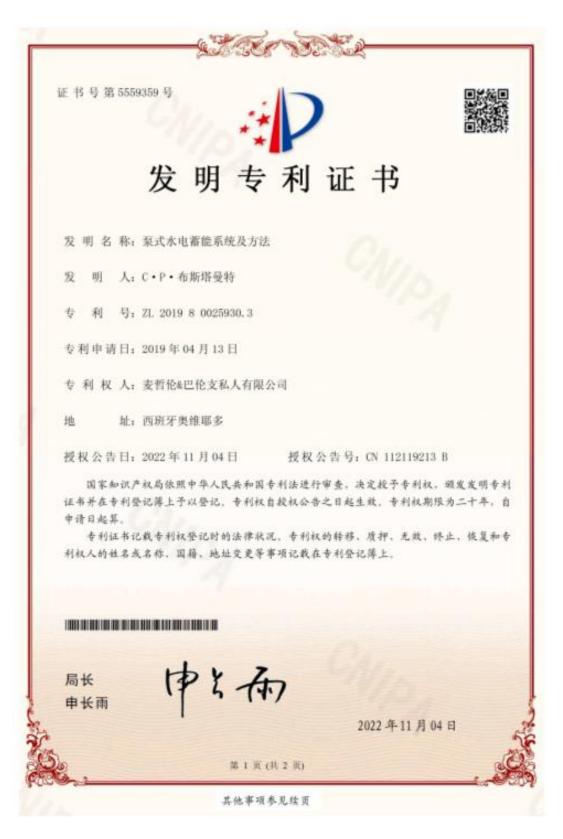


Figure 3-1. US patent 11365713B2



Green J BS







Deliverable 2.4 | Page 22 / 39



The first penstock portion is coupled to the upper reservoir port and a first cavity tank port located at a bottom of the cavity tank; the second penstock portion is coupled to the lower reservoir port and a second cavity tank port located at a top of the cavity tank. As shown, the first penstock includes first and second first penstock subsections 230ai and 230a2. The first penstock subsection is disposed above ground and coupled to the upper reservoir and the second penstock subsection is disposed below ground and coupled to the cavity tank.

In other words, the cavity tank is located below ground. In one embodiment, a turbine unit 240 is disposed proximate to the lower reservoir. For example, it is disposed between the penstock and the lower reservoir port. In one embodiment, the turbine unit includes a turbine 354 and a pump 356. The turbine, for example, is a Pelton turbine. Other types of turbines may also be useful. The turbine, for example, can sustain high pressures of the system.

The lower-density fluid flowing into the lower reservoir causes the turbine to turn in the first direction, generating power. To recharge the system, the pump pumps the lower-density fluid down to the cavity tank in the second direction, causing the high-density fluid to flow back into the upper reservoir.

Providing the high-pressure cavity tank below ground is advantageous as it can utilise the lithostatic pressure, thereby countering the pressure caused by the fluid. This reduces the construction costs of the lower reservoir. In addition, the mountain terrain provides a natural elevation for the upper reservoir. The height at which the upper reservoir is elevated can be configured based on output requirements. For example, lower elevations may be useful to reduce costs associated with building the upper reservoir and penstock if output requirements are met.

The fluid of the pumped hydro storage system is a high-density fluid. The high-density fluid has a density of greater than water. For example, the high-density fluid may have a density which is > 3x, where x is the density of water. In one embodiment, the high-density fluid is a slurry mixture.

Various types of slurry mixtures may be employed. The slurry mixture may include, for example, metal oxide particles mixed with a lower-density fluid, such as water.

Other types of particles and lower-density fluids may also be useful. The volume of particles in the slurry may be equal to or greater than about 50%.

For example, the percentage of particles may be about 50 -85%. In other embodiment, the percentage of particles may be 50 - 75%. The higher the volume of particles, the higher the density of the slurry. All percentages are volume percentages. Other percentages may also be useful.





To prevent the slurry from coalescing and to improve flow, a small amount of surfactant may be added. For example, about less than 1% of surfactant can be added. In some cases, antifreeze may be added to prevent freezing of the slurry. The concentration of antifreeze should be sufficient to prevent the slurry from freezing.

An example of high-density fluid is a magnetite slurry mixture. The magnetite slurry mixture may achieve a density of 3 to 4 tons/m, which is more than 3 times of the density of water. Other types of slurry mixtures, as discussed, can also be employed as the high-density fluid. The density may depend on the mineral content and composition.

By employing high-density fluid, a more compact pumped hydro energy storage system can be achieved. For a given reservoir or tank volume, the energy storage capacity is proportional to the density of the fluid. For example, in the case where the high-density fluid has a density of 3x, the energy storage capacity of the system is 3 times of that when water is used. This is due to the mass flow rate being about 3 times more than that of water.

Alternatively, the system can produce the same amount of energy output using less volume of fluid and/or less height differential between the upper and lower reservoirs. This results in lower costs as well as more flexibility in designing a system to satisfy output requirements.

An advantage, as discussed with using a high-density fluid, is a higher power output. The use of a high-density fluid can be easily retrofitted into existing pumped hydro storage systems by modifying the penstock and pump to handle the high-density fluid, thereby increasing the power output. Furthermore, existing designs of hydro storage systems can be modified to serve as models for highly efficient hydro storage systems which handle a high-density fluid. The cost to build, for a given power output requirement, would be reduced due to less volume needed, smaller penstocks and/or reduced elevation or height between the reservoirs.





4 Features of the implementation of "technology" in a mining area

Underground mines provide an attractive setting for energy storage because the caverns can be used to hold the working fluid, the power infrastructure is already built and available, and the skilled miners are trained, and familiar with the mine. In many cases, workers are redundant at the end of the lifetime of the mine, so finding alternative mining work is urgent. Their task would now be mining a reservoir for energy storage instead of extracting coal.

Under the very high hydraulic head conditions of Nicolasa, using dense fluids one MWh of storage requires some 250 m³ of excavated volume, at unit cost of some $\leq 12,000$ excavation cost per MWh, which is very competitive. The reason is that even the conveyor belts to remove the rock are ready. A possible expansion to 1 GWh would only take ≤ 12 million in excavation costs.

Compared to conventional pumped hydro on the surface, energy storage in mines needs less land and allows more compact installations, especially if a dense fluid is used. In that case, hydropower equipment can be installed on the surface. In Nicolasa, conditions appear extremely attractive for a first-of-a-kind project: Lithology and topography are favourable. A massive formation of quarzitic puddingstone with high strength and low permeability runs for 800 meters along an escarpment (Figure 4-1).

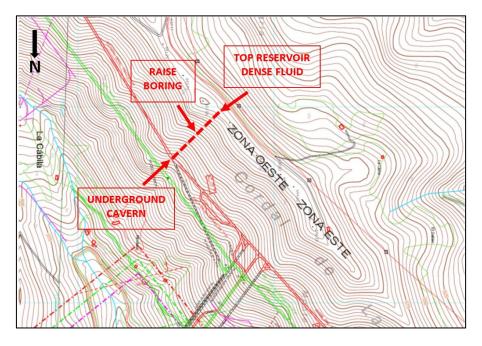


Figure 4-1. Layout of the Nicolasa-Llosorio project

The puddingstones in "La Catedral" area were formed more than 300 million years ago in an ancient delta. They were excavated some 30 years ago, and they do not require





any roof support, at 500 meter depth. The pebbles are rounded, roughly 20 cm diameter.

Mining infrastructure allows inspection of the cavern and even removal of rock for additional capacity, with existing conveyor belts in working condition. (Figure 4-2).



Figure 4-2. "La Catedral" area in 7th level in San Nicolás mine, left, and close view of the puddingstone formation, right (HUNOSA, 2023)

Dense fluid materials are available and can be sourced nearby (Figure 4-3). We have validated the suitability of materials from a coal washing installation.

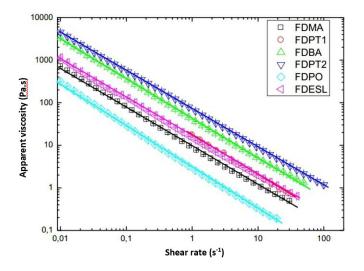


Figure 4-3. Apparent viscosity curves (Rubio Hernández, F.J., 2023)

Nicolasa is strategically located at the crossroads of the East-West Cantabrian corridor and the North-South León-Tabiella branch. It can store excess diurnal Solar PV from the





southern areas in the map, and nocturnal offshore wind from recently demarcated areas in the north coast of Spain which will generate more than 1.5 GW of power. Initially, it can back up the local grid of neighbouring Mieres, with 40,000 inhabitants and several industrial parks (Figure 4-4).





Figure 4-4. Grid map of NW of Spain and offshore wind demarcation (adapted from Red Eléctrica, 2023)

From a financial point of view, investments in Nicolasa can attract Just Transition Funds, well above 50% of total investment, which are compatible with other grants.





5 Demosite installation. Main financial/social/technical characteristics

5.1 Technical characteristics

The key geotechnical condition for unconventional pumped hydro is a strong, competent underground rock formation. That is met by the thick puddingstone formation.

Access to the pressure cavern is also mandatory, and in this case, it is amply met because Nicolasa mine is operational. At level 7, some 267 meters below sea level, there is already "La Catedral", a crossing of two conveyor belts that was built excavating the puddingstones. "La Catedral" will have to be enlarged, a task the miners will be happy to carry out.

Finally, a significant escarpment exists in the area. Close to Pico Llosorio (998 m.a.s.l.) there is a suitable location for the top tank or reservoir. The proposed site is 603 meters above sea level. It would be connected to "La Catedral" by a raise boring with a 20 degrees deviation from plumb and some 3 m diameter, for a section of 7 m^2 .

The main characteristics of the installation will be **80 MW** that are able to work during 4 hours per cycle (with two cycles a day), thus generating **320 MWh**.

Flow rate would be 5 m^3/s , generating some 80 MW at a dense fluid speed of about 0.7 m/s in power generation mode, to minimise risk of water hammer phenomena.

Reservoir or tank volume would be some 80,000 m³, allowing four hours operation at nominal power.

Typical diurnal operation would use excess Solar PV for 8 hours (10 AM to 6 PM) at 40 MW net pumping power with 80% efficiency. Daily cost of energy would be 8,000 Euros, at an average price of 20 \notin /MWh. Average peak power prices would be 80 \notin /MWh, power generation efficiency is 90% and net income for this cycle would be some \notin 15,000 per day.

Typical nocturnal operation would use onshore and offshore wind from 10 PM to 6 AM, supplying the grid from 6 AM to 10 AM. Net income for Spain would be \leq 11,000 per day so, together with the diurnal cycle, daily income is \leq 26,000 or \leq 9,360,000 per year. Additional revenue may accrue from grid services (Table 5-1).





Table 5-1. Income from unconventional pumped hydro per day with 80% pumping efficiencyand 90% turbine efficiency

TYPICAL OPERATION	PUMP (40MW) 10AM-6PM 10PM-6AM	AVERAGE COST (€/MWh)	COST OF POWER	TURBINE (80MW) 6PM-10PM 6AM-10AM	AVERAGE PRICE (€/MWh)	DAILY INCOME	NET
DIURNAL	8	20	-8000	4	80	23000	15000
NOCTURNAL	8	30	-12000	4	80	23000	11000

5.2 Capital expense (CAPEX)

Capital cost is:

- EUR 8 Million for cavern construction and conditioning.
- EUR 2 Million raise boring, penstock.
- EUR 5 Million for surface tanks or reservoirs.
- EUR 80 Million for pumps, Pelton turbine and ancillary electrical and mechanical equipment.
- EUR 10 Million for 80,000 m3 of fluid with density 2.5, or 200,000 Mt at 50 EUR/Mt.

Thus, a total **CAPEX of 105 M€** is foreseen for an installation of **80 MW – 320 MWh** able to develop two cycles per day as presented in Table 5-1.

It is remarkable that the dense fluid is about 10% of cost, but it helps to optimise cavern capacity and maintenance of equipment, which can be on the surface. Hydropower equipment becomes more competitive with higher power and head because of strong economies of scale (Figure 5-1).

However, high head locations are rare and only a few manufacturers work in that niche, mainly European companies such as Andritz, Voith and Siemens. Dense fluids multiply head and can grow the market for high head, high efficiency Pelton turbines dramatically.

In order to establish a comparison with published energy storage costs and performance database we will use Pumped Storage Hydropower (PSH) data from the Pacific Northwest National Laboratory (2022).





Table 5-2 presents the CAPEX of a Pumped Storage Hydropower (PSH) installation of 100MW-400 MWh.

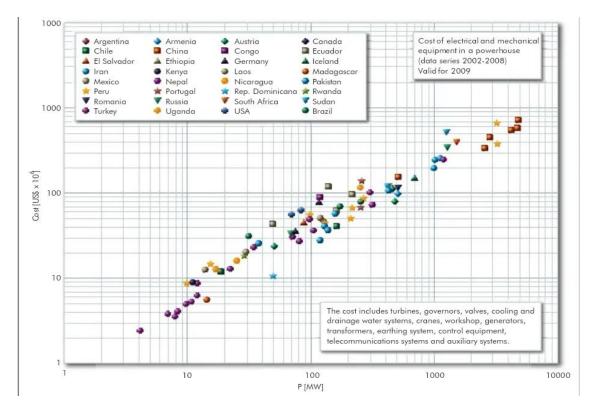


Figure 5-1. Cost of E&M equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa (Alvarado-Ancieta, 2012).

Table 5-2. Two thousand twenty-one capital price for Pumped Storage Hydropower (PSH), 100 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ = 0.93 €

Capital Price components	2021 Point Estimate
Reservoir construction and infrastructure	75.33 €/kWh
Powerhouse construction and infrastructure	690.06 €/kW
Electromechanical	434.31 €/kW
Contingency fee	475.23 €/kW
TOTAL INSTALLED COST (€/kWh)	475.23 €/kWh
TOTAL INSTALLED COST (€/kW)	1,900.92 €/kW

Thus, the cost of the plant will be 190 M€ which almost double the cost foreseen for our installation, something that can be considered reasonable due to the highest costs of reservoir construction and infrastructure in the case of Pumped Storage Hydropower (PSH).





In order to have a wider comparison, Table 5-3 presents the CAPEX of a Pumped Storage Hydropower (PSH) installation of 100MW-1,000 MWh.

Table 5-3. Two thousand twenty-one capital price for Pumped Storage Hydropower (PSH), 100 MW, 10 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ = 0.93 €

Capital Price components	2021 Point Estimate
Reservoir construction and infrastructure	70.68 €/kWh
Powerhouse construction and infrastructure	690.06 €/kW
Electromechanical	434.31 €/kW
Contingency fee	610.36 €/kW
TOTAL INSTALLED COST (€/kWh)	244.15 €/kWh
TOTAL INSTALLED COST (€/kW)	2,441.25 €/kW

5.3 Operating expenses (OPEX) and performance metrics

The operating costs for Pumped Storage Hydropower (PSH), 100 MW, 4 h, are presented in Table 5-3.

Table 5-4. Two thousand twenty-one operating costs for Pumped Storage Hydropower (PSH), 100 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ = 0.93 €

Operating Costs	2021 Point Estimate
Fixed Operations & Management (O&M)	26.13 €/kW-year
Round Trip Efficiency (RTE)	80%
Calendar life	60 years
Depth of Discharge (DOD)	80%

The operating costs for Pumped Storage Hydropower (PSH), 100 MW, 10 h, are presented in Table 5-5.

Table 5-5. Two thousand twenty-one operating costs for Pumped Storage Hydropower (PSH), 100 MW, 10 h (Pacific Northwest National Laboratory, 2022). Change used: 1 \$ = 0.93 €

Operating Costs	2021 Point Estimate
Fixed Operations & Management (O&M)	26.22 €/kW-year
Round Trip Efficiency (RTE)	80%
Calendar life	60 years
Depth of Discharge (DOD)	80%

The performance metrics are (Pacific Northwest National Laboratory, 2022):





- Round Trip Efficiency (RTE): Roundtrip efficiency is simply the ratio of energy discharged to the grid from a starting state of charge to the energy received from the grid to bring the ESS to the same starting state of charge. RTE is < 1 due to the following losses thermal management, electrochemical, power conversion, powertrain, energy conversion, evaporation, or gas/air leakage. According to McKinsey & Company (2022), the efficiency of Li-ion batteries is between 80 to 85 %.
- Depth of Discharge (DOD): It indicates the percentage of the battery that has been discharged relative to the overall capacity of the battery. The more frequently a battery is charged and discharged, and its lifespan will be shorter. Discharging a battery is generally not recommended, as that dramatically shortens the battery's useful life. Many battery manufacturers specify a maximum recommended DoD for optimal battery performance.
- Calendar Life: The maximum life of the system, regardless of operating conditions. For batteries, calendar life depends on the ambient temperature and state of charge (SOC), and McKinsey & Company (2022) states that the battery storage lifetime is 15 years.

In the case of unconventional pumped hydro 80% pumping efficiency and 90% turbine efficiency can be considered, so to assume a Round Trip Efficiency (RTE) of 80% looks quite reasonable.

Assuming an operating costs of 26.13 \notin /kW-year : 3 = 8.71 \notin /kW-year, just considering that the required space is approximately 1/3 of the pumped storage hydropower due to the use of dense fluids, it results in an OPEX of **697,000** \notin /year.

5.4 Demosite job creation potential

IRENA estimates that an additional 850 GW of newly installed hydropower capacity is needed by 2050 to help achieve the carbon reduction commitments of the Paris Agreement. This could generate an additional 600,000 skilled jobs over the next decade. However, applying these figures does not allow to achieve reasonable figures.

Thus, assuming that the impact on employment will be one-third of that of photovoltaic (POTENTIALS. FORM B1. Proposal Description), which according to Ortega et al. (2020) is 0.12 direct jobs/MW, it results in 0.04 direct jobs/MW.

Considering an 80 MW installation, we obtain approximately 3 direct jobs.





6 Best practices

The great majority of global electricity storage capacity deployed up to the present day is pumped hydro due to its favourable technical and economic characteristics.

The unconventional pumped hydro storage using dense fluids has similar efficiency to conventional pumped hydro but with a yield of up to three times more, depending on the density of the dense fluid. It allows large scale storage unlocking the potential of renewable energies, taking advantage of coal mines deep infrastructure but without the need to operate in a non-flooded mine.

On the other hand, the pump/turbine and electrical equipment are on the surface, representing easy maintenance. The galleries eliminate the need for a bottom pressure vessel, with pressure relatively stable and close to that due to overburden.

Coal mines have unquestionable potential for energy storage, especially if there is good access to competent rock, plus adequate topography and proximity to a strong grid.

All these conditions can be found in the Nicolasa-Llosorio system in Asturias, where strong puddingstone rock runs from 270 meters below sea level to more than 600 meters above sea level. The Mieres power grid node is just several kilometres away. The coal pit is expected to close in a few years, so this is the right time to study how it can get a new life and provide jobs to the skilled, specialised workforce.

We have examined the technical and market viability of a complete solution. The results are encouraging and open the way to a full viability study.

Market conditions in Iberia encourage energy storage, and the forecast for the short term is even better because renewable installed capacity is projected to double.

Other players in the unconventional pumped hydro energy storage ecosystem have independently solved most of the technical challenges that we face, and we have found there are many opportunities for cooperation.

Specifically, the Pyhäsalmi project has obtained €26.3 million from the Government of Finland, and the hydropower equipment is similar to what we would use. Their team has also cleared major hurdles, including optimising dimensions at 75 MW/530 MWh.

The unconventional pumped hydro installation that we propose has 80 MW power and 320 MWh energy storage capacity and can be expanded sequentially to 400 MW and 2 GWh capacity.

Such systems are not currently commercially available, but there is intense activity in the EU, the United Kingdom and North America. As with all hydroelectric installations,





unconventional pumped hydro must be adapted to the physical conditions of each specific site; the data to be analysed will address turbines, piping, tanks and other equipment, allowing the design of an optimal system according to different mine parameters.





7 Conclusions & lessons learnt

Unconventional pumping hydro is an exciting opportunity to use existing mining and electrical infrastructure to launch a new energy storage technology that can provide a timely solution for the swift deployment of renewable power in Iberia and the main markets in Europe and the world.

The lessons relevant to the Project from this deliverable can be summarised as follows:

- When wind power, and especially photovoltaic, become dominant, their daily generation patterns will induce volatile prices, with a long valley at daylight hours (which happen to be peak hours for power demand) and two price peaks before sunrise and after sunset when PV capacity falls sharply (somewhat paradoxically as both price spikes usually take place when demand is at a minimum).
- 2. Photovoltaics and wind power are causing energy storage to become a critical part of the energy transition because photovoltaics and onshore wind power are achieving cost leadership among all power generation technologies. Simultaneously, they depend highly on nature, which is undependable or unreliable at best.
- 3. While conventional hydropower systems stabilise the imbalances of supply and demand, which are inherent in photovoltaic and wind power, at the same time, the footprint required by the reservoirs is high. For its part, unconventional pumped hydro storage is directed to a small footprint, a method with high power output as this system uses high-density fluids that allow for a given reservoir or tank volume, an energy storage capacity proportional to the density of the fluid.
- 4. Magellan and Barents has developed high-density fluids that would benefit other concepts or initiatives such as Hydrostor. That is also the case with Rheenergise, and Pyhäsalmi is a particular case because hydropower equipment would be very similar. That project has been extensively analysed and has obtained funding from the Government of Finland, with authorisation from the EU.
- 5. A commercial-scale project will launch the industry and positively impact other concepts in the required clean, large-scale energy storage field.





8 Glossary

- AM Ante Meridiem
- E&M Electrical and Mechanical
- FAEN Fundación Asturiana de la Energía
- GW Gigawatt
- GWh Gigawatt hour
- HUNOSA Hulleras del Norte, S.A.
- m.a.s.l. meters above sea level
- M&B Magellan & Barents
- MW Megawatt
- MWh Megawatt hour
- OMIE Operador del Mercado Ibérico de Electricidad
- Solar PV Solar Photovoltaics
- UNIOVI Universidad de Oviedo
- USA United States of America





References

Papers in journals:

- Alvarado-Ancieta, C. (2009). Estimating E&M powerhouse cost. *Water Power Magazine*. <u>https://www.waterpowermagazine.com/features/featureestimating-em-</u> <u>powerhouse-costs</u>
- Bodis, K., Kougias, I., Taylor, N., & Jager-Waldau, A. (2019). Solar photovoltaic electricity generation: A lifeline for the European coal regions in transition. Sustainability 11(13), 3703. <u>https://doi.org/10.3390/su11133703</u>
- Madlener, R., & Specht, J.M. (2020). An exploratory economic analysis of underground pumped-storage hydropower plants in abandoned deep coal mines. Energies 13(21), 5634. <u>https://doi.org/10.3390/en13215634</u>
- McKinsey & Company (2022). Net-zero heat. Long Duration Energy Storage to accelerate energy system decarbonisation. LDES Council, November 2022. <u>https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zeroheat-long-duration-energy-storage-to-accelerate-energy-systemdecarbonization#/</u> (accessed 25 November 2022).
- Menendez, J., Ordonez, A., Alvarez, R., & Loredo, J. (2019). Energy from closed mines: Underground energy storage and geothermal applications. Renewable & Sustainable Energy Reviews 108, 498-512. <u>https://doi.org/10.1016/j.rser.2019.04.007</u>
- Ortega, M., del Río, P., Ruiz, P., Nijs, W., & Politis, S. (2020). Analysing the influence of trade, technology learning and policy on the employment prospects of wind and solar energy deployment: The EU case. Renewable and Sustainable Energy Reviews 122, 109657. <u>https://doi.org/10.1016/j.rser.2019.109657</u>
- Rodríguez-Huerta, E., Rosas-Casals, M., Sorman, A.H. (2017). A societal metabolism approach to job creation and renewable energy transitions in Catalonia. Energy Policy 108, 551-564. <u>http://dx.doi.org/10.1016/j.enpol.2017.06.024</u>
- Rubio Hernández, F.J. (2023). Estudio Reométrico. Prestación de servicios. Laboratorio de Reología. Universidad de Málaga. Informe inédito.
- Temiz, M., & Javani, N. (2020). Design and analysis of a combined floating photovoltaic system for electricity and hydrogen production. International Journal of Hydrogen Energy, 45(5), 3457-3496. <u>https://doi.org/10.1016/j.ijhydene.2018.12.226</u>

Viswanathan, V., Mongird, K., Franks, R., Li, X. Sprenkle, V., & Pacific Northwest National





Laboratory (2022). 2022 Grid Energy Storage Technology Cost and Performance Assessment. Technical Report, Publication No. PNNL-33283, August 2022. U.S. Department of Energy. URL:

https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performan ce%20Report%202022%20PNNL-33283.pdf (accessed 6 February 2023)

Reports & Legislation:

- Energy Interconnections Links Summit (2015). *Madrid Declaration*. Madrid: Spain-France-Portugal-European commission-EIB.
- IEA (2022). *Renewables 2022. Analysis and forecasts to 2027.*. Copenhagen: European Environment Agency. Available on line: <u>https://www.iea.org/reports/renewables-2022/executeve-summary</u> (accessed 28 Mar. 2023).
- International Renewable Energy Agency (IRENA) (2018). Power System Flexibility for the Energy Transition: IRENA FlexTool methodology. <u>https://www.irena.org/-</u> /media/Files/IRENA/Agency/Publication/2018/Nov/IRENA Power system flexibil ity 2 2018.pdf?la=en&hash=B7028E2E169CF239269EC9695D53276E084A29AE
- Red Eléctrica España. (2005). Sistema Eléctrico Ibérico. Diciembre 2005. https://www.ree.es/sites/default/files/downloadable/maptra2005.pdf
- SolarGIS (2020). Mapas de recurso solar y datos GIS para más de 180 países. <u>https://solargis.com/es/maps-and-gis-data/overview</u>

Webpages:

Euenergy (2023). Electricity Prices of Europe. https://euenergy.live/

Hydrostor (2023). <u>https://www.hydrostor.ca/</u>

Nord Pool Price Data (2023). Day-ahead prices. <u>https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-</u> <u>Prices/ALL1/Hourly/?view=table</u>

OMIE (2023). Operador del Mercado Ibérico de Electricidad. https://www.omie.es/

Pacific Northwest National Laboratory (2022). Energy Storage Cost and Performance Database. URL: <u>https://www.pnnl.gov/ESGC-cost-performance</u> (accessed 25 November 2022).

Pyhäsalmi (2023). <u>https://www.epv.fi/en/project/a-pump-storage-station-for-</u>





pyhasalmi-mine/

RheEnergy (2023). https://www.rheenergise.com/

Shell International (2023). https://patents.google.com/patent/US4691524

Relevant patents

- Magellan & Barents S.L. (2022). US patent 11365713B2. http://www.patents.google.com/patent/ US11365713B2/en?oq=Us+11%2c365713
- Magellan & Barents S.L. (2022). China patent CN 112119213 B. http://epub.cnipa.gov.cn/cred/CN112119213B
- WO 2019/202456 A1 (2019). "Pumped hydro energy storage system and method". 24 October 2019.

