Green JOBS

RFCS RESEARCH PROJECT

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

Grant Agreement 101057789

Deliverable 2.4

Deploying unconventional pumped hydro

European Commission

Research Fund for Coal & Steel

Authors

Aarne Pérez-Bustamante Ilander, Magellan & Barents

Gregorio Fidalgo Valverde, University of Oviedo

Juan José Álvarez Fernández, University of Oviedo

Pedro Riesgo Fernández, University of Oviedo

Deliverable 2.4	
Due date of Deliverable	31.03.2023
Start - End Date of Project	01.07.2022 – 31.12.2025
Duration	3.5 years
Deliverable Lead Partner	Magellan & Barents, S.L.
Dissemination level	Public
Work Package	WP 2
Digital File Name	D2.4 Unconventional pumped hydro deployment
Keywords	Dense fluids, energy storage, renewable energy, pumped hydro, unconventional

Disclaimer

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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.

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.

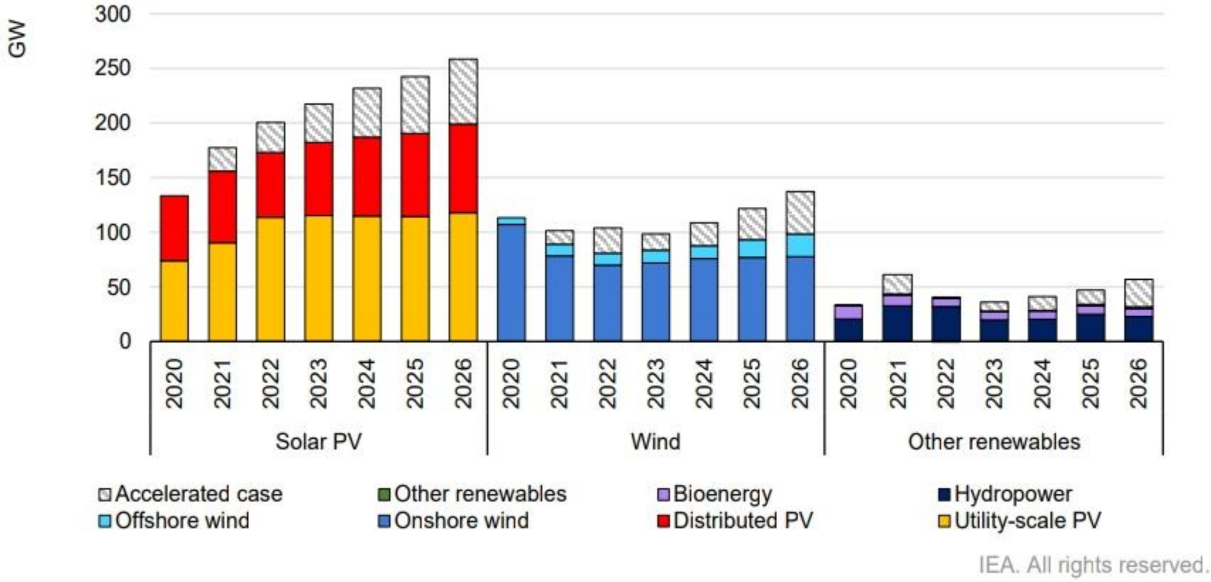

Figure 2-1. Annual capacity additions of solar PV, wind and other renewables, main and accelerated cases, 2020-2026 (International Energy Agency, 2022)

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 km^2 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.

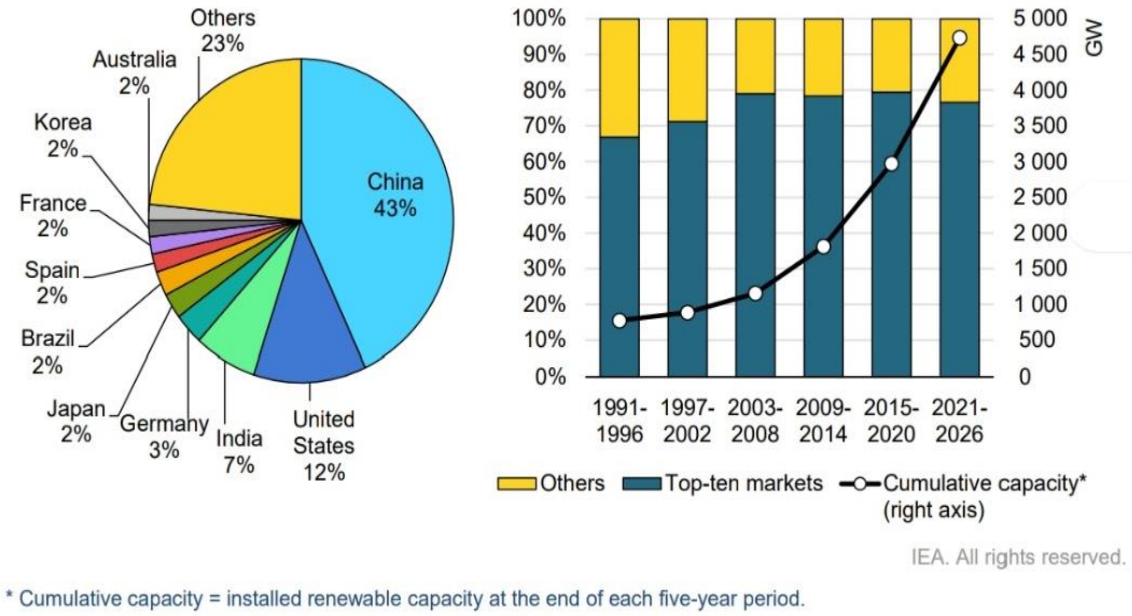

Figure 2-2. Top-ten countries share of total installed renewable capacity, historical and main case forecast, 1991-2026 (International Energy Agency, 2022)

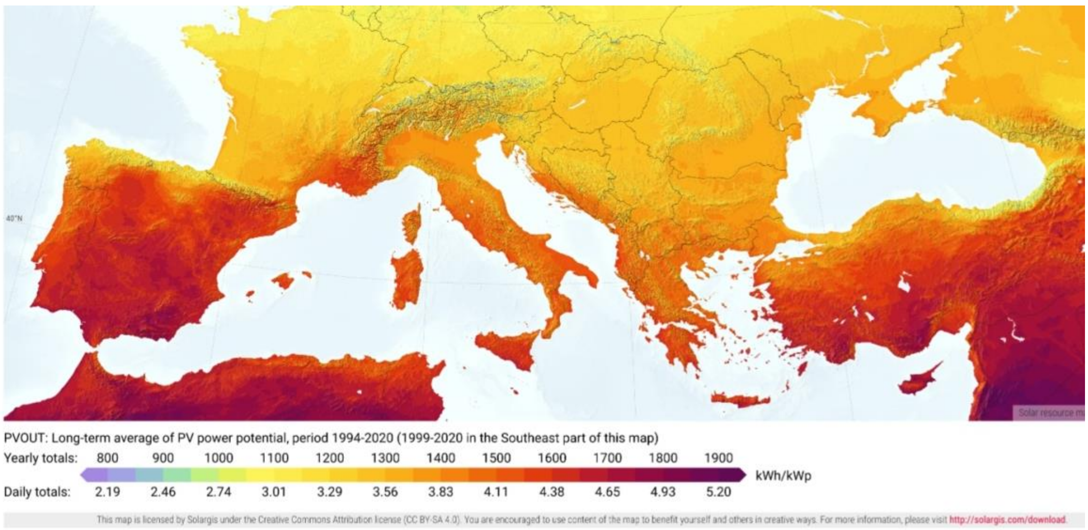

Figure 2-3. Solar irradiation data (SolarGIS, 2021)

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

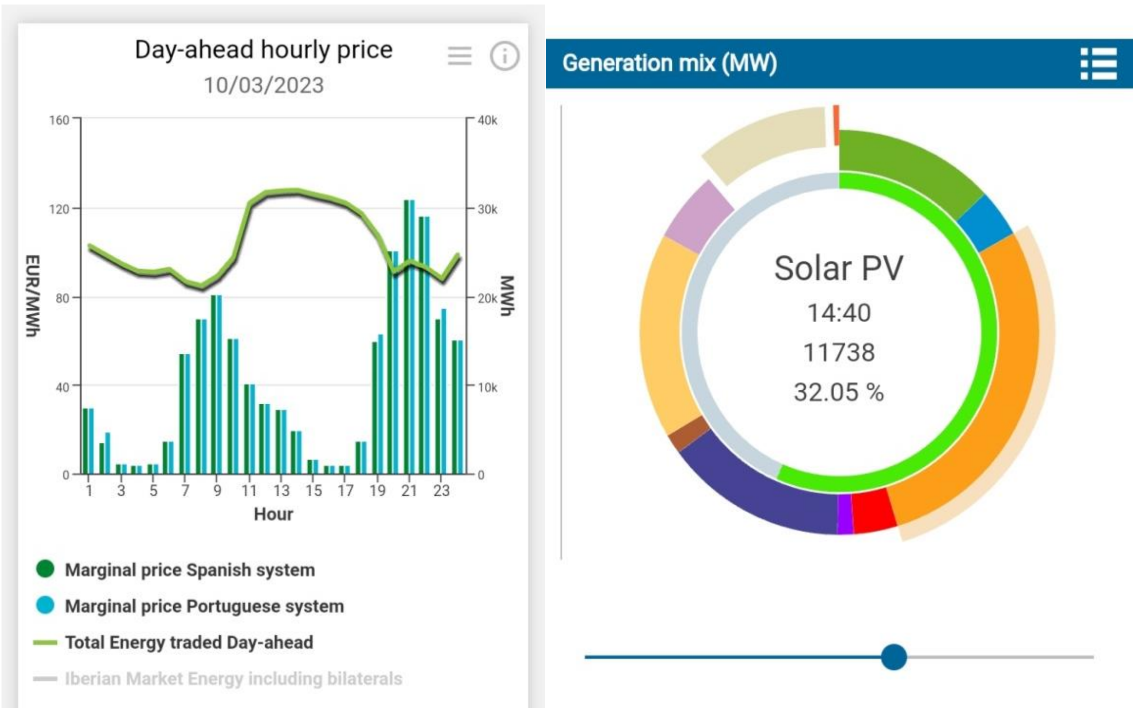

Figure 2-4. Day ahead price and demand in the Iberian Market. Instantaneous power generation by technologies (OMIE, 2023)

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.

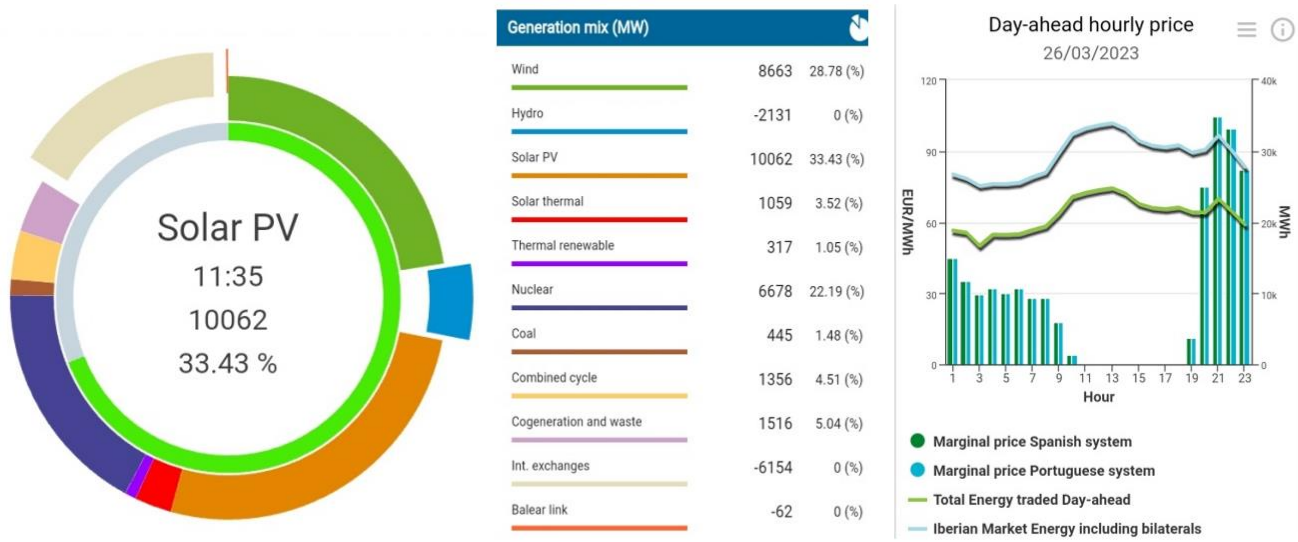

Figure 2-6. Generation and prices on Sunday March 26 (OMIE, 2023)

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.

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

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

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).

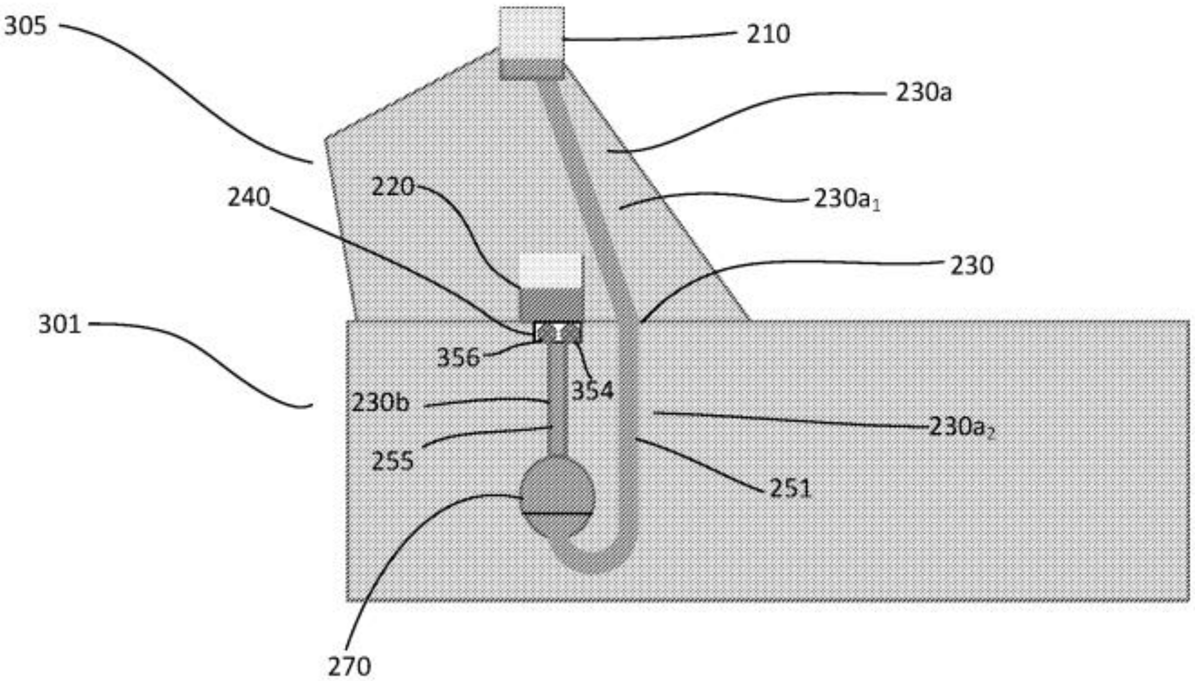

Figure 2-8. Simplified diagram of an alternative embodiment of the unconventional pumped hydro storage system (WO 2019/202456 A1, 24 October 2019)

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).

Table 3-1. Main energy storage technologies

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**

[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. https://www.hydrostor.ca/

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. https://www.rheenergise.com/

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. https://patents.google.com/patent/US4691524

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.

US011365713B2

(12) **United States Patent**
Bustamante

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

(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.: **WO2019/202456**
PCT 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.

(51) **Int. Cl.**
F03B 13/06 (2006.01)
F03B 3/10 (2006.01)

(52) **U.S. Cl.**
CPC ***F03B 13/06*** (2013.01); ***F03B 3/103*** (2013.01); *F05B 2210/13* (2013.01); *F05B 2210/20* (2013.01); ***F05B 2280/5008*** (2013.01)

(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.

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Primary Examiner — Viet P Nguyen
(74) *Attorney, Agent, or Firm* — Horizon IP Pte Ltd.

(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 higher-density 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

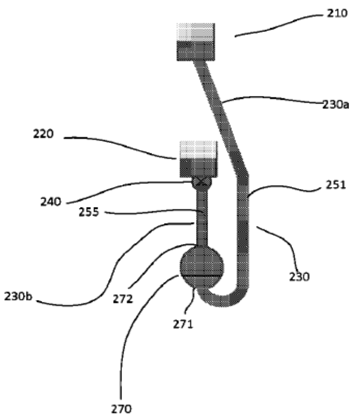

Figure 3-1. US patent 11365713B2


证书号第5559359号

发明专利证书

发明名称：泵式水电蓄能系统及方法

发明人：C·P·布斯塔曼特

专利号：ZL 2019 8 0025930.3

专利申请日：2019年04月13日

专利权人：麦哲伦&巴伦支私人有限公司

地址：西班牙奥维耶多

授权公告日：2022年11月04日　　授权公告号：CN 112119213 B

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局长
申长雨

2022年11月04日

第1页（共2页）

其他事项参见续页

Figure 3-2. China patent CN 112119213 B

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 m^3 of excavated volume, at unit cost of some €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).

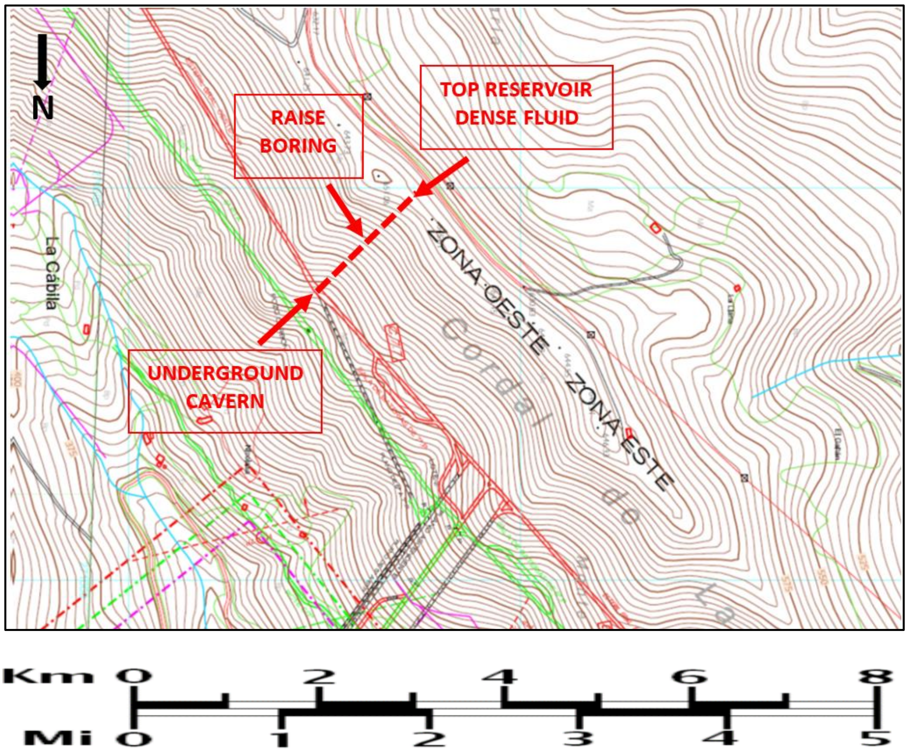

Figure 4-1. Layout of the Nicolasa-Llosorio project.

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.

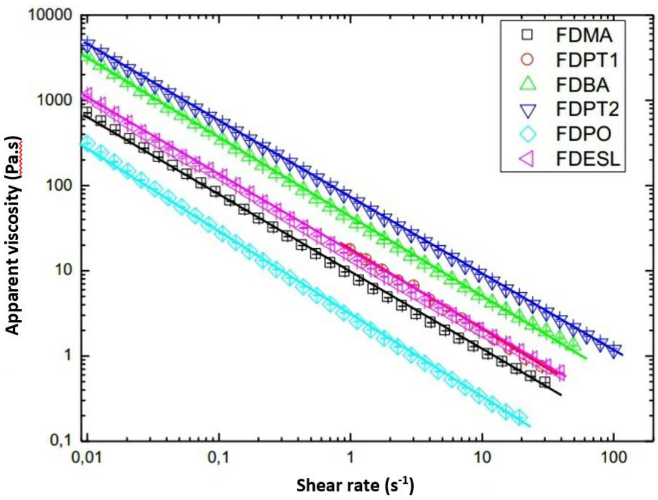

Figure 4-3. Apparent viscosity curves (Rubio Hernández, F.J., 2023)

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).

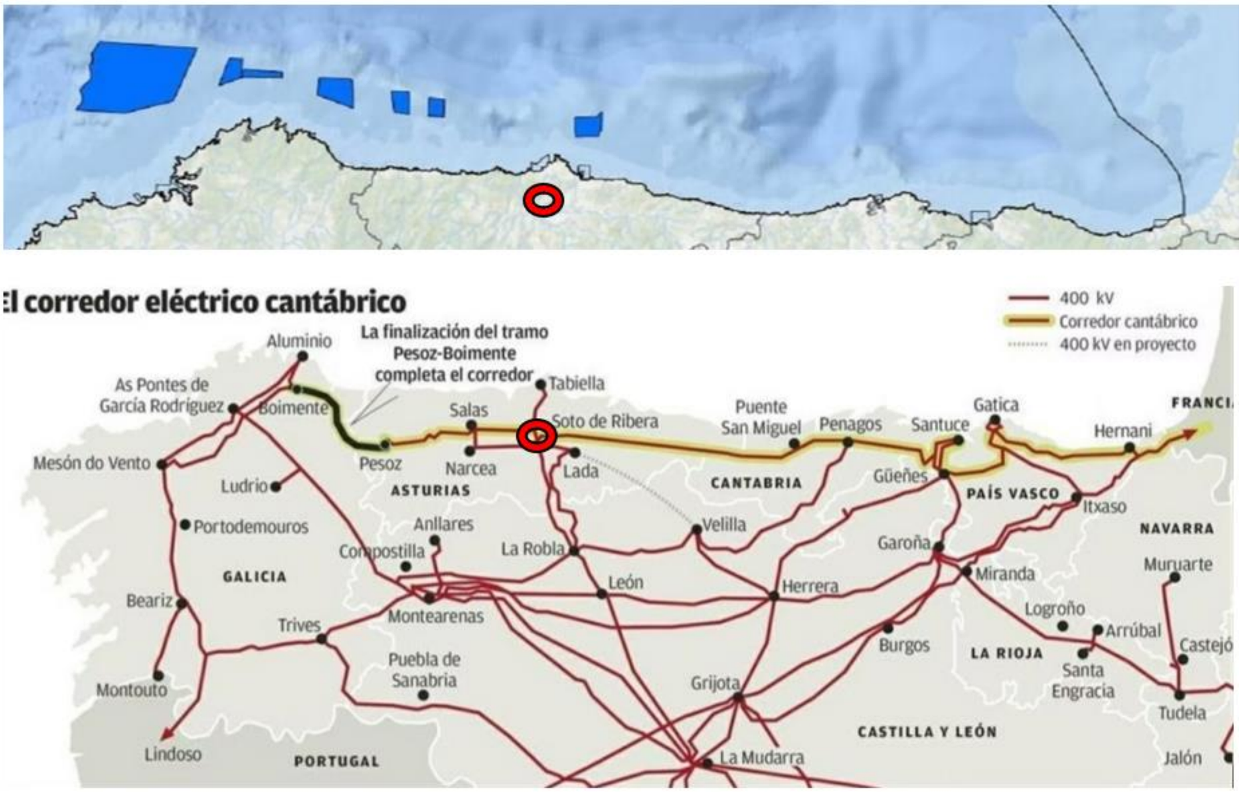

Figure 4-4. Grid map of NW of Spain and offshore wind demarcation (adapted from Red Eléctrica, 2023)

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 m^3, 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 €/MWh. Average peak power prices would be 80 €/MWh, power generation efficiency is 90% and net income for this cycle would be some €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 €11,000 per day so, together with the diurnal cycle, daily income is €26,000 or €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 efficiency and 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.

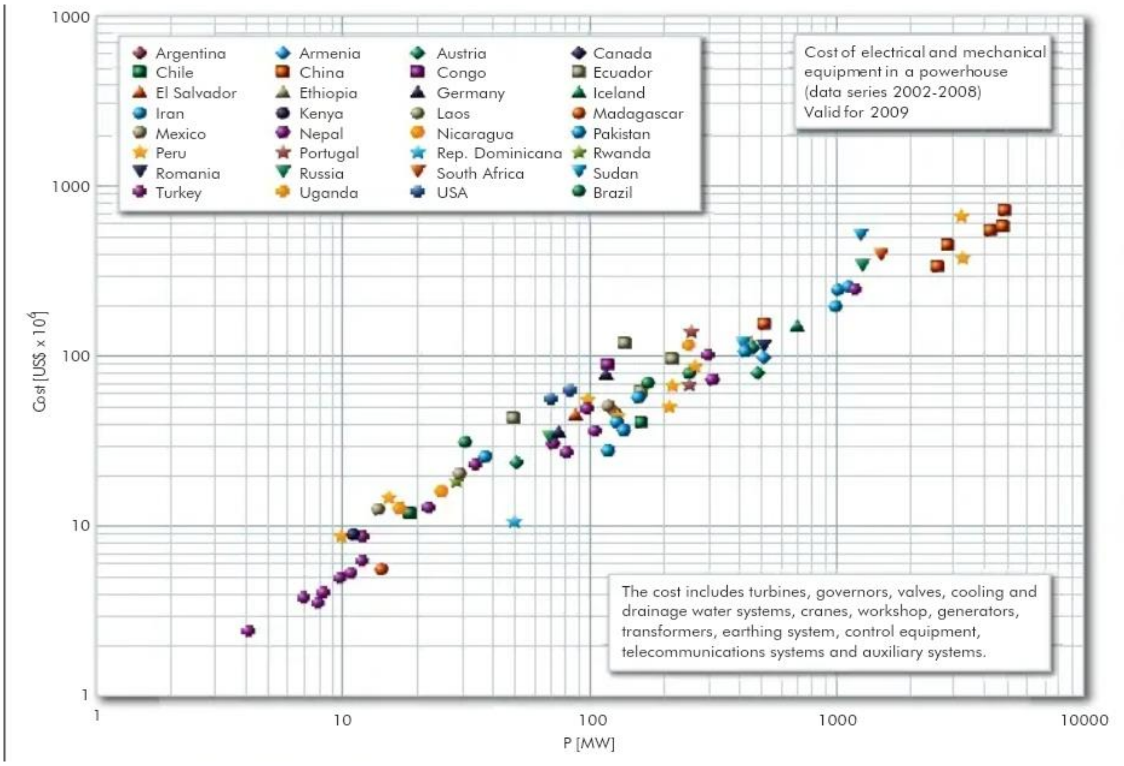

Figure 5-1. Cost of E&M equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa (Alvarado-Ancieta, 2012).

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 we can assume a Round Trip Efficiency (RTE) of 80%.

Assuming an operating costs of 26.13 €/kW-year : 3 = 8.71 €/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 €/year**.

5.4 Assessment of job creation potential

Within the GreenJOBS project, a detailed assessment of job creation potential per MW installed for the project's renewables (photovoltaics, wind energy, hydraulics, and geothermal) based on their production capacity, both for commissioning and operation, was developed.

First, the job-creation potential of renewable energy deployment was tried to be assessed using the input-output analysis introduced by Leontief in the 1930s and later adapted for different purposes. In recognition of his work, Leontieff received the Nobel Prize in Economics. The input-output model (Leontieff, 1986) is a quantitative model in the form of linear equations describing how a product from an industry is distributed within the economy. It represents the interdependencies between different national sectors or multi-regional economies and shows their production structure.

However, the equilibrium equation has several constraints or assumptions (Scholz, et al., 2020) that may pose extreme difficulties for the renewable energies analysed within the GreenJOBS project: (1) each unit of output requires the same amount of inputs, being independent of the production level, something that goes against the concept of the economy of scale, that represents the cost advantages due to the operation scale or, in other words, increased production, lower cost; (2) there should be no supply restrictions in, for example, the access to raw materials, employment, etc.; and (3) Changes on the output does not cause input substitution, something which implies having a fixed input structure.

As can be easily observed, these constraints affect almost every intrinsic characteristic of renewable energies, particularly the limited access to critical raw materials in Europe, as the EU heavily depends on imports of critical raw materials from third countries. This dependency and the growing global demand due to the shift towards a digital and green economy make supply chains vulnerable. Precisely, the European Critical Raw Materials Act (2023) aims to ensure a secure and sustainable supply of critical raw materials for Europe's industry, significantly lower the EU's dependency on imports from single-country suppliers and increase the EU's resilience by reducing dependencies, increasing preparedness and promoting supply chain sustainability and circularity.

This aspect, together with the fact that the renewable sector presents extraordinary high-scale economies that change really quickly in time (even for periods of less than one year) and that the input structure is far from fixed, makes it really difficult to analyse the input-output relationships between these renewable energies with this method. Thus, we will use the Employment factor method to analyse the potential job creation.

The employment factor approach estimates the average number of jobs per unit of capacity installed or per unit of energy generated and combines them with energy system data to derive the total number of jobs. Factors are specific to the value chain's technologies and stages/activities (Fragkos & Paroussos, 2018).

We will consider direct employment factors used by other authors, distinguishing per activity and component based on a literature review and using specific base years for the reference employment factors. Direct jobs, crucial for their immediate impact, are employment opportunities created to meet the demand for a product or service. They serve as critical indicators of the economic benefits of renewable energy projects, demonstrating the tangible job opportunities that arise from the development and expansion of renewable energy.

In the context of renewable energies, direct jobs refer to employment opportunities that are directly associated with the development, production, installation, operation, and maintenance of these systems, the key categories being:

- Operation and Maintenance (O&M): Jobs for ongoing operations and maintenance of the PV plant.
- Installation: Jobs for site preparation, construction, and installation.
- Manufacturing: Jobs Related to the production of components.

Then, learning curves developed considering the growing rate of each technology will update the employment factors by activity and component. Finally, if possible, a validation of results comparing them with ex-post results estimated by other authors will be developed.

Direct employment factors

Ortega et al. (2020) calculated the direct employment factors for 2008 for Photovoltaics and Wind on-shore, as presented in Table 1.

Table 6. Direct employment factors for 2008 for Photovoltaics and Wind on-shore (Ortega et al., 2020)

	Year	O&M (jobs-year/MW)	Inst. (jobs-year/MW)	Manuf. (jobs-year/MW)
Wind	2008	0.40	2.50	7.50
PV	2008	0.20	6.00	6.50

Rutovitz et al. (2015) calculated the direct employment factors for 2010 and 2012 for almost all renewable energy technologies, as presented in Tables 2 and 3.

Table 2. Direct employment factors for 2010 for renewable energies (Rutovitz et al., 2015)

	Year	O&M (jobs-year/MW)	Inst. (jobs-year/MW)	Manuf. (jobs-year/MW)
Wind	2010	0.40	2.50	12.50
PV	2010	0.40	9.30	29.00
Geothermal	2010	0.70	3.10	3.30
Hydro	2010	0.20	10.80	0.50
Biomass	2010	3.10	3.90	0.40

Table 3. Direct employment factors for 2012 for renewable energies (Rutovitz et al., 2015)

	Year	O&M (jobs-year/MW)	Inst. (jobs-year/MW)	Manuf. (jobs-year/MW)
Wind	2012	0.20	2.50	6.10
PV	2012	0.30	11.00	6.90
Geothermal	2012	0.40	6.80	3.90
Hydro-small	2012	2.40	15.00	5.50
Biomass	2012	1.50	14.00	2.90

Using data from Rutovitz et al. (2015) and from Cameron & Van der Zwaan (2015), Fragkos & Paroussos (2018) modelled the direct employment factors for 2015, Table 4.

Table 4. Direct employment factors for 2015 for renewable energies (Fragkos & Paroussos, 2018)

	Year	O&M (jobs-year/MW)	Inst. (jobs-year/MW)	Manuf. (jobs-year/MW)
Wind	2015	0.20	2.60	4.35
PV	2015	0.15	10.40	5.36
Geothermal	2015	0.51	11.20	5.40
Hydro-small	2015	0.28	15.80	10.90
Biomass	2015	0.24	14.00	2.90

Using a different approach, Brown et al. (2020) estimated the number of direct jobs resulting from investments in renewable energies in 2015, as presented in Table 5. The data for transmission and distribution can be assumed to be equivalent to battery deployment.

Table 5. Direct employment factors for 2015 for renewable energies (Brown et al., 2020). Change used: 1.1 USD = 1 EUR.

	Direct jobs-year/1 M€	Direct jobs-year/5 M€	Direct jobs-year/10 M€	Direct jobs-year/20 M€
Wind	0.43	2.14	4.27	21.36
Transm. & distrib.	0.64	3.18	6.36	31.82
Fossil fuel	0.58	2.91	5.82	29.09
Solar	1.82	9.09	18.18	90.91
Geothermal	1.14	5.68	11.36	56.82
Hydroelectric	1.20	6.00	12.00	60.00
Biomass	0.66	3.32	6.64	33.18

Regarding Green hydrogen production, Rhodium Group (https://rhg.com/research/clean-hydrogen-workforce-development/) estimated that 2023 a 100 MW electrolytic plant would create 45 ongoing jobs and 330 plant investment jobs. On the other hand, the literature focuses more on the global number of jobs than on the number of jobs resulting from power installations or investments.

Learning rates

According to Murphy (2012), the learning rate determines how much a model change at each iteration while moving towards a minimum value. The learning rate influences how the newly production efficiency influences overrides old production efficiency, representing in a metaphoric way the speed at which the production system of a company or product "learns".

Learning rates will be developed considering the growing rate of each technology to update the employment factors by activity and component.

To achieve this goal, we will use the latest data on European energy figures, the Statistical Pocketbook 2023 (European Commission, 2023).

Table 5 presents the installed electricity capacity in GW for several renewable energies from 2010 to 2021.

Table 5. Installed electricity capacity in GW (European Commission, 2023).

	2010	2015	2019	2020	2021
Wind	79.0	127.2	167.1	177.1	188.4
Solar	30.6	87.7	120.2	138.5	164.2
Geothermal	0.8	0.8	0.9	0.9	0.9
Hydro	143.0	148.2	150.8	151.1	151.7
Combustible fuels	414.8	412.2	395.7	388.1	379.4
Green hydrogen (MW)*			85.00		162
Batteries**				2.4 GW 3.9 GWh	4.6 GW 7.7 GWh

1. * Bolard et al. (2023). ** Bielewski et al. (2022).

According to the figures presented in Table 5, the derived linear learning curves for the renewable energies, except geothermal and batteries, are presented in Figure 1.

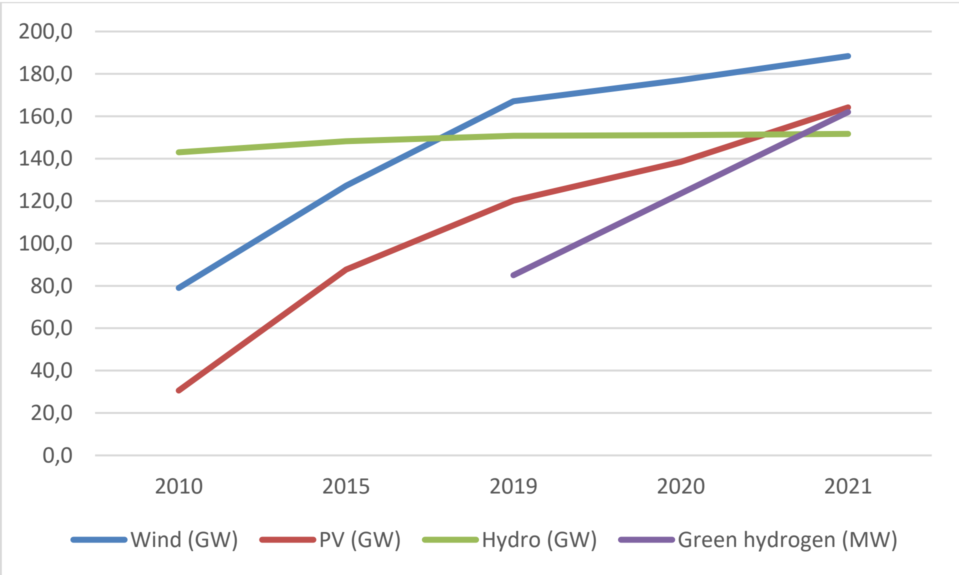

Figure 1. Installed electricity capacity for wind energy, PV, hydro and green hydrogen plants.

The trendline slopes to 10.65 for wind energy. The slope for PV energy is 24.78; for hydro, it is 1.08; and for green hydrogen, it is 38.5.

The case of geothermal and batteries is presented in Figure 2.

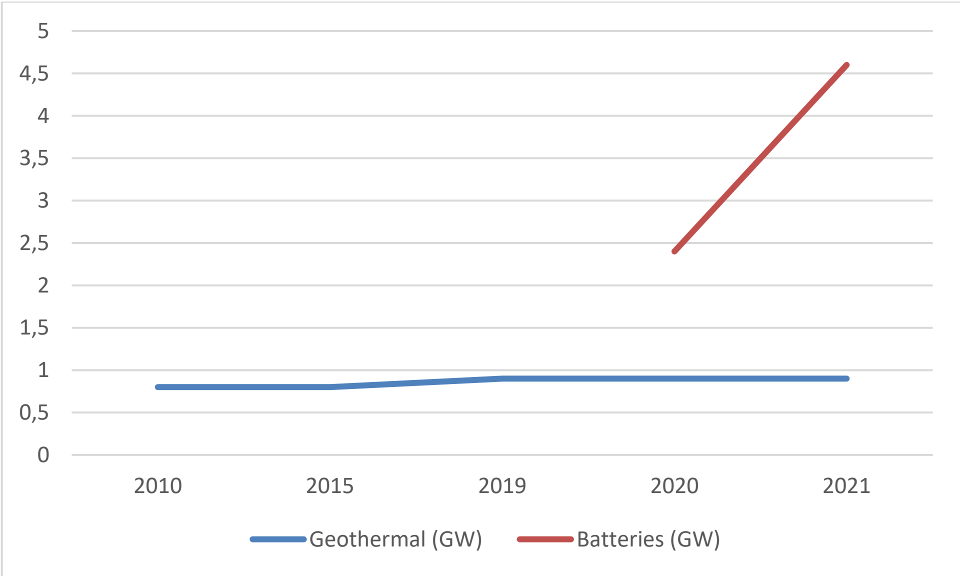

Figure 2. Installed electricity capacity for geothermal and batteries.

The trendline slopes to 2.2 for batteries and only 0.03 for geothermal.

For the cases of Wind energy, PV, Geothermal and Hydro-small, that we will use to estimate Unconventional pumped hydro, we will use the direct employment factors from 2010 obtained by Rutovitz et al. (2015) and the ones from 2015 obtained by Fragkos & Paroussos (2018). Simultaneously, when it is necessary, we will consider the trendline slope of the installed electricity capacity.

Estimation of direct, indirect, and induced employment

Finally, and to estimate the direct, indirect and induced employment across renewable energies, we will use as a reference an input/output table using the employment multipliers from Brown et al. (2020), that are presented in Table 6.

Table 6. Estimation of direct, indirect and induced employment: Full-time equivalent jobs/M€ investment in 2015 (Brown et al., 2020)

	Direct	Indirect	Induced	Total
Wind	0,43	1,35	1,47	3,25
Transmission & distribution	0,64	1,92	2,65	5,21
Fossil fuel	0,58	2,34	2,85	5,76
Solar	1,82	0,64	3,35	5,80
Geothermal	1,14	2,96	3,58	7,68
Hydroelectric	1,20	3,07	3,85	8,13
Biomass	0,66	5,34	3,88	9,88

Unconventional pumped hydro

Figure 3 presents the evolution of the O&M (jobs-year/MW) using the logarithmic trendline. Due to the high difference of 2012 data compared with 2010 and 2015 data, we will not consider it.

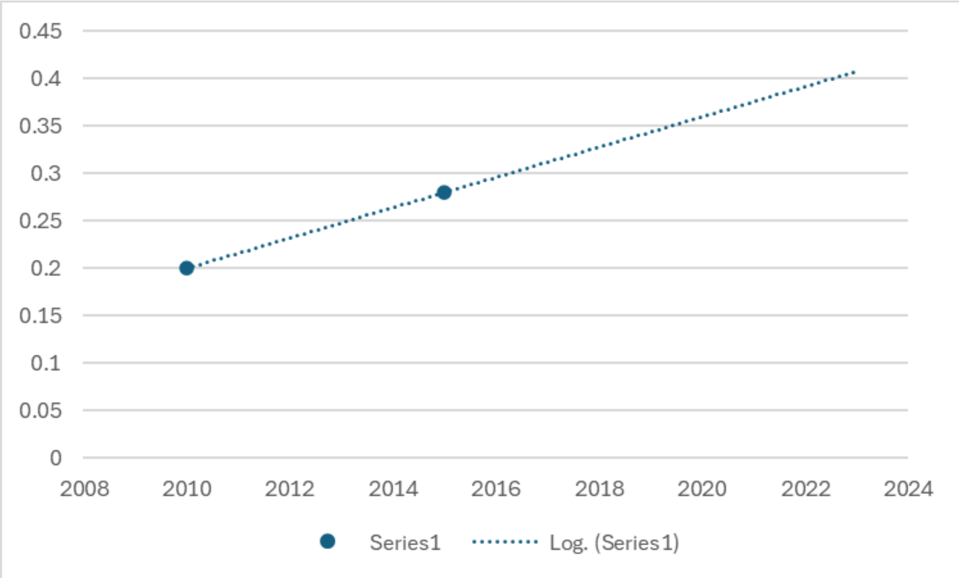

Figure 3. O&M (jobs-year/MW) evolution trendline.

Figure 4 presents the evolution using a linear trendline for the Installation (jobs-year/MW).

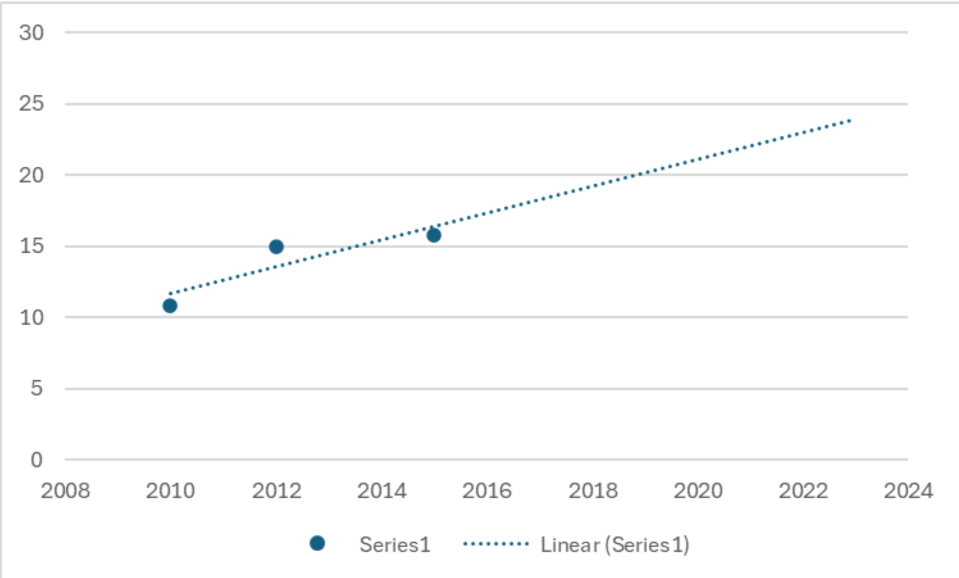

Figure 4. Installation (jobs-year/MW) evolution trendline.

In the case of manufacturing jobs, presented in Figure 5, we used a polynomial trendline.

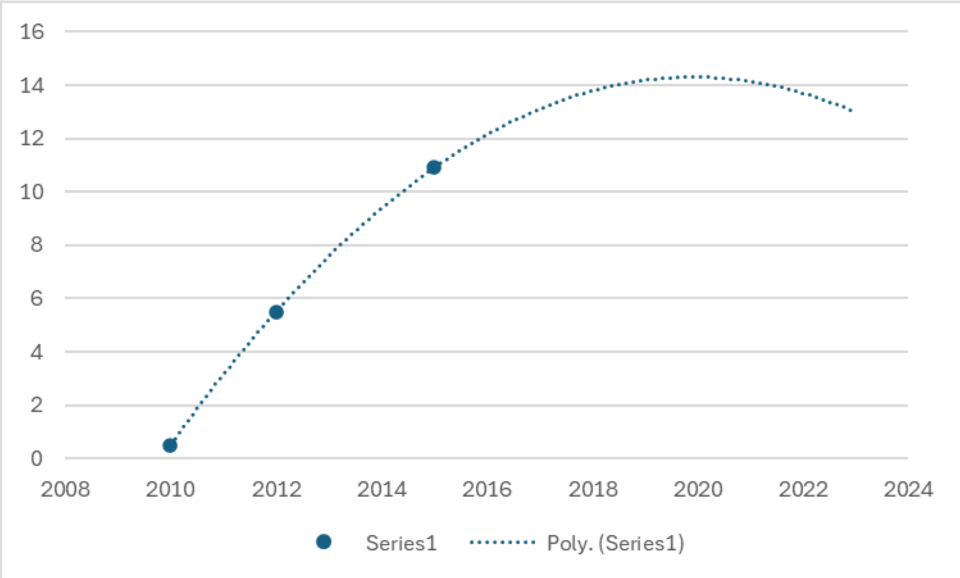

Figure 5. Manufacturing (jobs-year/MW) evolution trendline.

Table 7 presents the estimations of direct employment factors for Unconventional pumped hydro energy storage, establishing respective increases and decreases based on the derived learning curves but adapted to the usual trends.

Table 7. Direct employment factors for Unconventional pumped hydro energy storage

	2010	**2012**	**2015**	**2019**	**2020**	**2021**	**2023**
Installed capacity in GW	143.0	*145.6*	148.2	150.8	151.1	152.7	-
O&M (jobs-year/MW)	0.20	2.40	0.28	*0.34*	*0.36*	*0.38*	*0.4*
Inst. (jobs-year/MW)	10.8	15.0	15.8	*20.0*	*21.0*	*22.0*	*24.0*
Manuf. (jobs-year/MW)	0.5	5.5	10.9	*14.0*	*14.0*	*14.0*	*13.0*
Total (jobs-year/MW)	11.5	22.9	26.98	*34.34*	*35.36*	*36.38*	*37.4*

* Estimated values are presented in italics

Thus, we can estimate the number of direct jobs for 2023 in 37.4 direct jobs-year/MW.

Finally, using the estimation proportions obtained by Brown et al. (2020), presented in Table 6, we obtain the total employment of 253.1 full-time equivalent jobs/MW presented in Table 8.

Table 8. Estimation of direct, indirect and induced employment for Unconventional pumped hydro energy storage: Full-time equivalent jobs/MW

	Direct	Indirect	Induced	Total
UNCONVENTIONAL HYDRO	*37.4*	*95.7*	*120.0*	*253.1*

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:

1. 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

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