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 2.5
Batteries deployment

European Commission

Research Fund for Coal & Steel

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Deliverable 2.5	
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	UNIOVI
Dissemination level	Public
Work Package	WP 2
Digital File Name	D2.5 Batteries deployment
Keywords	Batteries, Lithium-ion, Lithium Iron Phosphate, Lead-acid batteries, Zinc-based batteries, batteries backup

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Executive Summary

This deliverable analysis batteries deployment to cover the unconventional pumped hydro operation in a Virtual Power Plant with an installed photovoltaic capacity for a 50 ha waste heap area of 1 MW/ha, totalising 50 MW.

The unconventional pumped hydro storage is calculated to cover daytime energy storage plus a 10% safety margin, with around half of the daytime hourly energy production twice the time (about 16 hours), resulting in an installed capacity of 200 MWh-10 MW. Thus, batteries will briefly cover the time needed to start energy generation with unconventional pumped hydro storage, so the duration of the battery supply should be less than 2 hours and the installed capacity of 20 MWh-10 MW.

To achieve this goal, in first place, the different battery technologies currently being used are analysed, and the characteristics of the various battery technologies are presented.

Second, the features of implementing this technology in mining areas are highlighted.

Third, the best technology for mining areas is identified with the selected technology’s operational requirements.

Four, the main economic/social/technical characteristics of the demosite installation are presented: capital price, operating costs, decommissioning costs, and performance metrics.

Finally, the demosite job creation potential is estimated by comparison with photovoltaic plants.

1 Introduction

Work Package Nº2 analyses energy harnessing technologies, strengthening technologies, and green hydrogen deployment. Specific objectives are:

1. To select, according to the project's needs, the most widespread and reliable units on the market for deploying the selected energy harnessing technologies: geothermal, photovoltaic and wind power.
2. To select, according to the project needs, the most widespread and reliable units on the market to deploy energy-strengthening technologies: unconventional pumped hydro and batteries.
3. Select the most widespread and reliable units to deploy green hydrogen according to the project's needs.
4. To analyse the technical specifications, cost data and operational constraints of the selected alternatives for each renewable energy technology.
5. To prepare a detailed assessment of the job creation potential of each alternative per MW installed, per MWh-MW of storage capacity and MW of electrolysers capacity, both for commissioning and operation.

Deliverable 2.5 will select the most widespread and reliable units on the market to deploy batteries according to the project's needs.

The data that will be analysed will address the following aspects, if possible:

a) Efficiency in %.
b) Roundtrip efficiency in %.
c) Minimum load of the unit in %.
d) Efficiency at minimum load in %.
e) The upward ramping constraint for units per unit per min in %.
f) The downward ramping constraint for units per unit per min in %.
g) Size of the unit in MW.
h) Operation and maintenance cost in € per MWh.
i) Availability of the unit when analysing investments.
j) The maximum contribution to the upward reserve from the available generation in the dispatch mode is in %.
k) Maintenance and operating costs per year in € per MW.
l) Investment cost in € per MW
m) Cost of starting up in € per MW.
n) The lifetime of units in years.
o) Energy consumption.
p) CO_2 emissions reduction due to installing the new facilities in tonnes per year.
q) Job creation potential per MWh-MW of installed storage capacity for commissioning and operation will be developed.

r) Storage capacity in MWh and charge/discharge capacity in MW.
s) Fixed relation between charge/discharge capacity and storage capacity in MW per MWh.
t) Response time in minutes/seconds.
u) The investment cost for storage in € per MW/MWh ratio.
v) Loss of stored energy from storage over time per unit per hour.

2 State of the art of "technology"

2.1 Energy storage systems (ESS)

According to Viswanathan et al. (2022), Diabatic compressed-air energy storage (CAES) is estimated to be the lowest-cost storage technology on an installed cost basis at durations equal to or bigger than 4 hours and 100 MW. Something similar happens with other technologies, such as Pumped storage hydropower (PSH). Indeed, no storage technology different from batteries is used when considering 10 MW.

Figure 2.1 presents the 2021 total installed cost comparison in €/kWh, using a change of 1 $ = 0.92 €. The costs displayed in the figure are Levelized costs of energy (LCOS), representing a cost per unit of energy metric (€/kWh or €/MWh) used to compare different storage technologies on an equal footing than comparing their installed costs.

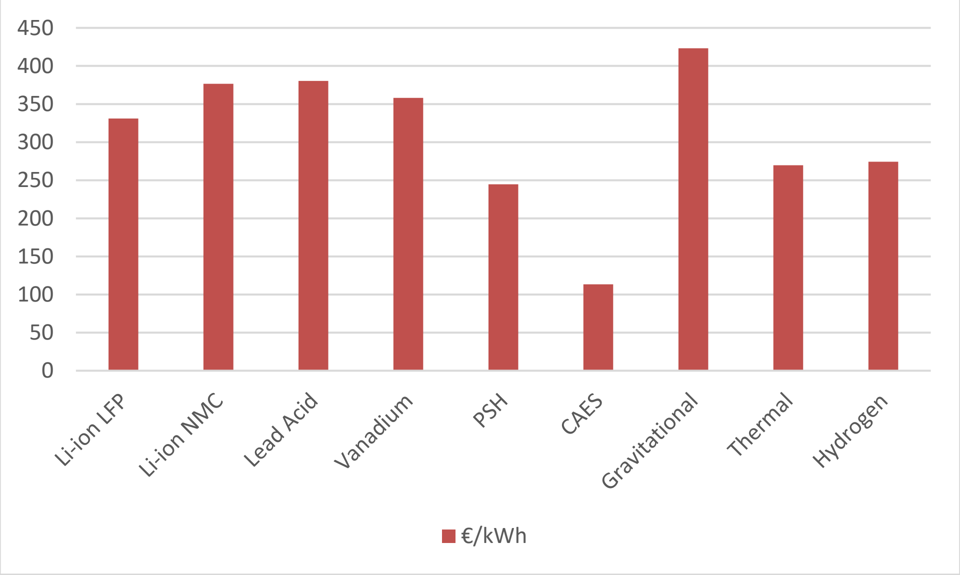

Figure 2-1. 2021 total installed cost comparison for 100 MW and 10 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Thus, CAES is the most economical energy storage system for 10 hours and 100 MW. It is followed by PSH and Thermal energy storage, predominantly molten nitrate salt. However, other storage media, such as crushed rock, sand, concrete, brick, or cast iron, can be considered.

When requiring storage for less than 4 hours and around 10 MW, only batteries are considered and used as feasible ESS.

2.2 Batteries technologies

The batteries technologies currently being used are the following:

2.2.1 Lithium-ion batteries

Lithium-ion batteries can refer to a wide array of chemistries. However, it consists of a battery based on charge and discharge reactions from a lithiated metal oxide cathode and a graphite anode.

Lithium-ion batteries are used in various ways, from electric vehicles to residential batteries to grid-scale applications (Pacific Northwest National Laboratory, 2022). They have high energy densities, high efficiency and a long life cycle, although with high production costs and require special charging circuits (Zhang et al., 2018). There are two more commonly used lithium-ion chemistries:

- Nickel Manganese Cobalt (NMC).
- Lithium Iron Phosphate (LFP).

2.2.2 Vanadium redox flow batteries

Vanadium redox flow batteries are composed of two tanks of electrolyte solutions, one for the cathode and the other for the anode. Electrolytes are passed by a membrane and complete chemical reactions to charge and discharge energy.

They are in an early phase of commercialisation, presenting the following advantages: scalability due to modularity, long cycle and calendar life, and the ability to change energy and power independently (Pacific Northwest National Laboratory, 2022).

They have many advantages, such as high capacity, power efficiency, fast charge and discharge, safety and long life. However, the investments needed are also really high, also requiring a large area. Currently, flow batteries techniques are pretty mature and include (Zhang et al., 2018):

- Vanadium redox flow batteries.
- Zn-Ce hybrid redox flow batteries.
- Iron-chromium flow batteries.
- Zinc/bromine flow batteries.

2.2.3 Lead-acid batteries

Lead-acid batteries use lead dioxide (PbO2) for the positive electrode and lead (Pb) for the negative electrode. This technology is typically well-suited for larger power applications.

This technology has two subtypes: vented and valve-regulated (Pacific Northwest National Laboratory, 2022). They are the most mature technology and the one with the lower cost. However, in the case of deep/rapid discharge, their capacity is reduced significantly.

Moreover, they have other disadvantages, such as low energy and power density, low cycle life and long charge times, and high self-discharge rates (Zhang et al., 2018).

2.2.4 Zinc-based batteries

Zinc-based batteries are several technologies and configurations that employ metallic zinc as the battery anode with aqueous electrolytes: Ni-Zn, Zinc-bromine (flow), Zinc-bromine (nonflow or static), and Zinc-air. Most zinc-based manufacturers have not deployed systems rated at > 10 MW (Pacific Northwest National Laboratory, 2022).

Their handicap is having poor rechargeability, with the technology being at a Technology Readiness Level (TRL) of only TRL 5 – TRL 6, according to the US Department of Defense. Zinc-based batteries are ecologically friendly as they are easy to recycle, and the abundant raw materials used promise large power densities and long cycle life (Borchers et al., 2021).

2.2.5 Sodium-sulfur batteries

Sodium-sulfur batteries treat molten sodium as the negative electrode and molten sulfur as the positive electrode, with ceramic tubes serving as solid electrolytes and separators between the electrodes.

Sodium-sulfur batteries have high power and energy densities, together with high efficiency. However, they have a high production cost and operate under high temperatures, which can lead to fire accidents (Zhang et al., 2018).

2.2.6 Aluminium-ion batteries

Aluminium-ion batteries use metallic aluminium as the negative electrode, a three-dimensional graphic foam as the positive electrode and an ionic liquid as an electrolyte.

Rechargeable Al-ion batteries have the potential to be cost-effective, with fast charge and discharge and high efficiency. However, they are under development, and the main disadvantage is low energy densities (Zhang et al., 2018).

2.3 Battery technology characteristics

Table 2-1 presents the main features of the battery technologies currently considered or in development.

Table 2-1. Characteristics of the different battery technologies

Battery technology	Rated power	Energy density	Efficiency	Life cycle	Charge/ discharge	Low costs	No specific needs	No dangers	Maturity
Li-ion NMC	+	+	+	+	+	-	-	+	+
Li-ion LFP	+	+	+	+	+	-	-	+	+
Vanadium-based	+	-	-	++	+	-	-	+	-
Lead-acid	-	-	-	-	-	+	+	+	+
Zinc-based		+	+	+	-	+	+	+	-
Sodium-sulfur	+	+	+	-	+	-	+	-	+
Aluminium-ion		-	+	+	+	+	+	+	-

Table 2-1 shows that Li-ion batteries are the most exciting technology. The one selected between NMC and LFP will depend mainly on the price. This aspect is analysed in point 4. Identification of best technology for mining areas. Operational requirements of the selected technology.

3 Features of the implementation of “technology” in a mining area

Figure 3-1 presents the graphical abstract of the GreenJOBS project with the case of a Virtual Power Plant where the energy produced will be sold to the grid or used to power electro-intensive industries or companies with constant energy consumption located close to mines, such as aluminium factories or green data centres.

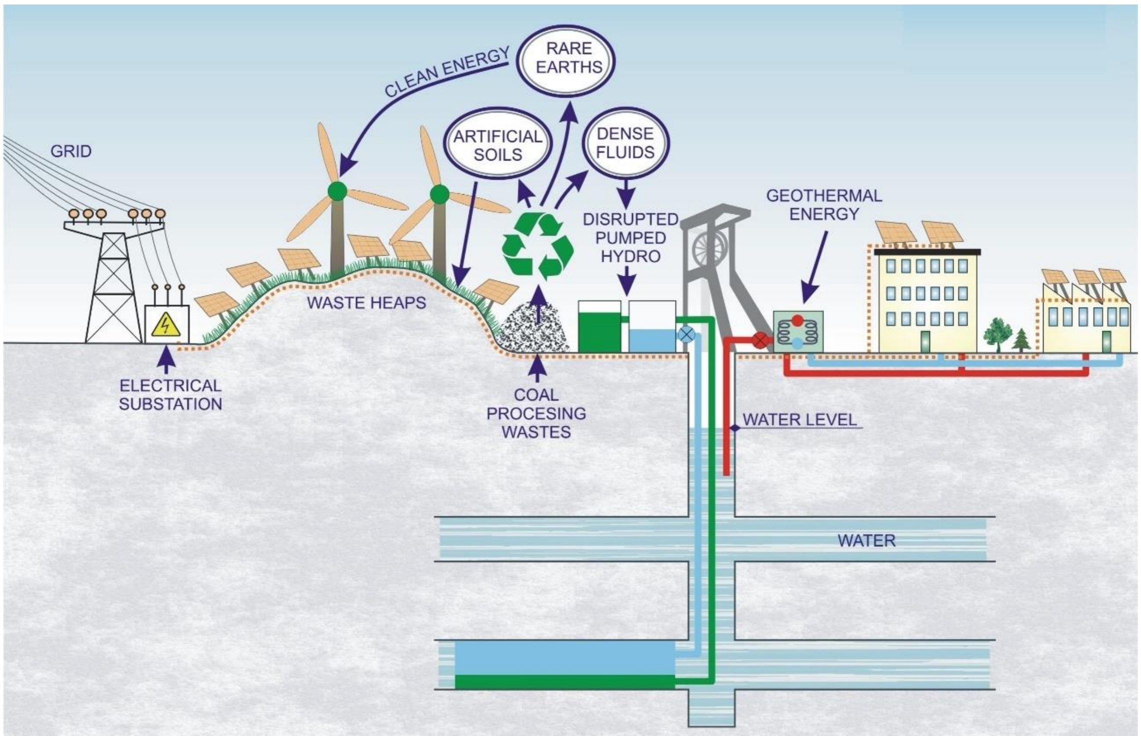

Figure 3-1. Graphical abstract of the GreenJOBS project: Virtual Power Plant

The unconventional pumped hydro energy storage using dense fluids proposed in GreenJOBS has two innovative values compared to what has been already offered at both European and worldwide levels: firstly, it can operate in flooded mines, mainly eliminating the costs of pumping mine water in general and water used for geothermal in particular, something that is not feasible with other energy storage alternatives such as Graviticitry; secondly, the use of dense fluids allows providing density differentials between the fluids and, the greater the difference, the more efficient the system will be.

The deployment of batteries will be designed to cover the unconventional pumped hydro operation.

The installed photovoltaic capacity for a 50 ha waste heap area with an installed capacity of 1 MW/ha is 50 MW. The capacity factor considered (% time of use of the installation per year) will be 30%, with 50% of energy to be stored to cover the periods when the energy is more expensive, and there is no photovoltaic production.

The unconventional pumped hydro storage was calculated to cover daytime energy storage plus a 10% safety margin, with around half of the daytime hourly energy production twice the time (about 16 hours), resulting in an installed capacity of 200 MWh-10 MW.

Batteries will briefly cover the time needed to start energy generation with unconventional pumped hydro storage. Thus, the duration of the battery supply should be less than 2 hours and the installed capacity of 20 MWh-10 MW.

Moreover, Figure 3-2 presents a Green Hydrogen Plant where renewable hydrogen will be produced by electrolysis of mine water and electricity from renewable sources.

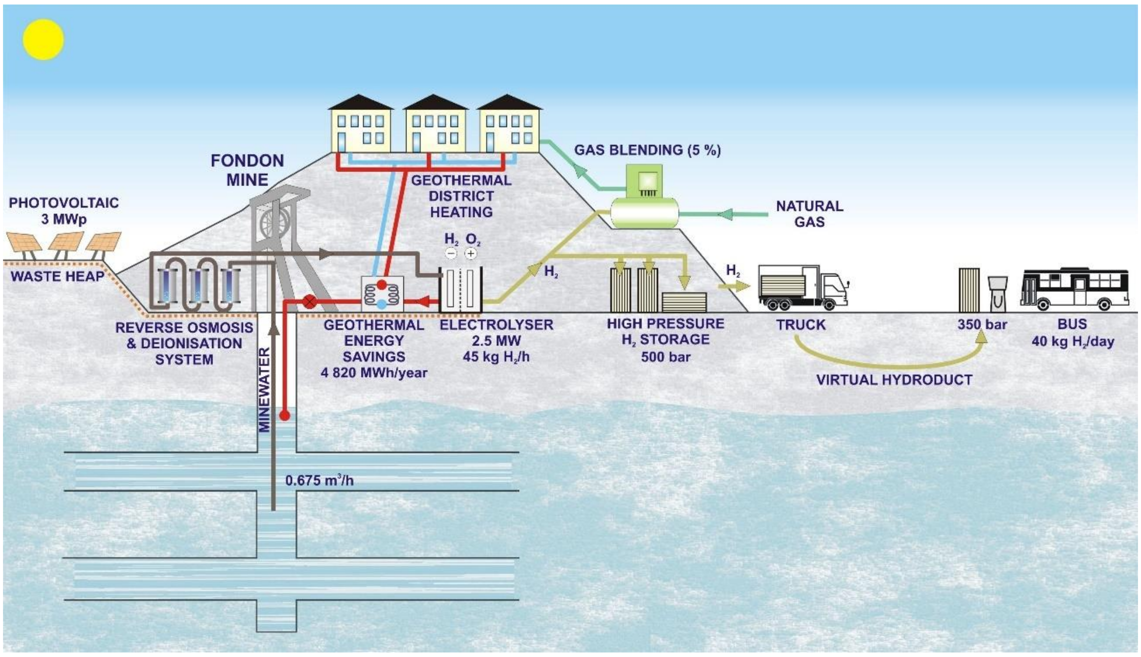

Figure 3-2. Green Hydrogen Plant

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

Figure 4-1 presents the 2021 total installed cost comparison in €/kWh, using a change of 1 $ = 0.92 €. Thus, Lithium-ion Iron Phosphate (LFP) batteries are the most interesting to be used for 2 hours and 10 MW, as they are more than 10% cheaper than Lithium-ion NMC.

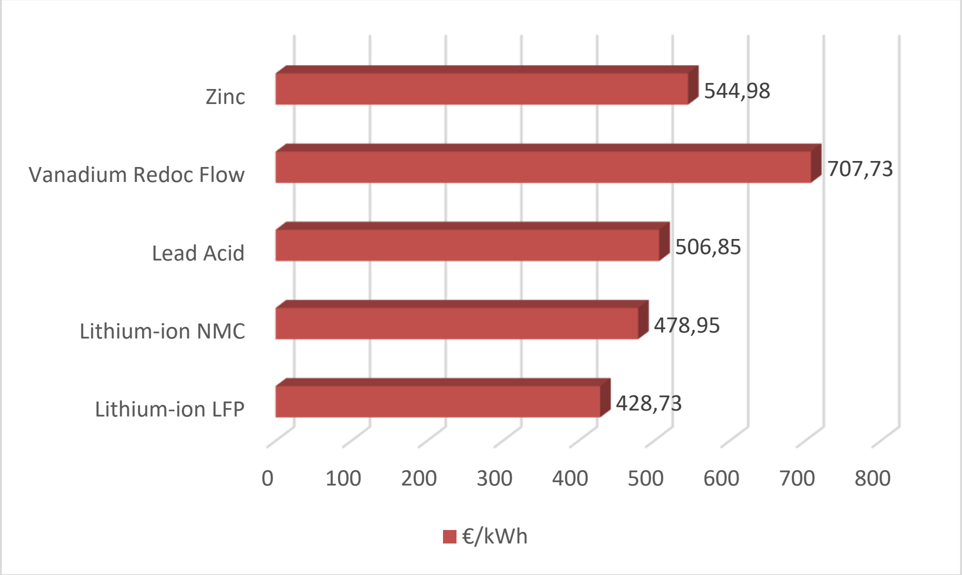

Figure 4-1. 2021 total installed cost comparison for 10 MW and 2 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Figure 4-2 presents the 2021 total installed cost comparison in €/kWh, using a change of 1 $ = 0.92 €. Thus, Lithium-ion Iron Phosphate (LFP) batteries are still the most interesting to be used for 4 hours and 10 MW, as they are again more than 10% cheaper than Lithium-ion NMC.

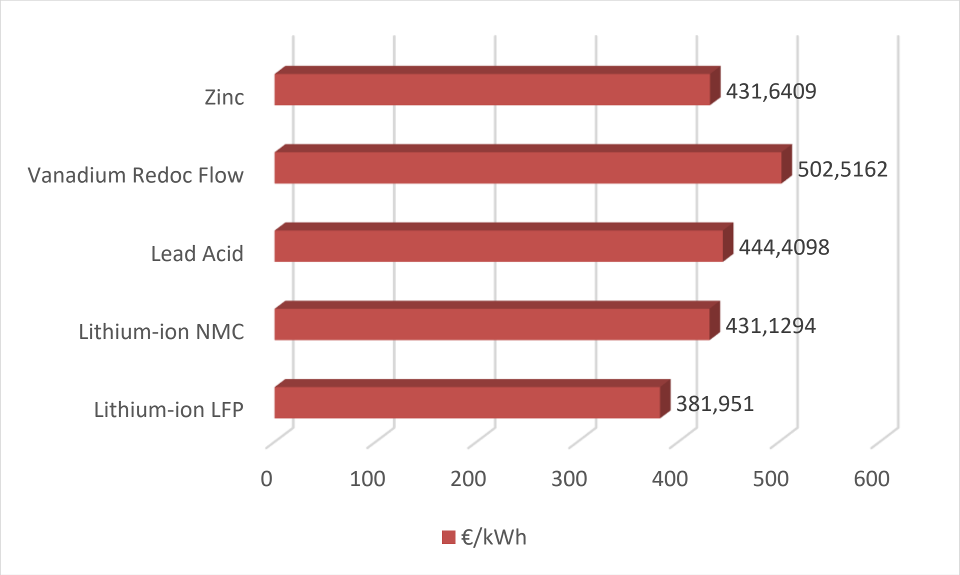

Figure 4-2. 2021 total installed cost comparison for 10 MW and 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

As stated in the previous chapter, batteries will briefly cover the time needed to start energy generation with unconventional pumped hydro storage. Thus, the duration of the battery supply should be less than 2 hours and the installed capacity of 20 MWh-10 MW.

Thus, Lithium-ion Iron Phosphate (LFP) batteries will be the ones to be used for 2 hours and 10 MW.

5 Demosite Installation. Main financial/social/technical characteristics

5.1 Demosite financial & technical characteristics

5.1.1 Capital price

The capital price components for Lithium-ion LFP batteries, 10 MW, 2 hours, are presented in Table 5-1.

Table 5-1. Two thousand twenty-one capital price for lithium-ion LFP, 10 MW, 2 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Capital Price components	2021 Point Estimate
Direct Current (DC) Storage Block	163.88 €/kWh
DC Storage Balance of systems (BOS)	40.36 €/kWh
Power Equipment	67.94 €/kWh
Controls and Communication (C&C)	7.21 €/kW
Systems Integration	48.01 €/kWh
Engineering Procurement & Construction (EPC)	57.97 €/kWh
Project development	69.55 €/kWh
Grid integration	23.07 €/kW
TOTAL INSTALLED COST (€/kWh)	**428.87 €/kWh**
TOTAL INSTALLED COST (€/kW)	**857.46 €/kW**

For the case of 10 MW, 4 hours, the capital price components are presented in Table 5-2.

Table 5-2. Two thousand twenty-one capital price for lithium-ion LFP, 10 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Capital Price components	2021 Point Estimate
Direct Current (DC) Storage Block	161.51 €/kWh
DC Storage Balance of systems (BOS)	37.55 €/kWh
Power Equipment	67.94 €/kWh
Controls and Communication (C&C)	7.21 €/kW
Systems Integration	43.39 €/kWh
Engineering Procurement & Construction (EPC)	52.25 €/kWh
Project development	62.70 €/kWh
Grid integration	23.07 €/kW
TOTAL INSTALLED COST (€/kWh)	**381.95 €/kWh**
TOTAL INSTALLED COST (€/kW)	**1,527.99 €/kW**

The installed Energy Storage System capital price is calculated by the sum of the following parts (Pacific Northwest National Laboratory, 2022):

The storage system:

- Direct Current (DC) Storage Block: Includes the price for the most basic DC storage element in an ESS (e.g., for lithium-ion, this price includes the battery module, rack, and battery management system and is comparable to an electric vehicle (EV) pack price).
- DC Storage - Balance of System (BOS): Supporting cost components for the storage block, including container, cabling, switchgear, flow battery pumps, Heating, Ventilating, and Air Conditioned (HVAC).

The energy storage system comprises the storage system plus the following:

- Power Equipment: Bi-directional inverter, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, and software. This is the power conversion system for batteries, the powerhouse for PSH, and the power island/powertrain for CAES.
- System Integration: Price charged by the system integrator to integrate sub-components of a battery energy storage system into a single functional system. Tasks include procurement and shipment to the site of battery modules, racks with cables in place, containers, and power equipment. At the site, the modules and racks are containerised with HVAC and fire suppression installed and integrated with the power equipment to provide a turnkey system.
- Controls & Communication: Includes the energy management system for the entire ESS and is responsible for ESS operation. It may also include annual licensing costs for software, typically represented as a fixed cost scalable concerning power and independent of duration.

Apart from these, the following parameters should also be considered:

- Engineering, Procurement and Construction: Includes non-recurring engineering costs, construction equipment, and shipping, siting, installation & commissioning of the ESS; cost is weighted based on duration.
- Project Development: Costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.

- Grid integration: Direct cost associated with connecting the ESS to the grid, including transformer, metering, and isolation breakers. It could be a single disconnect breaker or a breaker bay for larger systems.

5.1.2 Operating costs

The operating costs for Lithium-ion LFP batteries, 10 MW, 2 hours, are presented in Table 5-3.

Table 5-3. Two thousand twenty-one operating costs for lithium-ion LFP, 10 MW, 2 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Operating Costs	**2021 Point Estimate**
Fixed Operations & Management (O&M)	2.59 €/kW-year
Round Trip Efficiency (RTE) Losses	-
Warranty (estimation)	2.90 €/kWh-year
Insurance	-

The operating costs for Lithium-ion LFP batteries, 10 MW, 4 hours, are presented in Table 5-4.

Table 5-4. Two thousand twenty-one operating costs for lithium-ion LFP, 10 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Operating Costs	**2021 Point Estimate**
Fixed Operations & Management (O&M)	4.27 €/kW-year
Round Trip Efficiency (RTE) Losses	-
Warranty (estimation)	2.86 €/kWh-year
Insurance	-

The operating cost parameters are (Pacific Northwest National Laboratory, 2022):

- Fixed Operations and Maintenance (O&M): All costs necessary to keep the storage system operational throughout its life; costs, such as planned maintenance, parts, labour and benefits for staff, do not fluctuate based on energy throughput. Also includes major overhaul-related maintenance, which depends on throughput. According to the U.S. Energy Information Administration (2022), fixed O&M costs were estimated at $25.96 annually. which can be equivalent at 23.36 €/kW-year using a change of 1 USD = 0.9 EUR.

- Round Trip Efficiency (RTE) Losses: Includes HVAC and other auxiliary loads, DC losses, and power conversion system losses. When elaborating this Deliverable, they were unavailable for this technology.

- Warranty: Fees to the equipment provider for manufacturability and performance assurance over the designated lifespan.

- Insurance: Insurance fees to hold a policy to cover unknown and unexpected risks. Terms of this cost may depend on vendor reputation and financial strength. When elaborating this Deliverable, they were unavailable for this technology.

5.1.3 Decommissioning costs

The decommissioning costs for Lithium-ion LFP batteries, 10 MW, 2 hours, are presented in Table 5-5.

Table 5-5. Two thousand twenty-one decommissioning costs for lithium-ion LFP, 10 MW, 2 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Decommissioning Costs	2021 Point Estimate
Disconnection	-
Disassembly/Removal	-
Site Remediation	-
Recycling/Disposal	2.46 €/kWh

The decommissioning costs for Lithium-ion LFP batteries, 10 MW, 4 hours, are presented in Table 5-6.

Table 5-6. Two thousand twenty-one decommissioning costs for lithium-ion LFP, 10 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Decommissioning Costs	2021 Point Estimate
Disconnection	-
Disassembly/Removal	-
Site Remediation	-
Recycling/Disposal	2.46 €/kWh

The decommissioning costs are (Pacific Northwest National Laboratory, 2022):

- Disconnection, Disassembly, Removal, and Site Remediation: Costs associated with the disconnection, disassembly, removal, and site remediation. These costs vary widely based on whether the ESS is in or outside the built environment, how far materials must be transported, and whether site remediation is necessary. When elaborating this Deliverable, they were unavailable for this technology.

- Recycling/Disposal: Costs associated with recycling and disposing of components are less any costs recouped from the sale of materials.

5.1.4 Performance metrics

The performance metrics for Lithium-ion LFP batteries, 10 MW, 2 hours, are presented in Table 5-7.

Table 5-7. Two thousand twenty-one performance metrics for lithium-ion LFP, 10 MW, 2 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Performance metrics	**2021 Point Estimate**
Round Trip Efficiency (RTE)	83%
Depth of Discharge (DOD)	80%
Cycle Life	2,400
Calendar Life	16 years

The performance metrics for Lithium-ion LFP batteries, 10 MW, 4 hours, are presented in Table 5-8.

Table 5-8. Two thousand twenty-one performance metrics for lithium-ion LFP, 10 MW, 4 h (Pacific Northwest National Laboratory, 2022). Change used: 1 $ = 0.93 €

Performance metrics	**2021 Point Estimate**
Round Trip Efficiency (RTE)	83%
Depth of Discharge (DOD)	80%
Cycle Life	2,400
Calendar Life	16 years

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.

- Cycle Life: The cycle life for an ESS is a function of depth of discharge (DOD) and is the total number of cycles that an ESS can provide at any depth of discharge over its life.

- 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.

6 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, a validation of results comparing them with ex-post results estimated by other authors will be developed.

6.1 Direct Employment Factors

Ortega et al. (2020) calculated the direct employment factors for 2008 for Photovoltaics and Wind on-shore, as presented in Table 6-1.

Table 6-1. 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 6-2 and 6-3.

Table 6-2. 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 6-3. 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 that are presented in Table 6-4.

Table 6-4. 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 6-5. The data for transmission and distribution can be assumed to be equivalent to battery deployment.

Table 6-5. 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 in 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.

6.2 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 6-6 presents the installed electricity capacity in GW for several renewable energies from 2010 to 2021.

Table 6-6. 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 6-1.

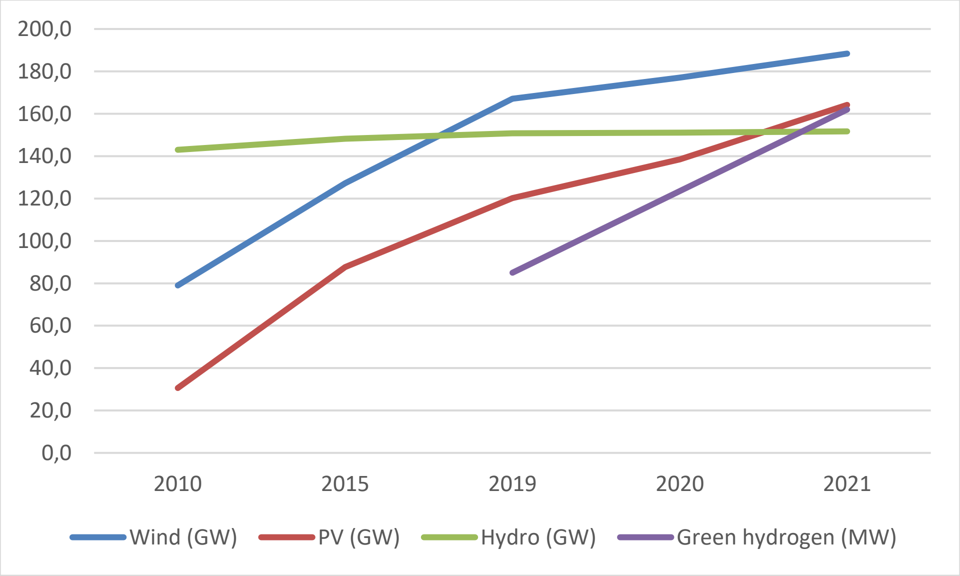

Figure 6-1. Installed electricity capacity for wind energy, PV, hydro and green hydrogen plants

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 6-2.

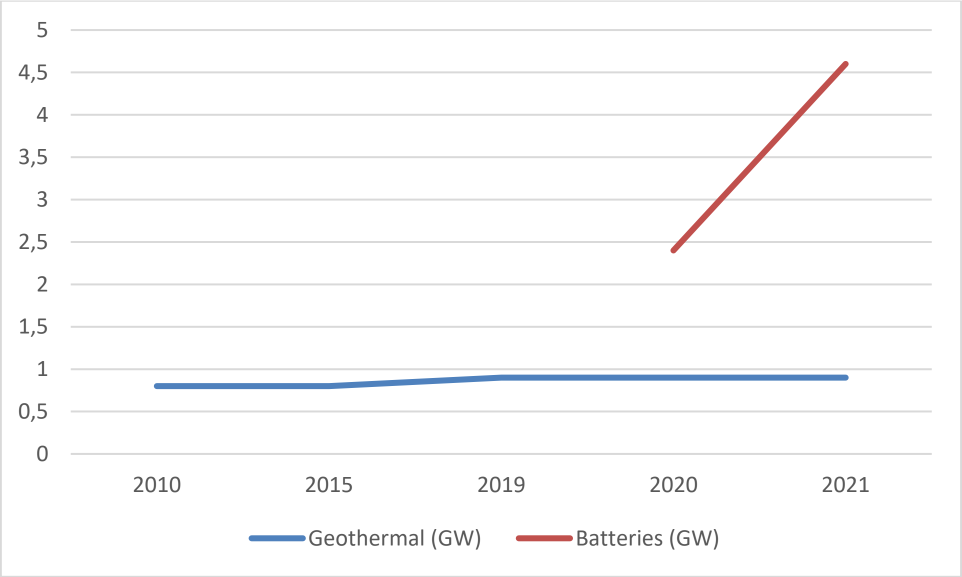

Figure 6-2. Installed electricity capacity for geothermal and batteries

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, 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 necessary, we will consider the trendline slope of the installed electricity capacity.

6.3 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 6-7.

Table 6-7. . 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

6.4 The case of batteries

Due to the highly new battery storage technology, we can only use the data from the Transmission and distribution sector given by Brown et al. (2020) for 2015 that estimated direct jobs-year/M€, presented in Table 6-5. To distribute the values between O&M, installation, and manufacturing, we will use a similar proportion to the case of Biomass, as they have very similar figures, according to Table 6-5.

Regarding the evolution, we will use a similar one to Photovoltaics as the trendlines from 2010 to 1015 are similar. The results are presented in Table 6-8.

Table 6-8. Direct employment factors for Batteries

	2015	2020	2021	2023
Installed capacity in GW		2.4	4.6	-
O&M (jobs-year/M€)	*0.01*	*0.01*	*0.01*	*0.01*
Inst. (jobs-year/M€)	*0.52*	*0.58*	*0.52*	*0.54*
Manuf. (jobs-year/M€)	*0.11*	*0.02*	*0.02*	*0.02*
Total (jobs-year/M€)	*0.64*	*0.61*	*0.55*	*0.57*

* Estimated values are presented in italics

Thus, we can estimate the amount of direct jobs for 2023 in 0.57 direct jobs-year/M€.

Finally, using the estimation proportions obtained by Brown et al. (2020) for the case of Transmission and distribution, presented in Table 6, we obtained the total employment of 4.64 full-time equivalent jobs/M€ presented in Table 6-9.

Table 6-9. Estimation of direct, indirect and induced employment for Batteries: Full-time equivalent jobs/M€

	Direct	Indirect	Induced	Total
Batteries	*0.57*	*1.71*	*2.36*	*4.64*

7 Best practices

When considering energy storage system (ESS) durations, diabatic compressed-air energy storage (CAES) is estimated to be the lowest-cost storage technology on an installed cost basis at durations equal to or bigger than 4 hours and 100 MW. It is followed by Pumped storage hydropower (PSH) and Thermal energy storage, predominantly molten nitrate salt. However, other storage media, such as crushed rock, sand, concrete, brick, or cast iron, can be considered.

Indeed, no storage technology different from batteries is used when considering 10 MW. Thus, only batteries are considered and utilised as feasible ESS when requiring storage for less than 4 hours and around 10 MW.

Addressing the main features of the battery technologies currently considered or in development, Li-ion batteries are the most exciting technology. The one selected between Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) will depend mainly on the price.

Lithium-ion Iron Phosphate (LFP) batteries are the most interesting to be used for 2 hours and 10 MW, as they are more than 10% cheaper than Lithium-ion NMC.

8 Conclusions & lessons learnt

Although diabatic compressed-air energy storage (CAES) is estimated to be the lowest-cost storage technology on an installed cost basis at durations equal to or higher than 4 hours and 100 MW, we have selected for GreenJOBS the unconventional pumped hydro energy storage using dense fluids, as the patent is property of one of GreenJOBS partners: Magellan & Barents.

However, the pre-existent underground mine infrastructure facilitates the implementation of unconventional pumped hydro energy storage, and coal wastes can be used for developing the dense fluids to be used. Thus, total installed costs may not be so different in the end.

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

1. Diabatic compressed-air energy storage (CAES) is the most economical energy storage system for 10 hours and 100 MW. It is followed by Pumped storage hydropower (PSH) and Thermal energy storage.

2. When requiring energy storage for less than 4 hours and around 10 MW, only batteries are considered and used as feasible energy storage system.

3. Currently, Li-ion batteries are the most exciting energy storage system to be used for 2 hours and 10 MW. According to the price, Lithium-ion Iron Phosphate (LFP) batteries are the most interesting, as they are more than 10% cheaper than Lithium-ion Nickel Manganese Cobalt (NMC).

4. The rest of characteristics of LFP and NMC are quite similar: rated power, energy density, efficiency, life cycle, charge/discharge, specfic needs, dangers and maturity.

5. One worker can take care of a geothermal installation of 1.5 M€ and a battery energy storage installation of 8.6 M€.

9 Glossary

AC – Alternating current

BOS – Balance of systems

CAES – compressed-air energy storage

CAPEX – Capital expenditure

COP – Coefficient of performance

DC – Direct current

DMT-THGA – DMT-Gesellschaft für Lehre und Bildung mbH

DOD – Depth of discharge

ESS – Energy storage system

FAEN – Fundación Asturiana de la Energía

GIG – Główny Instytut Górnictwa

HUNOSA – Hulleras del Norte, S.A.

HVAC – Heating, Ventilating and Air Conditioned

ICP-AES – Inductively coupled plasma-atomic emission spectrometry

ICP-OES - Inductively coupled plasma-optical emission spectrometry

IRR – Internal rate of return

LCOS – Levelized cost of energy

LFP – Lithium Iron Phosphate

M&B – Magellan & Barents

NMC – Nickel Manganese Cobalt

NPV – Net present value

O&M – Operation & maintenance

OPEX – Operational expenditure

PP – Payback period

PSH – Pumped hydro storage

PV – Photovoltaic

PVM – Premogovnik Velenje Mine

REA – Research Executive Agency

RTE – Round Trip Efficiency

SOC – State of charge

SWOT – Strengths, weaknesses, opportunities, and threats

TRL – Technology readiness level

UNIOVI – Universidad de Oviedo

WEGLO – Węglokoks S.A.

XRF – X-Ray Fluorescence

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