STUDY ON REFERENCE TECHNOLOGIES FOR ELECTRICITY STORAGE

Terna

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Annex B to the ARERA DCO 168/2025/R/EEL

In compliance with the requirements of Resolution 247/2023/R/EEL

Summary

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Executive Summary

1. This study on electricity storage technologies has been prepared by Terna in compliance with the requirements of Resolution 247/2023/R/EEL.
2. Storage plants will play a fundamental role in future scenarios characterized by a growing penetration of Renewable Energy Sources (RES), as they will allow the provision of a series of useful services to the electricity system, including "time-shifting" and dispatching services, functional to ensuring the security and adequacy of the electricity system. Storage technologies will make it possible to "structurally" shift part of the production of variable RES (vRES) from the hours of high availability of the resource to the hours of low or no availability, managing the "overgeneration" efficiently and thus ensuring the achievement of decarbonisation targets.
3. Legislative Decree No. 210/21 establishes the framework for a new Electricity Storage Procurement Mechanism (MACSE), which received approval from the European Commission in December 2023 (State Aid SA.104106 (2023/N)). This mechanism is designed to facilitate the integration of renewable energy sources with appropriate overgeneration levels, while taking into consideration planned grid enhancements.
4. Analyses performed by Terna and published in the 2024 Scenario Description Document (DDS) indicate that, under the "PNIEC Policy" 2030 scenario, approximately 50 GWh of additional utility-scale storage capacity will need to be developed, beyond the volumes already secured through capacity market auctions. The specific GWh requirement for new storage capacity is subject to future reassessment based on the actual development and geographic distribution of renewable energy sources in Italy.
5. By means of Resolution 247/2023/R/EEL, ARERA has assigned Terna the responsibility of compiling this report, which provides an assessment of electricity storage technologies, including those still in development and not yet fully commercially mature. This study examines multiple technologies capable of delivering the mentioned services and identifies those that have achieved technological and commercial maturity. For these selected technologies, the study outlines their performance characteristics, investment and operating costs, and potential for further development.
6. Numerous storage technologies exist, each differing in their level of technical, economic, and commercial development, as well as their appropriateness for particular electricity system applications. For the purposes of this document, a distinction is made between electrochemical storage (lithium-ion or non-lithium-ion), pumped hydro, mechanical storage that uses air or other gases as a carrier fluid, power-to-gas-to-power, power-to-heat-to-power and other types of storage (electrostatic and magnetic, electromechanical).
7. Lithium-ion batteries and pumped hydro are currently the only technologies with established technological and commercial maturity. At the beginning of 2024, approximately 89 GW / 190 GWh of utility-scale lithium battery plants were installed globally in the electricity sector. Projections indicate that this figure may reach 800 GW by 2030. Furthermore, the worldwide installed capacity of lithium-ion batteries across all sectors – including e-mobility, electronics, residential energy storage, and uninterruptible power supply (UPS) – is approximately 1,500 GWh. With respect to pumped hydro, the total installed capacity currently stands at approximately 160 GW, including 50 GW in Europe. Global capacity is projected to surpass 400 GW by 2028. In contrast, the global installed capacity of the other storage technologies referenced above is significantly lower, by several orders of magnitude, when compared to lithium batteries and pumped hydro.
8. Therefore, the reference technologies for this study are lithium-ion batteries and pumped hydro. Both technologies can offer the services necessary to integrate renewables and to manage the electricity system efficiently. In this regard, it is worth remembering that lithium-ion batteries and pumped hydro systems have some substantial differences, both in terms of services provided to the system (e.g. inertia, short-circuit power, starting the system) as well as in terms of characteristics (e.g. performance over time, useful life). Therefore, the system storage

requirement could also be different for the two technologies, depending on the services and performance required.

9. Alongside their established technological and commercial development, the two reference technologies identified demonstrate high efficiencies of approximately 70-75% for pumped hydro and 80-90% for lithium batteries. The performance of storage systems is a critical parameter, as the deployment of low-efficiency storage technologies can result in significant system inefficiencies. Such inefficiencies may impede progress toward decarbonization goals and hinder the effective integration of renewable energy sources into the overall system. For instance, in a scenario where 50 GWh of storage operates on a daily charge-discharge cycle with an efficiency of 85%, the resulting annual energy losses would be approximately 3 TWh. Should the storage efficiency decrease to 50%, these losses would rise to roughly 9 TWh per year. To meet equivalent decarbonisation objectives, these increased losses necessitate additional investments, not only in new renewable energy facilities – such as approximately 4 GW of further solar PV capacity – but also in grid infrastructure to support the integration of these extra assets.

10. Finally, it is important to emphasize that this storage procurement initiative is not intended as an experiment or pilot project for research purposes; rather, it is a market-driven endeavour designed to support the decarbonisation of the Italian electricity system through the deployment of large volumes of storage capacity. As these plants are expected to contribute to electricity system management in the coming decades, the focus is on developing technologies that have established reliability and technical and commercial maturity, as evidenced by the existence of several large-scale plants currently in operation. However, it is recognised that the inclusion of other technologies in the MACSE could promote technological innovation and reduce supply chain risks. While reiterating that, to date, the reference technologies for the MACSE are lithium batteries and pumped hydro, a limited participation of innovative technologies could bring long-term benefits, provided that these technologies match the technical performance of reference technologies, and that they are competitive in terms of costs.

11. As stipulated by Resolution 247/2023/R/EEL, Terna is required to update this study at least biennially to incorporate emerging reference technologies whose maturity is demonstrated by a notable increase in global installation rates. The remaining part of this study is focused on describing the additional performance characteristics exclusively for lithium-ion batteries and for pumped hydro power plants.

12. The two technologies identified demonstrate notable differences in core performance metrics, such as cost, useful life, and construction time.

13. Lithium-ion batteries today have an estimated useful life of around 15 years, a value that could increase in the future thanks to continuous technological innovations. However, lithium battery performance deteriorates over time because of usage patterns and charge-discharge cycles. Pumped hydro, on the other hand, has a useful life of at least 60 years. In contrast to lithium batteries, the decline in performance of a pumped storage plant over time is generally minimal. In fact, routine maintenance of electrical and mechanical components ensures sustained performance and prevents irreversible aging effects.

14. Construction[1] of a utility-scale lithium-ion battery system typically takes around two years. Pumped hydro projects generally take more than five years to build, although the duration may vary based on individual project factors. The required times are reduced when existing facilities undergo repowering or when conventional hydroelectric plants are converted into pumped storage plants.

15. The total cost of a new storage facility can be expressed as the CONE (Cost of New Entry), which refers to the annual revenue required to recover construction, financing, and operating costs. The main parameters involved in determining the CONE are CAPEX, OPEX, WACC and

[1] *Construction time excludes the authorization process, since only plants with prior authorization are eligible for the auction.*

useful life. The formula for calculating the CONE is provided in the decision of the European Commission (EC).[2]

16. CAPEX primarily depends on two factors: plant power and energy storage capacity. In this respect, lithium-ion batteries differ from pumped storage. In pumped storage systems, capital expenditure related to power output typically exceeds that of electrochemical batteries. On the other hand, the CAPEX linked to energy capacity is lower for pumped storage than for battery systems. Accordingly, a comprehensive cost comparison between these two technologies depends largely on their nominal storage durations.

17. Table 1 presents the economic values for the two reference technologies, for a storage duration of 8 hours (batteries and pumping) and for a duration of 4 hours (only batteries).

ECONOMIC PARAMETERS	LI-ION BATTERIES 4 H	LI-ION BATTERIES 8 H	PUMPED HYDRO 8H
INVESTMENT COSTS [k€/MWh]	*191 – 282*	*189 – 267*	*213 - 389*
ANNUAL FIXED COSTS [k€/MWh/YEAR]	*2,3 – 7,0*	*2,1 - 6,3*	*1,4 - 6,0*
USEFUL LIFE [YEARS]	*15 -20*	*15 – 20*	*≥60*
DELIVERY PERIOD [YEARS]	*15*	*15*	*30*

Table 1 – Economic parameters for storage systems lasting 4-8 hours.

It should be noted that the CAPEX outlined in the table does not account for risks associated with cost variability. For lithium batteries, market prices may fluctuate substantially due to supply and demand dynamics, as well as ongoing geopolitical events. In 2024, the prices of a 4-hour battery (excluding the costs of connection, development and land purchase) fell by around 40-45% compared to the values recorded in 2022. Furthermore, the capital expenditures associated with lithium batteries are exposed to $/€ exchange rate fluctuations, as battery manufacturing predominantly occurs outside of the European Union. Both risks should be considered when setting the auction's economic parameters.

18. It is important to highlight that applying the EC decision formula[3] with the cost parameters from Table 1, would underestimate the CONE value needed for a sufficient return on investment. This formula does not consider two important factors: firstly, the plant must be oversized to meet the contractual requirements of the MACSE, such as limitations on allowable degradation. Additionally, construction time should be factored into the calculation. As construction takes around two years, the developer must internalize financing costs during that time. In this study, the CAPEX and OPEX values presented in Table 1 have been adjusted upward by 21% and 12%, respectively, to accurately calculate the CONE[4]. Assuming these costs, a 9% nominal WACC, and a 15-year contract term, the resulting CONE is:

    - 31 - 47 k€/MWh/year for 8-hour lithium-ion batteries
    - 31 - 50 k€/MWh/year for 4-hour lithium-ion batteries

19. Lithium batteries can be developed on a large scale without specific geographic or volume restrictions. Pumped storage, on the other hand, is subject to geographical constraints related to the availability of water resources and the geomorphology of the territory. This difference is also reflected in the connection requests received by Terna. At the beginning of July 2023, 7.9 GW of requests were received from pumped storage plants and 74.3 GW of requests from lithium-ion battery plants (of which 54.4 GW are stand-alone plants and 19.9 GW are storage assets integrated mainly with wind and solar plants).

[2] State Aid SA.104106 (2023/N), Recital 68
[3] Ibid
[4] The 21% increase in CAPEX is attributed to two components: 12% is associated with additional sizing to comply with degradation standards specified in the MACSE technical report, and 9% arises from financing costs incurred during the construction phase, which is expected to last two years. OPEX has been increased by 12%, reflecting only the effect of the oversizing adjustment.

Definitions

The definitions listed below pertain exclusively to this document. For precise interpretation of the MACSE Regulation, reference should be made to the definitions contained within the Regulation itself.

Maximum C-rate: charge/discharge rate, i.e. the ratio between the maximum discharge current (expressed in ampere) and the extractable energy during discharge (expressed in ampere-hours); this value is specified by the manufacturer of electrochemical battery modules.

Capability curve: a curve displayed in the Cartesian plane (P, Q), that represents the potential stable operating conditions of the storage system connected to the grid via an electronic converter based on factors such as voltage, state of charge and power factor. Specific capability requirements, which may vary depending on connection voltage, are defined by relevant connection standards (refer to Annex A79 of the Network Code for details pertaining to specific applications).

Nominal discharge duration of storage or Nominal duration [h]: the ratio of nominal discharge energy (measured at the connection point) to nominal discharge power.

Nominal charge duration of storage [h]: the ratio between nominal charge energy (measured at the connection point) and nominal charge power; may differ from the nominal duration.

Nominal discharge energy (capacity) or Nominal energy (capacity) [Wh]: the total energy that a storage system can supply to the grid at the connection point, during a full discharge at nominal discharge power from the highest acceptable value to the lowest acceptable state of charge.

Nominal charge energy (capacity) [Wh]: the maximum amount of energy that the storage system is capable of absorbing from the grid, measured at the point of connection with the grid, during a full charge at a nominal charge power from the lowest acceptable value to the highest acceptable state of charge.

Nominal discharge power or Nominal power [W]: this is the maximum active power that can be stably supplied by the storage plant to the grid connection point, continuously at nominal conditions, i.e. in the state of charge range that does not involve power limitations; it may vary according to operating conditions.

Nominal charge power [W]: this is the maximum active power that can be permanently withdrawn by the storage plant from the grid connection point, continuously at nominal conditions, i.e. in the state of charge range that does not involve power limitations; it may vary according to operating conditions.

Depth of Discharge (DoD) [%]: a percentage value representing the complement of the State of Charge (SoC). It is calculated as the ratio, at a specific point in time, between the energy discharged from storage and the nominal energy.

Net Round-trip Efficiency (nRTE) [%]: this is equal to the energy, expressed in MWh, that can be fed into the grid for each MWh that the SdS has previously withdrawn from it.

State of Charge (SoC) [%]: The percentage ratio, at a specific moment in time, between the energy stored that can be delivered during continuous discharge at nominal power until reaching the minimum acceptable state of charge, and the nominal energy.

1. Role of storage capacity in the electricity system

Legislative Decree No. 210/21 paves the way for the introduction of a new Electricity Storage Procurement Mechanism (MACSE). This mechanism, which was approved by the European Commission in December 2023 (State Aid SA.104106 (2023/N))), will ensure the integration of renewables with an efficient level of overgeneration, considering the planned grid developments.

Storage needs are determined by how much renewable energy is installed and where it is located. In October 2024, Terna released the "Scenario Description Document" (DDS), outlining possible future scenarios for the Italian energy and electricity system, including estimates of storage needs. Prior to conducting auction procedures, these requirements will be reviewed and updated to reflect any changes in context.

The DDS outlines multiple scenarios with horizon years of 2030, 2035, and 2040, all marked by substantial growth in generation from Renewable Energy Sources (RES) and an increasing integration of electricity into end-uses. Both developments are considered vital for meeting decarbonisation objectives. Notably, the PNIEC Policy scenario for 2030 is distinguished by its alignment with government targets for that year. This scenario assumes an optimal combination of investments in grid infrastructure, renewable energy, storage solutions, and emerging digital technologies, while taking into account the technical, economic, and administrative constraints that could otherwise challenge the scenario's feasibility within the allocated timeframe. The PNIEC Policy scenario predicts that around 107 GW of solar and wind plants installed by 2030 will be needed to achieve the policy targets, an increase of +65 GW compared to 2023.

In all scenarios of high-RES penetration, storage plants will play a fundamental role in the integration of renewables, as they will make it possible to provide a series of useful services to the electricity system, including the "*time-shifting*" and dispatching services, functional to ensuring the safety and adequacy of the electricity system. Storage technologies will make it possible to "structurally" shift part of the production of variable RES (vRES) from the hours of high availability of the resource to the hours of low or no availability (see. Figure 1), managing the "*Overgeneration*" in an efficient manner and thus ensuring the achievement of decarbonization targets.

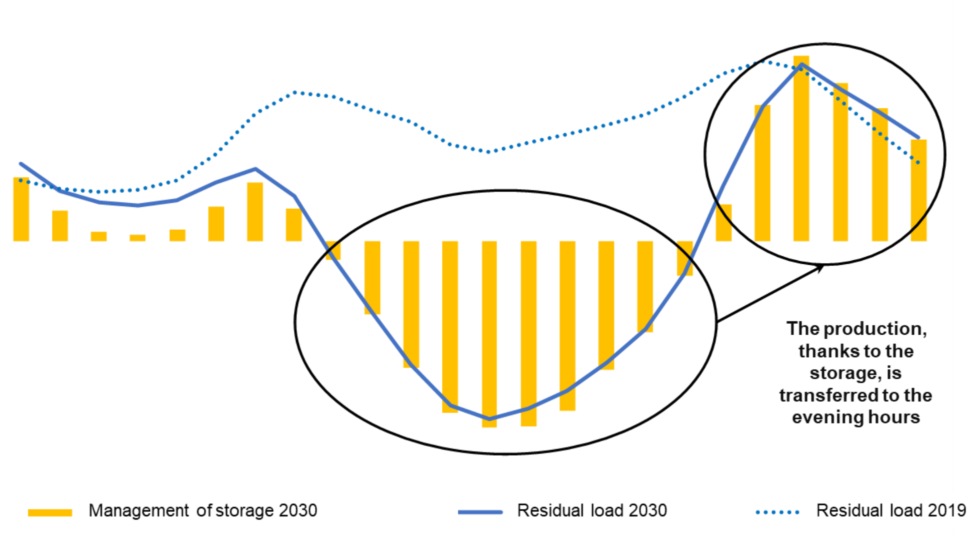

Figure 1 – Daily storage usage by 2030 (illustrative). Source: Terna

The analyses carried out by Terna show that, by 2030, it will be necessary to develop around 50 GWh of new storage capacity, in addition to distributed storage associated with small-scale solar, as well in addition to storage that has already been contracted through the Capacity Market auctions.

In the medium to long-term scenarios, the nominal discharge and charge power of these storage facilities is equal to one eighth of the nominal discharge and charge energy, corresponding to a nominal charge and discharge duration of 8 hours. Therefore, in order to meet the total 2030 storage demand identified in the DDS, storage will have to be built with both charge and discharge power approximately equal to 6 GW.

It should be noted that, with the same nominal energy, plants with a power greater than one eighth of the nominal energy would provide an additional contribution to the stability and adequacy of the system through "power" services. However, the cost of such plants would be even higher than that of plants with an output equal to one eighth of the nominal energy. Conversely, plants with a power lower than one eighth of the nominal energy would result in economic savings for the system, but at the expense of a lower contribution to the safety and adequacy of the system. The right compromise between the power of the storage and the cost for the system will have to be carefully evaluated when defining the auction parameters.

2. Identification of reference technologies

Currently, a diverse array of storage technologies exists, each varying in technical, economic, technological, and commercial maturity. These differences influence their suitability for specific services within the electricity system. It is important to note that this study is dedicated to electricity storage systems – technologies designed to absorb electricity from the grid and subsequently discharge it back at a later stage. In the context of this study, the following seven technological macro-categories can be distinguished:

1. **Lithium-ion electrochemical storage (Li-Ion):** Lithium-ion batteries that exploit ion exchange phenomena through the electrolyte between the cathode, consisting of lithium compounds, and the anode;
2. **Pumped Hydro Energy Storage (PHES):** mechanical storage of electricity in the form of gravitational potential energy of water that is moved to basins or reservoirs located at different heights;
3. **Compressed Air Energy Storage (CAES) and similar**: mechanical storage of electricity by compressing fluids in various ways: compressed air stored in natural underground caverns; air liquefaction (LAES); systems using gases other than air, etc.;
4. **Non-Li-Ion electrochemical storage**: batteries that accumulate electricity through chemical reactions of various types, among which we can distinguish: flow batteries (characterized by circuits for the circulation of liquid electrolytes, e.g. Vanadium-Redox-Flow); hybrid batteries (which use materials other than lithium and do not involve the pumping of liquid electrolyte, e.g. zinc batteries); high-temperature batteries (which require to maintain materials at high temperatures to allow electronic exchange, e.g. NaS, Zebra); solid-state batteries (with solid electrolyte); etc.;
5. **Power-to-gas-to-power (chemical storage) and power-to-heat-to-power (thermal storage)**: power-to-gas-to-power technology makes it possible to convert renewable electricity into hydrogen (or methane) through electrolysis (or methanation). These synthetic gases are then compressed and stored in a tank. During periods of reduced solar and wind generation, these gases are then converted back into electricity through fuel cells or conventional thermodynamic cycles. Power-to-heat-to-power technology, on the other hand, converts electricity into thermal energy, which can be stored using different technological solutions. Thermal energy is utilised to produce steam or expand fluids, which can generate electricity through turbomachinery.
6. **Electrostatic, magnetic and similar storage**: technologies that allow the storage of electrical energy in the form of an electric or magnetic field, which include supercapacitor systems (of various types), systems based on superconducting magnets (SMES), etc;
7. **Electromechanical storage**: this category comprises flywheel storage systems, which store electrical energy as rotational kinetic energy in a mass called a *flywheel* by increasing its rotational speed during charging and decreasing it during discharging. It also includes gravitational storage solutions, which involve moving large masses to utilize changes in gravitational potential energy.

In choosing the reference technologies for this report, it is important to highlight that tens of GWh of storage capacity will potentially be contracted in the auctions. Given the considerable need for storage capacity, the corresponding substantial investment required, and the range of services expected (including both time shifting and ancillary services), proven technological and commercial maturity is considered a key factor in identifying the references technologies.

Finally, it should be noted that the purpose of the MACSE is to enable the integration of renewables with an efficient level of overgeneration. By way of example, the DDS estimates 22 TWh of renewable energy stored by 2030. Therefore, the round-trip efficiency of storage is also an extremely important parameter of comparison.

The other technical and performance parameters that characterize the different storage technologies, such as useful life, construction times, performance in regulation, etc., although relevant for the definition of the auction regulation, do not represent a binding requirement for participation in MACSE. These parameters are described in Chapter 3 of this document for the identified reference technologies.

2.1 Technological and commercial maturity

A key feature for identifying reference technologies is proven technological and commercial maturity. It should be noted, in fact, that this initiative is not an experiment or pilot test for study or research purposes, but it is a market initiative functional to the decarbonisation of the Italian electricity system, which involves the commissioning of large volumes of storage capacity. Therefore, since these plants will be functional to the management of the electricity system in the coming decades, the intention is to contract primarily technologies with proven reliability, as evidenced by the presence, already today, of numerous plants of significant size and by the widespread and significant use of these technologies at global level.

Terna's expertise in storage systems, developed initially through pilot projects pursuant to resolutions 66/2013 and 43/2013, has been further enhanced and updated by conducting studies on current technology maturity, market analyses, and empirical data relating to installed systems. Experimental evidence indicates that innovative technologies, particularly those with a low level of technological maturity and limited operational experience, often require extended development periods before achieving the reliability necessary to qualify for participation in auctions such as the MACSE.

As far as lithium batteries are concerned, at the beginning of 2024 around 89 GW/190 GWh of stationary batteries for energy storage were installed worldwide[5], and forecasts estimate that they will be close to 800 GW by 2030[6]. At European level, in 2023 there were around 33 GW/44 GWh of installed capacity. In addition, the global installed capacity of Li-Ion batteries for all applications (e-mobility, electronics, residential storage, UPS, etc.) reaches around 1,500 GWh[7]. In 2022 alone, 700 GWh/year[8] of global production of lithium cells was reached (also covering the electric mobility sector), with various players active in the market for more than 10 years.

Pumped storage, on the other hand, has an installed capacity of 160 GW[9] worldwide, including 50 GW in Europe. By 2028, global capacity is expected to exceed 400 GW with the greatest increases expected in China, the United States, the European Union and India[10].

All the other storage technologies mentioned above show a global installed level which is orders of magnitude lower than lithium batteries and pumped storage. Conventional and innovative

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[5] *Most of these batteries are used for energy shifting. Also included are batteries installed at residential and commercial level, typically connected to photovoltaic panels*
[6] *Bloomberg, 1H 2024 Energy Storage Market Outlook, 2024*
[7] *S&P Global Mobility based on "IHS markit" data, 2022*
[8] *McKinsey, Battery 2030: Resilient, sustainable, and circular, 2023*
[9] *IEA, Energy Technology Perspectives, 2023*
[10] *IEA, Renewables 2023 - Analysis and forecast to 2028, 2024*

compressed air systems have an installed capacity of 1.2 GW[11]; batteries based on chemistries other than Li-Ion reache an installed capacity of 1.2 GW[12]; installed electromechanical storage is around 0.9 GW[13] while the installed capacity of power-to-gas-to-power[14], power-to-heat-to-power[15] as well as electrostatic and magnetic systems[16] deployed for energy storage applications is currently negligible.

Therefore, to date, the only technologies with high technological and commercial maturity are lithium-ion batteries and hydro pumped storage. Both technologies can offer the services necessary to integrate renewables and to manage the electricity system efficiently. In this regard, it is worth remembering that lithium-ion batteries and pumped hydro systems have some substantial differences, both in terms of services provided to the system (e.g. inertia, short-circuit power, re-powering the system) and in terms of characteristics (e.g. performance over time, useful life). As a result, storage requirement could also be differentiated between the two technologies, depending on the services and performance required.

2.2 Round-trip efficiency

The performance of storage systems is a parameter of fundamental importance: the European Commission itself has repeatedly emphasized the concept of "*efficiency first*", considering it the key factor in the energy transition process underway.

For storage systems, the concept of net round-trip efficiency (nRTE) is used, evaluated at the point of connection with the electricity grid, which therefore considers both the entire charging and discharging process, as well as the consumption and losses of the auxiliary systems supporting the storage plant. An adequate level of efficiency must be ensured to limit renewable energy that is "lost" in storage, conversion and transformation processes. For example, a plant with an 80% nRTE which absorbs 10 MWh of energy produced by RES, will be able to return only 8 MWh to the system, with a loss of 2 MWh of renewable energy which, although produced and injected into the grid, cannot be used by the end-consumer when needed.

The use of low-efficiency storage technologies would lead to the creation of major system inefficiencies that would jeopardize the achievement of the decarbonization targets and the integration of RES into the system. For example, assuming a scenario in which 50 GWh[17] of storage operates with a daily charge-discharge cycle, with a net efficiency of 85%, the losses would amount to around 3 TWh/year, which would increase to 9 TWh/year if the storage had a net efficiency of 50%. With the same decarbonisation targets to be achieved, the extra losses would therefore require further investments not only in new renewable generation plants (e.g. about 4 GW of additional solar PV) but also in grid infrastructure necessary to connect the additional plants to the electricity system.

In Figure 2, the various storage technologies are characterised according to the *Round-trip efficiency* and the typical range of nominal discharge duration.

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[11] *Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022*

[12] *Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022, and BASF, Stationary Energy Storage*

[13] *Frost & Sullivan, Future Developments for Global Energy Storage, 2020 and Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022*

[14] *It should be noted that around 1.4 GW of electrolysis projects have been carried out, capable of converting electricity into hydrogen, but without the possibility of returning it to the electricity system. Source: IEA, Global Hydrogen Review, 2022*

[15] *MIT, The Future of Energy Storage, 2022 and Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022*

[16] *Innoenergy, Unlocking New Possibilities Through Innovative Energy Storage, 2020; EERA, Superconducting Magnetic Energy Storage, 2019*

[17] *Nominal energy in discharge*

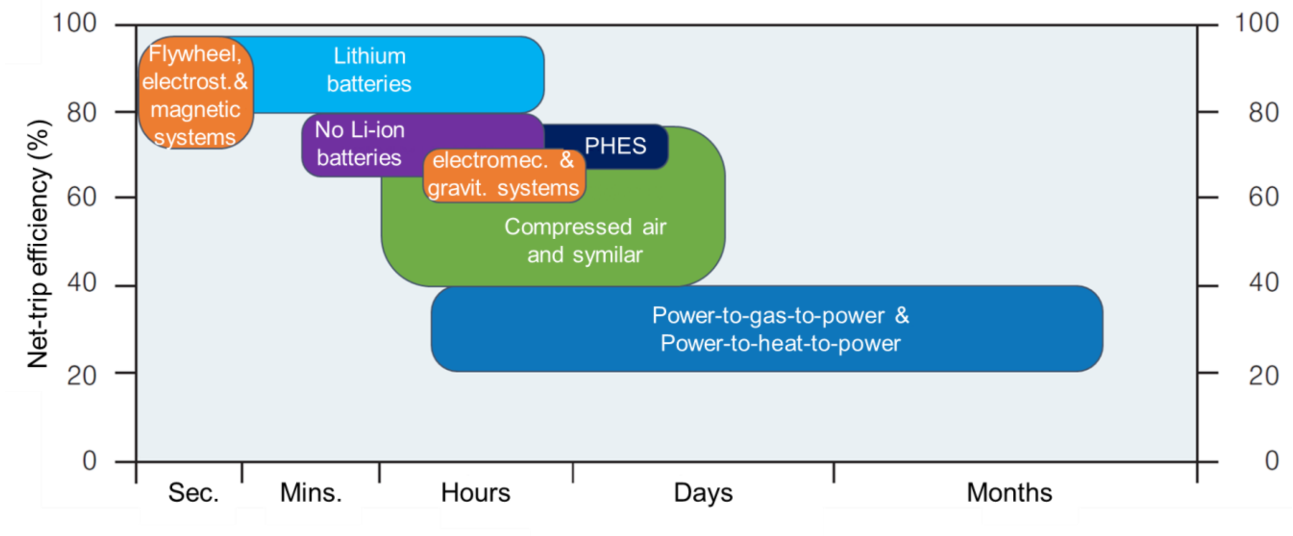

Figure 2 – Positioning of the different technologies. Source: Terna calculations based on WEO data

Figure 2 shows that that the nRTE varies significantly across the different technologies: the highest values characterize lithium batteries (80-90%), as well as flywheel and electrostatic systems (75-90%). Pumped storage (70-75%), other types of electrochemical storage (65-80%) and gravitational systems (60-75%) follow closely behind. CAES and similar systems have a wide variability of nRTE (40-75%) due to the different thermodynamic characteristics of the fluids used in the process and the specificities of each technological solution. Finally, power-to-gas-to-power and power-to-heat-to-power systems are at the lowest levels (20-40%), strongly penalized by the double transformation from electricity, chemical or thermal energy and vice versa.

Currently, due to the significant variability in efficiency among the storage technologies examined—partly attributable to differences in plant configurations—it is not deemed appropriate to establish a reference technology solely on the basis of efficiency. Instead, following the identification of suitable reference technologies, minimum performance thresholds will be defined and expressly included within the MACSE regulation.

The storage technologies analysed not only vary in efficiency, but also in how their performance changes over the system's lifespan.

2.3 Reference technologies

As already described in section 2.1, technological and commercial maturity is the determining parameter for identifying reference technologies. In particular, the diffusion in terms of worldwide installed capacity is considered adequate if it is at least of the same order of magnitude as the expected storage requirement (therefore in the range of 10-100 GWh).

On this basis, to date only lithium-ion batteries and pumped hydro power plants have the proven technological and commercial maturity required.

Given the type of use expected from these storage systems, another relevant parameter is the nRTE, which, as indicated earlier, exhibits a wide range of values across the technologies examined (20–90%). Notably, there is currently a strong correlation between technological maturity and operational efficiency.

As already indicated by Resolution 247/2023, Terna will have to update this study at least every two years, in order to integrate the list of reference technologies by including additional technological solutions, the maturity of which is proven by a significant increase in the global installation rate.

While only the reference technologies mentioned so far demonstrate proven technological and commercial maturity, it is recognised that the inclusion of other technologies in MACSE could promote technological innovation and reduce supply chain risks. Therefore, while reiterating that, to date, the reference technologies for MACSE are lithium batteries and pumped hydro, a limited participation in the mechanism of innovative technologies could bring benefits in the long term, provided that these technologies have technical performance equivalent to those of reference and that they are competitive in terms of cost.

The remaining part of this study focuses on describing the additional performance characteristics exclusively for lithium-ion batteries and for pumped hydro.

3. Technical and performance characteristics

The performance of electricity storage plants can be measured by a series of technical and operational parameters that vary according to the reference technology, including the already introduced concept of net round-trip efficiency, which represents the efficiency of storage technologies.

Regarding the nRTE and other technical parameters, it is crucial to maintain acceptable performance levels, within pre-established degradation limits, for the entire duration of the delivery period.

3.1 Duration of storage

The nominal duration of storage is the time it takes for a storage plant to fully discharge, assuming that it is initially fully charged and that it is discharged at a nominal discharge power, net of the consumption of auxiliaries. For example, a storage plant that can deliver 8 MWh of energy and has a nominal discharge power of 1 MW will have a duration of 8 hours.

For electrochemical batteries, a distinction must be made between the life of the storage facility and the maximum C-rate, a construction parameter of battery modules, which represents the maximum current with which the battery can be discharged in relation to the energy capacity. To date, the maximum C-rate values of the modules on the market varies between 0.25C and 6C. A maximum C-Rate of 0.25C indicates that the battery module will take 4 hours to discharge at maximum current; a maximum C-rate of 1C indicates that the module will take 1 hour to discharge. Modules with maximum C-rates above 1C are typically used for e-mobility applications, where the power performance in terms of short acceleration times is particularly relevant, while modules with lower maximum C-rates (e.g. between 0.25C and 1C) can be used for stationary energy storage applications. It should be noted that, if the maximum C-rate provides an indication of the maximum speed (and therefore the maximum current) with which the module can be discharged, it does not put any constraints on the possibility to discharge the module at lower currents. In fact, by appropriately sizing the entire DC/AC conversion chain, interface and transport, it is possible, with the same maximum C-rate of the modules, to vary the nominal duration of the system in charge and discharge, limiting the maximum current (and therefore the maximum speed) with which the batteries can be discharged or charged. For instance, a storage system equipped with battery modules rated at a maximum C-rate of 0.25C may achieve a duration of 4 hours when the DC/AC interface and conversion chain are configured for the batteries' nominal current, or a duration of 8 hours if these components are specifically engineered for longer operation. It is emphasised that this configuration will not affect system performance, provided that the design appropriately considers both the maximum C-rate of the modules and the nameplate specifications for the DC/AC conversion chain, including the interface and transport components.

However, it should be noted that by increasing the size of the DC/AC conversion chain, interface, and transport, the plant's power output can be enhanced relative to the previously stated ideal requirement (nominal power equal to at least 1/8 of the nominal energy). This plant, which performs better in terms of power, would be able not only to provide the same energy storage capacity but also to contribute to a greater extent to the stability and adequacy of the system through "power" services.

In Italy, over 650,000 small batteries (average power 6 kW) are connected to the low voltage grid, mainly paired with rooftop photovoltaics to boost self-consumption. These batteries typically offer around 2 hours of nominal storage duration. Regarding utility-scale storage plants contracted through forward mechanisms, it is important to highlight that Fast Reserve facilities (approximately 250 MW) feature relatively limited storage duration, as the Fast Reserve service is intended to deliver rapid power responses over short durations. In comparison, plants secured under the Capacity Market (approximately 2.2 GW) have an average storage duration that does not exceed four hours.

With respect to pumped hydro systems, the nominal storage duration may vary considerably between the charging and discharging phases. Specifically, while energy capacity is determined solely by the basin's topographical features, the charging and discharging power outputs are influenced by project-specific parameters and depend on plant design choices, such as the sizing of penstocks and the selection of pumping and turbine equipment. In Italy, existing pumped storage plants have a discharge capacity of around 7.6 GW, with an average storage duration of around 7 hours[18]. However, some plants present a significant gap between the nominal charging and discharging power capacity.

It should be emphasised that, in comparison to lithium-ion batteries, pumped storage offers superior versatility regarding the energy-to-power ratio. Specifically, the energy capacity – determined by the size of the reservoirs – is entirely independent from the charging and discharging power capacity. This independence is particularly significant when long-term flexibility of the electricity system is required. As previously mentioned, this study will focus on the nominal discharge duration of storage solutions.

Since no constraints have been placed on the duration of the plant, and since there are no technical limitations on the construction of plants with a nominal duration of 4-8 hours, both technologies are suitable for providing essential services for the integration of renewables and the management of overgeneration. For the avoidance of doubt, it is reiterated that the MACSE Regulation, together with the Technical Report, clarify the criteria that will be adopted to compare plants with different durations.

Finally, from a long-term perspective (beyond 2030/2035), as electricity continues to play an increasingly significant role in heating and mobility, there will be a corresponding rise in demand for storage solutions capable of meeting weekly, monthly, or even seasonal requirements. In this scenario, the adaptability of pumped storage, particularly regarding its energy-to-power ratio, may be considered as a key factor for differentiating the needs between the two different technologies.

3.2 Unavailability

The unavailability rate, expressed as a percentage of the hours of the year, represents the periods in which the plant is unavailable for operation due to ordinary or extraordinary maintenance following breakdowns.

For lithium batteries, this value is usually 2–5% of annual hours and may rise with plant cycling as the battery ages. Even for pumping, the expected level of unavailability is extremely low – unless exceptional events occur– as they are based on a relatively small number of technologically mature electromechanical components that have high levels of reliability.

From this point of view, therefore, both technologies have high levels of reliability.

3.3 Useful Life and Performance Degradation

The technical useful life of a plant is defined as the period in which the plant can function under normal operating conditions before degradation in performance requires total or partial replacement

[18] *The European House Ambrosetti, The strategic role of pumped hydroelectric power in the energy transition, March 2023*

of components. System performance declines over time with use, and the rate of deterioration varies across different technologies. In fact, the degradation over time of the performance of lithium-ion batteries differs significantly from that of hydroelectric pumping, thus leading to a significant difference in the useful life of the two types of plants.

For lithium-ion batteries, the nominal energy tends to decrease over time due to the use of the batteries themselves as a function of the cycling characteristics. The aging phenomena linked to battery cycling causes both an increase in the internal resistance of the modules and a reduction in the energy capacity of the battery which, assuming one cycle per day, can be estimated in the range of 1-3% per year, with a more marked degradation in the first years of life. These phenomena influence the nRTE value of the plant as well, as the nominal energy during charge and discharge is reduced in comparison to losses and auxiliary consumption.

Even when ensuring adequate routine maintenance of lithium-ion electrochemical storage, the performance of lithium batteries progressively degrades over time. Assuming, by way of example, that the system completes a full charge-discharge cycle every day, after 15 years the battery reaches an energy capacity level equal to around 70% of the value at the beginning of life, a limit conventionally associated with the end of life of the battery.

It is important to remember that the allowable degradation under the MACSE Regulations is reported in the Technical Report of the mechanism. If the constraint were more stringent than the "natural" degradation of the technology, the developer of the storage system would have two alternative (or complementary) ways to satisfy this constraint:

- oversizing installed energy capacity during plant construction;
- increasing installed energy capacity throughout its operational lifespan, commonly referred to as "augmentation".

The preferred solution, based on several feedback received by operators in the sector, turns out to be the oversizing, as it offers less complexity in managing technological compatibility over time.

Figure 3 shows how it would be necessary to oversize the plant by 12% compared to the committed capacity pursuant to the MACSE Technical Report, if the allowable annual degradation was 1%.

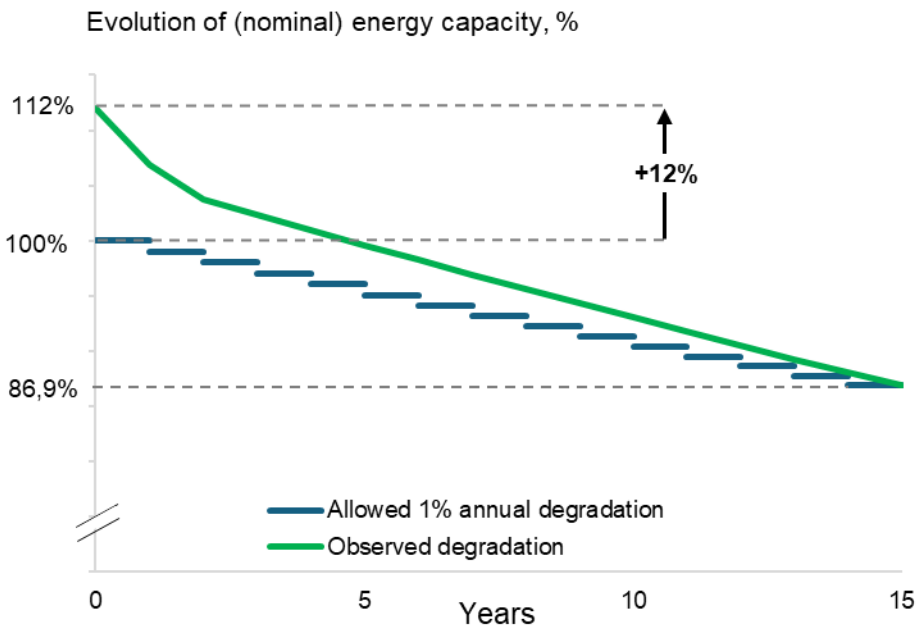

Figure 3 – Degradation of capacity (nominal energy) over the years

Unlike batteries, the degradation of the performance of a pumped storage plant can be considered negligible over time. The storage capacity of a pumped storage facility is determined primarily by the geomorphological features of its basins, which establish the volumes of water that can be retained both upstream and downstream, in addition to the elevation differential between the two reservoirs. Beyond geomorphological features, a key component of the pumping plant is the power section, which comprises pumps and turbines. These mechanical elements are inherently subject to natural wear over time. However, regular maintenance of electrical and mechanical parts helps preserve performance and prevent irreversible ageing. The operational lifespan of a pumped storage plant significantly exceeds that of lithium-ion batteries, with an expected duration of no less than 60 years.

CHARACTERISTIC	**LI-ION BATTERY**	**PUMPED HYDRO**
USEFUL LIFE [YEARS]	*15 - 20*	*≥ 60*
NUMBER OF CYCLES	*> 5,000*	*> 50,000*
ANNUAL DEGRADATION	*Capacity reduction of 1-3% per year*	*Negligible*

Table 2 – Useful life, number of cycles and annual degradation

3.4 Construction time

Construction time refers to the number of years necessary to build the storage system, including the design, supply, installation and testing of the system in all its components. The construction period excludes the authorization process, as only plants that have already received authorization are eligible under the MACSE. Lithium-ion batteries and pumped hydro storage systems differ greatly in terms of construction times.

A *utility-scale* plant with lithium-ion batteries takes around 2 years from the beginning to the end of the construction process, of which a significant part (about half) is needed to complete the procurement phase of the plant components. Pumped hydro projects, on the other hand, depend heavily on local terrain, require extensive civil works, and typically take at least five years to build. These durations are further shortened when existing facilities are repowered or when hydroelectric plants are converted into pumped storage facilities.

CHARACTERISTIC	**LI-ION BATTERY**	**PUMPED HYDRO**
TIME [YEARS]	*2*	*> 5*

Table 3 – Construction times

3.5 Performance in Regulation

Performance in regulation refers to how storage facilities help maintain grid safety and stability by controlling active and reactive power and offering advanced features.

Lithium-ion batteries charge and discharge by exchanging ions between the anode and cathode through the electrolyte, a process that occurs rapidly with nearly instant transients under normal conditions. In addition, the batteries, which naturally operate in direct current, are connected to the network through electronic DC/AC converters, whose high dynamic performance is well known in various areas of application. Therefore, even considering the delays introduced by the control and measurement systems, a battery storage asset can go from a condition of zero exchange with the grid to maximum charging or discharging in around one second, in compliance with the dynamic requirements of the transient (e.g. error at full capacity, ramp limits, etc.)[19]. Field tests[20] have shown how, with appropriate control configurations, starting from the condition of zero exchange with the grid, it is possible to move to a state of active power delivery in the order of hundreds of milliseconds,

[19] *Terna, Impianti con sistemi di accumulo elettrochimico – Condizioni generali di connessione alle reti AAT e AT e sistemi di protezione regolazione e controllo, Annex A79 to the Network Code*
[20] *Terna, Rapporto di fine sperimentazione progetti Power-Intensive Storage Lab https://www.terna.it/it/sistema-elettrico/innovazione-sistema/progetti-pilota-accumulo*

with complete reversals from maximum charging power to maximum discharging power in less than 200 milliseconds. Electrochemical systems can also contribute to voltage regulation according to operating conditions (voltage level, SoC, power factor, etc.), within the limits of the sizing of the system and, above all, of electronic converters. Electrochemical storage systems, which are stationary and connected to the grid via DC/AC converters, offer rapid adjustment capabilities but do not naturally provide inertia to the electricity grid due to the absence of rotating masses. Nevertheless, implementing specific control algorithms can enhance their ability to support grid stability, for instance, by providing synthetic inertia.

Pumped hydro plants provide various possible configurations of interface to the grid. Traditional plants typically use a synchronous electric machine and therefore have the typical regulation capabilities of a synchronous system when in generating operation, with slow responses in the order of minutes. Conversely, when energy is drawn from the grid, flexible adjustment of absorbed power is generally limited to on/off operations or can be achieved by modifying the number of active machines. However, the synchronous connection of a rotating machine has the advantage of being able to provide a mechanical inertial contribution to the grid, which is useful for frequency stability. To overcome the lack of regulation during pumped operation, advanced plant configurations known as "variable speed" systems have been developed over time: they involve the use of asynchronous machines with double fuel supply (*Doubly Fed Induction Generator* or *DFIG)* or synchronous machines interfaced with the grid by means of an electronic converter (*full-converter*), which guarantee greater modulation flexibility but entail, limited to *full-converter* technology, a limitation or elimination of the inertial contribution. Further solutions are also available based on ternary units with hydraulic short-circuit that allow the regulation of active power absorption without limitations on the mechanical inertial contribution to the grid.

Although able to provide the same services to the system, lithium-ion batteries and pumped hydro have some substantial differences:

- Synchronous pumping units provide the system with inherent mechanical inertia, whereas lithium-ion batteries, despite their ability to deliver inertia services, do so with a different quality standard. Specifically, batteries supply "synthetic inertia," which, while advantageous to the electricity system, does not match the electromechanical inertia provided by synchronous machines.
- In particular, while pumping plants can provide a continuous inertial contribution to the system, as they are also able to respond to micro-grid disturbances (in an interconnected electrical system at any moment there are continuous disturbances due to the combination of manoeuvres, faults, load and generation fluctuations that excite the electrical variables of the system, constantly causing frequency fluctuations similar to white noise, of the order of tens of mHz), the inverters of electrochemical batteries provide the inertial service only when a certain frequency threshold is exceeded (although the inertial response could theoretically be provided proportionally to the change in frequency, in order to avoid a continuous stress to the battery, the inertial response is conditioned when a threshold is exceeded, typically calibrated between 100 and 200 mHz). In other words, the inertia provided by hydroelectric pumping directly contributes to the reduction of the magnitude of frequency deviations, while synthetic inertia acts by modulating the active power only later, in response to a frequency deviation.
- Synchronous pumped storage assets provide higher short-circuit power than lithium-ion batteries, whose contribution to short-circuit power is limited by the characteristics of inverters. Furthermore, similarly to what has been highlighted with reference to inertia, batteries can provide short-circuit power (through their power converters) only after exceeding a certain voltage threshold and in a discontinuous manner, unlike pumping which provides this contribution in a non-discrete way.

CHARACTERISTIC	LI-ION BATTERY	PUMPED HYDRO
PERFORMANCE IN REGULATION	*- Fast response (< 1 sec.)* *- Absence of natural inertia (synthetic only)* *- Voltage regulation depending on the performance of the DC/AC converter* *- Discrete, limited contribution to short-circuit levels through fault support capabilities*	*- Slow response (<5 - 25 min.) depending on the system configuration* *- Natural mechanical inertia for synchronous groups or ternary groups with hydraulic short-circuit; absence of natural inertia (synthetic only) for full-converter* *- Voltage regulation as a synchronous system or depending on the performance of the DC/AC converter, based on the system's configuration* *- Continuous contribution to short-circuit levels*

Table 4 – Performance in regulation

In conclusion, in terms of regulation performance, the two technologies have some distinctive differences that must be appropriately considered when defining the storage requirement.

3.6 Other Performance Characteristics

In addition to the technical characteristics already mentioned, there are others that should be mentioned, and which are closely related to the operational use of storage technologies:

- **Operating temperature:** the optimal operating temperature of the system that must be ensured to maximize the performance of storage technologies. The optimal operating temperature is only relevant for lithium-ion batteries and is in the range of approx. 15°C to 30°C, range which could be more or less wide depending on the specifications of the battery modules. However, it should be noted that ambient temperatures can reach extremes much higher or lower than the optimal operating temperature (-10 °C / + 45 °C, depending on geographical location). In any case, it will be the operator's responsibility, including through the possible installation of appropriate air conditioning systems, to ensure that the operating performance of the batteries complies with the contractual specifications.
- **Self-discharge:** This refers to the chemical process within the battery that leads to a reduction in stored energy over long periods of inactivity. Additionally, auxiliaries may contribute to energy loss even when there is no exchange with the grid. According to Terna's analyses, by 2030 storage technologies are expected to primarily operate on daily cycles; therefore, at this frequency of use, the impact of battery self-discharge on performance can be considered negligible. Even for pumping, the phenomenon of self-discharge is considered negligible. However, for long-term cycles (weekly/monthly/seasonal) the technological difference linked to the phenomenon of self-discharge is relevant. In fact, electrochemical batteries are subject to a loss of stored energy greater than that of hydroelectric storage plants if they remain in a certain state of charge over time, the speed of which is a function of the initial charge level and the outside temperature. If long-term storage technologies are required, lower self-discharge rates may be a factor to consider when choosing between the two different technologies.
- **Technical minimum:** the technical minimum, expressed as a percentage of the nominal power, indicates the minimum value of power that can be permanently delivered by the system under nominal operating conditions. Electrochemical storage assets do not have a strict technical minimum, which enables stable regulation across the entire power range from maximum charge to maximum discharge capacity. In contrast, the technical minimum of pumped storage systems is determined by the system's specifications, such as the number of pumps and turbines involved and whether speed regulators are present. However, the technical minimum of pumped hydroelectric facilities can be substantially lowered through the implementation of full-converter technology.
- **Regulation of active power during absorption:** while electrochemical storage assets can regulate active power over the entire power operating range, only double-fed or full-converter hydroelectric pumped storage plants or solutions based on ternary units with hydraulic short-

circuits may be able to provide active power modulation services during absorption (primary, secondary and tertiary regulation).

- **System restart service:** Both technologies can provide black start service when this requirement is addressed during the design phase. Lithium-ion batteries, however, have some technological limitations – such as challenges with energizing equipment like transformers – which may restrict their ability to provide the service in all situations. In contrast, pumping plants have demonstrated reliable performance for black start service under various conditions.
- **Voltage regulation:** both technologies examined (electrochemical storage and pumped hydro) can effectively provide voltage regulation services.
- **Harmonic pollution:** synchronous machines help reduce the level of harmonic pollution of the grid, while inverter-based machines – such as electrochemical batteries – typically constitute a source of harmonic currents. Pumping units will therefore be able to help keep the level of harmonic pollution stable, in a context in which the diffusion of inverter-based devices will increase.

CHARACTERISTIC	LI-ION BATTERY	PUMPED HYDRO
OPERATING TEMPERATURE [°C]	*15 - 30*	*N/A*
MINIMUM TECHNICAL [%]	*0*	*variable depending on the system specifications*
SELF-DISCHARGE [%]	*Negligible for daily cycles*	*Negligible for daily cycles*
ACTIVE POWER REGULATION DURING ABSORPTION	*Yes*	*Only double-fed or full-converter pumped hydro plants or solutions based on ternary units with hydraulic short-circuit*
SYSTEM RESTART SERVICE	*Black start (with limitations)*	*Black start*
VOLTAGE REGULATION	*Yes*	*Yes*
HARMONIC POLLUTION	*Harmonic Current Source*	*Natural contribution to harmonic filtering*

Table 5 – Other performance characteristics

4. Investment and operating costs

This section details the key cost parameters associated with storage systems for the reference technologies identified in this study. The costs are categorised as follows:

- ***CAPital EXpenditure (CAPEX)***
- ***OPerational EXPenditure (OPEX)***
- ***Cost Of New Entry (CONE)***

These cost items can vary greatly depending on several factors, including the type of storage technology and the specifications of the project. It should be noted that all costs are expressed in €_2024 and that the CAPEX values indicated in the document are to be considered *ordinary*, i.e. they do not internalise financing costs during the construction period.

4.1 CAPEX

CAPEX ("*CAPital EXpenditure*" or capital expenditure), includes the initial investments required to acquire, build or improve the physical assets of a plant.

The main cost items that make up the CAPEX for Li-Ion storage systems are listed below:

1. Battery: this component covers around 50% of the CAPEX and includes the battery module, racks and BoS (Balance of System). This cost item varies considerably depending on the materials used (e.g. based on the lithium chemical specification), the desired storage capacity, the maximum C-rate and the selected supplier;
2. Power electronics: includes the Power Converting System (PCS), the Energy Management System and the Transformer;
3. Engineering, Miscellaneous Procurement and Construction (EPC), System Integration Costs (including Profit Margins), Shipping and Duties, Installation and Commissioning

4. Other cost items not typically reflected in international benchmark, including: connection costs[21], project development, permitting, acquisition and site preparation.

The CAPEX values reported in this study reflect investment costs only and do not take into account developers' profit margins.

Regarding CAPEX costs for hydroelectric storage systems, these expenses tend to vary significantly due to differences in system configurations, site morphologies, and the presence or absence of existing reservoirs. The factors influencing these costs include:

1. Construction of reservoirs: the design and construction may vary according to the size and desired storage capacity and above all by the presence or absence of existing dams/basins;
2. Construction of hydraulic works: pipes and valves to allow the controlled flow of water between the upper and lower reservoirs;
3. Purchase of turbines, generators and regulation systems to manage the flow of water and the operation of the turbines such as the control systems, sensors, meters, speed controllers and other devices necessary for the proper functioning of the system;
4. Construction of civil engineering and infrastructure: ground preparation, building support structures, and creating access roads, bridges, or canals;
5. Engineering, miscellaneous procurement and construction (EPC) and grid connection: the civil works, wiring and installation of other components necessary for an adequate connection to the electrical grid (electrical panels, transformer, auxiliary services, etc.).

Table 6 presents Terna's assumptions on the costs of lithium-ion batteries[22] and pumped hydro plants.

Benchmark analysis conducted by Terna with suppliers, developers, and market operators indicate that current storage systems operate across the full charge-discharge range without additional efficiency losses beyond the documented degradation shown in Figure 3[23]. Therefore, installed capacity is considered fully available for operational use.

CATEGORIZATION	**COST COMPONENT**	**LI-ION BATTERY 4H**	**LI-ION BATTERY 8H**	**PUMPED HYDRO 8H**
INSIDE BATTERY LIMITS[24]	*BATTERY [k€/MWh]*	*100 - 123*	*100 - 123*	
	POWER ELECTRONICS [k€/MWh]	*14 - 27*	*12 - 24*	
	EPC AND OTHER [k€/MWh]	*60 - 78*	*60 -78*	
OUTSIDE BATTERY LIMITS [25]	*DEVELOPER, LAND AND GRID CONNECTION COST [k€/MWh]*	*17 - 54*	*17 - 42*	
TOTAL CAPEX [k€/MWh]		*191 - 282*	*189 - 267*	*213 - 389*

Table 6 – CAPEX values. Source: Terna elaboration based on dedicated interviews and studies listed in the bibliography

For electrochemical storage, it is important to underline that, to date, solutions with a duration of 8 hours are not commercially common, and that the chemistry of the batteries is optimized for a

[21] It includes civil works, wiring and the installation of other components necessary for an adequate connection to the electricity grid (electrical panels, MV/HV substation development, auxiliary services, etc.), as well as the cost of the Minimum General Technical Solution

[22] It should be noted that the costs of lithium-ion batteries are consistent with the most recent BNEF estimates available (Energy Storage System Cost Survey 2024, December 2024)

[23] *Therefore, compared to what was reported in the previous version of the technical study, published for consultation in August 2023, any reference to the need to operate storage systems while maintaining a minimum charge level above 0% has been removed in this document*

[24] *It encompasses all equipment, processes, facilities, and systems that are within the functional boundaries of the main system*

[25] *It includes all the infrastructures and services outside the main functional boundaries of the system, necessary to support the operation of the "Inside Battery Limits" equipment*

duration of 2 or 4 hours. In fact, international benchmarks do not report costs for a duration of more than 4 hours. The cost estimate for systems with a duration of 8 hours is based on interviews with battery manufacturers and developers.

To construct systems with an operational duration of 8 hours rather than four – while maintaining the same energy capacity – the primary adjustment involves resizing the power components (such as the inverter and transformer) to decrease the nominal power rating. However, to ensure system safety and control short-circuit current, it is generally not feasible to reduce the number of inverters proportionally from 4 to 8 hours. Consequently, for commercially prevalent solutions currently available, the cost reduction (expressed in €/kWh) remains moderate when increasing duration from 4 to 8 hours. It is likely that in around 3 to 5 years we will also see economies of scale on the chemistry of 8 hours.

Finally, it should be noted that, unlike many international benchmarks[26], the costs reported in Table 6 also include the costs of connection, MV/HV substation, project development, authorization, acquisition and preparation of the site. These costs represent a non-negligible component of the CAPEX and can vary according to project specifications. The cost of connection to the high-voltage grid and for the construction of a new MV/HV substation alone affects the amplitude of the values indicated in Table 6. Further efficiencies could be realized for *brownfield* projects that use existing network infrastructures and/or by optimizing the sizing of the individual components (e.g. battery rack, inverter, first voltage elevation from LV to MV).

It is also important to highlight that, for lithium batteries, there is a risk related to the variability of the $/€ exchange rate. In fact, battery manufacturing predominantly occurs outside of EU member states. In defining the economic parameters for auctions, it is necessary to consider both the current exchange rate value and the potential risks related to its variability over time.

Finally, for both lithium batteries and pumped hydro power plants, there is the objective issue of cost variability. This risk is especially relevant for lithium batteries, as their market prices experience considerable volatility due to fluctuations in supply and demand, which are further influenced by ongoing geopolitical developments.

In 2022, the prices of a 4-hour battery (excluding the costs of connection, development, and land purchase) increased by almost 40% compared to 2021. This phenomenon, in contrast to the historical trend in battery prices, was mainly caused by geopolitical instability and inflation dynamics at global level, which then had negative repercussions on the market prices of lithium batteries.

Between 2022 and 2024, lithium battery costs experienced a reduction of approximately 40-45%, attributable to the following factors:

- The decrease in the cost of raw materials used to produce lithium cells (see Figure 4), which accounts for 40-45% of the 2022-24 reduction: prices for lithium carbonate, graphite and other materials peaked in 2022 due to the sharp increase in post-Covid demand, and have now returned to pre-crisis levels, thanks to growth in extraction and refining capacity that is now sufficient to support demand.
- The increase in lithium cell production capacity contributed to 25% of the reduction observed between 2022 and 2024. During this period, annual production capacity expanded from 200 GWh to over 800 GWh, with China accounting for 98% of this growth.
- Market dynamics of System Integrators (SI), a factor that accounts for 25-30% of the 2022-24 reduction: several SI have in fact standardized the production of BESS in containerized solutions, thus reducing the costs of System Integration engineering. Chinese companies have also adopted aggressive pricing to boost their global BESS market share.

[26] *For example: BloombergNEF, "Energy Storage System Cost Survey", December 2023*

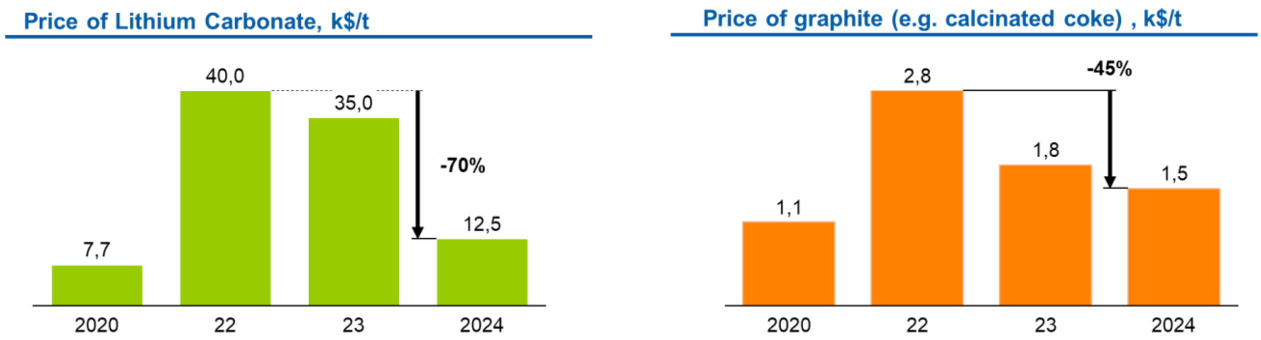

Figure 4 – Lithium carbonate and graphite cost trends

The future trajectory of battery prices is influenced by numerous unpredictable variables. Current market projections indicate that the cost of lithium batteries may decline at an annual rate of approximately 3-4% over the next two to three years. Nevertheless, shifts in market dynamics or geopolitical developments analogous to those previously mentioned may once more influence the trajectory of battery pricing. To account for inherent fluctuations in raw material prices and supply chain management, battery purchase contracts commonly tie costs to a "Raw Material Index."

It is important to note that the variability of costs may be considerable and should be carefully assessed when establishing the economic parameters for the auction.

4.2 OPEX

OPEX costs (*OPerational EXPenditure*) represent the recurring operating expenses necessary to ensure the normal operation of the storage system.

The components of this cost item may include, but are not limited to:

1. Maintenance and operation (O&M): involves inspecting and verifying batteries, electrical machines, and other related equipment; replacing faulty components; performing maintenance on auxiliary systems; and managing the measurement, monitoring, and control devices within the facility.
2. Insurance policies provide coverage for incidents like fire or damage resulting from natural disasters.
3. Additional extraordinary maintenance expenses incurred for the replacement of key system components due to failure or premature ageing, with the objective of ensuring the continued performance standards of the storage system.

Table 7 shows the OPEX values for the two reference technologies[27]. The variability of OPEX arises from multiple factors. For pumped storage facilities, both system size and complexity significantly influence OPEX costs. In the case of lithium batteries, differences in service agreements and insurance coverage represent the primary sources of variability.

It should also be noted that the OPEX shown in the table do not include the cost of energy consumption of auxiliary systems. In line with international benchmarks, the maximum OPEX value of lithium-ion batteries is approximately 3% of CAPEX. This value also includes extending the warranties to 15 years, which is required to maintain storage system operation in accordance with the supplier's stated performance specifications during the delivery period.

PARAMETER	LI-ION BATTERY 4H	LI-ION BATTERY 8H	PUMPED HYDRO 8H
OPEX [k€/MWh/year]	*2.3 – 7.0*	*2.1 – 6.3*	*1,4 - 6,0*

Table 7 – OPEX values with a nominal storage duration of 4-8 hours. Source: Terna elaboration on dedicated interviews and studies listed in the bibliography

[27] *The minimum Opex value reported in the range refers only to the minimum Capex value reported in Table 6, vice versa the maximum value of Opex refers only to the maximum value of Capex*

4.3 CONE

The CONE (*Cost Of New Entry*) is defined as the annual revenue required during the delivery period to cover construction, financing, operating expenses, and an appropriate return on investment. The primary parameters employed in evaluating the value of the CONE include investment costs, annual fixed costs, contract duration, and the weighted average cost of capital (WACC).

The European Commission[28] provides the formula to be used for calculating the CONE. Applying this formula directly with the cost parameters specified in Table 6 and in Table 7 may result in underestimating the value of CONE required to achieve an adequate return on investment. To accurately estimate the CONE, two key factors must be considered.

The primary consideration involves oversizing the plant's installed capacity to ensure compliance with contractual requirements that may exceed standard technological performance. As shown in Chapter 3.3, the nominal capacity is expected to be oversized, resulting in a 12% increase in the total CAPEX shown in Table 6. As a result, the OPEX value applied in the calculation of the CONE has also been increased by 12%.

The second element relates to construction time: lithium-ion storage systems are not built "overnight"[29], but typically require approximately two years to build, as noted in Table 3. The developer receives the auction prize once the project is completed and the delivery period commences. Therefore, the developer must cover financing costs throughout construction. To ensure proper application of the formula, the investment cost to be considered must represent the equivalent construction cost that already internalizes the financing costs during the construction period. Assuming a construction period of 2 years, consistent with the contractual requirements specified by the MACSE, the CAPEX has been adjusted upward by a further 9% compared to the total CAPEX presented in Table 6.

Furthermore, as outlined in Section 4.1, there exists an inherent risk of price volatility, which increases in proportion to the length of time between the establishment of the auction cap and the commencement of the auction process. Specifically, there is a risk that, following the determination of the auction cap, subsequent geopolitical or market developments could lead to increased battery costs. This may result in a significant decrease in the number of projects submitted for auction, thereby jeopardising the fulfilment of required storage capacity. The risk associated with cost variability is challenging to quantify; as a result, it has not been explicitly addressed in this study for defining the CONE. Nonetheless, it is an aspect that warrants consideration when determining the auction cap.

Overall, in the present study, the CAPEX values reported in Table 6 have been increased by 21% for the purposes of calculating the CONE. The 21% increase can be broken down as follows: the first component, equal to 12%, is attributable to the oversizing necessary to comply with the constraints on admissible degradation imposed by MACSE. The remaining 9% is attributable to financing costs incurred during the construction period, assuming that the construction time is 2 years. Also, for the purpose of calculating the CONE, the OPEX values reported in Table 7 have been increased by 12%, to take into account only the effect of oversizing.

With these cost assumptions and assuming, for example, a nominal WACC of 9% and a contract duration of 15 years for lithium-ion batteries, the CONE is equal to:

- 31 - 47 k€/MWh/year for 8-hour lithium-ion batteries
- 31 - 50 k€/MWh/year for 4-hour lithium-ion batteries

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[28] *State Aid SA.104106 (2023/N) (recital 68)*

[29] *The use of overnight investment costs implies a zero-construction period*

5. Development potential

The development of new storage capacity should align with projections for renewable energy expansion, particularly in southern regions and islands where wind and solar resources are most abundant. Additionally, this process should also take into account expected improvements to the electricity grid.

Assessing the development potential of lithium batteries and pumped hydro power plants requires a thorough evaluation of the specific constraints affecting the implementation of these technologies within the region.

The land requirements for electrochemical plants must consider not only the battery section and associated auxiliary systems but also the conversion systems. Consequently, the total area needed varies depending on the intended storage duration. For reference, considering Lithium Ferrophosphate (LFP) technology in a utility-scale application with a 4-8 hour duration, the land use of a lithium-ion facility can be estimated at approximately 50–400 MWh per hectare[30]. This estimate includes batteries, conversion systems, transformation and control equipment, and potential high-voltage infrastructure. Additionally, flexible system configurations may allow for reduced land requirements as energy capacity increases. From a locational perspective, lithium-ion batteries impose no significant restrictions that would impede their deployment, regardless of plant scale or geographical setting.

Hydro pumped storage plants, on the other hand, is subject to geographical constraints related to the availability of water resources and the geomorphology of the territory. In fact, the connection requests received by Terna for hydroelectric pumped storage plants are about an order of magnitude lower than those for lithium-ion batteries.

6. Risks

The economic and performance characteristics that differentiate the two reference technologies are also reflected in the risks associated with their development.

Table 8 shows the main risks associated with the two reference technologies. The qualitative values provided denote an average indicative level of risk; however, it should be noted that individual operators may perceive these risks differently.

MAIN RISKS	LI-ION BATTERY	PUMPED HYDRO
IMPLEMENTATION TIMES	*LOW*	*HIGH*
DIFFERENCE BETWEEN FINAL AND BUDGETED COSTS	*HIGH*	*HIGH*
PROCUREMENT & SUPPLY CHAIN	*MEDIUM*	*MEDIUM*
TECHNOLOGICAL RISK	*MEDIUM*	*LOW*

Table 8 – Main risks of the two identified reference technologies

[30] *Terna elaboration on the basis of data collected from operators*

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