STUDY ON REFERENCE TECHNOLOGIES FOR ELECTRICITY STORAGE

Terna

In compliance with ARERA Resolution 247/2023/R/EEL

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Executive Summary

1. This study on electricity storage technologies was prepared by Terna in compliance with the requirements of ARERA Resolution 247/2023/R/EEL.

2. Storage facilities will play a key role in future scenarios characterised by an increasing deployment of renewable energy sources (RES). They will provide a number of valuable services to the electricity system, including time-shifting and grid services, which are instrumental in ensuring the security and adequacy of the electricity system. Storage will make it possible to 'structurally' shift part of the production of variable Renewable Energy Sources (vRES) from hours of high resource availability to hours of low or no availability, managing their overgeneration efficiently and thus ensuring that decarbonisation targets are met.

3. Legislative Decree No. 210/2021 foresees the introduction of a new mechanism for the forward procurement of electricity storage capacity. The mechanism will be designed and dimensioned with the objective to integrate renewables with an efficient level of overgeneration, taking into account the planned grid developments.

4. Analyses carried out by Terna and published in the 2022 Future Energy Scenarios document (“Documento di Descrizione degli Scenari”, DDS) show that in the 'Fit-for-55' 2030 scenario, about 71 GWh of new utility-scale storage capacity will need to be developed. The rated power in discharge and charge of these storage facilities will have to be greater than or equal to one-eighth of the nominal energy in discharge and charge. The actual needs for new storage capacity (GWh) to be procured by the new mechanism will have to be re-evaluated over time, taking into account the actual development and geographical location of RES in Italy.

5. With its Resolution 247/2023/R/EEL, ARERA assigned Terna the task of preparing this report, which is a study of electricity storage reference technologies, including those under development that have not yet reached full commercial maturity. Among the various technologies suitable for providing above-mentioned services, this report identifies the ones that demonstrate to have reached technological and commercial maturity. It then describes their performance characteristics, investment and operating costs, and development potential.

6. There is a wide range of storage technologies that differ not only in technical and economic terms, but also in terms of technological and commercial maturity, and which may be more or less suitable for providing a given service to the electricity system. For the purposes of this report, a distinction will be made between electrochemical storage (lithium-ion or non-lithium-ion), pumped hydroelectric storage, mechanical storage using air or other gases as carrier fluid, power-to-gas-to-power and other types of storage (electrostatic and magnetic, electromechanical flywheel).

7. To date, the technologies with proven technological and commercial maturity are lithium-ion batteries and pumped hydroelectric storage. About 16 GW / 35 GWh of utility-scale Li-Ion plants have already been deployed worldwide in the electricity sector and forecasts estimate a target of 63 GW by 2026. The global installed capacity of Li-Ion batteries for all applications (e-mobility, electronics, residential storage, UPS etc.) is approximately 1,500 GWh. As far as pumped hydro storage is concerned, the global installed capacity is about 160 GW, of which 50 GW in Europe. This figure is expected to exceed 200 GW globally, by 2026. In contrast, all the other storage technologies mentioned above have global installed capacity that is several orders of magnitude lower compared to Li-Ion batteries and pumped hydro.

8. Therefore, the reference technologies for this study are lithium-ion batteries and pumped hydroelectric storage. Both technologies can offer the services required for the integration of renewables and the efficient operation of the electricity system.

9. In addition to their proven technological and commercial maturity, the two identified reference technologies also have high efficiencies, of around 70-75% for pumped hydro and 80-90% for lithium batteries. The efficiency of a storage system is fundamentally important, as the use of low-efficiency technologies would lead to major system inefficiencies, and this would jeopardise the fulfilment of decarbonisation and RES integration targets. For example, assuming a scenario

where 10 GW / 80 GWh of storage operates on a daily charge-discharge cycle, at an efficiency of 85% the conversion losses would amount to about 3 TWh per year. However, losses would increase to about 11 TWh per year for storage with a conversion efficiency of 50%. Therefore, to achieve the same decarbonisation targets, the extra losses would require additional investments, not only in new renewable capacity (around 6-7 GW of additional solar power) but also in grid infrastructure to connect the additional plants.

10. Finally, it should be noted that this storage procurement mechanism is not an experimental or pilot test for study or research purposes; it is a market initiative aimed at enabling the decarbonisation of the Italian electricity system by deploying large volumes of storage capacity. As these plants will be instrumental in the operation of the electricity grid over the coming decades, the intention is to contract technologies with proven reliability, evidenced by the presence, already today, of a significant number of large-scale plants, thus excluding those technologies tested only in lab environments or in small-scale prototype plants.
11. As already indicated in Resolution 247/2023/R/EEL, Terna will have to update this study at least every two years in order to extend the list of reference technologies, if additional solutions are found to have reached technological and commercial maturity as proven by a significant increase in global installations. The second part of this study describes the performance characteristics exclusively for the two reference technologies, i.e. lithium-ion batteries and pumped hydroelectric storage.
12. These two technologies differ significantly in several performance aspects, including cost, technical lifetime and lead time.
13. Lithium-ion batteries have a relatively short lifetime of 12-14 years. Battery performance tends to decrease over time, both due to calendar aging but also as a function of the cycling characteristics. By contrast, the decline of a pumped hydro plant's performance over time can be considered negligible. Routine maintenance of the electrical and mechanical components ensures that performance is maintained without irreversible ageing. For this reason, the lifetime of a pumped hydro plant can easily reach around 50 years.
14. As far as the construction time is concerned, a utility-scale lithium-ion battery system takes about 1-3 years to be deployed. For pumped hydro, on the other hand, the time needed to build a new plant is 5-7 years.
15. The total cost of a new storage facility can be represented by the so-called CONE (Cost of New Entry), which is the annual revenue required to fully recover the construction, financing and operating costs. The main parameters for calculating the CONE are CAPEX, OPEX, WACC and lifetime.
16. CAPEX can be expressed through two components: the first as a function of the plant's power output (power-related CAPEX), the second as a function of the energy storage volume (energy-related CAPEX). In this respect, lithium-ion batteries differ from pumped hydroelectric storage. For pumped hydro, the power-related CAPEX component is typically considerably higher than for electrochemical batteries. Conversely, the energy-related CAPEX component is lower for pumping than for batteries. For this reason, the overall cost comparison of the two technologies will depend on the nominal storage duration required.
17. The Table 1 shows the current reference values for both technologies with a storage duration of 8 hours. While the overall CAPEX for pumping is typically higher than the CAPEX for batteries, the CONE has a comparable value between the two technologies, when calculated as a function of lifetime.

ECONOMIC PARAMETERS	**LI-ION BATTERY**		**PUMPED HYDRO**	
INVESTMENT COSTS [k€/MWh]	*207 - 228*		*213 - 363*	
ANNUAL FIXED COSTS [k€/MWh/year]	*2.1 - 2.8*		*1.4 - 4.5*	
WACC [%]	*6*		*8*	
MINIMUM STATE OF CHARGE [%]	*17*		*-*	
ECONOMIC LIFETIME [YEARS]	*12*	*14*	*30*	*50*
CONE [k€/MWh$_{USABLE/YEAR}$]	**[31 – 35]**	**[29 – 32]**	**[20 – 37]**	**[19 – 34]**

Table 1 - Economic parameters for storage facilities with a duration of 8 hours

18. The development potential of lithium batteries is not subject to any particular locational constraints that would limit their deployment in large volumes and in predefined geographical locations. Pumped hydro, on the other hand, is subject to geographical constraints related to the availability of the water resource and the geomorphology of the area. This difference is also reflected in the grid connection requests received by Terna. At the beginning of July 2023, 7.9 GW of grid connection requests came from pumped hydroelectric storage plants and 74.3 GW from lithium-ion battery plants (of which 54.4 GW are stand-alone plants and 19.9 GW are storage plants integrated mainly with wind and solar).

Definitions

C-rate: the ratio between the maximum discharge current (expressed in ampere) and the extractable energy in discharge (expressed in ampere-hours); this is a specification provided by the manufacturer of electrochemical battery modules.

Capability curve: curve identified in the Cartesian plane (P, Q), describing the possible stable operating conditions of the storage system interfaced to the grid via an electronic converter on the basis of the operating conditions (voltage, state of charge, power factor etc.).

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

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

Nominal discharging energy or Nominal energy [Wh]: the maximum amount of energy that the storage system is capable of delivering to the grid, measured at the point of connection and reduced by the consumption of auxiliary services, during a full discharge at nominal discharge power, from the maximum acceptable to the minimum acceptable state of charge value.

Nominal charging energy [Wh]: the maximum amount of energy that the storage system can absorb from the grid, measured at the point of connection and reduced by the consumption of auxiliary services, during a full charge at nominal charging power from the minimum acceptable value to the maximum acceptable value of state of charge.

Rated discharging power or Rated power [W]: The maximum active power that a storage system can continuously deliver to the grid at the point of connection; may vary depending on operating conditions.

Rated charging power [W]: The maximum active power that a storage system can continuously absorb from the grid at the point of connection; may vary depending on operating conditions.

Depth of Discharge (DoD) [%]: a percentage value, complementary to the SoC, equal to the percentage ratio, referred to a given instant of time, between the energy discharged from the storage, and the nominal energy

Round-trip Efficiency (RTE) [%]: the percentage ratio between the nominal discharging energy (from which the energy absorbed by the auxiliary services in discharge is subtracted) and the nominal charging energy (to which the energy absorbed by the auxiliary services in charge is added) during a complete charge-discharge cycle (within the acceptable range of charge state) at nominal discharge and charge power; efficiency net of consumption of auxiliary services is therefore considered.

State of Charge (SoC) [%]: the percentage ratio, referred to a given instant of time, between the energy stored in the storage and deliverable during a continuous discharge phase at nominal discharge power until the lower State of Charge limit is reached, and the nominal energy.

1. Role of storage capacity in the electricity system

Legislative Decree No. 210/2021 foresees the introduction of a new mechanism for the forward procurement of electricity storage capacity. The mechanism will be designed and dimensioned with the objective to integrate renewables with an efficient level of overgeneration, taking into account the planned grid developments.

The storage needs depend on the quantity of renewables installed and their geographical location. In August 2022, Terna published the possible future scenarios of the Italian energy and electricity system ('Documento di Descrizione degli Scenari', DDS), which also included an estimate of the storage requirement pursuant to Art. 18 of Legislative Decree No. 210/2021. Before the auction procedure takes place, the storage needs will be reevaluated by Terna to consider the latest evolution of the Italian and European electricity system.

The DDS presents various scenarios up to the horizon years 2030 and 2040. All of them are characterised by a strong increase in generation from Renewable Energy Sources (RES) and an ever-increasing penetration of the electricity carrier in final energy uses, two fundamental elements for reaching the decarbonization targets. Among the scenarios described in the document, the Fit-For-55 (FF55) scenario with a 2030 horizon plays a special role, not only because it targets the policy objectives to 2030, but primarily because it is based on an efficient mix of investments in grid infrastructure, renewables, storage and new digital technologies. The scenario is coherent with the main technical, economic and administrative constraints, which might otherwise prevent the scenario from being realised in such a tight timeframe. The FF55 scenario foresees that nearly 102 GW of installed solar and wind power systems will be needed by 2030 in order to meet policy targets, with an increase of as much as +65 GW compared to 2022.

In all scenarios of high-RES deployment, storage facilities will play a key role in the integration of renewables, as they will provide a number of services which are valuable to the electricity system, including time-shifting and grid services, which are instrumental in ensuring the security and adequacy of the electricity system. Storage will make it possible to 'structurally' shift part of the production of variable Renewable Energy Sources (vRES) from the hours of high resource availability to the hours of low or no availability (see Figure 1), managing their overgeneration efficiently and thus ensuring that decarbonisation targets are met.

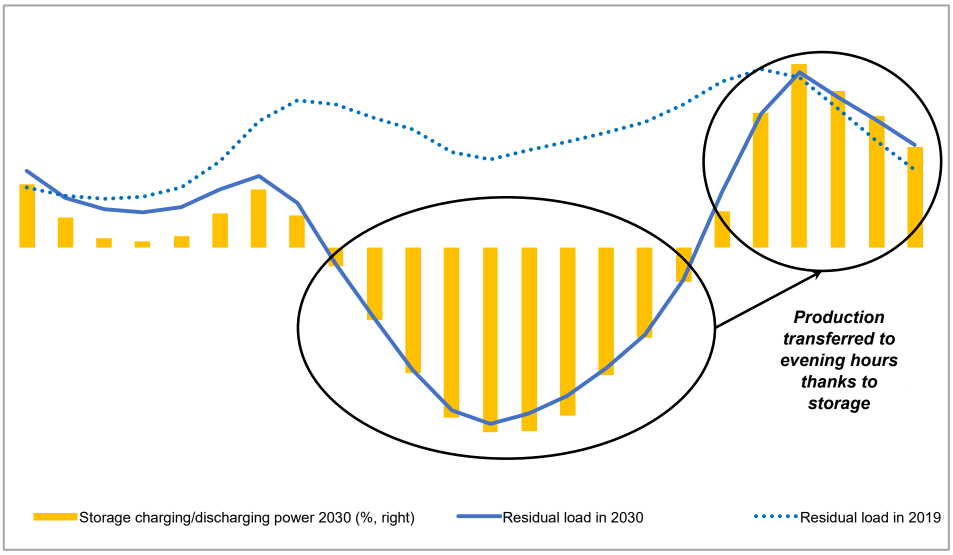

Figure 1 - Daily storage utilisation to 2030 (illustrative). Source: Terna

Studies conducted by Terna show that by 2030, some 71 GWh of utility-scale storage capacity will need to be developed, in addition to the distributed storage essentially associated with small-scale solar and the storage which has already been contracted in the recent Capacity Market auctions.

The rated charging and discharging power of these storage facilities must be greater than or equal to one-eighth of the nominal energy in discharge and charge, i.e. a nominal storage duration in discharge and charge of 8 hours[1] is targeted.

Therefore, in order to meet the entire storage needs identified in the DDS, storage facilities with at least 9 GW of both charging and discharging power will need to be built.

2. Identifying the reference technologies

Today, there is a wide range of storage technologies, which differ not only technically and economically, but also in terms of technological and commercial maturity, and which may be more or less suitable for providing a given service to the electricity system. Within the scope of this study, the following seven technological categories have been identified:

1. **Lithium-ion (Li-Ion) electrochemical storage**: Lithium-ion batteries exploit ion exchange phenomena through the electrolyte between cathode, consisting of lithium compounds, and anode;
2. **Pumped Hydroelectric Storage (PHES)**: mechanical storage of electricity in the form of potential energy from water, which is moved to basins or reservoirs located at different altitudes;
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; liquefaction of air (LAES); systems using gases other than air, etc.;
4. **Non-Li-Ion electrochemical storage**: Batteries which store electrical energy through chemical reactions of various types, including flow batteries (which have circuits for the circulation of liquid electrolytes, e.g. Vanadium-Redox-Flow); hybrid batteries (which do not involve the pumping of liquid electrolyte); high-temperature batteries (which require materials to be kept at high temperatures to allow electronic exchange, e.g. NaS, Zebra), etc.;
5. **Power-to-gas-to-power chemical storage**: this technology makes it possible to produce (green) hydrogen or methane by consuming (renewable) electricity in an electrolysis and methanation process, then compressing and storing this synthetic gas in a tank. During periods when solar and wind generation is low, the synthetic gases are then converted back into electricity through fuel cells or conventional thermodynamic cycles;
6. **Electrostatic, magnetic and similar types of storage**: technologies enabling the storage of electrical energy in the form of an electric or magnetic field—these include supercapacitor or supercapacitor systems (of various types), systems based on superconducting magnets (SMES) etc.;
7. **Electromechanical flywheel storage**: electromechanical storage that stores electrical energy in the form of the rotational kinetic energy of a mass known as a flywheel, by increasing the speed of rotation during the charging process, and decreasing its speed during the discharging process.

In the context of evaluating the reference technologies for this report, it is important to underline that tens of GWh of storage capacity will potentially be contracted in the auctions. Considering the significant amount of storage needs and that the cost of the mechanism will be borne directly by the final consumers, the main criterion used to identify the technologies eligible for the auctions is the proven technological and commercial maturity.

In addition, we recall that the purpose of the mechanism is to enable the integration of renewables with an efficient level of overgeneration. As an example, the DDS scenario estimates 30 TWh of

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[1] *The storage duration, found in the Definitions, is described in section 3.1 of this report.*

stored renewable energy by 2030. Therefore, the round-trip efficiency of the storage facilities is also an extremely important parameter of comparison.

The other technical and performance parameters that characterise the different storage technologies, such as lifetime, lead time, performance in regulation, etc., while relevant for the definition of the auction rules, are not relevant to identify the technologies eligible to participate in the procurement mechanism. These parameters are described in section 3 of this document and only for the identified reference technologies.

2.1 Technological and commercial maturity

A key characteristic for the identification of reference technologies is their proven technological and commercial maturity. The storage procurement mechanism is not configured as an experiment or a pilot test for the purposes of study or research, but as a market initiative functional to the decarbonisation of the Italian electricity system, involving the deployment of large volumes of storage capacity. As these plants will be instrumental in the operation of the electricity grid over the coming decades, the intention is to contract technologies with proven reliability, evidenced by the presence, already today, of a significant number of large-scale plants, thus excluding those technologies tested only in lab environments or in small-scale prototype plants.

Terna's know-how on storage-related matters has been developed within the pilot projects referred to in the ARERA Resolutions 66/2013 and 43/2013. For this study, our empirical evidence has been complemented and updated through various external studies and market analyses that describe the current maturity of technologies and give evidence of the global installed base. The empirical evidence gathered so far has shown that innovative technologies, especially those with a low level of technological maturity and limited experience with continuous plant operation, often need many years of development to reach the minimum level of reliability necessary to be eligible to participate in an auction mechanism such as this one.

As far as lithium batteries are concerned, around 16 GW/35 GWh[2] of utility-scale systems are installed worldwide. Forecasts estimate a target of 63 GW by 2026; at the European level, around 4.6 GW/7.7 GWh were reported to be installed in 2021. Furthermore, the global installed capacity of Li-Ion batteries for all applications (e-mobility, electronics, residential storage, UPSs etc.) is approximately 1,500 GWh[3]. In 2022 alone, global lithium cell production (also covering the e-mobility sector) reached 700 GWh per year[4], with several players having been active in the market for more than 10 years.

In contrast, pumped hydroelectric storage has 160 GW[5] of installed capacity worldwide, of which 50 GW in Europe. This figure is expected to reach 201 GW globally by 2026, with the most expected growth in Asia (47%) and only limited growth in Europe (5%), as this technology is already widely exploited on the old continent[6].

All the other storage technologies mentioned above have a lower global installed capacity, compared to lithium batteries and pumped hydro. Compressed air systems, both conventional and new technology, have an installed capacity of 0.5 GW[7]; the total capacity of all electrochemical batteries other than Li-Ion is 0.9 GW[8]; flywheel installed storage is about 0.9 GW[9] while the installed capacities

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[2] *Bloomberg, 1H 2023 Energy Storage Market Outlook, 2023.*
[3] *S&P Global Mobility on 'IHS market' data, 2022*
[4] *McKinsey, Battery 2030: Resilient, sustainable, and circular, 2023.*
[5] *IEA, Energy Technology Perspectives, 2023.*
[6] *IEA, Renewables 2021 - Analysis and forecast to 2026, 2021.*
[7] *Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022.*
[8] *Bloomberg, Beyond Lithium-ion long duration storage technologies, 2022, e BASF, Stationary Energy Storage.*
[9] *Frost & Sullivan, Future Developments for Global Energy Storage, 2020.*

of power-to-gas-to-power systems[10] and electrostatic and magnetic systems in energy storage applications[11] are currently negligible.

Therefore, to date, the only technologies with high technological and commercial maturity are lithium-ion batteries and pumped hydro. Both technologies can offer the services required for the integration of renewables and the efficient operation of the electricity system.

2.2 Round-trip efficiency

The efficiency of storage systems is a parameter of fundamental importance: the European Commission has repeatedly emphasised the concept of '*efficiency first*', considering it the key factor in the current energy transition process.

For storage systems, the concept of round-trip efficiency (RTE) is used, which considers the entire charging and discharging process and also the consumption and losses of the ancillary plants. An adequate level of efficiency must be ensured to limit the renewable energy 'lost' during the storage, conversion and transformation processes. For example, a plant with a net RTE of 80% loaded with 10 MWh of energy generated from RES can return 8 MWh to the system, with a loss of 2 MWh of renewable energy that, although produced and transmitted to the grid, cannot be used by the end consumer when needed.

The use of low-efficiency technologies would lead to major system inefficiencies, and this would jeopardise the fulfilment of decarbonisation and RES integration targets. For example, assuming a scenario where 10 GW / 80 GWh of storage operates on a daily charge-discharge cycle, at an efficiency of 85% the conversion losses would amount to about 3 TWh per year. However, losses would increase to about 11 TWh per year for storage with a conversion efficiency of 50%. Therefore, to achieve the same decarbonisation targets, the extra losses would require additional investments, not only in new renewable capacity (around 6-7 GW of additional solar power) but also in grid infrastructure to connect the additional plants.

Figure shows the various storage technologies, characterised according to their round-trip efficiency and the typical range of nominal storage discharge duration.

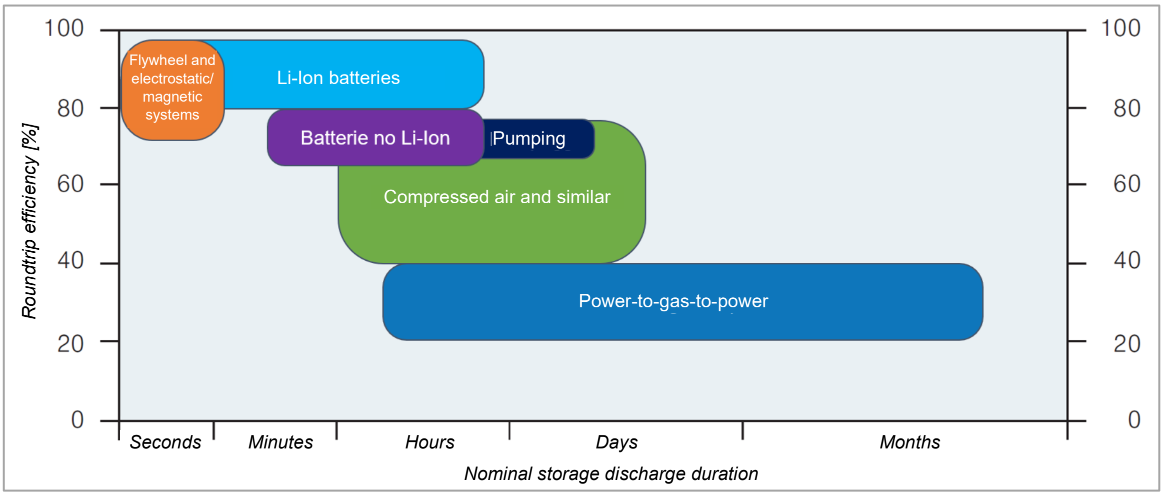

Figure 2 - Positioning of the different technologies. Source: Terna elaborations based on WEO data

It is evident that the variability of RTE is very wide: the highest values are achieved by lithium batteries (80-90%), followed by flywheel and electrostatic systems (75-90%). This is closely followed

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[10] *Around 1.4 GW of electrolysis projects have been completed. However, most of these projects are designed to in a mono-directional way: they convert electricity into hydrogen, but do not offer the possibility of converting it back into electricity. Source: IEA, Global Hydrogen Review, 2022.*

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

by pumped hydroelectric storage (70-75%[12]) and other types of electrochemical storage (65-80%). CAES and similar systems show a wide variability of RTE (40-75%) due to the different thermodynamic characteristics of the fluids used in the process, and the specificities of each technological solution. Finally, at the lowest level (20-40%) are power-to-gas-to-power systems, heavily penalised by the double conversion from electromechanical to thermochemical energy and vice versa.

Given the wide efficiency ranges among the storage technologies analysed (which is also partially dependent on the plant configurations), it is not currently considered appropriate to define the reference technology based on efficiency requirements.

Moreover, the storage technologies analysed not only have different ranges of efficiency; they also vary depending on how their efficiency evolves during the lifetime of an installation.

However, it is crucial that both efficiency and other plant characteristics such as storage duration, can meet the contractual obligations of the mechanism throughout the duration of the contract. It will therefore be up to the successful bidder to decide whether, for example, to oversize the storage capacity at the beginning of its lifetime or to arrange for extraordinary maintenance over the years.

2.3 Reference technologies eligible for auctions

As already described in section 2.1, technological and commercial maturity is the determining parameter when identifying which storage technologies eligible for the auctions. In particular, their deployment in terms of worldwide installed base is considered adequate if it is within the same order of magnitude as the projected storage needs (i.e. within the 10-100 GWh range).

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

Considering the utilization cycles that these storage systems will have to follow, the other potentially discriminating parameter is RTE, which widely varies among the technologies analysed (20-90%). We point out that there is a high degree of coherence between the most mature and the most efficient storage technologies. Therefore, at least at this stage, it does not seem necessary to define a minimum value or efficiency range as a limitation on participate to the auction.

As already indicated in ARERA Resolution 247/2023/R/EEL, Terna will have to update this study at least every two years in order to extend the list of reference technologies, if additional solutions are found to have reached technological and commercial maturity as proven by a significant increase in global installations.

The second part of this study will therefore focus on describing additional performance characteristics only for the two reference technologies, i.e. lithium-ion batteries and pumped hydroelectric storage.

IDENTIFICATION OF REFERENCE TECHNOLOGIES – Question for consultation

- Does the list of seven technological categories include all the electrical storage technologies currently available?

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[12] *Full-converter hydroelectric pumping systems may have even higher efficiencies, especially when operated at partial loads*

3. Technical and performance characteristics

The operational performance of electricity storage facilities can be described by several technical and performance parameters that vary depending on the reference technology, including the mentioned concept of round-trip performance, which represents the efficiency of the storage technology.

As with RTE, with regard to the other technical characteristics it is also fundamentally important to ensure that acceptable performance is maintained throughout the contractual period.

3.1 Storage duration

The nominal storage duration is the time it takes for a storage system to discharge completely, assuming it is initially fully charged and discharged at rated discharge power, net of auxiliary consumption. For example, a system with storage capacity to deliver 8 MWh of energy and a rated discharge power of 1 MW, will have a duration of 8 hours.

For electrochemical batteries, a distinction should be made between storage duration and the C-rate, a design specification of battery modules that represents the maximum current with which the battery can be discharged in relation to its energy capacity. Currently, the C-rate of the commercially available modules varies between 0.25C and 6C. A C-rate of 0.25C indicates that the battery module will take 4 hours to discharge at maximum current; a C-rate of 1C indicates that the module will take 1 hour to discharge. Modules with C-rates higher than 1C are typically used in electric mobility applications, where the power performance in terms of reduced acceleration times is particularly important, while modules with lower C-rates (between 0.25C and 1C) may be used for energy storage applications. Although the C-rate gives an indication of the maximum speed (and thus the maximum current) at which the module can be discharged, it does not limit the possibility of using the same module at lower discharge current values. In fact, by appropriately sizing the DC/AC converter, it is possible, with the same module C-rate, to vary the nominal storage duration of the system in charge and discharge, thereby limiting the maximum current (and thus the maximum speed) with which the batteries can be discharged or charged. For example, a storage system with battery modules having a C-rate of 0.25C could have a storage duration of 4h if the converter is sized for the nominal current of the batteries, or 8h if it is sized for half that. Given that cost of the converter is typically lower than the cost of the modules, with a relatively low additional expenditure (at least compared to the overall investment), it would be possible to increase the size of the converter, which would give a higher performance plant in terms of rated power with respect to the duration requirement (rated power equal to at least 1/8 of the nominal energy). This type of plant, with greater power performance, would not only be able to provide the same energy storage capacity, but would also provide a higher contribution to the stability and adequacy of the electricity system.

Analysing the installed situation in Italy, we observe that to date there are mainly small-scale batteries (more than 350,000 systems with an average rated power of about 8kW) connected to the low-voltage grid, typically coupled with rooftop solar photovoltaics to maximise self-consumption and having a nominal storage duration of less than 2 hours. At the utility-scale level, there is a significant number of the storage plants contracted under the Fast Reserve (about 250 MW) and Capacity Market (about 2.1 GW) forward procurement mechanisms. In the first case, the storage capacity is relatively low, as the Fast Reserve service is designed to provide a quick power response for a relatively short period, while the storage duration of the Capacity Market plants does not exceed 4 hours. However, as explained above, there are no technical limitations on building lithium battery systems with a nominal storage duration of even longer than 4 hours.

As far as pumped hydro is concerned, the nominal storage duration can vary considerably between charging and discharging. While the energy capacity dimensioning depends exclusively on the topographical profile of the reservoirs, the rated power values in charging and discharging also depend on the plant engineering decisions, such as the sizing of the power conduits and of the pumps and turbines. In Italy, the existing pumped storage plants have a rated discharging power of about 7.6 GW and an energy capacity of about 53 GWh, with an average storage duration of about 7 hours.[13] However, some plants show a clear diparity between rated charging power and rated discharging. As already specified, the focus in this study will be on the nominal discharge duration of storage.

In conclusion, as there are no lower bounds on the nominal storage duration and no technical limitations on building plants with a nominal duration of 8 hours, both technologies are suitable to provide the essential services for the integration of renewables and the management of overgeneration.

3.2 Performance in regulation

Performance in regulation refers to the ability of a storage facility to contribute to the security and stability of the electricity system, through the regulation and control of active and reactive power as well as other advanced functionalities.

The charge/discharge processes in lithium-ion batteries are based on ion exchanges between anode and cathode through the electrolyte: by their very nature, these phenomena, within the limits of the operating conditions, are particularly fast with almost instantaneous transients. In addition, the batteries, which “naturally” run on direct current, are networked via electronic DC/AC converters whose high dynamic performance is well known in various other applications. Therefore, even taking into account the delays introduced by the control and measurement systems, a battery storage system can go from a condition of zero exchange with the grid to a reference value of active charge or discharge power in about 1 second, while meeting the dynamic requirements of the transient (e.g. steady-state error, ramp limits etc.)[14]. Test activities in the field[15] have shown how, with appropriate control configurations, starting from the condition of zero exchange with the grid, it is possible to switch to a state of active power delivery in the order of hundreds of milliseconds, with complete reversals from maximum power in charge to maximum power in discharge in less than 200 milliseconds. Electrochemical systems can also contribute to voltage and condition-dependent regulation (voltage level, SoC, power factor etc.) within the limits of the sizing of the system and most importantly of the electronic converters. Although electrochemical storage systems provide very fast adjustments, they are stationary by nature and interfaced to the grid with DC/AC converters and cannot provide a “natural” inertia contribution to the electricity grid (as they do not have rotating masses): however, appropriate control algorithms can be implemented in order to maximise their contribution to grid stability, for example by providing synthetic inertia.

Pumped hydro plants have several possible configurations of grid interface. Conventional pumping typically employs a synchronous electric machine and therefore has the typical regulation capabilities of a synchronous system in generator operation, with slow responses in the order of minutes. Conversely, in pumping, flexible adjustments of the absorbed power (on/off operation) are typically not possible, except by acting on the number of active machines. However, the advantage of a synchronous connection of a rotating machine is that it can provide a mechanical inertia contribution to the grid, which is useful for frequency stability. To overcome the lack of regulation during pumping operation, over the years, additional 'variable speed' plant configurations have been developed: these involve the use of asynchronous doubly fed induction generators (DFIG), or synchronous machines interfaced with the grid by means of a full converter, which guarantee greater modulation flexibility, but which - with full-converter technology - limit or eliminate the inertia contribution.

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[13] *The European House Ambrosetti, Il ruolo strategico dei pompaggi idroelettrici nella transizione energetica, March 2023.*

[14] *Terna, Impianti con sistemi di accumulo elettrochimico - Condizioni generali di connessione alle reti AAT e AT e Sistemi di protezione regolazione e controllo (Annex A.79 of the Grid Code).*

[15] *Terna, Rapporto di fine sperimentazione progetti power-intensive Storage Lab https://www.terna.it/en/electric-system/system-innovation/pilot-storage-projects.*

SPECIFICATIONS	LI-ION BATTERY	PUMPED HYDRO
PERFORMANCE IN REGULATION	*- Fast response (< 1 sec.)* *- Absence of natural inertia (synthetic only)* *- Voltage regulation depending on performance of the DC/AC converter*	*- Slow response (5 - 25 min.)* *- Natural mechanical inertia for synchronous units; no natural inertia (only synthetic) for full-converter* *- Voltage regulation as a synchronous system, depending on system configuration*

Table 2 - Performance in regulation

In conclusion, in terms of regulation performance, the two technologies have some clear differences, but are both suitable for the provision of energy storage services.

3.3 Unavailability

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

For lithium batteries, this value is typically around 2-3% of the annual hours, with a possible increase over the lifetime due to cycling aging of the system. For pumping, on the other hand, the unavailability rate is not a straightforward figure to estimate, as it depends on several factors which may relate to the plant engineering profile of the individual installation and the level of design redundancies. However, assuming that the pumping plants undergo adequate planned maintenance, their expected unavailability rate is still low, as they rely on a relatively small number of technologically mature electromechanical components with high levels of reliability.

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

3.4 Lifetime

The technical lifetime of an installation is defined as the period during which the installation can be operated under normal operating conditions before performance degradation requires the total or partial replacement of components. The progressive deterioration of the plant's performance compared to the specifications at the beginning of its lifetime is related to its hours of use but is not the same for all technologies. The degradation in the performance of lithium-ion batteries over time differs significantly from that of hydroelectric pumping, thus leading to a significant difference in the lifetimes of the two types of systems.

For lithium-ion batteries, the nominal energy tends to decrease over time due to the use of the batteries themselves and also depending on the cycling characteristics. By guaranteeing the operation of the system in the optimal range of SoC[16], e.g. without going below 15-20%, it is possible to partially limit the capacity degradation due to cycling and to avoid premature ageing phenomena (for example, it is essential to avoid the occurrence of undervoltage phenomena which can permanently damage the battery modules).

The ageing phenomena associated with battery cycling cause both an increase in the modules' internal resistance with a consequent reduction in power performance, and also an annual reduction in the energy capacity of the battery which is estimated in the range of 1-3% of capacity at the start of life. These phenomena also have an effect on the system's RTE, due to the decrease in nominal energy in charging and discharging with respect to losses and auxiliary consumption. At this point, it should be noted that regardless of how the battery is used, it is still necessary to ensure that the performance of the system, in terms of e.g. RTE and nominal energy, meets the contractual

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[16] *15-20% of the State of Charge (SoC) is the minimum SoC that must be maintained during operation in order to avoid premature ageing of the modules and reduce the impact of cycling on degradation of battery performance. This value corresponds to a DoD not exceeding 80-85%.*

obligations throughout the contractual period and that the efficiency does not fall below a certain threshold, thus impacting the way the electricity system is operated.

Even when there is adequate routine maintenance of the lithium-ion electrochemical storage, and operation is within the optimal SoC range, after about 4,500 to 5,000 complete charge-discharge cycles, the battery will still reach an energy capacity level of 70% of its start-of-life value, a limit conventionally associated with end-of-life and which may require the complete replacement of the battery modules. Assuming that the system completes a full charge-discharge cycle every day, the useful life of a lithium electrochemical system can be estimated at around 12 to 14 years.

Unlike batteries, the performance degradation of a pumped hydro system over time can be considered negligible. The storage capacity of a pumping plant depends solely on the geomorphological characteristics of the reservoir, which determine the volume of water that can be stored upstream and downstream of the plant, as well as the water jump between the two basins. In addition to geomorphology, another characteristic of the pumping plant is the power section, i.e. the pumps and turbines, both of which are subject to natural mechanical wear and tear. However, the routine maintenance of electrical and mechanical components can ensure that performance is maintained over time without any irreversible ageing phenomena. The lifetime of a pumped hydro system is therefore far longer than that of lithium-ion batteries and can be considered to be at least 50 years.

SPECIFICATIONS	LI-ION BATTERY	PUMPED HYDRO
LIFETIME [YEARS]	*12 - 14*	*>50*
NUMBER OF CYCLES	*4500 - 5000*	*> 50,000*
OPTIMAL SOC RANGE [%]	*15/20 - 100*	*0 - 100*
ANNUAL DEGRADATION	*Capacity reduction of 1-3% per year*	*Negligible*

Table 3 - Lifetime, number of cycles, State of Charge and annual degradation

3.5 Lead time

Construction time or lead time is defined as the number of years required to build the storage facility, including the design, supply, installation and testing of all its components. Lithium-ion batteries and hydroelectric pumping systems differ considerably in terms of the time required for completion.

A utility-scale plant with lithium-ion batteries takes 1-3 years from start to finish, of which a large part (about half) is needed to complete the procurement of the plant components. Pumped hydroelectric storage plants, on the other hand, are structures which are closely linked to the morphology of the land. They take at least 5-7 years to build, and their construction time depends heavily on the scope and complexity of the engineering works.

SPECIFICATIONS	LI-ION BATTERY	PUMPED HYDRO
TIME [YEARS]	*1 - 3*	*5 - 7*

Table 4 – Lead time

3.6 Other performance characteristics

In addition to the technical characteristics already mentioned, there are others worth mentioning and which are closely related to the operational usage of storage technologies:

- **Operating temperature:** the optimal operating temperature of the system, which must be ensured in order to maximise the performance of the storage technologies. The optimal operating temperature is only relevant for lithium-ion batteries and lies in the range between approximately 15°C and 30°C. However, the ambient temperatures can reach extremes much higher or lower than the optimal operating temperature (-10°C / + 45°C, depending on geographical location). It remains the operator's responsibility to ensure that the operational performance of the batteries meets the contractual specifications.

- **Self-discharge:** an internal chemical process within the battery by which the stored energy tends to decrease when the battery is not used for long periods; this may be augmented by the effect of the auxiliaries, which need to be supplied even when there is no exchange with the grid. Terna analyses have shown that by 2030, storage technologies will predominantly cycle daily and thus the impact of self-discharge on battery performance can be considered negligible. Also for pumped hydro plants, the self-discharge phenomenon is considered negligible.
- **Technical minimum power:** the technical minimum power, expressed as a percentage of the rated power, indicates the minimum power that can be stably delivered by the system under nominal operating conditions. Electrochemical storage systems do not have a relevant technical minimum power and can therefore stably regulate the entire power range from maximum charge to maximum discharge power. Instead, the technical minimum power of a pumped hydroelectric storage system depends on its specifics (such as the number of pumps and turbines in the system and the presence or absence of speed controllers). Still, the technical minimum of hydroelectric pumping plants can be significantly reduced by using full-converter devices.
- **Active power regulation in the charging phase:** while electrochemical storage systems have the natural ability to regulate active power throughout the power operating range, only double-fed or full-converter hydroelectric pumped storage systems can provide active power modulation in the charging phase (e.g. primary, secondary and tertiary regulation).
- **Restart capability:** Both technologies can provide the restart service even without external power supply ("blackstart") if this is properly considered in the design phase.
- **Voltage regulation:** both technologies examined (electrochemical storage and hydroelectric pumping) can effectively provide voltage regulation.

SPECIFICATIONS	LI-ION BATTERY	PUMPED HYDRO
OPERATING TEMPERATURE [°C]	*15 - 30*	*N/A*
TECHNICAL MINIMUM [%]	*0*	*variable, depending on plant specifications*
SELF-DISCHARGE [%]	*Negligible for daily cycles*	*Negligible for daily cycles*
ACTIVE POWER REGULATION DURING ABSORPTION	*Yes*	*Only double-fed or full-converter hydroelectric pumping plants*
RESTART CAPABILITY	*Black start*	*Black start*
VOLTAGE CONTROL	*Yes*	*Yes*

Table 5 - Other performance characteristics

PERFORMANCE CHARACTERISTICS - Questions for consultation

1. Does this section accurately describe the performance characteristics of the reference technologies?
2. Do you agree that full-converter hydroelectric pumping plants can be designed to provide active power regulation in the charging phase?

4. Investment and operating costs

This section presents the main cost items of storage systems, for the reference technologies identified in this study. We distinguish the following costs:

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

These cost items can vary widely, depending on several factors including the type of storage technology and the project specifications.

4.1 CAPEX

CAPEX, which stands for 'CAPital EXpenditure', includes the initial investment required to acquire, construct or upgrade the physical assets of a plant.

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

1. The battery: this component covers about 50% of the CAPEX and mainly includes the cost of materials and machining. This cost item varies widely depending on the materials used (e.g. according to the chemical specification of the lithium), the desired storage capacity, the C-rate and the selected supplier;
2. The conversion and control equipment: the DC/AC converter, the SCADA/controller system and the measurement and monitoring systems required for the efficient and safe operation of electrochemical storage facilities;
3. Engineering, Miscellaneous Procurement and Construction (EPC) and grid connection: engineering works, cabling and installation of other components required for adequate grid connection (switchgear, transformer, auxiliary lines etc.).

As far as CAPEX for pumped hydroelectric storage systems are concerned, these are impacted by various factors:

1. Construction of storage reservoirs: their design and construction may vary depending on the desired size and storage capacity and, above all, on the presence or absence of existing dams/reservoirs;
2. Construction of the hydraulic works: pipework, lines 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 water flow and turbine operation such as control systems, sensors, meters, speed controllers and other devices required for proper system operation;
4. Civil engineering and infrastructure works: the adaptation of land, the building of supporting structures and the ancillary infrastructure such as access roads, bridges or canals;
5. Engineering, Miscellaneous Procurement and Construction (EPC) and grid connection: engineering works, cabling and installation of other components required for adequate grid connection (switchgear, transformer, auxiliary lines etc.).

CAPEX can be expressed as the sum of two components: the first as a function of the plant's power output (power-related CAPEX), the second as a function of the energy storage capacity (energy-related CAPEX). In terms of the relative weight of these components, lithium-ion batteries differ significantly from hydroelectric storage. For pumping plants, the power-related CAPEX component is typically considerably higher than for electrochemical batteries. Conversely, the energy-related CAPEX component is typically lower for pumping than for batteries. For this reason, the overall cost comparison of the two technologies will depend on the nominal duration of storage required. The *Power-related* CAPEX of pumping plants also has a rather wide range of variation, depending on the size of the project and the complexity of construction.

The CAPEX values for the two storage technologies are shown at Table 6. Please note that, for both technologies, developer margins are excluded from the cost item. Also, the energy capacity in MWh refers to the installed energy capacity and does not consider any operational limitations relative to the optimal SoC.

ECONOMIC PARAMETERS	LI-ION BATTERY	PUMPED HYDRO
CAPEX [k€/MWh]	*207 - 228*	*213 - 363*
Power-related CAPEX [k€/MW]	*133 - 147*	*1300 - 1700*
Energy-related CAPEX [k€/MWh]	*190 - 210*	*50 - 150*

Table 6 - CAPEX values with nominal storage time of 8 hours. Source: Terna processing of studies listed in the bibliography

4.2 OPEX

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

The components of this cost item may include, by way of example:

1. Maintenance and Operation (O&M): the inspection and testing of batteries or electrical machines and other equipment, the replacement of defective components, the maintenance of auxiliary services, measurement, monitoring and control equipment;
2. Insurance policies to cover unforeseen events such as fire or natural disasters;
3. Additional extraordinary maintenance costs for the replacement of key components due to failure or premature ageing, in order to guarantee the performance characteristics of the storage system.

The expenses incurred for the operation and maintenance of an electrochemical storage system can be considered relatively low compared to those of a hydroelectric storage system. Again, however, OPEX for a pumping plant can vary considerably depending on several factors such as size and complexity of the plant.

Table 7 shows the OPEX values for the two reference technologies.

ECONOMIC PARAMETERS	LI-ION BATTERY	PUMPED HYDRO
OPEX [k€/MWh/year]	*2.1 - 2.8*	*1.4 - 4.5*

Table 7 - OPEX values with nominal storage time of 8 hours. Source: Terna processing of studies listed in the bibliography

4.3 CONE

The CONE *(Cost Of New Entry*) represents the annual revenue required during the contract period in order to fully recover the construction, financing and operating costs. The main parameters for the evaluation of the CONE are the investment costs, the annual fixed costs, the duration of the contract and the weighted average interest rate used to finance the investment in the plant (WACC). It is important to emphasise that the CONE is expressed in k€ per MWh of usable energy, i.e. the actual energy made available by the storage system, thus considering the minimum state of charge of the technology (17% for batteries).

Table 8 shows the economic parameters for the two technologies identified with storage durations of 8 hours. Note that the investment costs refer to the installed energy, while CONE is calculated based on the usable energy. While the overall CAPEX for pumping is typically higher than the CAPEX for batteries, the CONE has a comparable value between the two technologies when calculated on a lifetime basis.

ECONOMIC PARAMETERS	LI-ION BATTERY		PUMPED HYDRO	
INVESTMENT COSTS [k€/MWh]	*207 - 228*		*213 - 363*	
ANNUAL FIXED COSTS [k€/MWh/year]	*2.1 - 2.8*		*1.4 - 4.5*	
WACC [%]	*6*		*8*	
MINIMUM STATE OF CHARGE [%]	*17*		-	
ECONOMIC LIFETIME [YEARS]	*12*	*14*	*30*	*50*
CONE [k€/MWh$_{USABLE/YEAR}$]	**[31 – 35]**	**[29 – 32]**	**[20 – 37]**	**[19 – 34]**

Table 8 - Economic parameters for storage facilities with a duration of 8 hours

Figure shows the trend in CONE as a function of the contract duration, considering the CAPEX and OPEX values shown in Table 8. For lithium-ion batteries, the CONE graph ends at 14 years, which reflects the lifetime of this technology (12-14 years, as described above). The graph clearly shows how the CONE progressively decreases as the contract term increases, reaching its minimum value when the contract term is equal to the lifetime of the technology (for pumped hydro, it is assumed that although the lifetime is around 50 years, the contract duration cannot exceed 30 years). The graph also shows how the construction complexity of pumped hydroelectric systems results in a wider CONE range than for Li-ion batteries.

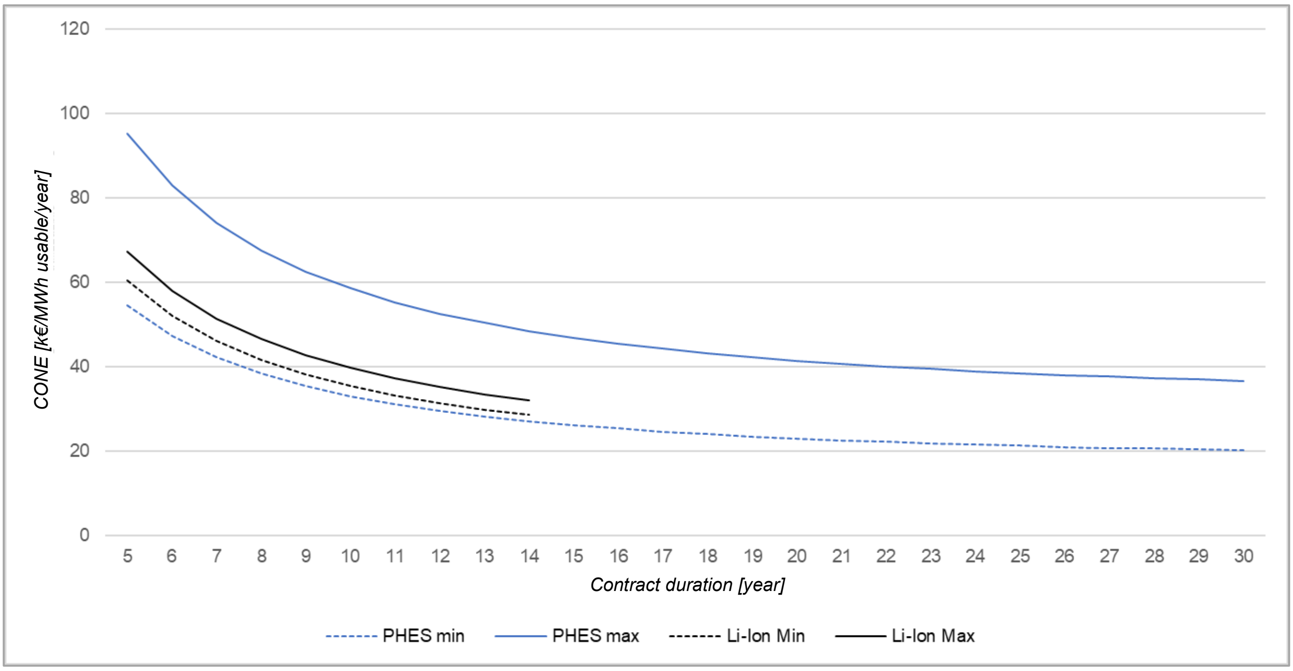

Figure 3 - Variation in CONE according to contract period

INVESTMENT AND OPERATING COSTS - Question for consultation

- Do you consider the CAPEX and OPEX ranges given for the two reference technologies to be consistent with current market values?

5. Development potential

The new storage capacity will need to be deployed in areas that are coherent with the expected growth in renewables (mainly in the South and Islands, where there are more wind and solar resources) and will need to consider the expected developments of the electricity grid.

To estimate the development potential of lithium batteries and pumped hydro, it is necessary to examine the specific constraints on the development of these two technologies.

The land occupancy for electrochemical plants must not only consider the battery section and its auxiliaries, but also the conversion systems, and is therefore also variable depending on the duration of the storage. As an indication, taking the example of Lithium Iron Phosphate (LFP) technology for a utility-scale plant with a storage duration of 4-8 hours, the land occupancy of a lithium-ion plant can be estimated at around 250 - 350 MWh per hectare[17], including batteries, conversion, transformation and control systems, excluding the high voltage bay. Flexible plant configurations are also possible, and this could reduce land occupancy as the energy dimensioning increases.

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[17] *Terna elaborations, based on available footprint data for Morro Bay (600 MW / 2,400 MWh) and Tesla Megapack farm (182 MW / 730 MWh) and market references.*

Therefore, lithium-ion batteries do not present relevant locational constraints that could limit their development in terms of either plant size or geographical location. Pumped hydro systems, on the other hand, are subject to geographical constraints related to the availability of the water resource and the geomorphology of the area.

This difference is also reflected in the grid connection requests received by Terna. At the beginning of July 2023, 7.9 GW of grid connection requests came from pumped hydro storage plants[18] and 74.3 GW from lithium-ion battery plants (of which 54.4 GW are stand-alone plants and 19.9 GW are storage plants integrated mainly with wind and solar). Figure 4 shows the technological and geographical breakdown of connection requests.

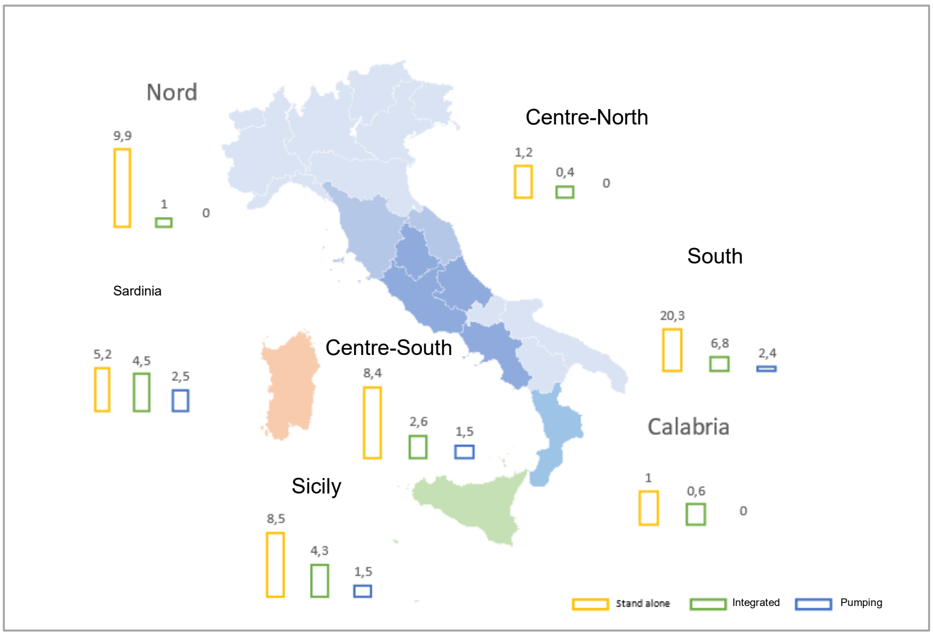

Figure 4 - Zonal distribution of storage and pumped hydro grid connection requests (GW)

6. Risks

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

The main risks associated with the two technologies are listed in Table 9:

MAIN RISKS	LI-ION BATTERY	PUMPED HYDRO
BUILD TIMES	*LOW*	*HIGH*
VARIABILITY OF FINAL COSTS COMPARED TO BUDGET	*LOW*	*HIGH*
PROCUREMENT AND SUPPLY CHAIN	*MEDIUM*	*MEDIUM*

Table 9 - Main risks of the two identified reference technologies

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[18] *It includes both new-build plants and repowering projects.*

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