Energy storage systems: a comparison of different technologies and possible application in Sicily

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***Abstract*—The increasing demand for sustainable and reliable energy sources necessitates advancements in energy storage technologies. In the light of a better integration of renewable energies, communities promoting self-consumption such as renewable energy communities are being developing all over the world. In these communities, energy storage becomes of paramount importance to allow differing in time energy production and consumption. This paper reviews the current state of various energy storage technologies, examining their principles of operation, advantages, limitations, and potential for future development. Technologies covered include electrochemical batteries, supercapacitors, flywheels, compressed air energy storage, pumped hydroelectric storage, and emerging technologies such as hydrogen-based energy storage and superconductive magnetic energy storage. Moreover, the paper aims to provide a comprehensive understanding of each technology's role in the evolving energy landscape and propose a new concept of technology for electrical energy storage based on the resources locally available. This kind of technology might greatly help the development of energy communities based on realities characterized by water scarcity.**

***Index Terms*—desalination, energy community, hydrogen, renewable, storage**

I. Introduction

Climate change is forcing humanity in finding new solutions to everyday problems such as the production of energy. Since renewable energy technologies integration in power systems has reached a non-negligible share of the electricity production mix, it has become necessary to manage the energy feed in. In detail, the exploitation of intermittent Renewable Energy Sources (RES) like wind and solar power has highlighted the need for effective energy storage systems. Electrical energy storages are systems consisting of a set of devices, management, and control equipment use to alternatively absorb and release electrical energy, allowing to be installed over various levels of the power system, including the joint installation with RES plants [1]. Nevertheless, although the concept of energy storage has developed greatly, the development of storages for power system applications has begun only in the recent past, mainly exploiting lithium-ion technology originally conceived for small mobile devices. These systems play a key role in the modern power systems, helping balance supply and demand, stabilizing the grid, and ensuring a reliable energy supply. The classic balancing system between power fed into the grid and consumed involves the use of active systems that control grid frequency and voltage. The use of batteries, on the other hand, involves the possibility of regulation with static systems. With specific reference to intermittent RES, these systems can thus improve the stability of the electric grid by balancing the generation of energy from renewables and the final loads.

In general, this approach could be a solution for balancing demand and production in small islands or in small final loads aggregates such as renewable energy communities, where energy self-consumption is promoted and remunerated [2].

Another prominent issue deriving from climate change is the rising of average temperatures, impacting on the lakes evaporation rate and on the average annual precipitations. In this context, Sicily island is currently facing a large drought issue that led to the reduction of available freshwater of about 250 Mm^3 from July 2023 to July 2024 over a total availability of 1011 Mm^3 of freshwater over the whole island [3]. Old and dismissed desalination plants are being recovered and renovated to fight the current water crisis [4], although their cumulated capacity is only about 120.000 m^3/day [5], insufficient to fully restore the regional freshwater reservoirs.

On the other hand, Sicily is rich with intermittent renewable energy systems, mainly solar and wind, with 2164 MW of photovoltaic installed by the end of 2023 [6] and 2127 MW of wind turbines installed by the end of 2022 [7]. Exploiting renewables to feed desalination units would help solving several current issues such as the reduction of wind energy curtailment [8] or reverse power flow from MV to HV grids, together with new freshwater production.

For what illustrated above, this paper provides a brief re-

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view of the most common electrical energy storage technologies, providing insights into their operational mechanisms, current applications, and future prospects. Technologies assessed in this paper are:

- Electrochemical storage
- Electrostatic storage (supercapacitors)
- Mechanical storage (flywheels, compressed-air energy storage, and pumped hydroelectric storage)
- Chemical storage (hydrogen)
- Electromagnetic storage (superconductive magnetic energy storage).

Subsequently, the proposal for an innovative water-based electricity storage system is provided, based on the exploitation of the local resources. The potential performance of the proposal is further analyzed through a case study in Sicily (Italy).

In particular, in authors' mind, water storage can play a double role: the first is to address the problem of water scarcity in Southern Italy, the second allows the production of energy from renewable sources to be stored when the electrical grid does not require it.

II. Brief Review on Most Common Electrical Energy Storage Technologies

A. Electrochemical Batteries

Electrochemical batteries, such as lead-acid, lithium-ion, and sodium-sulfur types, store energy via chemical reactions. These batteries typically consist of an anode, cathode, electrolyte, and separator. They are the most common technology for converting chemical energy directly into electrical energy, operating through oxidation-reduction and electrolysis processes that allow reversible energy transformation. Each battery has two half-cells with metal electrodes (anode and cathode) in an electrolyte solution. Oxidation at the anode releases electrons that flow to the cathode, which undergoes reduction, creating an electron flow captured by a conductor.

Different accumulators vary based on the electrochemical species, electrolyte type, and structural design. Their modularity and diverse sizes make them crucial in the global storage systems market. Despite their maturity, research continues to improve performance, focusing on new electrode types, better state of charge estimation, and advanced management systems.

Lead-acid batteries, being heavy and bulky, are gradually being replaced by lithium-ion batteries. Although slightly less mature technologically, lithium-ion batteries are favored for residential PV and electric vehicle applications due to their durability, efficiency, and energy density. The environmental impact of battery disposal varies; lead-acid batteries have low disposal costs with over 90% recyclability, while nickel/cadmium batteries have a high environmental impact due to cadmium pollution. Lithium-ion battery recycling for rare earth elements, metals, and lithium exists but is limited by economic factors.

Charging and discharging rates are a limitation, requiring specific current parameters, especially for lithium batteries, to prevent damage and potential explosions. Batteries also degrade over time and have operational temperature constraints; for instance, lithium batteries do not function below 0°C.

Future challenges in battery technology include increasing energy density, reducing costs, and improving longevity. Promising developments include solid-state and lithium-sulfur batteries.

B. Supercapacitors

Supercapacitors, or electrochemical capacitors, are a recent development in energy storage technology. They consist of two electrodes immersed in an electrolyte solution and separated by a permeable membrane. Unlike traditional capacitors, supercapacitors use porous electrodes, significantly increasing the surface area and enabling high energy storage capabilities [9].

Traditional batteries have high energy density but low power density, suitable for slow charge and discharge cycles over hours. Conventional capacitors, in contrast, have low energy density but high power density, ideal for extremely fast charge and discharge cycles lasting fractions of a second. Supercapacitors bridge this gap with intermediate energy and power densities, making them suitable for charge-discharge cycles lasting about one minute.

Supercapacitors are categorized based on the electrode materials (carbon, metal oxides, polymers) or the type of electrolyte used (organic, aqueous). Carbon-based electrodes are the most common due to their low cost, high surface area, availability, and established production technology. These can be further divided into activated carbons (powders and fabrics) and nanostructured carbons (e.g., nanotubes). Activated carbon electrodes are inexpensive and offer high surface areas, while nanostructured carbons, though more costly, provide higher porosity and capacities ranging from a few farads to thousands of farads per cell.

Metal oxide electrodes offer low resistivity and high specific capacitance, allowing for capacitors with both high energy and power density. However, they are expensive and have low cell voltage ratings (around 1 V). Conducting polymers are another alternative, capable of accumulating or releasing electrical charge through oxidation-reduction reactions. These polymers enable charge accumulation throughout the electrode's volume, resulting in high specific capacitance. However, the structural deterioration caused by the contraction and expansion during charge-discharge cycles poses a challenge.

Despite having lower energy density compared to electrochemical accumulators, supercapacitors excel in specific power output. Their ability to be rapidly charged and discharged over numerous cycles makes them ideal for applications requiring high power delivery for short durations, from fractions of a second to a few minutes.

Ongoing research aims to increase energy density and reduce costs. Hybrid systems combining batteries and supercapacitors are also being explored, offering the potential to harness the strengths of both technologies.

C. Mechanical storage systems

Mechanical storage systems can be divided essentially into three categories [10]:

- Compressed air energy storage (CAES)
- Flywheels
- Pumped Hydro Storage (PHS)

1) CAES: CAES technology involves storing electrical energy in the form of compressed air stored in underground caverns or tanks. When energy is needed, the compressed air is released, heated, and expanded to drive turbines that generate electricity. This method allows for large-scale and long-duration energy storage, making it suitable for balancing supply and demand over extended periods. However, the efficiency of CAES can be limited by the energy required for compression and the geographic constraints for suitable storage sites. Advances in thermal management and hybrid systems combining CAES with other technologies could improve efficiency and applicability. Despite these challenges, CAES remains a valuable technology for integrating renewable energy sources and stabilizing power grids.

2) Flywheels: Flywheels store energy in the form of rotational kinetic energy. Energy is stored by accelerating a rotor (flywheel) to a high speed and maintaining the energy in the system as rotational energy. Improvements in materials and engineering techniques aim to increase the energy density and efficiency of flywheel systems.

3) PHS: Pumped water storage systems are widely used for stabilizing national power grids. These systems typically feature two reservoirs situated at different elevations. A pump moves water to the higher reservoir, storing electrical energy as hydraulic potential energy during periods of low energy demand. When demand peaks, the stored water is released to flow back to the lower reservoir, passing through a turbine that converts the potential energy into electrical power. The energy storage capacity is determined by the elevation difference between the reservoirs and the volume of water stored. Pumped storage technology is well-established, benefiting from decades of operational experience, and is unlikely to see major advancements in cost, design, or efficiency in the near future. This is currently the main technology used worldwide for electricity storage in HV power systems. While these systems leverage the extensive knowledge gained from hydropower plants, they require significant space and specific land conditions for implementation. Additionally, the construction of large reservoirs involves substantial engineering and careful consideration of environmental and ecological impacts on surrounding flora and fauna.

D. Hydrogen-based storage

The hydrogen molecule (H_2) is highly stable at room temperature. However, in its atomic state (H), hydrogen is highly reactive and must be handled with care.

Several energy storage systems based on the exploitation of hydrogen have been proposed in recent years. Nevertheless, all of these systems might be schematized as follows [11]:

- hydrogen production from electricity;
- hydrogen storage;
- hydrogen conversion in electricity.

In detail, hydrogen can be produced from electricity via electrolysis. If excess renewable energy is used, the product is called ”green hydrogen”. Fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, producing water as a byproduct. This components operates somehow with the opposite reaction of the electrolysis.

Regarding hydrogen storage, several physical and chemical methods are being explored: compression to high pressures (700 bar), liquefaction and storage in cryogenic tanks (-252 °C), adsorption on materials with high surface areas ($T < 700$ °C), adsorption in interstitial sites (ambient temperatures and atmospheric pressure), formation of chemical compounds involving ionic and covalent bonds (at atmospheric pressure), and oxidation of reactive metals with water.

In the close future, the development of more efficient and cost-effective electrolyzers and fuel cells, along with expanded hydrogen infrastructure, could enhance the viability of hydrogen-based electricity storage.

E. Superconductive Magnetic Energy Storage

Superconductive Magnetic Energy Storage (SMES) systems store energy through the use of superconducting magnets. These systems leverage the unique properties of superconductors, which can conduct electricity with zero resistance when cooled to extremely low temperatures. SMES consists of a superconducting coil that, when charged, creates a magnetic field to store energy. This energy can be rapidly released back into the grid, making SMES highly efficient for quick power delivery and grid stability. The main advantage of SMES is its exceptional efficiency, with almost no energy loss during storage and retrieval, unlike conventional energy storage systems. Additionally, SMES systems can undergo unlimited charge-discharge cycles without degradation, providing a durable and reliable solution for applications requiring frequent and rapid energy exchanges. These features make SMES particularly suitable for stabilizing power grids, supporting renewable energy integration, and providing uninterruptible power supplies. However, the need for advanced cooling systems and the high costs associated with superconducting materials pose significant challenges to widespread adoption. Ongoing research focuses on reducing these costs and improving the practicality of SMES, potentially transforming energy storage and distribution by harnessing the power of superconductivity.

F. Technologies Comparison

As a final remark of the literature review, a comparison of the main features of the technologies illustrated in the previous section is shown in Table I [9]–[12].

TABLE I
COMPARISON OF ADVANTAGES AND LIMITATIONS OF ENERGY STORAGE TECHNOLOGIES

Technology	Advantages	Limitations
Batteries	- High energy density - Scalability - Rapid response times	- Degradation over time - Environmental concerns for disposal - High initial costs
Supercapacitors	- High power output - Long cycle life - Fast charge/discharge	- Low energy density - Higher cost per watthour compared to batteries
Flywheels	- High efficiency - Long lifespan - Low maintenance	- High initial cost - Issues to minimize friction and air resistance
CAES	- Large-scale storage capability - Long duration storage	- Geographic limitations - Lower round-trip efficiency compared to batteries
PHS	- High efficiency - Large-scale and long-duration storage	- Geographic limitations - Environmental and ecological impacts
Hydrogen Storage	- High energy density - Zero emissions - Versatility and flexibility	- High production and storage costs - Infrastructure challenges
SMES	- High efficiency - Rapid response time - Durability	- High production costs - Complex cooling system - Limited energy capacity

III. Proposal for a Storage System based on Renewable Energies, Desalination Units and Existing Basins

In this paper, the authors propose a concept of large-scale, integrated electrical energy storage system based on the exploitation of the following geographical and natural resources:

- large availability of seawater
- large availability of RES (*i.e.*, wind or solar)
- lake basins located at different elevations and linked to each-other.

In detail, during periods of high RES generation, the electrical output usually exceeds the local load. This excess electricity can be used by power desalination units located on the coastal areas, producing freshwater from seawater. Freshwater can be injected into the lake basins system through pipelines or tank trucks. Additionally, if lakes close to each-other are linked through pipelines including reversible pump-turbine groups, surplus energy can be employed to pump water from the lower reservoir to the upper reservoir, storing energy in the form of gravitational potential energy.

On the other hand, when RES production is low (*e.g.*, nighttime or calm days), the stored water in the upper reservoir can be released to flow back to the lower reservoir. The falling water drives turbines connected to electrical generators, converting the potential energy back into electrical energy to supply the grid during peak demand periods.

The system described above might be used to support areas of the world characterized by large RES and seawater availability but relatively low electricity demand and high freshwater demand. This reality fits well with the scenario that Sicily island is currently facing.

During the operation of this integrated energy storage system, the desalination units should operate during excess energy periods, ensuring a steady supply of freshwater while reducing general costs for the local community. Freshwater produced can be stored in local reservoirs or directly supplied to communities, supporting both domestic and agricultural needs. Moreover, the exploitation of two energy carrier should enhance the Sicilian power system flexibility, increasing the inertia of the system and allowing for desalination units to provide ancillary services, if managed properly. In detail, the integrated management of intermittent RES, pumped hydro between lakes, and desalination units might help solving some of the major issues that most of the world is facing in integrating renewables: the curtailment of large scale production plants (typically, wind farms), the reverse power flow from MV to HV grids and the residual load (or duck-shaped curve).

In this way, with specific reference to Sicilian situation, the water missing from regional lakes might be restored while the reliability of the power system would be enhanced.

IV. Numerical Example

In order to quantify the potential benefits deriving from the electrical energy storage illustrated in the previous section, some numerical examples were developed, starting from regional level and then using a specific lakes basin system.

Sicily currently has 29 large lakes equipped with dams, having a cumulated capacity of 1010.7 Mm^3 of freshwater. Nevertheless, only a few of these lakes are already interconnected. The reduction of available freshwater between July 2023 to July 2024 was equal to 240.38 Mm^3, almost a quarter of the total capacity. Assuming an average value of 4 kWh/m^3 of freshwater from reverse osmosis desalination plants [13], restoring the missing freshwater would require 961.52 GWh of electricity. This energy might be produced by RES plants already installed in Sicily, since the total production in 2021 (last year available [14]) overcame 5600 GWh, mainly from solar and wind sources. Nevertheless, as already stated in the introduction section, desalination plants capacity is to low to allow this large freshwater production.

Regarding the surplus energy only, the most recent available data show that 32.1 GWh from wind farms were curtailed in 2022 in Sicily [15]. No data is publicly available on energy related to the reverse power flows. Assuming an average value of 4 kWh/m^3 of freshwater from reverse osmosis desalination plants [13], the exploitation of this energy might allow producing 8.025 Mm^3 of freshwater, roughly 1/30 of the freshwater missing from 2023 to 2024. Considering the installed capacity of desalination units, this kind of freshwater production would be allowed in less than 100 days with full capacity operation. This numerical analysis conduced at regional level did not take into account for several aspect, first of all that desalination plants are not fully integrated with the lake basins system.

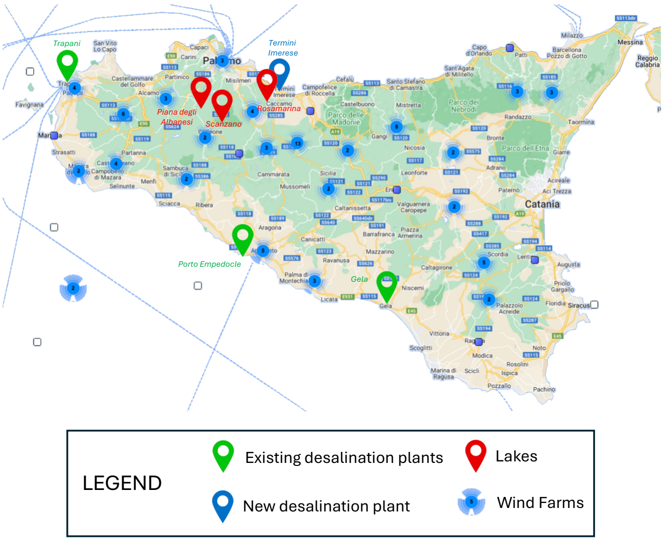

Fig. 1. Sicily island view with indication of existing and proposed desalination plants, analyzed lakes, and wind farms

V. Hypothesis of Application

An hypothesis of application of the integrated electrical energy storage system described in this paper might be done in the district of Palermo, the capital city of Sicily.

In detail, Fig. 1 shows that the area surrounding Palermo is filled with wind farms. There are also several photovoltaic plants that were not shown in the map to not overfill the figure. Renewables might be exploited to feed a pumping system to be installed between the Piana degli Albanesi and Scanzano lakes, that are about 9 km distant, have a difference in height of about 90 m, and are already linked to each-other through pipelines to the public freshwater system. Nevertheless, these lakes are too far from the sea to be integrated with a desalination unit. The total capacity of the Piana degli Albanesi lake is 33 Mm^3, while the Scanzano lake is 18 Mm^3 large. The pumping station might be used during

RES overproduction periods to increase water elevation and using this potential energy during RES production is low. Such a system would allow storing about 3700 MWh of electrical energy in the form of water.

Conversely, the Rosamarina lake is at 170 m height but is close enough to the coast to suppose the installation of a new desalination plant in the close city of Termini Imerese (blue pin), since the existing desalination plants are too far from this area. Rosamarina lake is also linked to the same public freshwater system as the other two lakes, although is too far from the other lakes. An hypothetical pumped hydro plant might be located between the lake and the desalination plant, equipping the latter with an adequate storage capacity. Supposing 1 Mm^3 of capacity might allow storing about 400 MWh of energy available for low production periods, even as seasonal storage.

VI. Conclusion

Energy storage technologies are critical to the integration of renewable energy sources and the stability of modern power grids. Each technology has its unique advantages and limitations, and the future of energy storage lies in the continued development and hybridization of these systems. Advances in materials science, engineering, and policy support will drive the evolution of these technologies, enabling a more sustainable and reliable energy future. This paper provided a brief review of most common electrical energy storage technologies and proposed an integrated technology for exploiting natural resources to fight water scarcity as well as integrating intermittent renewables. Further development of the study will focus on testing this integrated storage system on a regional level, also studying its capacity of providing ancillary services to the grid hosting capacity of additional intermittent RES generation.

References

[1] D. Milone, D. Curto, V. Franzitta, A. Guercio, M. Cirrincione, and A. Mohammadi, "An economic approach to size of a renewable energy mix in small islands," *Energies*, vol. 15, no. 6, 2022.

[2] M. L. Di Silvestre, F. Montana, E. Riva Sanseverino, G. Sciumè, and G. Zizzo, "An algorithm for renewable energy communities designing by maximizing shared energy," in *2023 AEIT International Annual Conference (AEIT)*, 2023, pp. 1–6.

[3] Basin Authority for the Sicilian Idrographic District, "Drought Report - June 2024 (Report Siccità - Giugno 2024, in Italian)," Sicily Region, Tech. Rep., 2024. [Online]. Available: https://www.regione.sicilia.it/sites/default/files/2024-07/0_Report_siccita_giugno_2024.pdf

[4] Quotidiano di Sicilia, "Newspaper article on Sicilian water crisis (in Italian)." [Online]. Available: https://qds.it/emergenza-siccita-sicilia-schifani-poteri-deroga-speciali-dichiarazioni/

[5] A. Cipollina, G. Micale, and L. Rizzuti, "A critical assessment of desalination operations in sicily," *Desalination*, vol. 182, no. 1, pp. 1–12, 2005, desalination and the Environment.

[6] GSE S.p.A., "Rapporto Statistico 2023 - Solare Fotovoltaico," GSE S.p.A., Tech. Rep., 2024. [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Solare%20Fotovoltaico%20-%20Rapporto%20Statistico%202023.pdf

[7] TERNA S.p.A., "Dati Statistici 2022 - Impianti di Generazione," TERNA S.p.A., Tech. Rep., 2024. [Online]. Available: https://download.terna.it/terna/3%20-%20IMPIANTI%20GENERAZIONE_8db99b7c8a48aab.pdf

[8] S. D. Carlo, A. Genna, F. Massaro, F. Montana, and E. Riva Sanseverino, "Optimizing renewable power management in transmission congestion. an energy hub model using hydrogen storage," in *2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2021, pp. 1–5.

[9] J. Zhang, M. Gu, and X. Chen, "Supercapacitors for renewable energy applications: A review," *Micro and Nano Engineering*, vol. 21, p. 100229, 2023.

[10] P. Cronk, J. Van de Ven, and K. Strohmaier, "Design optimization, construction, and testing of a hydraulic flywheel accumulator," *Journal of Energy Storage*, vol. 44, p. 103281, 2021.

[11] A. Irham, M. Roslan, K. P. Jern, M. Hannan, and T. I. Mahlia, "Hydrogen energy storage integrated grid: A bibliometric analysis for sustainable energy production," *International Journal of Hydrogen Energy*, vol. 63, pp. 1044–1087, 2024.

[12] M. Krichen, Y. Basheer, S. M. Qaisar, and A. Waqar, "A survey on energy storage: Techniques and challenges," *Energies*, vol. 16, no. 5, 2023.

[13] M. Crainz, D. Curto, V. Franzitta, S. Longo, F. Montana, R. Musca, E. Riva Sanseverino, and E. Telaretti, "Flexibility Services to Minimize the Electricity Production from Fossil Fuels. A Case Study in a Mediterranean Small Island," *Energies*, vol. 12, no. 18, 2019.

[14] GSE S.p.A., "Rapporto Statistico 2021 - Energia da Fonti Rinnovabili," GSE S.p.A., Tech. Rep., 2023. [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Rapporto%20Statistico%20GSE%20-%20FER%202021.pdf

[15] TERNA S.p.A., "Piano di Sviluppo 2023 - Stato del Sistema," TERNA S.p.A., Tech. Rep., 2023. [Online]. Available: https://download.terna.it/terna/Terna_Piano_Sviluppo_2023_Stato_Sistema_Elettrico_8db254887149b77.pdf