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RESEARCH ARTICLE

Energy Storage Technologies for Modern Power Systems: A Detailed Analysis of Functionalities, Potentials, and Impacts

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ABSTRACT Power systems are undergoing a significant transformation around the globe. Renewable energy sources (RES) are replacing their conventional counterparts, leading to a variable, unpredictable, and distributed energy supply mix. The predominant forms of RES, wind, and solar photovoltaic (PV) require inverter-based resources (IBRs) that lack inherent synchronous inertia desired for the grid and thereby warrant additional interventions for maintaining grid stability by organizing various contingency planning. Such scenarios become more pertinent in the wake of rapid decarbonization objectives adopted by different countries, stringent grid code compliance, and improved grid resilience milestones. Energy storage technologies can potentially address these concerns viably at different levels. This paper reviews different forms of storage technology available for grid application and classifies them on a series of merits relevant to a particular category. The varied maturity level of these solutions is discussed, depending on their adaptability and their notion towards pragmatic implementations. Some specific technologies that require particular mention are - hydrogen (H_2) storage with fuel cells (FC) as the reconversion medium, molten metal, and gravity batteries due to their highly scalable and siteable characteristics participating in load shifting; batteries and H_2 FC due to their high flexibility for peak shaving; and flywheels and supercapacitors for quick response applications, such as frequency regulation and voltage support. Various performance metrics are critically evaluated by comparing them on their usability scale, thus helping readers make a subjective judgment on a particular technology while being aware of the forthcoming limitations. Finally, the paper delves into some emerging trends that decide the selection of a particular technology based on life cycle assessment, economic viability, and commercial and environmental considerations that are presented under the given circumstances. The paper is believed to offer a broad overview of possible directions for the electric grid business, eventually emphasizing the need for more hybrid solutions with opportunities for short and long-term storage options.

INDEX TERMS Energy storage, compressed air, hydrogen fuel cells, frequency regulation, gravity battery, molten metal, li-ion, peak shaving, power systems, pumped hydro, renewable energy, sustainability, voltage support.

I. INTRODUCTION

Electricity plays a central theme in all walks of life in modern society. Because of its importance, issues related to the availability and cost of energy for electricity and its environmental impact are never far from the daily news. Currently, most energy worldwide is generated from fossil-based sources. The increasing trend in energy production and consumption, as well as visible negative impacts thereof, in the form of air quality, health, and environment has shifted the focus towards Renewable Energy Sources (RES) [1], [2], [3]. This trend is on the rise due to scientific, political, and philanthropic

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interests towards building a sustainable eco-system [4], [5] and so are the challenges that are associated with it [6].

The power system forms the essential backbone of the electric energy system that helps facilitate its production, transportation, and consumption. However, due to the inherent volatility of RES, energy production and consumption in a given time do not become sustainable. Management of the energy resources, therefore, requires a sophisticated strategy to reap the benefits of the installed base and also to be adaptive in using the mutual strengths of production and consumption. Storing the electricity seems to be a viable option to solve this conundrum.

Energy storage in different forms is necessary to support the energy system of the future to drive net-zero targets and deliver reliability and resilience, power quality (PQ), electrification of heat and transport, grid modernization, and coordination of markets. It takes part in relieving the power system from the intermittent production and consumption problem. By doing so, the energy storage technologies become relevant, when they participate in some key application areas such as load shifting, peak shaving, frequency regulation, etc. From an environmental perspective, it increases flexibility and unlocks solutions to the erratic nature of variable renewable energy (VRE) production curtailment [7], increasing the system's total efficiency. From an economic perspective, storage can support deferring of transmission and distribution (T&D) investments, provide better value for existing assets, and reduce costs through energy management.

This paper aims to offer a broad overview of various competing technologies that are evolving in this space, existing in different forms (electrical, mechanical, thermal, chemical, etc.), and how exactly they try to assist the specific application needs of the utility sector by satisfying a bunch of key performance criteria. The paper also tends to diverge at times to mention other sector couplings, where the storage technologies could be prevalent, and this is purely because of their mutual inclusiveness.

There have been previous attempts to consolidate different storage techniques for grid applications. Gustavsson [8] compared different storage technology without mentioning their usability for a given utility application, thus rendering this analysis rather incomplete. Luo et. al. aggregated current developments of storage techniques for power system applications that dates back to 2015 [9]. It lacks exploration of the existing techniques in more demanding power quality applications that becomes relevant now, due to the changing power system dynamics mentioned above. In addition, a lot of emerging techniques that came into vogue in recent times and bear the potential to become mainstream, and hence forms the basis of the current manuscript. A semantic comparison of conventional versus modern technology is offered here, alongside the numerical characteristic and notable usage. Besides, the manuscript offers a range of characteristics that is useful for different stakeholders, addressing power quality improvement measures, as well as energy trading objectives. A technical assessment is also offered for the commercial viability of a given technology based on its maturity level. These elements differentiate the manuscript from its peers.

The remaining sections of this paper are organized in the following ways. The next section, Section II highlights the changing dynamics in a power system, discussing different actors involved in the process, including the characteristics of the VRE sources and the challenges, offered thereof. Section III elaborates on various applications catered by energy storage technology, primarily divided into two larger buckets, namely- energy management and ancillary services. It also discusses in detail different performance indicators employed in defining a particular technology. Section IV forms the heart of the paper, which offers a broad view of different technologies of interest for grid storage applications, classified in one of the four physics-based domains. Each technology is explained based on its functionality, impacts, advantages, and disadvantages. A series of numerical characteristics of concerned performance indicators are also offered based on the accumulated literature. Representative examples of some of those technologies are also offered, as deemed appropriate, for the sake of completeness. An attempt has been made to compare different technology based on several performance traits in Section V. The technologies are mapped in appropriate baskets of application-specific requirements, based on their relevance and usability. Section VI sheds light on important takeaways, emerging trends and conclusions obtained from this technology review.

II. CHANGING DYNAMICS IN A MODERN POWER SYSTEM

The power system is undergoing a significant transformation. Whereas in the recent past and present, it was mainly fossil energy sources that fed energy into the power grids, the share of RES is growing, especially VRE such as wind and solar [10]. This condition is leading to a massive change in the behavior of power grids and is creating scientific and engineering challenges. In the process, there are improved electrification opportunities and overall gains in energy efficiency and power security. There are also lateral ambitions of improvements in PQ indices, in terms of grid stability, grid reliability, and grid resilience [11], by addressing environmental impacts through increased use of RES, and economic improvements by cutting down on natural resource dependencies [12].

As at the beginning of energy consumption [13], RES will play a more crucial role in tomorrow's power system. More investors and companies account to a greater extent for long-term climate risks and opportunities. Technological advancements and a societal push toward sustainability [6] enable a development towards RES with everlasting structural changes to energy supply, demand, and prices to reduce greenhouse gas emissions through various forms of decarbonization. After regulation- and subvention-dependencies for growth in the sector, RES have become a powerful and cost-effective source of electricity. Solar PV and wind energy costs have fallen so drastically that in some regions

TABLE 1. Characteristics of VRE sources.

Characteristic	*Description*
Variability	Mismatch between prediction and actual production, as its amount may spread and VRE behavior can vary rapidly - results in increased spot prices and penalties
Uncertainty	Generation remains challenging to predict perfectly, despite increasingly accurate weather-forecasting tools - can lead to huge unbalanced load demand
Distributed	Small-scale distributed generations are largely grid connected - volatility leads to increased supply fluctuations
Inverter-based	Inverters are an integral part of PV and wind generation - harmonics and other PQ pollutions by them is inevitable
Zero variable cost	Capital costs are unpredictable due to global inflation, and geo-political situations - but variable costs of production remain almost zero

TABLE 2. Challenges resulting from increased VRE generation.

Challenge (Time to act)	*Description*
Resource adequacy (years to hours)	Reliable system operation expects an electricity demand and supply match, with the availability of a sufficient portfolio of energy sources
Network adequacy (years to hours)	Grid capacity adequacy is a must to ensure flawless transportation of power between generation and transmission corridors
Frequency stability (minutes to seconds)	The system frequency must be maintained within acceptable limits by near-instant balancing of supply and demand
Voltage stability (seconds to milliseconds)	The system operators must maintain voltage waveform and phase angle, following disturbances in the entire power spectrum

wind power has become cheaper than conventional energy sources [6]. This has been possible, thanks to massive research in all the supporting areas involving insulated-gate bipolar transistor- (IGBT) and integrated gate-commutated thyristor- (IGCT) based converter technology, the introduction of high voltage (HV) and ultra-high voltage direct current (DC) and alternating current (AC) technology, improvement in underground cables aiding transmission above 600 kV and higher, relevant improvements in cooling technology, digitally enabled control, protection and monitoring paradigm, etc. [14]. Costs of technology are continuing to fall and as wind and solar PV are becoming mainstream, the renewable energy sector will keep growing and solidify as a substantial investment opportunity [1].

A. CHARACTERISTICS OF A MODERN POWER SYSTEM

This shift to RES and especially VRE brings different challenges to the power system [15] as they have significantly different characteristics compared to conventional energy sources. VRE generation depends on the availability of the said resources, making it highly unpredictable against a given time, despite the best forecast abilities available in recent times. This takes a huge toll on the spot pricing and associated penalties, in the event of not being able to produce that promised energy from an energy trading standpoint. This scenario might as well work to the benefit of the VRE players when demand is favorable to surplus production, which does not lead to a curtailment. VRE is also more distributed, as against centralized conventional sources. It also relies on IBRs for integrating the power into mainstream AC. Table 1 explains the definition of a particular characteristic and its potential impacts, concerning VRE sources.

B. CHALLENGES OF A MODERN POWER SYSTEM

Besides the characteristics, VRE are also fraught with challenges that need special mention. Table 2 explains the challenges brought by VRE sources and time frame at which the challenge can be resolved.

- Resource adequacy
  The network planning currently suffers from resource adequacy in form of higher intraday variability, seasonal imbalances, and VRE droughts. The intraday variability increases due to higher peaks of energy supply and deeper valleys of low supply. When the sun sets in the daily cycle, the energy supply ramp is extremely steep. In addition to those daily imbalances, the demand for electricity peaks in the winter, while the solar energy supply is higher in the summer resulting in seasonal imbalances as well. Weather events also contribute to sudden shifts from sunny to cloudy or wind storms causing imbalances in renewable generation, bringing in additional ripples, including shutting down of the wind farms, as a result of ultra-high wind speeds, beyond the cut-out limit. Resulting power droughts also challenge power system operators to find sufficient energy generation sources [16]. The variability can also be caused due to PQ problems, such as voltage surges, and is not necessarily a cause of VRE volatilities. Additionally, network planning also impacts the long-term prospects when the storage options are constrained by the arbitrage between available traditional reinforcement and fresh investments for storage. Therefore, depending on the capacity of the ESS the resource planning can be extended for years in advance in order to accommodate the volatility generated by weather as well as governing principles and market dynamics that have a fair contribution in this space.
- Network adequacy
  Large conventional power plants generate the majority of electrical energy, and networks are designed to transport it to decentralized consumption areas. Network adequacy becomes a challenge in modern grids as distributed generations from RES continue to overwhelm the traditional grid infrastructure by changing the conventional power flow from upstream to downstream and sometimes giving rise to reverse power flow into upstream scenarios. Network congestion and capacity allocation thus become more familiar concerns for T&D system operators, where the infrastructure fails to cope with the unprecedented RES integration into the grid [16], [17].
- Frequency stability
  Traditionally the controllable operating reserve was supplied by the conventional power plants, those were

available on demand, based on the source they were operating on. With the gradual integration of solar and nuclear-based RES towards the mainstream and phasing out of fossil or nuclear-based sources at the same time, the controllability of the operating reserve tends to diminish. This results in the requirement of more operating reserves to compensate for system imbalances. The active spinning reserve also disappears due to a lack of rotating mass in the system, those are not replenished by the IBR-based devices, thereby causing system imbalance and frequency stability issues.

- Voltage stability
  Conventional and dispatchable generation include synchronously connected machines, which can inject or absorb reactive power to improve system strength. These capabilities diminish when using RES that are not synchronously connected to the power system. Wind and solar generators are coupled to the network using inverters with less or no reactive power provision capabilities resulting in voltage instability [16].

These challenges mentioned above need to be addressed in modern power grids by various means. Offering a storage solution for the electricity to be able to use it during the time of its need, for the designated period of interest, appears to be the most favorable solution to bridge the gap, primarily arising due to the intermittency. This can to a great extent improve resource adequacy, as variability, imbalances, and droughts can be corrected by providing compensation from stored energy. Storing energy does address the network adequacy challenge as storage systems can charge when networks are congested and discharge to provide power to residual loads. Stored reserves can also supply power to engage in frequency and voltage stability. The following sections explain the energy storage applications in a more detailed way.

III. ROLE OF ENERGY STORAGE BASED ON SPECIFIC APPLICATION NEEDS

Different forms of energy storage can help build an energy storage system (ESS) that can be integrated into the modern power system to serve the intermittent energy demands, requested by the grid. The utilization of ESS can be majorly divided into two application areas, viz. *Energy Management* and *Ancillary Services*. Energy management relates to enabling a secure and reliable supply of energy. The aim is to make the grid reliable, flexible, cost-effective, safe, and stable, and enable sector coupling with no negative impacts. Ancillary service is about facilitating and supporting continuous electricity flow to meet the demand in real-time and in a qualitative way [18]. This orchestrates the improvement of PQ indices elaborated in various standards [11]. Due to the changing power system mentioned in the previous section, the integration of RES is creating new challenges, both for energy management and PQ ancillary services. The integration of RES aims to maximize the usage of renewable resources while minimizing negative impacts caused by them, especially on power security and quality.

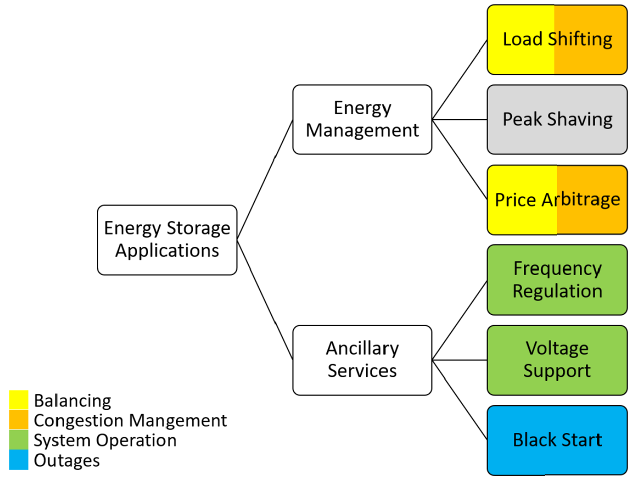

FIGURE 1. Classification of energy storage applications and assignment to ENTSO-E grid services.

The paper covers six ESS applications within the two support areas mentioned above. Those applications are listed in Figure 1, as contextualized by European Network of Transmission System Operators for electricity (ENTSO-E). ENTSO-E operates and offers services on the pan-European power grid market. From yellow to blue, energy storage applications can be classified as balancing, congestion management, system operation, and outage services. Different roles played by these services and their potential impact on the functioning of the grid are elaborated further below.

A. ENERGY MANAGEMENT

Integrating higher shares of RES and especially VRE, such as wind and solar PV jeopardizes the stability of the power systems. The leading cause is that the power ratio between the supply and demand may not be balanced by the generation plants. Energy management systems are utilized to secure the balance between supply and demand efficiently and to reduce the effects of demand peak loads resulting in energy shortages or rising prices. An excess/shortage in the increasingly intermittent generation or power consumption may perturb the network and create severe problems, resulting in initiation of ancillary services due to frequency or voltage drops (or rises), and in severe conditions, blackouts.

Without energy storage, energy management can be divided into two folds. The first one is in the electricity supply, such as in conventional controllable power plants, the possibility for electric utilities to turn on or off generators to follow the fluctuation of the load demand. The second acting point is demand-side management and includes actions on the consumer side. In demand-side management, the consumers affect their energy consumption in order to meet the available power. Energy storage can, in both cases, enable profitability as it can lead to higher controllability of generation and more balanced external electricity consumption from the power grid, in cases of high consumption peaks. The main goal of using storage in energy management is to reduce the cost of operation and consumption, reduce energy losses and increase the reliability of the network [19]. In the following subsections, different applications of energy management are presented.

1) LOAD SHIFTING

Electricity is defined as a perishable product [20], which means that in its original state, it has to be consumed at the exact time of production. While reactive loads or rotational inertia in the system store power for short duration, larger capacities of energy cannot be used in a later time frame. This introduces a problem in power systems where the share of intermittent energy sources increases and excess energy peaks take part more often with higher power ratings and longer duration [21]. Curtailment will be more common in the coming days, according to global predictions. It is highly unsolicited to not deliver excess energy because there is no price for it or negative pricing. This situation can change by being able to harvest that energy in another form. ESS offer the ability to temporarily shift excess energy and match the provided energy with the load to reduce or impede energy deficits and curtail usable energy [22], even if the round trip efficiency for such a method is relatively poor. This forms the philosophy of many storage technologies discussed in this paper, where they are linked to surplus RES productions.

The most common advantages of matching generation and load with energy storage are [21] the possibility of a more efficient implementation of RES with possibly no curtailment of usable excess energy, cost reductions (as described in subsections III-A2 and III-A3), improvements in PQ, and an improved utility usage (maintenance of power facilities can be postponed). While the storage for hours to days enables balancing available excess energy with today's share of RES, larger amounts of excess energy, as predicted for higher shares of RES may need to be charged for a longer period, even resulting in seasonal energy storage. The duration of energy storage has been growing with the increasing penetration of VRE [6], [23], albeit without any definite timeline attached to it and the context could be quite geographically specific.

While integrating RES is a challenge to the complete power system, it is a desirable goal, especially in microgrids. Completely islanded microgrid systems present significant opportunities, especially in an economical way [24], for load shifting through energy storage. Islands are usually very dependent on expensive fossil fuel imports, which must be transported to the island. As a result, the utilization of renewables by exploiting the island's RES potential can assist the load-demand supply, reducing its fossil fuel dependency and pollutant emissions [24]. Compared to connected power grids, supply fluctuations through VRE or the consumed load can lead to larger consequences towards PQ [25]. Without large energy storage capacities, independence from fossil fuels has significant risks in microgrids.

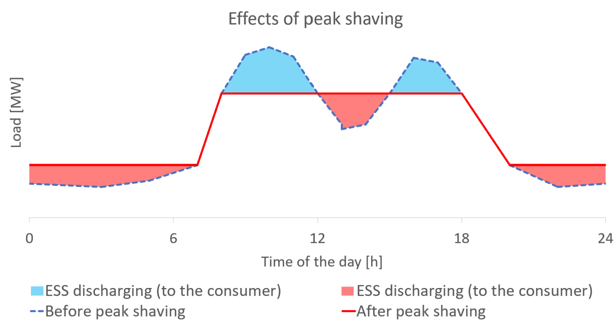

FIGURE 2. Load redistribution following peak shaving.

2) PEAK SHAVING

Industrial electricity consumers usually have an uneven load profile during the day, resulting in load peaks [26], as seen through the blue corrugated line in Figure 2.

The power system needs to be dimensioned for that peak load, while it is under-utilized during other parts of the day. The extra cost of keeping up with the peak demand is passed to the consumers depending on the maximum peak load. By utilizing an ESS, peak loads can be reduced and hence the cost for the consumer. The ESS is controlled to charge up during off-peak hours (charged energy in the red areas of the figure) and discharge during peak hours (blue areas) [27]. Especially industrial consumers with short peaks can profit from an ESS for peak shaving. ESS systems for peak shaving are said to be more versatile in their use than load shedding, the alternative where peak load is also reduced but by negatively affecting the load as it must be reduced or completely shut down [20]. Peak shaving reduces the energy price as an upgraded grid which would be underutilized for a large part of the time, is not necessary. Other than industrial consumers, peak shaving can also help TSOs decongest the transmission grid, whereas appropriate long-term planning can help better manage the demand response.

3) PRICE ARBITRAGE

Arbitrage is an investment strategy where the investor buys and sells the same asset in different markets or timeframes to profit from the difference in prices and thus generate profit. The highly volatile energy prices make arbitrage extremely profitable with large volumes of energy. Energy storage serves a potentially key role by eliminating high price periods. In times of high energy prices, energy market participants can profit from revenues selling energy that was bought in times of low prices [28]. To profit from arbitrage, the price difference needs to be higher than the losses from energy efficiency in the storing and releasing process. Therefore, another factor for fitting ESS is the storage capacity [28]. A study showed that nearly 60 % of utility-scale energy storage was used to profit from energy price arbitrage in 2021 [29].

B. ANCILLARY SERVICES

Ancillary services are defined as the series of actions separated from the energy production related to a power system's security and reliability [30]. In this paper, ancillary services to ensure PQ are reviewed. The transmission and distribution system operators (TSOs and DSOs) must ensure the required level of quality and safety to enable integrity, reliability, and resilience of the power system, take preventive measures for contingency control, and perform many other duties. The operators should be able to adjust the frequency and voltage of the system within certain limits to avoid overloads on the T&D system, and, if necessary, reestablish the system after an instability or a blackout [9]. Energy consumption patterns have changed significantly recently, with the addition of unsynchronised loads at multiple feed-in points and voltage levels, such as electric vehicles (eV) charging or solar household use. Adverse effects are load imbalances, low power factor, rapid voltage fluctuations, and harmonic pollution leading to capital losses. Furthermore, these phenomena might cause shortened equipment lifetimes, disconnection, failure to reconnect renewable energy to the grid, and numerous unplanned service interruptions [11]. This section also reports the need for ancillary services, in the form of black start capabilities, that are aimed at bringing back power for an islanded or microgrid scenario, when the grid supply is not present. While this functionality was predominantly offered by dedicated captive generations, such as diesel generators, batteries are invading this space, offering relatively lesser capital investment or acting in coordination with captive generation. Likewise, this section also discusses more demanding applications, where the criticality of the power supply is addressed by an uninterrupted power supply, thus reducing the response time to ms.

1) FREQUENCY REGULATION

Maintaining constant frequency for the electric power grid is important for the system's reliability, stability, and resilience [31]. The frequency is dependent on the balance between energy generation and energy consumption: When the energy demand weighs more than the supply, the frequency drops and vice versa. An imbalance can cause severe electrical damage to the generators and electrical equipment connected to the grid. The slower the system returns to the nominal frequency, the more likely this is to happen [32]. If the frequency can not be maintained within a given limit by increasing the generating capacity (in renewable-based grids), in response to an increased load, the system might disconnect some of the loads using low frequency demand disconnection (LFDD) principles. A frequency deviation can cause rotating machines on the grid to disconnect as a safety precaution, increasing the likelihood of partial or total blackouts [32].

In the case of demand-supply imbalances, there is a systematic rate of change of frequency (RoCoF) involved. The lowest frequency (frequency nadir), is dependent on the RoCoF as well in case of a restoration of the frequency. The RoCoF is impacted by following factors [33]:

- Size of contingency
- System inertia
- Speed of response
- Magnitude of response.

Inertia is the tendency of an object in motion to remain in motion (e.g., Newton's cradle). In the power system, inertia is the kinetic energy stored in the rotating masses of generators and motors synchronously connected to the power system divided by the rated apparent power (S) of those machines [34]. The inertia constant (H) describes the inertia of an individual turbine-generator and can be calculated in the following equation.

$$H_T = \frac{1}{2}\frac{I\omega_T^2}{S_T} \tag{1}$$

with I as the moment of inertia of the turbine-generator, ω_T^2 as the rated mechanical angular velocity of the rotor, and S_T as the rated apparent power of the single turbine. Inertia in power systems has been traditionally determined by considering all the rotating masses directly and synchronously connected to the grid.

For synchronously rotating generators, the inertial contribution varies for different power generation types depending on the moment of the rotating masses. The frequency of the voltage needs to stay at a steady level, and the RoCoF is heavily affected by the integration of the IBRs wind and solar PV resulting in lower inertia. Thus, a controlled regulation of the system's frequency is required. The variation in frequency is usually within a certain acceptable range for the secure operation of the electrical system and the safe and reliable operation of connected devices. Depending on the state of the frequency stability, actions are required [35].

According to grid codes, system operators are responsible for keeping the frequency in certain ranges and only having varying frequency for a certain maximum time [36]. In Germany, a frequency between 49 and 50.5 Hz is the continuous operational level. A frequency of 48.5 to 49 Hz must happen maximally for 30 min, between 48 and 48.5 Hz for 20 minutes, between 47.5 and 48 Hz for 10 minutes, and disconnect within 10 seconds if the frequency is between 46.5 and 47.5 Hz [36]. A drop in frequency typically looks as visible in Figure 3. The frequency control is divided into the passive element inertia given by the system and three active control levels: primary, secondary, and tertiary frequency control [31]. Each control level has specific features and purposes.

The *primary control* action acts to arrest the frequency decline and restabilize it. In case the frequency is not returned to its nominal value, the response time needs to be as fast as possible, typically under 15 seconds. Within 30 seconds, *the secondary control* response kicks off. The system frequency is returned to a non-critical value, typically over minutes. The secondary control is usually performed automatically by all

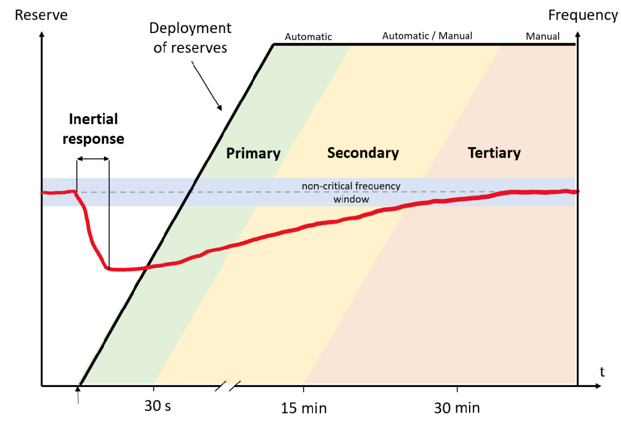

FIGURE 3. Illustration about the deployment of different types of reserves to arrest unwanted frequency excursions [31].

the generators that participate in this regulation through a specific "set-point" sent by a central controller. The secondary control does also restore the power generators for the primary frequency control. The response time needs to be fast, and the duration is longer than that in the primary frequency control. To restore the control after the completion of secondary control, *the tertiary control* (or replacement reserve) is employed as the last level of frequency control. This control level may not be automatic and is executed upon request from the grid operator [37]. Compared to secondary control, the response time is less important, while the operational duration can be much longer, indicated by the restoration of the cause for the decline of frequency.

The frequency control for the primary and secondary response is usually achieved by having energy reserves through ESS, while the tertiary response could be supported by dedicated generation sources. In general, there is a separation of spinning reserves and non-spinning reserves of energy and supplemental reserves. Spinning reserves are always held in reserve (not used for arbitrage for example) and are used only in case of loss of generation on the grid. Spinning reserve is a generation capacity that is online and in sync with the grid frequency but unloaded, and that can respond within a short time to compensate for generation or transmission outages. Spinning reserves are the first type of energy used when shortfalls occur [30], [38]. Non-spinning reserves can also act as reserves to support the grid but are not continuously online. Thus, the response time has disadvantages compared to the spinning reserves. Supplemental reserves have a higher response time and longer duration than the spinning and non-spinning reserves and replace and restore them [30].

2) VOLTAGE SUPPORT

Voltage support is the power injected into the electrical distribution grid to maintain voltages within the acceptable range at every stage between each end of power line. Unlike system frequency, which is consistent across the network, voltages experienced at points across the system depend on the real and reactive power characteristics of the load and a low power factor results in low voltages at the load points [39]. While frequency regulation involves feeding active power to the grid, the voltage support or Volt Ampere reactive (VAR) control provides reactive power to the system. Most grid-connected loads, such as motors, transformers, and cables, are inductive in nature and cause a reactive component of current within distribution systems supplying them as well as a resistive current flow. The energy to supply this reactive current has to be supplied by the generator, which must divert some of its available energy to satisfy this demand. Consequentially, the voltage falls, reducing the voltage across the network and thus the power available to the load. This means that the voltage at any point in the network will be less than the voltage available to a purely resistive load and will depend on the magnitude of the reactive power carried by the transmission line.

Because the energy within the distribution grid supplies many different loads and the network operator has no direct control over their number or nature, the voltage can vary widely depending on the use and reactance of the loads which happen to be connected. The voltage instability problem becomes more severe in future power grids with more VRE sources and the necessity to absorb the random power surges generated by wind turbines which could also cause the line voltage to swing wildly. As a result, the following voltage stability problems may be encountered [39]:

- Voltage Sags or Dips and Brownouts: The voltage is lower than the nominal voltage for short periods because of higher demand or network faults.
- Voltage Swells: Increased line voltage is caused by switching off of large loads, or by power surges from wind turbines.
- Transients (Fast Disturbances): Starting or stopping high-power equipment causes rapid changes and spikes in the line voltage.
- Harmonics: Voltages at multiples of the supply frequency are caused by high power switching systems and electronic loads.
- Flicker: There are random or repetitive variations in the voltage caused by intermittent high-consumption processes such as electric arc furnaces and welding equipment.

There are acceptable tolerance limits for voltage quality, failing which both the producers and consumers are liable to penalties [11]. Nearly all electric devices require a combination of real power and reactive power. A remote generation plant supplies real power but reactive power can be supplied either by a remote generator or a local reactive voltage supply. Looking at power factor compensation and voltage control in a different way, it is recognized that reactive loads need real power to do the work and reactive power to set up necessary magnetic or electric fields to enable this work to take place. Instead of the generator providing the total apparent power, the generator can be arranged to provide real power, operating in its most efficient mode with minimum losses through the generation and transmission network, while the reactive power can be inserted by an additional source at a point closer to the load. Voltage support is mainly applied to the T&D lines. The fluctuations need to be regulated fast in order to maintain the real and reactive power which means the energy storage sends out pulses of high power. However, since the pulses only occur for a few seconds, the capacity needed is not that large.

3) BLACK START CAPABILITY

Blackouts are highly unlikely but impactful non-momentary power outages affecting larger areas and causing electrical devices to turn off. Momentary outages of less than 60 seconds are called power flickers [40], and thus are excluded from blackout definitions. Power plants of the future with a larger share of VRE would be impacted by unpredictable extreme weather conditions and run the risk of blackout scenarios.

A black start is the process of restoring energy in an electrical device, station, or part of a power plant following a blackout (momentary outages are excluded). Black start service consists of generating units to start without an external electrical supply. Black start service is necessary to help ensure the quick and reliable restoration of the grid following a blackout. The capability of black start has the characteristic to start from a shutdown at any cost of its production units and integrate into the system to support a portion of the system and be coordinated to the system [41].

Today, the most common power source for black start operation is auxiliary gas turbines or diesel engines. There has not been much development to upgrade auxiliary generators because these generators have a high technical maturity. The investments and maintenance of these units are customary more for regulatory reasons. These generators, however, have a slow response time, and may also fail to provide sufficient power to the main load units, causing voltage and frequency fluctuations and risking a black start. Diesel engines and gas turbines are also not ultimately cost-effective as they are solely used for black start and could not provide other grid services, viz. frequency regulation and load shifting. These services become important ingredients to black start operations in the wake of emerging critical loads such as data centers, where stringent PQ dynamics are expected. Despite their irregular use, these existing auxiliary generators are not both economically and environmentally sustainable. Therefore, replacing the existing auxiliary generators with renewable energy generators, or ESS, is prevailing [42].

An uninterruptible power supply (UPS) is an electrical device providing emergency power to a load when the power supply fails. A UPS differs from solely for black start used auxiliary or emergency power systems or standby generators by providing near-instantaneous protection from momentary power interruptions, by supplying energy stored in fast response ESS, such as batteries, supercapacitors, or flywheels for a duration of few minutes or less [43]. A UPS enables the supply of power for frequency regulation and voltage support, besides its black start duties. The typically short discharge duration of previously named storage technologies weakens their position against longer blackouts. Subsequent backup could still be augmented with slow-responding power sources, depending on the budget of the operating stations.

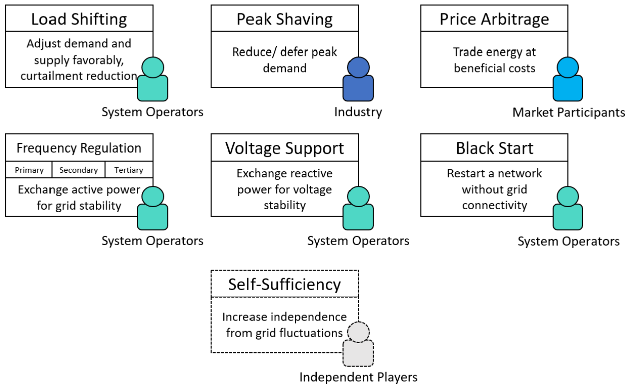

FIGURE 4. Goals and stakeholders of different ESS applications.

C. CHARACTERISTIC INDICATORS OF ENERGY STORAGE SYSTEMS

As presented in the previous sections, in order to cater to different application areas, contingency planning is needed for maintaining the continuity, quality, and stability of the power supply. As will be seen in the remainder of the paper, the ESS has the ability to fill in this space, quite effectively, though it comes with its own set of challenges and limitations. To set some universal benchmark and compare different available technologies, it becomes imperative to define certain characteristics which will be representative of what to expect from the storage solutions. The next section elaborates on this.

Six energy storage applications are presented in the previous sections, Figure 4 presents the goal of each of those applications and the main stakeholder. In addition to the six above-mentioned stakeholders, there is an increasing presence of players, both on domestic and industrial scales, who tend to become self-sufficient by employing small to large-scale storage solutions of their own, thus inhibiting the grid fluctuations by their own means. When this certainly alleviates the pressure on the grid operators, such participation is not actively meant for solving the power quality problems, nor contribute to the grid demand of load shifting, peak shavings, etc. This, instead largely helps address power interruptions of varying time scales. Nevertheless, the use of innovative technology to bring this stakeholder participation into the larger context of grid stability is an area that needs to be explored.

Several pieces of literature attempted cross-technology comparisons of different ESS [8], [9], [12], [44], [45], and [46]. Table 3 enumerates some vital characteristics which are relevant for this discussion along with their units of measurement.

TABLE 3. **Characteristics of energy storage systems.**

Key characteristic	*Unit of measure*
Rated energy capacity & power	megawatt hours & megawatts
Storage duration	minutes, hours, days, years
Charge & discharge duration	minutes, hours, days
Response time	milliseconds, seconds, minutes, hours
Round-trip efficiency	%
Discharge efficiency	%
Daily self-discharge	none, small, medium, large
Lifetime	years
Cycles	total numbers or per day/year
Energy & power density	watthours & watts per liter (= 0.001 cubic meter)
Specific energy & power	watthours & watts per ton
Siteability	good, medium, limited
Energy and power capital cost	Dollars per megawatt hour & megawatt
Operating and maintenance cost	Dollars per megawatt hour & megawatt
Environmental Impact	small, medium, large
Maturity level	developing, demonstration, proof of concept, commercialized, mature

TABLE 4. **Desired ESS Characteristics for different applications.**

Application	*Response Time*	*Power Rating (MW)*	*Discharge Duration*	*Cycles per Year*
Load Shifting	10 - 30 min	1 - 2,000	Minutes - hours	>3,000
Peak Shaving	10 - 30 min	0.1 - 10	30 - 240 min	250 - 500
Price Arbitrage	Minutes - hours	50 - 2,000	Hours	300 - 400
Primary Frequency Control	<10 s	1 - 2,000	<15 min	>10,000
Secondary Frequency Control	10 - 30 s	1 - 2,000	<120 min	<primary frequency control
Tertiary Frequency Control	10 - 30 min	1 - 2,000	Hours	<secondary frequency control
Voltage Support	Milliseconds	0.5 - 50 (MVAr)	Seconds - minutes	>15,000
Black Start	<10 s	0.1 - 400	Minutes - hours	<1

Not all the characteristics are necessarily important within a given context. In the following section, the necessary characteristics will be presented only for the presented applications. For the presented applications of energy storage, the characteristics of response time, power rating, discharge duration, and cycles are relevant. The required rated energy capacity of the applied ESS needs to fit into those requirements, efficiencies, lifetimes and costs do play important roles in the profitability of the storage. The siteability of the ESS can limit its usability for the given applications. Energy storage applications require the following characteristics from the ESS as seen in Table 4:

The data have been collected from [12] (load shifting, price arbitrage, voltage support, black start capability), [30] (load shifting), [26] (peak shaving), [39] (price arbitrage, voltage support, black start capability), and [47] and [48] (frequency regulation).

The six presented energy storage applications load shifting, peak shaving, price arbitrage, frequency regulation, voltage support, and black start need to be addressed more frequently and profoundly in modern RES-based power systems. They have different requirements. Energy management applications have a slower response time but, generally, have a higher discharge duration and fewer cycles compared to ancillary services. Ancillary services have a quick response time, a shorter discharge duration, and much more frequent cycles than other applications. Black start does represent an exception, as blackouts are highly unlikely. The following section elaborates different ESS types along with their proposed application areas.

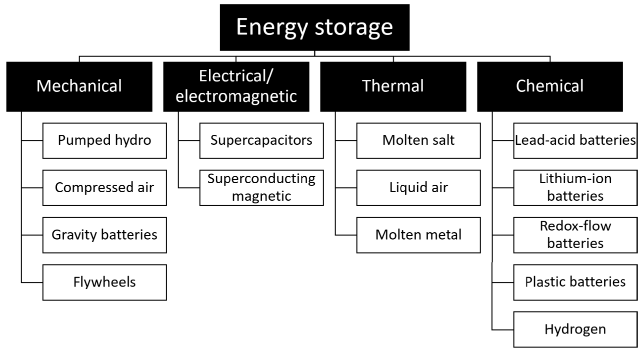

FIGURE 5. **Classification of ESS based on the first principles.**

IV. DIFFERENT ENERGY STORAGE SYSTEMS

Energy storage systems can be classified into different forms. A suitable way of structuring the different ESS is dividing the systems and technologies based on their physical attributes as highlighted in Figure 5. While there are six primary forms of energy, transforming electrical energy into any form of energy as a storage medium and converting the energy back to electrical energy has been mostly executed in mechanical, electrical and electromagnetic, thermal, and chemical ways. Further subordinated divisions are possible to derive, namely-potential and kinetic beneath mechanical energy storage, sensible, latent, and thermo-chemical as part of thermal energy storage, and batteries and hydrogen under electro-chemical energy storage.

Pumped hydro storage (PHS), compressed air (CAES), and gravity batteries use mechanical potential energy, flywheels kinetic energy. Supercapacitors and superconducting magnetic energy storage (SMES) include an electrical or electromagnetic form of energy. An example of sensible heat storage is molten salt. Molten metal and liquid air energy storage (LAES) are forms of latent thermal energy storage systems. Lead-acid, Lithium-ion (Li-ion), redox-flow, and plastic batteries are electro-chemical batteries, while hydrogen fuel cells (H_2 FC) use the chemical process of electrolysis and a galvanic cell.

Following subsections dive into those technologies. However, the usability of different ESS in a specific usefulness context depends on the location (availability of that technology in a particular site due to physical, metaphorical, scientific, or political reasons), scalability of the technology (from

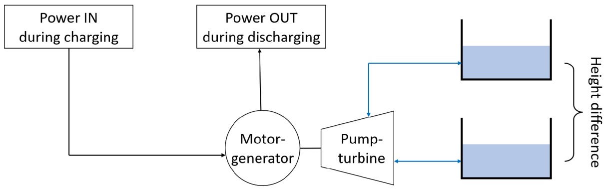

FIGURE 6. A schematic illustration of a PHS system.

TABLE 5. Characteristics of PHS system.

Technology			
Technology Pumped Hydro	*Power Rating* 100 - 5,000 MW [54]	*Response Time* Seconds [55]	*Discharge Duration* Hours - days [56]
	Energy Capacity >100,000 MWh [55]	*Cycles* >100,000 [54]	*Power Density* 0.5 - 1.5 W/l [56]
	Energy Density 0.5 - 1.5 Wh/l [56]	*Lifetime* 40 - 60 years [56]	*Round-trip Efficiency* 70 - 85 % [54]
	Daily Discharge Very small [54]	*Power Cost* 2,000 - 4,300 $/kW [9]	*Energy Cost* 5 - 100 $/kWh [9]
	Siteability Limited [54]	*Environmental Impact* Large [54]	*Maturity* Mature [54]

proto-type, proof-of-concept level to full-scale deployments), the economy of scale (a technology could be brilliant but not competitive to its peers for the metrics of interest from investors as well as users), etc.. Some additional emerging technologies are also presented in brief, in the following subsections, those are not listed in Figure 5.

A. MECHANICAL ENERGY STORAGE

Mechanical energy storage is a way of storing energy involving the mechanical form of energy. Mechanical energy can be stored as either potential or kinetic energy. In a system without friction, the mechanical energy is given by the equation

$$\triangle E_{Mech.} = \triangle E_{Pot.} + \triangle E_{Kin.} = mG\triangle h + \frac{1}{2}mv^2, \quad (2)$$

where m, G, h, and v are the mass, gravitational constant, height available for work, and the pendulum's velocity, respectively [49]. Mechanical energy storage systems (MESS) convert electrical energy into mechanical energy and store the energy as potential (e.g., PHS, CAES, and gravitational batteries) or kinetic energy (e.g., flywheels). To convert energy between electrical and mechanical energy, an electric motor that acts as an electric generator when discharging the stored energy [49] is used in combination with compressors or turbines, and other machinery.

1) PUMPED HYDRO STORAGE

PHS systems have been the most commonly used energy storage systems for a long time. They amount to 95 % of total stored electrical energy worldwide, which is 8.5 PWh of energy and close to 169 GW of power [50], [51]. PHS is the most mature ESS available [52].

a: FUNCTIONALITY

The functionality of a PHS system is based on electrical energy being transformed to gravitational energy of water, which can be used to transform electrical energy back when needed. Therefore, water can be stored in an upper reservoir which is interconnected to a lower reservoir allowing it to flow through a turbine connected to a generator into the lower reservoir to convert potential energy into electrical energy, as visualized in Figure 6. To convert electrical energy into potential energy again, a pump connected to a motor raises the water from the lower to the upper reservoir.

The ideal potential energy which can be generated can be calculated with

$$\triangle E_{Pot.} = mg\triangle h = v\rho g\triangle h, \quad (3)$$

where v and ρ are the volume of stored water in the upper reservoir and the density of water. To get the real potential energy of a PHS system, the efficiency η_{valve} of turbine, and motor-generator needs to be multiplied by the ideal potential energy.

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

PHS systems have the highest rated energy capacity of all ESS with a high power rating [53]. PHS stations have a long lifetime and a medium efficiency of 70 to 85 % [54] with a response time of seconds [55]. The operation and maintenance costs are low and allow a comparatively low cost for energy and power. The technology is the most mature being the first central energy storage station built in 1929 [56]. Thus, its capital cost is not expected to change substantially in the future [57]. PHS's construction cost and time are very site specific but high compared to other ESS. A disadvantage of PHS systems is the limitation of specific geographic properties requiring a height difference between the two reservoirs including dams that have negative environmental impacts, especially during construction but also while in use [58] and water availability resulting in long transmission distances [59] between energy storage station and consumer. PHS systems are only suitable for large scale. Different numeric characteristics of PHS has been consolidated in Table 5, including the relevant references they are picked from. Likewise, the subjective advantages and disadvantages have also been collected in Table 6.

The power rating shows at which full power the system can operate. The response time indicates the time it takes for a system to provide energy at its full rated power. The discharge duration is how long the ESS can typically fully discharge, and the energy capacity is the total dischargeable energy. Cycles and lifetime are indicators of how long the ESS can be used, including little maintenance. The power and energy density are parameters that describe how much power and energy can be stored per volume. The round-trip efficiency indicates the percentage of electricity put into storage and later retrieved. The daily discharge is the amount of energy lost within a day without discharging the system and, thus,

TABLE 6. Advantages and disadvantages of PHS system.

Advantages	*Disadvantages*
Large energy capacity [53]	Limitation to geographic properties [58]
High power rating [53]	Most potential sites already used [58]
Long lifetime [56]	Environmental impacts [58]
Low self-discharge [54]	High capital cost [51]
Low operational cost [54]	
Proven technology [56]	

indicates if the ESS is suitable for long-term storage. The power and energy costs are, respectively, costs for capital and maintenance. Finally, siteability, environmental impact of a power plant, and maturity describe how easily the ESS can be sited in different regions if it burdens the environment, and how developed the technology is.

Especially for load shifting including long-term storage, PHS systems are beneficial as they can store large energy capacities and do not have any significant losses while being ''charged'' [60]. Electricity trading through price arbitrage is usually the major source of revenue for PHS systems. For price arbitrage, the electricity price during pumping mode (in general off-peak/excess of energy available) has to be at least 20 to 30 % lower than the selling price during generating mode (on peak electricity) in order to compensate for energy losses. This implies that significant volatility must be present in the wholesale price of electricity to generate revenue [61]. PHS systems connected at the transmission level offer significant load balancing services and time shifts between energy generation and energy consumption, for example, to respond to the variable output from VRE and have strong characteristics for price arbitrage. PHS can also be used for frequency regulation services despite slower response time and lower efficiency than other ESS.

Some of the limitations of PHS are already being addressed by alternative technology.

- Closed loop networks isolate the two hydrological reservoir networks, with better control and minimized risk (as opposed to the explosion-related challenges posed by Li-ion options) towards the connected environmental ecosystem [62].
- The UK-based start-up Rhernergise is using 2.5 times denser fluid (called R-19) than water to use as the storage medium, which eliminates the need for a head difference by 2.5 times [63].

c: REPRESENTATIVE EXAMPLE

The Dinorwig pumped storage station in Wales, as seen in Figure 7, with a peak power of 1,728 MW can generate 1,320 MW within 10 seconds and deliver the full 1,728 MW power for 5 hours corresponding to a storage capacity of 9.1 GWh. The station, built in 1974, connects reservoirs with a height difference of more than 500 m through 16 km of tunnels inside the mountain. Six fully reversible turbines sit within the mountain in the largest artificial cavern in Europe. The turbines are reversible, allowing water to be pumped back up to the top reservoir when electricity demand is low.

FIGURE 7. Side cut of Dinorwig PHS station [64].

At peak power output, water flows through the turbines at 390 m^3/s. The plant runs on an average efficiency of 74 to 76% [65]. To assist in restarting the National Grid in the event of a complete power failure – a black start - it includes diesel generators for the start of the turbines. Being Britain's largest energy storage system it was primarily built to provide peak capacity, very rapid response, energy storage, and frequency control. Dinorwig's rapid response capability significantly reduced the need to hold spinning reserves from fuels such as coal or gas, which are more expensive. Especially when most people's consumption was predictable due to advertisements for popular TV shows, those surges could be balanced by the Dinorwig Power Plant [60], [66]. Today the Dinorwig Power station is mainly used for price arbitrage to store energy in times of low prices, as in the night time, and generate energy when the consumption is high. An accurate model of the Dinorwig pumped storage system and its impacts on the power system are defined in [67]. The authors name load shifting and frequency regulation as the main functionalities of PHS power stations in a power system.

The biggest PHS currently available stands tall at an output capacity of 3 GW in Bath County, Virginia, US, which consists of six reversible turbines that operate at a 366 meters height difference, offering a response within 15 minutes [68]. This is soon going to be overshadowed by Fengning PHS plant in China, which will house the maximum twelve turbines, with a peak power output of 3.6 GW [69], [70]. Furthermore, there are ambitious expansion plans of the state grid corporation of China (SGCC) on cards, to produce up to 100 GW of PHS power by 2030 from the current capacity of 26.3 GW. This trend clearly does not sign off PHS as a technology growing, in the coming decades.

2) COMPRESSED AIR

Water is not the only promising technology for bulk storage, there are some waterless technology, such as CAES also begs for attention. While the process itself is mechanical, there are also thermal aspects being looked at, for improved energy efficiency.

a: FUNCTIONALITY

In CAES power plants, electrical energy from the power grid (arguably from a VRE source) drives a compressor to inject large volumes of air under high pressure into a storage facility. When electricity is required, this air can be released from the storage and passed through a turbine and generator to regenerate electrical power. In general, compressing air does generate heat, and releasing air does release heat. Regarding large-scale energy storage, CAES systems can store the air either diabatically or adiabatically. A diabatic process occurs with gain or loss of heat which occurs through the loss of heat in the compression process and a gain of external heat through gas combustion in the releasing process. In an adiabatic process, however, there is no loss of heat as it is stored in the meantime [8]. Compressed air should not be stored at high temperatures to ensure the stability and sealing of the storage cavern [71].

b: DIABATIC COMPRESSED AIR ENERGY STORAGE

Most currently built CAES power plants are diabatic, meaning there is a loss of heat involved. To store the energy, a motor drives a compressor to compress atmospheric air. Before being filled into underground caverns, the compressed air which is heated during the compression process needs to be cooled down. To regenerate energy from the compressed air, heat needs to be added into the process [71], e.g. by burning natural gas in a combustion chamber (with alternatives of even using H_2- sourced in grey, blue or green way) thereby, heating the air released through a turbine to generate electricity. This certainly compromises the efficiency gain of the ESS due to the involved process.

c: ADIABATIC COMPRESSED AIR ENERGY STORAGE

The system efficiency of diabatic CAES systems is reduced due to the rejection and inclusion of additional heat to and from the caverns respectively. The notion of adiabatic CAES therefore is to use a heat storage unit as the central element of the system, as seen in Figure 8. The diabatic system would be without the heat storage, but with a gas combustion system. The aim is to store the compressed heat via thermal energy storage and provide the required heat for the expansion process [71].

d: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Conventional diabatic CAES plants in Huntorf and McIntosh have an efficiency of 42 % and 47 % [72], [73], and the maximum efficiency of this energy storage system is said to be at around 54 % [71]. The motor, compressor, turbine, and generator unit are the same as in the diabetic CAES. Compared to the efficiency of a maximum of 54 % in diabetic CAES systems, the adiabatic CAES systems with more emerging projects [74] have an appropriate efficiency of 60% with potential up to 70 %. The CAES ESS has many advantages. The diabatic CAES based on gas turbine technology is proven and reliable. It can be ramped up to full output power in less than 10 minutes, thus, it can also provide black start support. The compressed air can also be stored for a long time. Since the compressed air storage volume is underground, even large reservoirs have a little overground footprint, and for adiabatic CAES without the combustion of gas, there is just a modest environmental impact [75], [76]. The adiabatic CAES has a potential of 100 % freedom of carbon dioxide. A restricting factor for CAES plants is the availability of suitable underground formations nearby VRE generation plants. While some areas have thick salt deposits or salt domes, others do not. Traits including the advantages and disadvantages of diabatic and adiabatic CAES can be seen in Table 7 and 8.

While diabatic CAES is a developed application, adiabatic CAES is still under development and not yet implemented. The theoretical efficiency of advanced CAES systems is expected to touch 70% [77], as against the conventional efficiency numbers of 40%, which is a welcome move, considering the safety benefits it brings to the table, compared to its other waterless peers, e.g. Li-ion batteries. The most

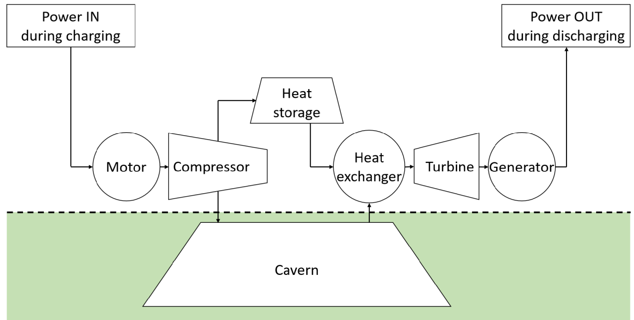

FIGURE 8. A schematic illustration of an adiabatic CAES system.

TABLE 7. Characteristics of CAES system.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Compressed air	3 - 400 MW [53]	Minutes [75]	Hours - days [56]
	Energy Capacity	*Cycles*	*Power Density*
	100 - 10,000 MWh [53]	8,000 - 12,000 [8]	0,5 - 2 W/l [56]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	3 - 6 Wh/l [56]	>20 - 40 years [56]	(Diab.) 42 - 54 % [72] (Adiab.) 60 - 70 % [53]
	Daily Discharge	*Power Cost*	*Energy Cost*
	Small [56]	400 - 800 $/kW [56]	2 - 50 $/kWh [56]
	Siteability	*Environmental Impact*	*Maturity*
	Limited [56]	(Diab.) Large [56] (Adiab.) Small [56]	(Diab.) Mature [71] (Adiab.) Demonstr. [77]

TABLE 8. Advantages and disadvantages of CAES system.

Advantages	*Disadvantages*
Large energy capacity [53] Long lifetime [56] Low operational cost [56] Small overground footprint [53]	Limitation to geographic properties [8] Low efficiency [72] High capital cost [56]

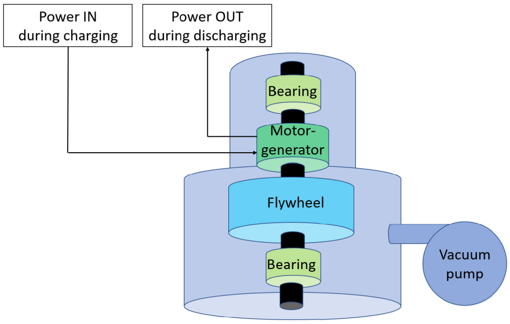

FIGURE 9. A schematic illustration of flywheel energy storage.

common applications would be load leveling, black start support, secondary and tertiary frequency control, and VAR support [75].

3) FLYWHEELS

Flywheel energy storage systems are another example of MESS. Other than PHS, CAES, and gravity batteries, flywheels include kinetic energy to store energy.

a: FUNCTIONALITY

The main components for flywheels are seen in Figure 9. Kinetic energy is the motion of a rotating mass. The rotating mass (the flywheel) spins in a nearly frictionless enclosure and powers the motor generator. Through the flywheel's inertia, the rotor continues to spin, and the resulting kinetic energy is converted to electricity [78], when short-term backup power is required. Ideal kinetic energy can be described as follows:

$$\triangle E_{Kin.} = \frac{1}{2}mv^2. \quad (4)$$

Rotational energy (K) does include rotational inertia (I) as mass and angular velocity ω as the velocity and transforms the equation as follows:

$$K = \frac{1}{2}I\omega^2. \quad (5)$$

Flywheels can either be high-mass and low-speed made of metal or high-speed made of strong light materials. Modern high-speed flywheels use composite rotors made with carbon-fiber materials. The rotors have a very high strength-to-density ratio and rotate at speeds up to 100,000 revolutions per minute (rpm) in a vacuum chamber minimizing aerodynamic losses. Superconducting electromagnetic bearings can virtually eliminate energy losses through friction as the flywheel does not directly touch the bearings [32].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Flywheels have various advantages and disadvantages, limiting them to specific applications. Flywheels require low maintenance, have a long life (some flywheels are capable of well over 100.000 up to 175.000 full depth of discharge cycles), and have a negligible environmental impact. Flywheels have a quick charge and discharge with a fast response and are highly efficient, with an efficiency between 85 and 95 %. With excellent cyclic and load-following characteristics, flywheels can bridge the gap between short-term ride-through power and long-term energy storage [78]. On the other side, the application of flywheels is limited by a high self-discharge. Table 9 and 10 show various properties of flywheels.

TABLE 9. Characteristics of flywheels.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Flywheels	0.1 - 20 MW [79]	<1 s [8]	Seconds - minutes [8]
	Energy Capacity	*Cycles*	*Power Density*
	0.1 - 5 MWh [79]	>20,000 - 175,000 [78]	1,000 - 5,000 W/l [9]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	20 - 80 Wh/l [9]	>15 years [32]	85 - 95 % [32]
	Daily Discharge	*Power Cost*	*Energy Cost*
	Full (20 % per hour) [80]	150 $/kW [81]	400 - 800 $/kWh [80]
	Siteability	*Environmental Impact*	*Maturity*
	Very good [79]	Small [80]	Commercialized [79]

TABLE 10. Advantages and disadvantages of flywheels.

Advantages	*Disadvantages*
Quick response time [82]	High self-discharge [80]
Low maintenance / regulation [82]	Low energy density [80]
Low operational cost [82]	
Quick charge and discharge [82]	
Siteability [82]	
Scalability [79]	

FIGURE 10. Beacon flywheel energy storage plant [83].

c: REPRESENTATIVE EXAMPLES

The reliability, long functional life, and quick response of flywheels allow using it for frequency regulation without burning fossil fuel and, therefore, no produced emissions. For example, in Stephentown, New York, a flywheel-based power plant storing 5 MWh with up to 20 MW during 15 minutes is used for frequency regulation with a response time of fewer than 4 seconds. The plant seen in Figure 10 comprises more than 200 flywheels, and each flywheel weighs 1.150 kg and spins magnetically levitated at 16,000 rpm [83].

Especially system operators can profit from implementing this technology as it has advantages within ancillary services. The direct competition for FESS-based plants for frequency regulations are those based on Li–ion batteries. These plants based on Li–ion batteries are more inexpensive to install, but the high-speed cycling requirements might limit the depth of discharge and degrade the energy storage capability [83].

Especially in a combination of wind energy coupled with flywheel storage, flywheels play an essential role. As wind energy as a form of VRE is expected to grow [84], the problem of continuous mismatches between supply and demand due to the variation from the wind and the volatile load is growing. Therefore, a fast response energy storage technology is required to smooth the supply for better PQ [85]. The combination of a single flywheel to the wind turbine of a windmill, also known as an isolated wind power system (IWPS), allows an immediate smoothing of the power provided to the system. Thus, the variability of power injected into the grid is smoother than the power that the wind turbine would inject without flywheel support [86]. The flywheel provides power between the loss of utility-supplied power and either the return of utility power or the start of a good backup power system (i.e., diesel generator). Flywheels can discharge at 100 kW for 15 seconds and recharge at the same rate, providing 1-30 seconds of ride-through time. Backup generators are typically online within 5-20 seconds [87].

4) GRAVITY BATTERIES

Another potential energy storage technology similar to PHS is the gravity battery that transports massive concrete weight instead of water over a height, to transform the gravitational energy into electrical energy.

a: FUNCTIONALITY

Gravity batteries use the same basic principle of energy conversion as every potential energy storage system with the movement of an object due to its position. An object of massive weight is lifted using VRE or cheap electric sources by conserving its potential energy located at a certain height, and is lowered in order to capture the stored energy, by means of regenerative braking. The generated energy can be calculated with

$$\triangle E_{Pot.} = mg\triangle h. \tag{6}$$

and m as the moved object's mass, g as the gravitational constant, and h as the object's vertical movement. Utmost precision and synchronized switching can be adopted to scale it up for a massive amount of energy. The vertical distance $\triangle h$ is explained as the difference between the upper and lower position.

$$\triangle h = h_{upperposition} - h_{lowerposition}. \tag{7}$$

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

As there are different designs of gravity batteries, there are different numerical impacts. In general, gravity batteries compared to PHS, are less dependent on geographical properties. Neither do they require access to large water pools, nor do they need mountains for the height difference. The elevation difference can be achieved by digging holes (or using existing mine shafts) or building towers allowing projects to be completed on flat terrains. Thus its land footprint is much smaller than that of PHS, and the positioning is much more flexible [88]. The environmental footprint of the concrete blocks, their durability, and tandem operations are still debatable.

The density of the lifted objects is much higher than the density of water leading to quicker discharge time (it can be tailored to the system operator's needs) and higher energy density. In general, more than 80 % efficiency can be achieved and a service time of more than 50 years with low operational cost [89]. Especially the cost of delivery can be minimized due to the flexible placement. Characteristics of gravity batteries can be seen in Table 11 and 12.

TABLE 11. Characteristics of gravity batteries.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Gravity Batteries	4 - 8 MW [89]	<1 s [90]	Hours [91]
	Energy Capacity	*Cycles*	*Power Density*
	>10 MWh [91]	No data available	No data available
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	No data available	25 - 50 years [90]	80 - 85 % [91]
	Daily Discharge	*Power Cost*	*Energy Cost*
	Very small [91]	250 - 350 $/kW [91]	65 - 250 $/kWh [91]
	Siteability	*Environmental Impact*	*Maturity*
	Good [91]	Small [91]	Demonstration

TABLE 12. Advantages and disadvantages of gravity batteries.

Advantages	*Disadvantages*
Scalability [91] Long lifetime [90] Usability of waste materials as mass [91] Safety [91] Siteability [91]	No proven technology High capital costs

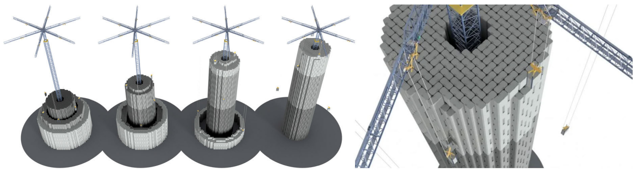

FIGURE 11. Charging of Energy Vault Tower 1 gravity battery [94].

c: REPRESENTATIVE EXAMPLES

Swiss-American company Energy Vault has been awarded several projects [92], [93], thus scaling up the concept for large-scale storage in the range of 500 and 220 MWh, etc. The objects could be concrete blocks with 32 tons (T) of mass each and are stacked and unstacked using up to 50 meters (m) high cranes. The tower is designed to be modular, and flexible with a plant capacity range of 20, 35, and 80 MWh storage capacity and a 4 to 8 MW of continuous power discharge for 8-16 hours and an efficiency of 85 % [89]. The controlled decline of the blocked weight helps achieve the desired power dispatch as seen in Figure 11.

The company names economical advantages, no degradation over time, the possibility of using locally sourced materials or waste materials such as coal combustion residuals (coal ash), fiberglass from decommissioned wind turbine blades, and waste tailings from mining processes, scalability, the suitability for industrial and non-urban locations and the possible combination with PV solar or wind plants as drivers of this technology. The possible instability in windy regions for this system in the form of a single tower led the company to focus on a system called "Energy Vault Resiliency Center" [89].

The bricks are moved up and down inside the building on rolling carts. An artificial intelligence system controls these carts to generate as much energy as needed at any given moment. It also determines the optimal time to charge and discharge energy. The area required for the Energy Vault Resiliency Centers will vary, ranging from 1.5 to 20 hectares, depending on storage capacity. However, they are often expected to be installed in locations where space is not an issue, such as near existing wind or solar facilities. Typically, the Energy Vault system runs once daily with a possible continuous power discharge of 4-8 MW. With a downtime of five days per year, a 75 MWh Energy Vault Resiliency Center with 10,000 bricks has an annual output of 27 GWh, which puts the 14-acre footprint into great perspective [95]. The claimed efficiency is in the range of 85 %.

Besides Energy Vault, Gravitricity, a British company, uses potential energy while not building up but using openings downwards. For this energy storage technology, a mass, a channel opened underground, a reducer system, a pulley system, and generator units are required. The mass weighs more than 3,000 T, and through movement, extremely high power can be achieved due to the high power density of the mass made out of, e.g., concrete. The response time thus is less than one second at total power rating. The system has a service life of up to 50 years with periodic maintenance [90].

Within a study, mine shafts from the United Kingdom Midlands have been analyzed, resulting in an approximation of more than 3,000 usable mines with a total storage capacity of 1.07 GWh involving 350 mines with a capacity between 1 and 6.7 MWh [88].

5) OTHER EMERGING TECHNOLOGIES IN MECHANICAL ENERGY CATEGORY

The authors came across some emerging technologies that could be classified in the mechanical ESS category. Two such technology worth mentioning are Ocean Batteries and and CO_2 batteries, which are explained briefly in the following sections.

a: OCEAN BATTERIES

While PHS has been the single most reliable storage technology available at the disposal of the utilities, there are certain spin-offs from this technology that is making headlines, claiming to be offering similar round trip efficiency, life, and far-reaching scalability. One such technology worth reporting is Ocean Batteries, which is particularly aimed at offshore installations comprising wind farms and floating solar PVs alike [96]. The intention is to capitalize on the excess RES-produced energy to store them, which is otherwise curtailed if produced during a non-demand cycle. In the UK alone the year 2021 witnessed 15% curtailed wind power, amounting to a £507m revenue loss [97].

Dutch startup Ocean Grazer is the promoter of this technology, which uses a PHS principle, but the dam was replaced with an inflatable bladder and a low-pressure rigid reservoir [98]. By being coupled to a RES, the excess energy is diverted to pump the water from the rigid reservoir to the bladder, performing the storage function. Multiple hydro turbines are used to use this water for producing electricity. The technology claims to tick off certain environmental and ecological concerns on the way. It avoids using rare earth materials for the turbine generators, uses conditioned seawater as the working fluid, and the rigid reservoirs are built of eco-friendly concrete. The arrangement even claims to support marine life by acting as an artificial reef between wind farm structures [97].

Some characteristics of this technology are worth mentioning. The claimed round-trip efficiency is around 80%. Though the energy density is significantly lower compared to electrochemical batteries, it has higher operating life (claimed in excess of 20 years), and unlimited operational cycles [96], which makes it a promising alternative.

Besides, Ocean Grazer, there are other promoters of comparing technologies of ocean batteries. A few such examples which are in the conceptual stage are Subhydro, hollow concrete spheres from MIT [99], leveraging buoyancy force under ocean water [100]. The technical feasibility, widespread adoption, and commercial success of these concepts remain to be seen.

b: CO_2 BATTERIES

Liquid carbon dioxide (CO_2) has traditionally been used for the carbonization of aerated beverages, and water treatment, even during testing of aviation-specific and other electronic components at low temperatures. It's condensation property when pressurized, even at ambient temperature has been exploited for storage by an Italian startup Energy Dome [101].

Using surplus RES-based electricity, it retracts CO_2 from a large dome holding the gas at atmospheric pressure, and stores it under pressure at ambient temperature. The stored gas is discharged on demand by dispatching it through a turbine after evaporation and expansion cycle, back to the dome. The entire operation is held in a closed thermodynamic process. It has progressed from a concept to complete testing at a multimegawatt scale in just over two years. The company claims to have an energy density twice that of CAES and two-thirds that of LAES [102]. A round-trip efficiency of 75 % is claimed with meager costs and the possibility of storing energy for a long duration [102]. The technology is about to be commercialized in 2022 [103].

The technology is very similar to thermal latent heat ESS liquid air energy storage which is presented in Section IV-C2 but does not require extremely cold temperatures during the liquifying process and thus is not classified as thermal but rather as a mechanical ESS.

B. ELECTRICAL AND ELECTROMAGNETIC ENERGY STORAGE

Electrical and electromagnetic energy storage (EES) is a way of storing energy involving the form of an electric or magnetic field, where the latter is typically generated by a current-carrying coil [104].

The electrical and electromagnetic energy is given by the addition of inductive and capacitive energy as in the following equation

$$\triangle E_{El.} = \triangle E_{Ind.} + \triangle E_{Cap.} = \frac{1}{2}LI^2 + \frac{1}{2}CU^2, \quad (8)$$

where L, I, C, and V are the inductance, current, capacity, and voltage respectively [105].

Electrical and electromagnetic energy storage technologies include supercapacitors and superconducting magnetic energy storage (SMES). Compared to the other storage systems, EES systems store energy in electrical or electromagnetic form and do not require energy transformations (except for the conversion between AC and DC, if required) [106], typically leading to a high round-trip efficiency.

1) SUPERCAPACITORS

Supercapacitors (also ultracapacitors) are capacitors that have been designed specifically to store large amounts of electrical charge. Supercapacitors have attributes between electrolytic capacitors and rechargeable batteries by storing 10 to 100 times more specific energy or energy density compared to electrolytic capacitors [107].

a: FUNCTIONALITY

A traditional capacitor is made up of two metallic plates (electrodes) separated by a dielectric. When one of the electrodes receives a voltage, electrons gather at that electrode, storing the electrical charge. Meanwhile, dielectric polarization occurs in the dielectric material sandwiched between the two electrodes, which contributes to boosting the capacitance of the system's ability to store an electric charge. The wedging material in a supercapacitor is an electrolytic solution rather than a dielectric substance as seen in Figure 12, and it functions on the same principles as a capacitor.

When a supercapacitor is charged, an "electric double layer" forms, aligning both positive and negative charges along the electrodes' and electrolytic solution's borders. This space serves as a repository for electrical energy.

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Supercapacitors can store more energy than capacitors and supply it at higher power outputs than batteries. These features, combined with high cyclability and long-term stability, make supercapacitors attractive devices for energy storage. Supercapacitors are already present in many applications, either in combination with other energy storage devices (mainly batteries) or as solitary energy sources [108]. Operating temperatures for supercapacitors are between −40°C to +65°C. Storing energy in an electric field instead of chemicals also leads to increased safety, lower fire hazards, and explosion risk, and increased service life of the capacitor to between 10 and 30 years. Table 13 and 14 summarize various characteristics and traits of supercapacitors.

Due to the advantages of higher power and longer cycle life than batteries, the following applications can profit from supercapacitors [111]

- Application of high power
  Thanks to high power ratings, supercapacitors find new opportunities in power electronics, where short-time power peaks are required. Typical examples are the fast energy management in hybrid vehicles or the starting of heavy diesel engines.
- Application of long cycle life

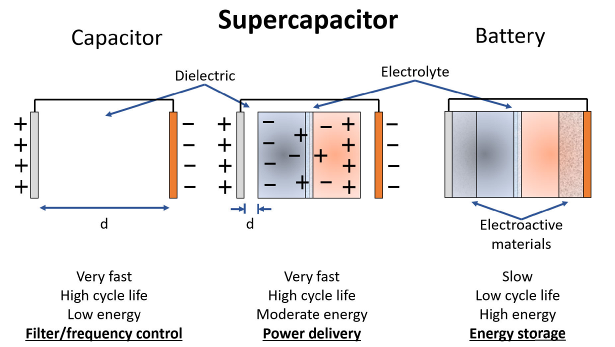

FIGURE 12. Functionality of a supercapacitor compared to capacitor and battery.

TABLE 13. Characteristics of supercapacitors.

Technology	Power Rating	Response Time	Discharge Duration
Super-capacitors	0 - 0.3 MW [9]	Milliseconds [109]	Seconds - minutes [109]
	Energy Capacity	*Cycles*	*Power Density*
	0.0005 MWh [9]	10,000 [56]	1,100,000 W/l [109]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	10 - 30 Wh/l [9]	30 years [109]	84 - 98 % [110]
	Daily Discharge	*Power Cost*	*Energy Cost*
	5 - 40 % [56]	50 - 100 $/kW [81]	500 - 2,000 $/kWh [81]
	Siteability	*Environmental Impact*	*Maturity*
	Very good	Small [56]	Proof of concept

TABLE 14. Advantages and disadvantages of supercapacitors.

Advantages	Disadvantages
Response time [109] Power density [109] Lifetime [109] Safety [8] Scalability Siteability Cyclability [109]	Energy capacity [9] High self-discharge [56]

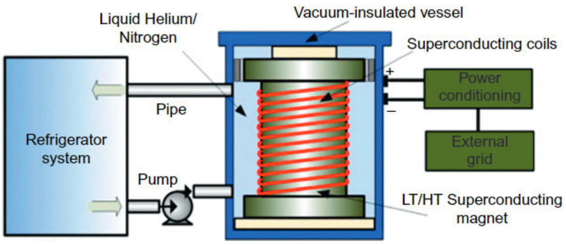

FIGURE 13. A schematic illustration of a superconducting magnetic energy storage system [9].

At higher power, batteries suffer from maintenance problems or insufficient lifetime performance. Supercapacitors can present a good solution for this issue. The UPS, as well as security installations, are the most representative examples, including frequency control and voltage support, together with STATCOM devices.

2) SUPERCONDUCTING MAGNETIC

Superconducting magnetic energy storage (SMES) is a technologically advanced method of storing energy in a magnetic field, which is formed when a current flows around a coil. For this to operate efficiently as an ESS, the coil must be made of a superconductor with no electrical resistance so that there are no resistive energy losses as the current circulates [112].

a: FUNCTIONALITY

AN SMES system consists of a superconducting magnet with its supporting structure including a coil, a cyrogenic refrigirator, a power conditioning system, and a control system. The larger the size of the coil, the greater is the energy [113]. An electrical current in the coil creates a magnetic field, and the changes in this magnetic field create an electrical field. The magnetic flux is a reservoir of energy. Superconducting wires do not deliver energy when conducting a current, so a coil made with that material maintains the current, and the magnetic flux can be stored [114]. A regular conducting material such as copper will still have a small electrical resistance when it is cooled close to absolute zero due to impurities in the material. However, in a superconductor, once the temperature drops below the critical temperature, its electrical resistance falls abruptly to zero, and a new quantum state is set up within the superconducting material. A superconducting current can only be maintained in the coil by keeping it below its transition temperature, which requires extreme refrigeration. A schematic is shown in Figure 13. The cooling system accounts for one of the main running costs of such a system. High-performance insulating materials can help keep heat transfer rates low [112].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

An advantage of SMES over other types of energy storage is that an SMES coil has no moving parts so it should have a very long lifetime, in excess of 30 years [112]. SMES systems can achieve high efficiency by minimizing losses and fast response time due to pure electrical energy conversion, while other energy storage devices involve electrical or mechanical energy conversion, which is much slower. SMES systems can discharge and recharge fully an unlimited number of times [115] and are not affected by states of charge. The capacity of the stored energy is scalable [114]. Traits including advantages and disadvantages of this ESS can be seen in Table 15 and 16.

TABLE 15. Characteristics of superconducting magnetic.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Super-conducting Magnetic	0.1 - 10 MW [9]	Milliseconds [43]	Minutes - hours
	Energy Capacity	*Cycles*	*Power Density*
	0.1 - 100 MW [9]	No degradation [43]	1,000 - 4,000 W/l [9]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	0.2 - 6 Wh/l [9]	>30 years [112]	>95 % [43]
	Daily Discharge	*Power Cost*	*Energy Cost*
	10 - 15 % [9]	1,000 - 72,000 $/kW [9]	200 - 489 $/kWh [9]
	Siteability	*Environmental Impact*	*Maturity*
	Size dependent [9]	Small [112]	Proof of concept [9]

TABLE 16. Advantages and disadvantages of superconducting magnetic.

Advantages	*Disadvantages*
Response time [43] Number of cycles & lifetime [43] Power density [43] Low maintenance [43] Efficiency [43]	Costs [9] High self-discharge [9] Energy density [43]

SMES can be used in any PQ application, such as frequency control, voltage support, and thus as UPS, in flexible AC transmission systems (FACTS), and within pulse power sources [43]. While it is suitable for larger load-shifting applications, dimensioning the system for more than 10 MW is not economical at the moment [114].

C. THERMAL ENERGY STORAGE

Thermal energy storage (TES) is a way of storing energy involving the thermal form of energy. The equation of heat energy shows how temperature and heat energy are connected.

$$\triangle E_{Therm.} = q = mC\triangle T, \tag{9}$$

where q is the quantity of transferred heat, m is the object's mass releasing or absorbing heat, C is the specific heat capacity of the object, and $\triangle T$ is the change in temperature.

Different TES may use different properties of materials when a specific temperature is applied to them to achieve energy storage. TES can be classified into three types: Sensible, latent, and thermo-chemical reactions. Sensible storage takes place when the temperature of a material is changed, whereas latent storage occurs when there is a phase change of a material (solid to liquid or liquid to vapor) without a change in temperature. Both mechanisms can occur in the same material. The third mechanism is a chemical reaction that takes place on the surface of a material. In all cases, heat can be released or absorbed from the material [116].

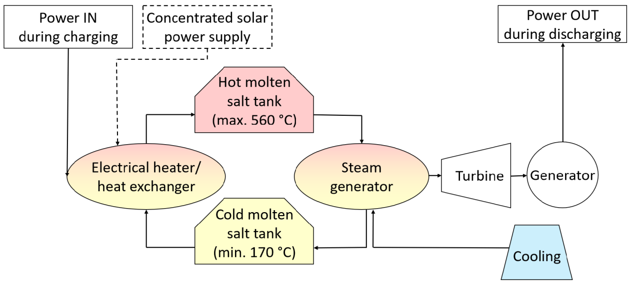

FIGURE 14. A schematic illustration of a molten salt energy storage station.

TES systems usually have comparatively low efficiency due to yet inefficient methods of converting heat energy to electrical energy. However, the cost of storage is potentially low, and storage systems can often be scaled and profit from economies of scale.

1) MOLTEN SALT

Molten salt is a way of storing energy as an example of sensible heat storage, which either increases or decreases in a medium's temperature. This type of storage is the most developed and commercially available TES system. The materials are generally inexpensive and safe. Other than salt, there are applications with water and molten aluminum. Water has the disadvantage of not being able to be heated to as hot temperatures as salts or metals and thus has the disadvantage of lower storage capacities [117].

a: FUNCTIONALITY

The process of storing molten salt is visualized in Figure 14. The charging part consists of technologically mature electrical heaters connected to the grid to heat salt. Those electrical heaters heat salt to temperatures as high as 600°C [118]. The molten salt is pumped into a hot storage tank at a temperature of 550 - 570°C. Temperature losses are about 1°C per day, equating to about 0.3 % of the stored energy. A second tank stores salt at approximately 270 to 300°C. Both tanks are insulated. Typical durations of storage between charge and discharge are 8 to 16 hours [118].

When discharging, hot steam directly feeds turbines, and the molten salt is stored in the lower-temperature cold storage tank to be reheated while recharging. Within the discharge cycle, there is an option of reheating the fuel instead of directly transporting it to the cold storage tank if a more prolonged discharge is required. This heater can be powered by different energy sources and enables higher reliability and enable seasonal storage [118]. There are direct and indirect configurations of molten salt energy storage: Indirect storage includes different storage media, whereas direct storage systems utilize a single medium. There are new technologies that could replace turbines in the process of transforming heat energy into electric energy, as their loss of energy is very significant. Thermal Photovoltaic cells have even the potential to increase efficiencies and decrease costs [119].

TABLE 17. Characteristics of molten salt.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Molten Salt	0.1 - 300 MW [9]	Slow [120]	Hours [118]
	Energy Capacity	*Cycles*	*Power Density*
	1 - 5,000 MWh [120]	10,000 [120]	80 - 500 Wh/l [9]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	No data available	20 - 30 years [121]	30 - 60 % [9]
	Daily Discharge	*Power Cost*	*Energy Cost*
	0.3 % [118]	No data available	4 - 20 $/kWh [121]
	Siteability	*Environmental Impact*	*Maturity*
	Very good [121]	Small [121]	Commercialized [121]

TABLE 18. Advantages and disadvantages of molten salt.

Advantages	*Disadvantages*
Large energy capacity [121] Siteability [121] Combined heat and power storage for higher efficiency [120] Energy cost [121] Inexpensive, safe medium [121]	Slow response time [120] Low efficiency [9]

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

The advantage of salt compared to other storage media is that up to 600°C salt is not vapored pressurized and thus easier to handle, and the higher the temperature, the higher the energy efficiency. Secondly, salt does not have environmental dangers in cases of leakages such as oil as salt does simply harden at ambient temperature, is not toxic, and has cost and durability advantages (the same salt can be reused for decades (about one cycle per day) [118]. Numerical attributes of molten salt energy storage can be seen in Table 17 and the advantages and disadvantages in Table 18.

c: REPRESENTATIVE EXAMPLE

Molten salt energy storage in combination with concentrating solar power (CSP) systems is gaining significant attention in different parts of the world, for example from CSP Gen3 - "Liquid Pathway" [122]. CSP systems consist of a large area of reflective objects, such as mirrors that concentrate the sunlight into a receiver, often a solar power tower, that converts the light to heat [123]. Figure 15 shows the structure of such a combined CSP and molten salt energy storage system.

Such systems are being deployed in different regions, such as a 510 MW CSP plant with molten salt in the Drâa-Tafilalet region in Morocco [124], a 110 MW plant in Tonopah, U.S. [125], or a 100 MW plant in Hami, China that can store and supply 800 MWh of thermal energy [126].

2) LIQUID AIR

Liquid air energy storage is a latent heat technology comparable to previously presented CAES as it uses energy to form the voluminous characteristics of air and store it. While CAES technology uses mechanical compressors to compress high-pressure air, liquid air uses vessels to liquefy and store the air using temperature [127] as a latent heat storage technology. Using standard industrial equipment, the air can be cooled

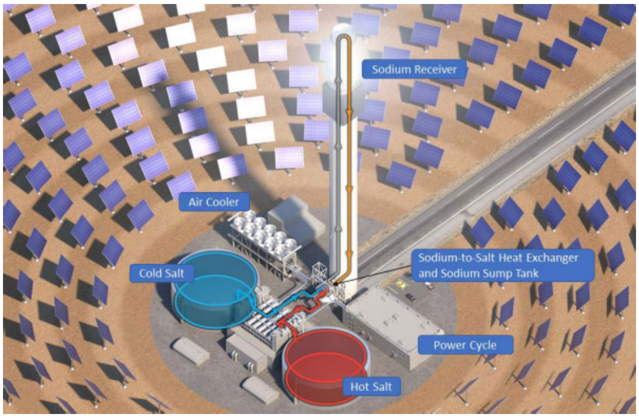

FIGURE 15. Concentrated solar power with molten salt [122].

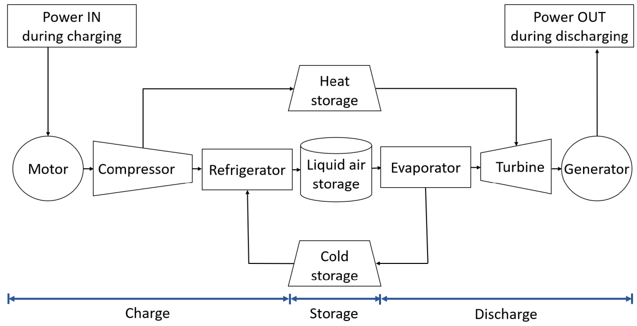

FIGURE 16. A schematic illustration of LAES technology.

to low temperatures of -196°C to liquefy air. This makes this technology a cryogenic energy storage technology [128]. 700 liters of ambient air becomes about 1 liter of liquid air, which can then be stored in an unpressurized insulated vessel. When heat is reintroduced to liquid air, it boils and turns back into a gas, expanding 700 times in volume. This expansion can be used to drive a piston engine or turbine to do usable work.

a: FUNCTIONALITY

A typical LAES system operates in three steps, as seen in Figure 16. The first step, as in other ESS is the charging process, whereby excess energy is used to clean, compress, and liquefy air. First, the air must be cleaned through a dust filter and compressed to a pressure of about 6 bar. The compressed air is cooled down to close to liquefaction temperatures by repeatedly compressing and expanding the gas and passing it through a heat exchanger [129]. This process consumes about 20 % of the energy [129]. The second step is the storing process through which the liquefied air produced in the charging process is stored in an insulated tank at -196°C and at approximately ambient pressure [129]. The third step is the discharging process, which recovers the energy through pumping, reheating, and expanding to regenerate electricity [129], [130]. The efficiency of the process is increased by exploiting both waste heat and waste cold. The use of low-grade waste heat during expansion generates additional power that improves the overall round-trip efficiency of the cycle: the cycle's maximum efficiency is determined by the highest and lowest temperatures, so raising the higher temperature with waste heat increases the available work. An example could be a biomass power station next to the LAES station [129].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

The LAES system profits from the mature technology of liquefying air but it is an overall developed but yet not completely commercialized ESS. First demonstration projects have been implemented [127]. The technology has a strong

TABLE 19. Characteristics of LAES.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Liquid Air	1 - 3,000 MW [131]	Minutes [131]	Hours [9]
	Energy Capacity	*Cycles*	*Power Density*
	2.5 - 10,000 MWh [131]	No data available	No data available
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	50 - 200 Wh/l [131]	20 - 40 years [131]	45 - 70 % [131]
	Daily Discharge	*Power Cost*	*Energy Cost*
	Small [9]	1,100 - 2,700 $/kW [131]	300 - 1,000 $/kWh [131]
	Siteability	*Environmental Impact*	*Maturity*
	Good [131]	Small [131]	Demonstration [131]

TABLE 20. Advantages and disadvantages of LAES.

Advantages	*Disadvantages*
Siteability [131] Scalability [131] Long lifetime [131]	Low efficiency [131]

lifetime of more than 30 years and can store energy with no significant self-discharge [129]. The run time of such storage is very long, and the energy capacity, due to the possibility of scaling the amount of stored energy up within additional storage tanks, is very large [129]. The slow response time of this technology of more than 10 minutes includes applications such as load shifting (also in seasonal storage), peak shaving, and tertiary frequency control. While the efficiency is around 50 to 60 % (lower compared to PHS), the flexible placement makes LAES a plausible alternative [129]. Several technologies under development might offer superior characteristics to LAES, but the development time for such technologies should not be underestimated. As a result, LAES has the potential to be highly competitive against current and emerging alternatives [129]. While the energy cost of 40$ per kWh in demonstration stations, it is not at the level of PHS with down to below 10 $ per kWh in some stations. Other than PHS, the technology can profit from economies of scale [127]. Characteristics of LAES can be seen in Table 19 and 20.

3) MOLTEN METAL

Molten metal is a latent heat energy storage system including heaters, storage, and steam production in an extremely compact way [132] within a block. The technology profits from

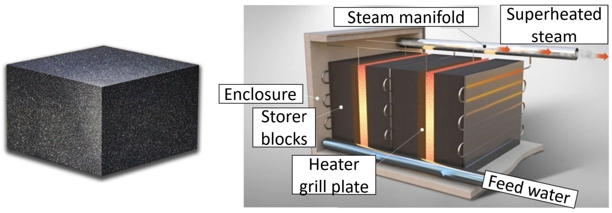

FIGURE 17. **Aluminum-graphite block (left) and TWEST structure (right) demonstrating thermal storage [129].**

its scalability and has the potential to be used in conventional thermal generation plants that are slated for phase-out [133].

a: FUNCTIONALITY

The technology converts surplus electrical energy into heat that is stored through molten metal and returned into electrical energy in the form of superheated steam running existing steam turbines and generators. The Traveling wave energy storage technology (TWEST) utilizes two sets of storage blocks (see Figure 17), approximately the size of a large brick. The blocks from aluminum particles are given structural integrity by graphite and have a long lifetime with no degradation over time. Aluminum provides latent heat through thousands of cycles of melting and solidifying [132].

During the charging process, the first set of aluminum-graphite blocks is heated to a temperature of 700 °C, while the second set is heated to a lower temperature required by the steam turbine. In the discharging process, steam is initially generated in the first set of blocks through the provision of water and then is cooled down by the second set of blocks to the turbine inlet temperature. During this process, the heat is moved in the form of traveling waves from the hotter to the moderate thermal storage blocks. The generated steam can power turbines and, thus, generators [134].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Each block has a mass of around 6 kg and can store approximately 1 kWh of energy. Those dimensions are fitted more to utility-scale applications instead of domestic use, and the technology is most efficient when used at a very large scale. Pilot plants store between 20 and 50 MWh of energy [133]. There is a concept to utilize most of the infrastructure of coal-fired plants and turn them into fossil-fuel-free energy storage plants enabling utility-scale storage fitting into existing power plant facilities and, moreover, offering the lowest levelized cost of storing electricity [135]. The features of molten metal energy storage can be seen in Table 21 and 22.

Molten metal has a quicker response time compared to other TES, but also suffers from low efficiency. It could provide frequency support and energy services. Especially in countries with planned coal phase-outs, the technology can profit from existing plants as it has many similarities to coal power plants and could be deployed comparatively fast [137].

TABLE 21. **Characteristics of molten metal.**

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Molten Metal	0.1 - 100 MW [133]	Minutes [136] Seconds w. standby [132]	1 - 8 hours [132]
	Energy Capacity	*Cycles*	*Power Density*
	20 - 50 MWh [133]	1 per day [132]	No data available
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	No data available	30 years [136]	40 % [136]
	Daily Discharge	*Power Cost*	*Energy Cost*
	<1 % [132]	No data available	No data available
	Siteability	*Environmental Impact*	*Maturity*
	Very good [132]	Small [132]	Developing [132]

TABLE 22. **Advantages and disadvantages of molten metal.**

Advantages	*Disadvantages*
Compactness [132] Scalability [132] Siteability [132] Provision of inertia [132] Long lifetime [132] Abundant, safe, and recyclable materials [132]	Low efficiency

4) OTHER EMERGING TECHNOLOGIES IN THERMAL ENERGY CATEGORY

There are some new entrants in this category that shows tremendous promise of being a viable storage alternative for grid applications.

Sand batteries consisting of sand within tanks that can store heat at low costs are another thermal ESS, planned to be commercialized in 2022 [138], [139]. Many thermal ESS that store electrical energy within heat do not convert the heat back but feed heat to the heating system. The drawback of many thermal storage systems is the low efficiency due to losses in converting heat to electricity. There is also ongoing research on thermal photovoltaic cells to replace conventional steam turbines [140].

D. CHEMICAL ENERGY STORAGE

This is a storing technique involving the chemical form of energy and can be broadly classified into electrochemical batteries and chemical fuels such as H_2, which can be electrified with FC. Generated through chemical reactions it can be characterized through either a reversible or an irreversible reaction [105].

Batteries are common devices that store chemical energy and convert it to electrical energy. They can be either non-rechargeable (primary) or rechargeable (secondary). The rechargeable batteries are however of interest for large-scale stationary energy storage [8]. Battery energy storage systems (BESS) are one of the fastest growing technologies in the sustainable energy industry [141], [142].

H_2 storage with FC is another chemical energy storage technology and are also part of major research projects with high potential for various sector coupling [8].

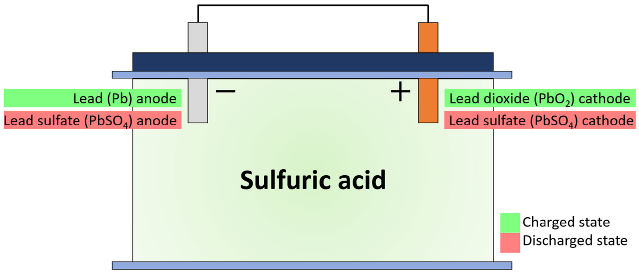

FIGURE 18. Functionality of lead acid batteries.

TABLE 23. Characteristics of lead-acid batteries.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Lead-Acid	0 - 40 MW [9]	Milliseconds [9]	Seconds - hours [9]
	Energy Capacity	*Cycles*	*Power Density*
Batteries	0.001–40 MWh [9]	250 - 1,500 [144]	90 - 700 W/l [144]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	50 - 80 Wh/l [144]	3 - 15 years [144]	50 - 90 % [144]
	Daily Discharge	*Power Cost*	*Energy Cost*
	0.1 - 0.3 % [9]	300 - 600 $/kW [144]	50 - 200 $/kWh [145]
	Siteability	*Environmental Impact*	*Maturity*
	Very good [146]	Medium [147]	Mature [144]

TABLE 24. Advantages and disadvantages of lead-acid batteries.

Advantages	*Disadvantages*
Mature technology [143] Cost [146]	Short lifetime [9] Lead as a toxic material [143] Degradation at high power discharge [143] Energy density [143]

1) LEAD-ACID BATTERIES

Lead-acid batteries have been commercially deployed since the 19th century [143] and are used in both mobile and stationary applications.

a: FUNCTIONALITY

As seen in Figure 18, a lead acid battery consists of a negative lead electrode. The positive electrode consists of lead oxide. Both electrodes are dipped into an electrolytic sulfuric acid and water solution. An electrically insulating but chemically permeable membrane separates the two electrodes [143].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Lead-acid batteries offer a mature and well-researched technology, but especially for utility-scale energy storage, there are various drawbacks such as a decrease of capacity when high power is discharged or the use of lead, a hazardous material prohibited or restricted in various jurisdictions [143] and a lower energy density compared to other batteries. Numerical characteristics can be seen in Table 23 and 24.

Their typical applications are starter batteries in vehicles as emergency power supply systems and battery systems to smooth output fluctuations from wind power plants [143], [148].

2) LITHIUM-ION BATTERIES

Lithium-ion (Li-ion) batteries constitute by far the most competing technology that has been finding wide applications in both mobile and stationary applications. Many emerging storage technologies are being benchmarked against this due to its wide prospects, applicability, and technological maturity [141].

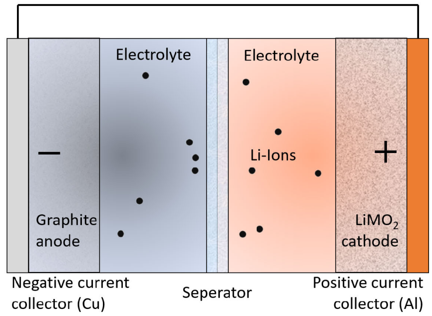

FIGURE 19. Structure of a Li-ion cell and its functionality during discharging.

a: FUNCTIONALITY

As seen in Figure 19, a Li-ion cell consists of two different electrodes: a negative electrode (anode) and a positive electrode (cathode). Each electrode is made up of a current conductor (also called a collector) and an active material applied to it. Between the electrodes, there is an ion-conducting electrolyte, which enables the necessary exchange of charge, and the separator, which separates the electrodes electrically [141].

The negative electrode of the Li-ion cell consists of a copper foil and a layer of carbon or silicon, such as graphite. This is completely depending on the specific cell chemistry. The positive electrode consists of mixed oxides applied to an aluminum collector and a material including Lithium. The electrolyte acts as an intermittent liquid between the reaction areas on the electrodes during the charging and discharging processes and serves to transport the Li-ions. It needs to be highly conductive for ions and be stable in 0 to 4.5 V voltage range as well as in the temperature range in which the battery is to be operated [141].

During the discharge process, as seen in the previous Figure 19, Lithium ions travel through the electrolyte and separator from the anode to the cathode, where they are reversibly located. Electrons are released by the ongoing oxidation process taking place on the anode, thus flowing from the negatively charged anode to the positive cathode via an external electrical connection. Electrical consumers can be powered by this external flow of current. During charging, the process takes place in a reversed way [141].

The power of a battery module depends of the number of cells connected in series. A certain number of cells or modules are connected in parallel to provide the required total energy capacity of the ESS. The combination of parallel and series connections determines the rated power and energy capacity of the battery [141].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Li-ion batteries have high energy densities, high power, high efficiency, a low self-discharge, and they are scalable, resulting in variable power or energy capacity depending on

TABLE 25. Characteristics of Li-ion batteries.

Technology	Power Rating	Response Time	Discharge Duration
Lithium-ion Batteries	0 - 300 MW [149]	Milliseconds [9]	Minutes - hours [9]
	Energy Capacity	***Cycles***	***Power Density***
	0 - 1,200 MWh [149]	1,000 - 3,000 [145]	1,300 - 10,000 W/l [144]
	Energy Density	***Lifetime***	***Round-trip Efficiency***
	200 - 400 Wh/l [144]	5 - 20 years [144]	85 - 95 % [144]
	Daily Discharge	***Power Cost***	***Energy Cost***
	0.17 - 0.33 % [150]	333 - 428 $/kW [151]	100 - 2,000 $/kWh [145]
	Siteability	***Environmental Impact***	***Maturity***
	Very good	Medium [146]	Mature [146]

TABLE 26. Advantages and disadvantages of Li-ion batteries.

Advantages	*Disadvantages*
High Power and energy density [9]	Degradation over lifetime [8]
Scalability	Flammability
Siteability	Protection required
Available as second-life batteries	Supply of materials
Object of massive research and development	High costs for larger capacities
	Critical disposal possibilities

the needs. They have a strong response time and are the object of competitive research. On the other hand, they have some significant disadvantages as well, such as high costs, no economies of scale, a relatively short cycle life, and high risks of fire and explosion (primarily because, there is still a lot left to understand, about its chemistry) and they are made out of rare earth materials which have negative environmental and health issues.

Li-ion batteries connect materials with a high energy content to flammable electrolytes. Safety-critical situations can be triggered in the event of extreme external influences such as short circuits, high temperatures, or mechanical deformation. Especially, overcharged cells cause dangerous reactions, as this can lead to uncontrollable heating and, in the worst case, to a so-called "thermal runaway, a circle of heat resulting in an exothermic reaction, an increase in a reaction rate and, thus in increasing heat again. A thermal runaway that starts in a single cell can spread to neighboring cells as a slow chain reaction, potentially causing fire and triggering explosions in the cells [141]. Traits of Li-ion batteries can be seen in Table 25 and 26.

c: REPRESENTATIVE EXAMPLES

In the last years, increasingly large battery-storage plants have been implemented such as a plant in East Yorkshire, UK that can store up to 196 MWh of electricity to optimize the efficiency of RES to support in energy management being operated by the national grid [152]. Another example of a 200 MW, 500 MWh large grid-scale battery system has been installed in Texas, USA to increase the flexibility of energy supply for grid support and energy resource optimization [153].

Vehicle-to-grid (V2G) technology as a topic is gaining momentum due to several evaluations of economic incentives to vehicle owners, utility providers as well as consumers [154]. Due to massive electric vehicles (eV) penetration around the globe across the transportation industry both from light to heavy-duty vehicles, this forms a perfect business case for bulk storage acting as a distributed grid storage infrastructure, catering to load shifting and a variety of ancillary services. Therefore, it's imperative to assess the power quality and stability impact of this distributed solution on the grid both at distribution and even sub-transmission levels [155]. The utilization of the concept for frequency regulation prospects was also evaluated in the Danish grid [156]. Overall, V2G offers significant promise in organizing the demand response, for multiple stakeholders presented in Fig. 4.

In the coming years, a considerable number of batteries in eV will be retired [157], [158]. In some applications outside the automotive industry, second-life Li-ion batteries could be sufficient to meet the desired results. Especially in many stationary applications, the energy and power per mass or volume are not too decisive as they do not have space limitations, such as in eV. Retired batteries may be effectively used in sectors such as energy management or ancillary services since it fits the bill from a criticality and cost-effectiveness perspective [158]. At the same time, there is also a good amount of skepticism about the usefulness of second-life batteries, primarily due to the frequent cycling expected of them [159].

3) REDOX-FLOW BATTERIES

A flow battery is a rechargeable battery consisting of one or more electroactive species dissolved into liquid electrolytes in which energy is stored [160]. Compared to other batteries, redox-flow is a technology that is highly promising for stationary energy storage [161].

a: FUNCTIONALITY

In redox-flow batteries, the electrolytes are stored in externally positioned tanks. To convert electrical and chemical energy, the electrolytes are pumped through electrochemical cells. The power density depends on the size and specific design of those electrochemical cells. The energy density, and thus energy capacity, depends on the size of the external tanks [160].

The anode and cathode electrolytes are stored in the external tanks, as seen in Figure 20, and contain metal ions. Those ions are the active masses of a flow battery and are pumped into the flow battery stack to the opposite sides of the electrochemical cell. The fluids are separated by an ion exchange membrane which allows protons to pass through it for the electron transfer process. Power can either be supplied or absorbed through a change of the oxidation state of those electrolyte fluids. During the exchange of charge, a current flows over the electrodes, which electrical loads can use. During discharge, the electrodes are supplied with the dissolved active masses from the tanks; once they are converted, the resulting product is returned to the tank [161], [162].

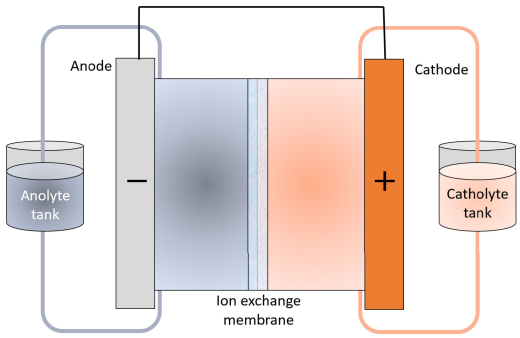

FIGURE 20. Functionality of redox-flow batteries.

Different redox couples have been investigated and tested, of which the vanadium redox-flow battery has been developed the furthest; it uses a V2+/V3+ redox couple as the negative electrolyte pair and a V5+/V4+ redox couple as the positive pair. The use of ions of the same metal on both sides is advantageous compared to other combinations. Despite the fact that the crossing of metal ions over the ion exchange membrane cannot be prevented completely, a combination of two vanadium fluids only results in a small loss in energy. In other redox-flow batteries, which use ions of different metals, crossing electrolytes cause an irreversible degradation of the electrolytes resulting in a loss in capacity [160].

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

Redox-flow batteries are low-cost devices that profit from advantages, such as strong modularity, easy transportability, high efficiency, and scalability. The cost-effective scalability resulting from economies of scale, an advantage to other batteries, such as Li-ion, allows flow batteries to be useful from kW to MW range easily. As a result, the focus of the development of those batteries is in standalone remote area power systems or utility-scale grid systems for load shifting applications [160]. By using larger storage tanks or cell stacks, energy and power can be independently and unlimitedly scaled, allowing using this technology for various applications, especially for large capacities. The self-discharge within the fluid electrolytes is low as the electrolytes are stored in different tanks, the state of charge can easily be monitored through the cell voltage, and the cell temperature can be easily controlled through the flow of the electrolytes. The cells can be left discharged for a long time with no negative impacts. Compared to other high-energy ESS, the response time is extremely quick. Redox-flow batteries are safe and do not need much maintenance [161]. Redox-flow batteries have the disadvantages of low energy and power densities and, thus, are unsuitable for mobile applications. Different aspects, such as the electrolytes shunting currents and the negative effects of not fulfilling the operative temperature, decrease the efficiency of this ESS [161]. Table 27 and 28 present attributes of redox-flow batteries.

A more extensive comparison of different battery technologies including lead-acid, nickel–cadmium, nickel–metal hydride, sodium–sulfur, Li-ion and redox-flow batteries is offered in [147].

TABLE 27. Characteristics of redox-flow batteries.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Redox-Flow Batteries	0.03 - 3 MW [9]	Milliseconds [147]	Seconds - hours [9]
	Energy Capacity	*Cycles*	*Power Density*
	2 - 60 MWh [9]	>12,000 [144]	<2 W/l [144]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	20 - 70 Wh/l [144]	5 - 10 years [144]	80 - 90 % [144]
	Daily Discharge	*Power Cost*	*Energy Cost*
	Small [9]	600 - 1,500 $/kW [144]	150 - 1,000 $/kWh [144]
	Siteability	*Environmental Impact*	*Maturity*
	Very good	Small [163]	Commercialized [163]

TABLE 28. Advantages and disadvantages of redox-flow batteries.

Advantages	*Disadvantages*
Scalability [146]	Requirement of large electrodes [146] High maintenance [146]

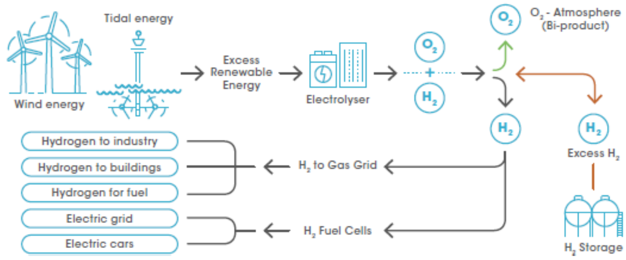

FIGURE 21. Overview of wide usability of Hydrogen [166].

4) HYDROGEN STORAGE

Power-to-gas (P2G) is a process of transforming electric power to produce a gaseous fuel [164]. While H_2 is the most common chemical element on the planet, it is not found in its elemental form, so energy is needed to liberate it from its chemical source [165]. Other than using electricity to win H_2, the more common way is to reform natural gas with steam, this technology is environmentally less convenient [8] and does not fit in this scope as it does not necessarily affect the grid or include electricity.

The gas can be used in different ways, as shown in Figure 21: H_2 is harvested using an electroyliser which is powered through excess energy from the grid and can be used in its gaseous form to supply the gas grid for the industry, for buildings or as direct fuel [166]. By using FC, H_2 can electrically power the power grid or eV [166], alternatively powering the grid can also be achieved through conventional generators such as gas turbines using H_2 as fuel [167].

In this paper, as before, only electric applications of H_2 will be taken into account. Thus, the process P2G in general terms is referred to as power-to-power (P2P).

a: TYPES OF ELECTROLYSERS

An electrolyser is an apparatus that produces H_2 through a chemical process (electrolysis) capable of separating the H_2 and oxygen (O_2) molecules of which water is composed using electricity [168].

$$2H_2O \rightarrow 2H_2 + O_2. \tag{10}$$

There are different electrolyser technologies: diagrams of alkaline (ALKEL), proton-exchange membrane (PEMEL), and solid-oxide electrolysers (SOEL) can be seen in Figure 22.

- ALK electrolyser
  These electrolysers use a liquid electrolyte solution and water. H_2 is produced in a cell consisting of an anode, a cathode, and a membrane. The cells are assembled in series to liberate more H_2 from oxygen at the same time. When an electrical current is applied to the electrolysis cell stack, hydroxide ions move through the electrolyte from the cathode to the anode of each cell and generate bubbles of H_2 gas on the cathode side of the electrolyser and oxygen gas at the anode [168]. The system is operated at 60 to 90°C. The efficiency is about 68 to 77 % and could potentially reach 82 % [165]. ALK electrolysers are a mature technology [169] but require bulky equipment that obtains medium purity H_2 and is not very flexible in operation [168]. ALK electrolysers have the lowest power cost [170]. This technology can be used for large-scale applications but has limited potential of further reducing costs.
- PEM electrolyser
  These electrolysers use a proton-exchange membrane and a solid polymer electrolyte. Water is supplied at the anode. When an electrical current is applied to the electrolyser, water splits into H_2 and oxygen, and the H_2 protons pass through the membrane resulting in the formation of H_2 gas on the cathode side [168]. PEM electrolysers that are commercially available today are more flexible and tend to have a smaller footprint than the alkaline electrolysers. The cell temperature of a PEM cell is 50 to 80°C. This system has an efficiency of 62 to 77 %, with a potential of 84 % in the future [165]. They are best suited to match the variability of VRE, are compact, and produce high-purity H_2. On the other hand, they are more expensive because they use precious metals as catalysts [169]. PEM electrolysers require a higher capital cost than ALK electrolysers. The price difference between ALK and PEM electrolysers is largely explained by the maturity of the technology and the use of precious metals in PEM electrolysers [170]. They are a promising competitor to ALK electrolysers but need to prove to be cost-competitive on large-scale applications.
- Solid-oxide electrolyser
  This is a high-temperature electrolyser that performs solid-oxide electrolysis and operates at temperatures of 700 to 900°C. An SOEL includes a solid ceramic material as the electrolyte. Electrons from the external circuit combine with water at the cathode to form H_2 gas and negatively charged ions. Oxygen then passes through the ceramic membrane and reacts at the anode to form oxygen gas and generate electrons for the external circuit [168]. Currently, the technology is not in a mature stage and has only been tested at a laboratory scale with an efficiency of about 89 % and potentials above 90 % [165]. High-temperature operation results in higher electrical efficiencies than ALK and PEM electrolysers, but it has challenges in material stability and also depends on waste heat. The high temperature steam is either supplied by an external heat source or by an electrical heater, thus negatively contributing to the overall efficiency. There is an uncertainty regarding the investment cost due to the pre-commercial status for SOEL [170]. This technology has extremely high potentials due to the high energy efficiency but is currently on a low maturity level.

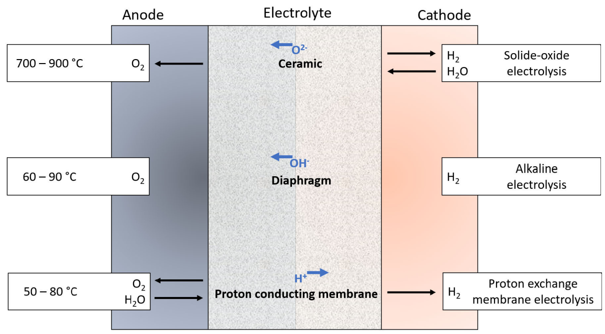

FIGURE 22. **Functionality of different electrolysis types.**

All the above three types of electrolysers are faced with the challenge of optimizing their costs, efficiency, and flexibility of starting to produce H_2 during the surplus electrical energy production.

b: TYPES OF HYDROGEN STORAGE

H_2 can be stored physically as either a gas, a liquid, or as a metal hydride bond. Storage of H_2 as a gas requires high pressure, and in liquid form it requires extremely low temperatures due to its extremely low boiling point (-252.8°C) [171]. H_2 can also be chemically stored on the surfaces of solids via adsorption or within solids by absorption [172].

- Compressed gas storage
  It is the simplest solution for storage, requiring only a compressor and a pressure tank. However, the energy density is low, and for higher pressures, the capital cost and the operating costs increase [173]. The efficiency, including the process of compression, is between 85 % and 91 %, with higher efficiency at lower pressure. The capability for long-duration storage is high as there is effectively no leakage [165]. For large volumes up to several TWh, salt caverns can be used, they have only insignificant leakage and are also highly capable of long-duration storage with efficiencies going upwards, even up to 95 %, including the compression process [8], [165]. For the pressurized gas tanks, there are risks of explosion [165].
- Liquid form storage
  H_2 boiling (and liquefaction point) is -253°C. H_2 is compressed, then cooled in a heat exchanger, and then it is

expanded through a throttle valve [172]. The efficiency is the lowest with 55 to 75 %, and the capability for long-duration storage is low as there is a self-discharge of 0.1 to 0.5 % per day. There are risks of fire and explosion [165]. This technology is not suitable for grid applications.

- Metal hydride bond
  This method typically bonds H_2 at or below atmospheric pressure and release the H_2 when heated at higher pressure. Metal hydrides only store 2 to 6% of the mass of H_2 by weight. The metal hydride storage medium has a high volumetric density but low weight density in terms of H_2 stored, resulting in a typical metal-hydride storage tank being relatively compact but rather heavy [172]. The capability for long-duration storage is high as there is no leakage. There are no significant safety issues with this system, and the efficiency is up to 98 % being extremely promising [165].
  Few peer comparison between different forms of H_2 storage is worth noting here.
  - From a cost perspective, liquid, and compressed storage have advantages over metal hydride [174].
  - For stationary applications, H_2 storage is most applicable in H_2's gaseous form, so pressurized tanks or caverns are the main means of storing it at the moment. Underground storage in salt caverns is by far the most advantageous option for large energy capacities, as long as the geology allows it. Other than salt caverns, there is research on the use of aquifers (bodies of permeable rocks that can contain groundwater).
  - Metal hydrides have potential mainly in niche markets such as backup storage after natural disasters or for black starts, due to their efficiency and safety, but prohibitive costs are an essential deterrent at the moment.
  - While, liquefied H_2 in many ways is ill-suited for stationary storage purposes, it could find applications for long-distance transport in large quantities, mostly to cater to the transport refueling stations, but not for long-term storage objectives [165]. Economics of scale works in its favor while avoiding the need for compressors.

c: TYPES OF FUEL CELLS

H_2 can be electrified in a direct electrochemical process with FC but also using conventional combustion turbines that are not specifically described within this section as their efficiency can not compete with fuel cells and the stored H_2 is just an addition to the conventional fossil fuel [165].

H_2 fuel cells (FC) use the reaction between H_2 and oxygen to produce water and electrical energy. As electrolysers, FC are highly modular. FC technologies can be separated into low-temperature FC such as proton-exchange membrane FC (PEMFC), high-temperature FC such as molten carbonate FC (MCFC) or solid-oxide FC (SOFC). While the functionality of each is very comparable, the operational temperature, the usable fuel, and the electrolyte do differ from each other as seen in Figure 23. Some FC can run in a combined heat and power process to increase efficiency. Mature FC technologies are extremely reliable because they lack moving parts and need low maintenance [165]

- PEM fuel cell
  PEMFCs have an operating temperature of 40 to 100°C. They have an efficiency of 35 to 50 % and have a typical stack size of >1 kW to 100 kW. The advantages of PEMFC are the low temperature [175] and thus the possibility of a quick start-up within less than a second [176]. This FC is very compact and requires low maintenance [175]. The disadvantages are being expensive and sensitive to fuel impurity [175]. This FC is mainly used in transportation, as backup power or portable power [175], and there is potential for PEMFCs to be used for stationary power generation. PEMFCs are best for small-scale systems and transportation until pure H_2 is available to an economically profitable extent [177].
- MC fuel cell
  MCFCs have an operating temperature of 600 - 700°C. They have an efficiency of 45 to 50 %, which can be increased when it is combined in electricity and heat output up to 72 %, and have a typical stack size of 300 kW to several MW. They have the advantages of high efficiency, and fuel flexibility and are suitable for combined heat and power plants. The disadvantages are the slow start-up time or the need for standby mode due to the necessity of heat, those temperatures also cause corrosion and the quicker degradation of components. MCFC can be used in electric utilities especially combined with heat [175].
- Solid-oxide fuel cell
  SOFC have an operating temperature of 700 to 1000 °C with an efficiency of 50% and up to 80% in combination with heat. The stack size varies from 1 kW to 2 MW. Advantages are the highest efficiency of all FC, fuel flexibility, the suitability of systems with heat output, and even with gas turbines. The disadvantages of high temperatures, as with MCFC are a slow start-up or modulation and reduced lifetime. This system can be used as auxiliary power and as distributed power supply [175]. While there is no broad availability of hydrogen, SOFC potentially are superior to other technologies as they can run with natural gas, biogas, and also with less pure hydrogen that could also be blended into mentioned gases. High capital cost and high efficiency leading to low operating costs are superior with less H_2 availability but lower capital costs might strengthen PEMFC in a later stage.
- Regenerative hydrogen fuel cell
  A regenerative hydrogen fuel cell (RHFC) is a configuration of electrolyser, storage, and FC, encompassed together [178]. The most widely installed RHFC

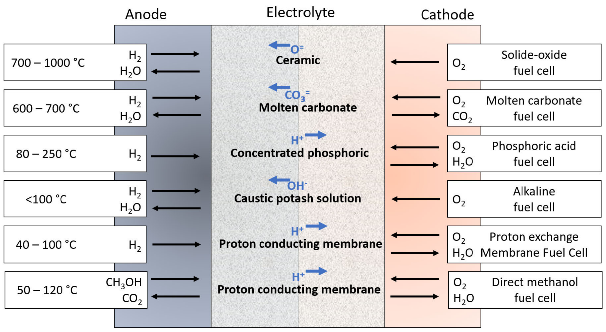

FIGURE 23. Functionality of different fuel cell types.

TABLE 29. Characteristics of hydrogen fuel cells.

Technology	*Power Rating*	*Response Time*	*Discharge Duration*
Fuel Cells	(LT) 0 - 1 MW [179] (HT) 0 - 100 MW [179]	(LT) <Seconds [174] (HT) Hours [174]	Flexible
	Energy Capacity	*Cycles*	*Power Density*
	Flexible	/	>500 W/l [9]
	Energy Density	*Lifetime*	*Round-trip Efficiency*
	500 - 3,000 Wh/l [9]	(LT) 50,000 hours [179] (HT) 90,000 hours [179]	(LT) 35 - 38 % (>85 % w. heat) [175] (HT) 35 - 60 % (>80 % w. heat) [179]
	Daily Discharge	*Power Cost*	*Energy Cost*
	None	(LT) >250 $/kW [175] (HT) 3,500 $/kW [179]	Fuel dependent, HT cheaper than LT due to efficiency
	Siteability	*Environmental Impact*	*Maturity*
	Very good	Small [175]	(LT) Proof of concept (HT) Demonstration

configuration contains an ALKEL, compressed storage and a PEMFC [178]. RHFCs have several characteristics that are well-suited to large-scale energy storage, such as load-shifting. They are not subject to geological requirements, which are important restrictions on PHS and CAES. As redox-flow batteries, the energy capacity and power capacity of a regenerative FC can be configured independently while profiting from economies of scale.

d: IMPACTS, ADVANTAGES, AND DISADVANTAGES

H_2 is a flexible energy storage medium that can be used in stationary FC (electricity only or combined heat and power), combustion turbines, or FC vehicles. Storing H_2 has a very low rate of self-discharge and is extremely applicable for seasonal storage [178]. Also, the electrification of H_2 through FC is well-suited for large energy capacities, as the efficiency of FC systems is nearly unaffected by size expansions. This flexibility means that small (several hundred kW to 1 to 2 MW), relatively highly efficient power plants can be developed to be sited at the user's facility as well as large-scale FC systems. FC are not usable for price arbitrage, as the two vectors round trip efficiency and capacity cost are too low compared to other storage technologies [28]. As backup power for black start, FC can be used. Properties of H_2FC are presented in Tables 29 and 30.

5) PLASTIC BATTERIES

Plastic batteries are completely made from conductive polymers [180], a class of substances composed of very large molecules, a compound that is not a metal but can act like one [181], also known as plastic [182]. The batteries by the company PolyJoule potentially offer a less expensive and longer-lasting alternative to Li-ion batteries for storing electricity from intermittent sources like wind and solar. Plastic, as its material, does provide cheaper material costs and higher safety [180].

TABLE 30. Characteristics of hydrogen fuel cells.

Advantages	*Disadvantages*
Siteability Scalability Variable power rating and energy capacity Low storage cost at large capacities H_2 usable in many non-electric applications Object of massive research and development Combined heat and electricity storage possible	No proven technology at utility scale Low efficiency Costs (at the moment)

a: FUNCTIONALITY

The company has not reinvented the structure of the battery: There is still a cathode, an anode, and a liquid, non-flammable electrolyte. The innovation, however, is that the two electrodes contain no metals. This is thanks to a carbon-graphene hybrid, which is one of the conductive polymers. In the polymer chain inside the battery, carbon-carbon single bonds alternate with double bonds. These bonds are what make the flow of electrons in the metal-free battery possible in the first place: the ions inside the conductive polymers first store energy by oxidation (by giving up electrons), then they are discharged in a process known as reduction (the process of accepting electrons). In the process, the resulting charges flow back and forth between the cathode and anode, as in a conventional battery [181]. The PolyJoule battery cell is constructed using the same traditional methods of many battery types. Alternating anodes and cathodes are interwoven and then connected in parallel to form a cell.

b: IMPACTS, ADVANTAGES, AND DISADVANTAGES

The PolyJoule battery lasts more than 20 years and does not have cycle per day limitations such as Li-ion as it charges within 5 min compared to 2h for Li-ion and 6h for Lead-Acid to achieve 80 % state of charge. A response time of milliseconds and discharge of 1 MW within 10 s (compared to 30s for Lead-Acid and 60s Li-ion) make them usable for frequency regulation and voltage control. After 12000 cycles, the PolyJoule battery still has a depth of discharge of 100 %, which is more than double, compared to Li-ion and more than 20 times compared to average lead-acid, so that it can operate in the harshest of power profiles, including significant partial-state-of-charge applications. The cells can be used in both extremely high and low temperatures without the use of active climate control and with minimal capacity degradation. Overheating, destruction, and short circuits were tested not to

TABLE 31. Characteristics of plastic batteries.

Technology			
Plastic Batteries	*Power Rating* Variable	*Response Time* Milliseconds [181]	*Discharge Duration* Seconds - minutes [181]
	Energy Capacity Flexible	*Cycles* 12,000 with no degradation [181]	*Power Density* No data available
	Energy Density 200 Wh/l [180]	*Lifetime* >20 years [183]	*Round-trip Efficiency* No data available
	Daily Discharge No data available	*Power Cost* No data available	*Energy Cost* 65 $/kWh [180]
	Siteability Good	*Environmental Impact* Small	*Maturity* Developing [183]

TABLE 32. Advantages and disadvantages of plastic batteries.

Advantages	*Disadvantages*
Siteability Scalability Not dangerous [181] Low energy price [181] Quick charge, response, and charge time [181] No cycles per day limitation [181]	No proven technology Low energy and power density [180]

happen and no thermal management is needed, making these batteries ultra-safe and robust from themselves. Properties of plastic batteries can be seen in Tables 31 and 32.

The first-generation cell is suited for mission-critical power applications in the utility and commercial/industrial spaces: peak shaving, frequency regulation, voltage control, hybrid power energy storage, and high-power data center backup. [183]. One disadvantage of polymer batteries is their low energy density. The battery packs are two to five times larger than a Li-ion system of similar capacity resulting in a significantly higher physical footprint that makes it suited for only stationary applications [180], where space is not a challenge. Currently, $65 per kilowatt-hour of storage is targeted for plastic battery systems, where it can potentially compete with Li-ion battery solutions in long life cycle and cost-effectiveness fronts [180].

6) OTHER EMERGING TECHNOLOGIES IN CHEMICAL ENERGY CATEGORY

There are also other forms of chemical energy storage coming into the market. Though some of them are in the nascent stage, they offer tremendous promise to become mainstream, with an adequate push from chemistry developments and application perspectives.

a: SODIUM-ION BATTERIES

One such technology which is worth mentioning is Sodium-ion batteries, where Sodium technically replaces Lithium, the former being easier to mine. The non-inflammability, relatively higher energy density, and ability to operate in cold temperature, makes an ideal case for it. It also ticks the environmental footprint box adequately, with the possibility of being sourced from biomass materials. However, there are contradicting research opinions about the high flammability of the organic solvents involved in sodium batteries [184]. Hence, the topic in general invites a lot of R&D attention to disclaim the myths.

Notwithstanding the above-mixed attributes, HiNa Battery (a subsidiary of China Three Gorges Corporation (CTG), which is a state-owned company of China has delivered commercial operation of 1 GWh, with a steady capacity increase underway. The reported energy density from HiNa is 145 Wh/ kg with 4,500 cycles of operation, with the aim to reach up to 200 Wh/ kg and 8,000-10,000 cycles [185]. Contemporary Amperex Technology Co., Ltd. (CATL) also reportedly reached an energy density of 160 Wh/ kg from Sodium-ion battery pack in 2021 [186], with other Chinese players, such as BYD, steadily joining the race. Thus, it is a matter of time for such technologies to offer a viable alternative and become a dominating option for certain specific applications.

b: ALUMINIUM-ION BATTERIES

Aluminum-ion (Al-ion) batteries are yet another promising technology that knocks the door of both research fraternity, investors as well as start-up and mature industries. Al can exchange three electrons in an ion, which is a big plus compared to Lithium (which can do only one). This potentially increases the power density and capacity envelope, since the volumetric capacity (at around 8.046 mAh/cm^3) is 4 times higher that of Li, and offers a comparable gravimetric capacity (at around 2.980 mAh/g) [187]. There are other advantages of Al being abundant in nature is cheaper and has lesser flammability performances compared to Lithium.

The Graphene-Al-ion battery originally conceptualized by the University of Queensland [188] is now getting commercialized by the Australian start-up CMG, whose (the latter) scope is to build energy storage solutions for eV, laptops to grid storage applications using this technology [189]. The carbon and Al bring extreme conductivity, overcoming the inherent internal resistance quite well compared to Li-ion, with the benefits seen in charging 70 times faster, claimed by CMG. With good heat transfer abilities, it also eliminates the need for sophisticated cooling arrangements and inhibits thermal runaway problems. The energy density currently stands at 150 Wh/ kg, which is not close to what Li-ion has managed to achieve so far (250-300 Wh/kg), but the performance is expected to rise. Another concept developed by MIT about Aluminum-sulphur (Al-S) also offers promising characteristics of batteries with 100 cycles of operation with 520 mAh/g and an energy density of 526 Wh/l [190]. This however uses a molten salt electrolyte and shows increasing charging rate capabilities at higher temperatures (25 times faster at 110 °C).

Both Al-S and Al-ion might suffer from alumina and dendrite deposits and subsequent corrosion, reducing their efficiency over time. There are some solutions to alleviate these problems are already on cards, such as using zinc oxide as a corrosion inhibitor. The technology is still picking up and its viability and usability in the long-term, including commercial success, are yet to be seen and are hard to speculate.

V. COMPARISON OF DIFFERENT ENERGY STORAGE SYSTEMS AND ASSIGNMENT TO APPLICATIONS

Fourteen different storage techniques were compared in this paper, based on mechanical, electrical and electromagnetic, thermal, electrochemical, or mixed physical forms, each having certain unique characteristical strengths and weaknesses and of course few overlaps in some of their properties. Different numerical characteristics are summarized in Table 33, 34, and 35 corresponding to the technology option.

- *Mechanical* ESS profit from quick response times (exception: CAES), high power ratings and energy capacities, many cycles and a high lifetime, efficiency of more than 70 % (again, CAES an exception), and low energy costs.
- *Electrical and electromagnetic* ESS have the fastest response times and efficiency, many total cycles, but relatively low energy capacities and an extremely high self-discharge.
- *Thermal* ESS (CAES and FC also have thermal attributes) have high energy capacities but slow response times and low efficiency.
- *Electrochemical* batteries have high efficiency, moderate response times, scalable power ratings, and energy capacities but unfortunately do not profit from cost reduction at higher energy capacities. They also have risks of accidents or consist of critical materials that have supply chain issues and even involve human rights and geo-political connotations. FC has the potential for high energy capacities at low storage costs, despite low efficiency and maturity.

A. MATURITY LEVEL

Participation of various stakeholders mentioned in Figure 4 in the respective ESS technology adoption, purely depends on the maturity level of the available technology, as well as the budget and technical feasibility of the proposed solution. Different storage technology can be ranked based on their maturity level and commercial acceptance factors from developing (no sites yet), via demonstrating (majorly non-commercial pilots), proof of concept, commercialized to mature technology- limited potential for further development (see Figure 24). An essential aspect of evaluations of technology maturity is the required investments for improvement multiplied by the technology risk, producing a curve that fits the maturity stages peaking at the early demonstration phase [12]. Technologies in early maturity stages do not require much investment as there are no large-scale projects yet. However, the risk of failure is high. Thus the curve starts at a low level. When entering the stage of first demonstration projects, high capital is required, with a high risk of failure while testing the technology. Missing experience requires capital compared to more mature technologies. The further the maturity stages, the less the required capital and the technology risk.

Examples such as Li-ion batteries require significant capital investments, but due to experience and already successful projects a low placement on the curve. It is noticeable that mechanical technologies are primarily mature, electrical and electromagnetic, and thermal energy storage systems are at the medium level of development as far as commercial projects are concerned, and chemical technologies are either more mature or at a very early stage of maturity (depending on the picked technology in this category). Following subsections compare different storage technology and application areas on a different comparison matrix basis.

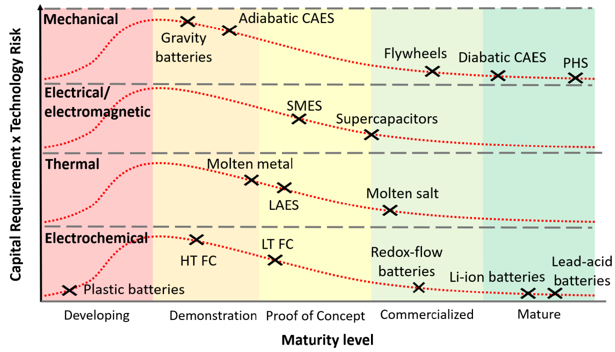

FIGURE 24. Maturity ranking of energy storage systems.

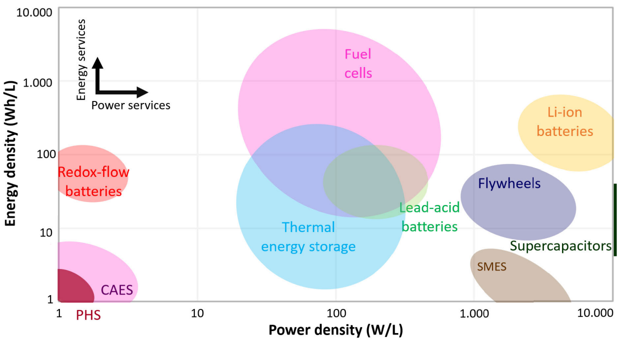

FIGURE 25. Comparison of energy density vs. power density of different storage technology.

B. ENERGY DENSITY VS. POWER DENSITY

Figure 25 offers a comparison of energy density against power density for different technologies of interest. Each technology with sufficient data about its characteristics presented in Tables 33, 34, 35 represent an ellipse, depending on its volumetric energy and power density position. High-energy ESS are more favorable for energy management applications, thus lying on the upper half of the figure. While high-power ESS have advantages within the power and ancillary services, which are represented in the right part of the figure. The lower size of the ellipse implies that the ESS needs to be volumetrically larger, implying large footprints, such as PHS and CAES. On the contrary, FC and thermal ESS are quite lean compared to the PHS and CAES. Supercapacitors have a power density of about 1,100,000 W/l [109], much beyond the range of the power density presented in Figure 25, and thus are just represented through a vertical line with an energy density in the range of 10 - 30 Wh/l [9].

TABLE 33. Characteristics of all presented ESS (1/3).

Technology	*Power Rating*	*Response Time*	*Discharge Duration*	*Energy Capacity*	*Cycles*
Pumped Hydro	100 - 5,000 MW [54]	Seconds [55]	Hours - days [56]	>100,000 MWh [55]	>100,000 [54]
Compressed Air	3 - 400 MW [53]	Minutes [75]	Hours - days [56]	100 - 10,000 MWh [53]	8,000 - 12,000 [8]
Flywheels	0.1 - 20 MW [79]	<1 s [8]	Seconds - minutes [8]	0.1 - 5 MWh [79]	>20,000 - 175,000 [78]
Gravity Batteries	4 - 8 MW [89]	<1 s [90]	Hours [91]	>10 MWh [91]	No data available
Supercapacitors	0 - 0.3 MW [9]	Milliseconds [109]	Seconds - minutes [109]	0.0005 MWh [9]	10,000 [56]
Superconducting Magnetic	0.1 - 10 MW [9]	Milliseconds [43]	Minutes - hours	0.1 - 100 MW [9]	No degradation [43]
Molten Salt	0.1 - 300 MW [9]	Slow [120]	Hours [118]	1 - 5,000 MWh [120]	10,000 [120]
Liquid Air	1 - 3,000 MW [131]	Minutes [131]	Hours [9]	2.5 - 10,000 MWh [131]	No data available
Molten Metal	0.1 - 100 MW [133]	Minutes [136] Seconds with standby [132]	1 - 8 hours [132]	20 - 50 MWh [133]	1 per day [132]
Lead-Acid Batteries	0 - 40 MW [9]	Milliseconds [9]	Seconds - hours [9]	0.001–40 MWh [9]	250 - 1,500 [144]
Lithium-ion Batteries	0 - 300 MW [149]	Milliseconds [9]	Minutes - hours [9]	0 - 1,200 MWh [149]	1,000 - 3,000 [145]
Redox-Flow Batteries	0.03 - 3 MW [9]	Milliseconds [147]	Seconds - hours [9]	2 - 60 MWh [9]	>12,000 [144]
Fuel Cells	(LT) 0 - 1 MW [179] (HT) 0 - 100 MW [179]	(LT) <seconds [174] (HT) hours [174]	Flexible	Flexible	/
Plastic Batteries	Variable	Milliseconds [181]	Seconds - minutes [181]	Flexible	12,000 with no degradation [181]

TABLE 34. Characteristics of all presented ESS (2/3).

Technology	*Power Density*	*Energy Density*	*Lifetime*	*Round-trip Efficiency*	*Daily Discharge*
Pumped Hydro	0.5 - 1.5 W/l [56]	0.5 - 1.5 Wh/l [56]	40 - 60 years [56]	70 - 85 % [54]	Very small [54]
Compressed Air	0,5 - 2 W/l [56]	3 - 6 Wh/l [56]	>20 - 40 years [56]	(Diab.) 42 - 54 % [72] (Adiab.) 60 - 70 % [53]	Small [56]
Flywheels	1,000 - 5,000 W/l [9]	20 - 80 Wh/l [9]	>15 years [32]	85 - 95 % [32]	Full (20 % per hour) [80]
Gravity Batteries	No data available	No data available	25 - 50 years [90]	80 - 85 % [91]	Very small [91]
Supercapacitors	1,100,000 W/l [109]	10 - 30 Wh/l [9]	30 years [109]	84 - 98 % [110]	5 - 40 % [56]
Superconducting Magnetic	1,000 - 4,000 W/l [9]	0.2 - 6 Wh/l [9]	>30 years [112]	>95 % [43]	10 - 15 % [9]
Molten Salt	80 - 500 Wh/l [9]	No data available	20 - 30 years [121]	30 - 60 % [9]	0.3 % [118]
Liquid Air	No data available	50 - 200 Wh/l [131]	20 - 40 years [131]	45 - 70 % [131]	Small [9]
Molten Metal	No data available	No data available	30 years [136]	40 % [136]	<1 % [132]
Lead-Acid Batteries	90 - 700 W/l [144]	50 - 80 Wh/l [144]	3 - 15 years [144]	50 - 90 % [144]	0.1 - 0.3 % [9]
Lithium-ion Batteries	1,300 - 10,000 W/l [144]	200 - 400 Wh/l [144]	5 - 20 years [144]	85 - 95 % [144]	0.17 - 0.33 % [150]
Redox-Flow Batteries	<2 W/l [144]	20 - 70 Wh/l [144]	5 - 10 years [144]	80 - 90 % [144]	Small [9]
Fuel Cells	>500 W/l [9]	500 - 3,000 Wh/l [9]	(LT) 50,000 hours [179] (HT) 90,000 hours [179]	(LT) 35 - 38 % (>85 % w. heat) [175] (HT) 35 - 60 % (>80 % w. heat) [179]	None
Plastic Batteries	No data available	200 Wh/l [180]	>20 years [183]	No data available	No data available

C. DISCHARGE DURATION VS. RESPONSE TIME

Another important characteristic that begs a similar comparison is the discharge duration at a given power rating against the response time. Figure 26 offers a suite of different applications, specified based on discharge duration as well as response time separately. The discharge duration indicates how long the storage device can remain in action at a given power rating for performing a specific task of load shifting,

TABLE 35. Characteristics of all presented ESS (3/3).

Technology	*Power Cost*	*Energy Cost*	*Siteability*	*Environmental Impact*	*Maturity*
Pumped Hydro	2,000 - 4,300 $/kW [9]	5 - 100 $/kWh [9]	Limited [54]	Large [54]	Mature [54]
Compressed Air	400 - 800 $/kW [56]	2 - 50 $/kWh [56]	Limited [56]	(Diab.) Large [56] (Adiab.) Small [56]	(Diab.) Mature [71] (Adiab.) Demonstr. [77]
Flywheels	150 $/kW [81]	400 - 800 $/kWh [80]	Very good [79]	Small [80]	Commercialized [79]
Gravity Batteries	250 - 350 $/kW [91]	65 - 250 $/kWh [91]	Good [91]	Small [91]	Demonstration
Supercapacitors	50 - 100 $/kW [81]	500 - 2,000 $/kWh [81]	Very good	Small [56]	Proof of concept
Superconducting Magnetic	1,000 - 72,000 $/kW [9]	200 - 489 $/kWh [9]	Size dependent [9]	Small [112]	Proof of concept [9]
Molten Salt	No data available	4 - 20 $/kWh [121]	Very good [121]	Small [121]	Commercialized [121]
Liquid Air	1,100 - 2,700 $/kW [131]	300 - 1,000 $/kWh [131]	Good [131]	Small [131]	Demonstration [131]
Molten Metal	No data available	No data available	Very good [132]	Small [132]	Developing [132]
Lead-Acid Batteries	300 - 600 $/kW [144]	50 - 200 $/kWh [145]	Very good [146]	Medium [147]	Mature [144]
Lithium-ion Batteries	333 - 428 $/kW [151]	100 - 2,000 $/kWh [145]	Very good	Medium [146]	Mature [146]
Redox-Flow Batteries	600 - 1,500 $/kW [144]	150 - 1,000 $/kWh [144]	Very good	Small [163]	Commercialized [163]
Fuel Cells	(LT) >250 $/kW [175] (HT) 3,500 $/kW [179]	Fuel dependent, HT cheaper than LT due to efficiency	Very good	Small [175]	(LT) Early commercialized (HT) Demonstration
Plastic Batteries	No data available	65 $/kWh [180]	Good	Small	Developing [183]

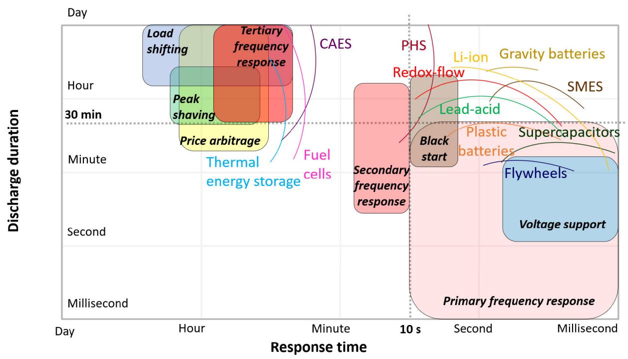

FIGURE 26. Operational perimeter of different storage technology and applications with reference to discharge duration and response time.

peak shaving, frequency response, etc.. The response time on the other hand represents how fast the particular technology can be deployed. Each grey rectangle represents the objective of a specific task and is accordingly positioned depending on its length of operation (discharge duration, increased from bottom to top) and response time (decreased from left to right-higher means poor response and vice versa).

This is largely formulated based on the data received from the literature that are captured in Table 4. The response time and discharge duration are sometimes represented subjectively, meaning the secondary frequency control starts before the disappearance of primary frequency control, and likewise for secondary and tertiary frequency control, as already illustrated in Figure 3. This is precisely why there is sometimes an overlap in the start and stop operation of these services, exhibited by differently colored rectangles in Figure 26. Technologies that are applicable to either of these classes are arched next to it, depending on their period of operation.

The technology those are relevant for ancillary support could operate on a longer time horizon of discharging the storage that lasts minutes to even several hours, depending on the specific technology and the scale. This way, CAES, FC, and TES cover a broad spectrum of ancillary services while running, but at the same time suffer from poor reaction time, which can be triggered not less than a few minutes after the support is requested. Thus they lie on the left half of Figure 26 (i.e. response time is a few minutes after the event is triggered), but on the upper half of the figure, where the discharge duration is relatively longer (from few minutes to several hours).

Similarly, there exists a bunch of technologies that are intended for fast response operations, thus participating in applications like primary and secondary frequency response, voltage support, or even black start. In such cases, the response time requested is within a few cycles of the event to a maximum of a few seconds. Many immature technologies such as plastic batteries, gravity batteries, and SMES, promise to contribute here. In addition, matured technology such as flywheels, lead-acid batteries, and Li-ion batteries are also preferred for this task. The arch for PHS is special here, as it offers a fast response and still offers a long discharge duration, thus acting as the best of both worlds. The same statement applies to Li-ion batteries as well, which have a larger spectrum of operation- a response time of milliseconds to seconds, and can last even for a few hours.

D. FIGURE OF MERITS OF DIFFERENT TECHNOLOGY AGAINST APPLICATION AREAS

An explanation of the application areas with the respective figure of merits is further explained below for the sake of completeness, including an assessment of the respective technology. This is based on the authors' understanding and interpretation of various metrics that have been captured in the collected literature. A logical explanation of a radar chart is offered to validate the current standing of the technology for the specific application area. It must be noted that the indicators of the radar charts differ for every discussed application area, thus highlighting the most pertinent technology for a given application.

Two groups of radar charts were prepared based on the data obtained from Tables 33, 34, 35 for defining the overall and specific contribution from respective storage technologies, in realizing application specific targets. Figure 27 corresponds to the energy management-related applications, namely- load shifting, peak shaving, and price arbitrage. Whereas, Figure 28 represents ancillary services related traits, viz. primary frequency response and voltage support (together), followed by secondary and tertiary frequency control. The following steps were followed to arrive at the formation of the radar chart.

1) For each application area, only the relevant characteristics are picked (as shown in the left part of the figures). Applicable storage technologies catering to those characteristics are assembled together (in the middle part). Finally, the most plausible technologies of interest are picked and presented in the right part of the figure.
2) Each characteristic is ranked between a minimum value of one and a maximum of ten, representing the worst and best performance respectively from the available technologies. The ranks of those technologies falling in between are decided by leveling them as an exponential growth function, limited by the lower and upper limits of 1 and 10, respectively. This way, it helps maintain a uniform distance between the ranking of different technology in the radar chart.
3) Sometimes there is missing information about a particular characteristic of a specific technology. In such occasions, the ranking is not performed for that characteristic and is left blank, resulting in a disconnected radar chart for that technology. This is done to avoid misrepresentation of certain information in an erroneous way.

a: ENERGY MANAGEMENT

This section summarizes responses of different technologies pertaining to energy management related application areas.

- Load Shifting
  Load shifting is expected to be the most crucial energy storage application in VRE-based power systems. Large energy capacities need to be stored temporarily and shifted to lower energy supply time frames. The key physical properties contributing to load shifting are discharge duration and energy capacity. However, there are environmental, geographical as well as economic considerations of a particular technology that makes it suitable to be utilized at a particular location. Therefore, siteability, and environmental impact play a role in the first two criteria, whereas the economic consideration decides the maturity, cost of the technology, lifetime, and aspects of a chosen technology. The radar chart thus helps in the best trade-off on choosing a particular technology, depending on which attributes are prioritized over the others. Other than intra-day shifting, seasonal energy shifting may become a trend in the future. Load shifting requires ESS that are able to operate daily to multiple times per day. The state of charge of load shifting ESS may vary from being fully charged to being almost empty. The required response time does not have to be fast, but the energy capacity and discharge duration are expected to be high. The top charts in Figure 27 presents the behavior of different technologies, in response to load shifting. PHS can be seen to satisfy all the vital attributes desired for this application. Besides, CAES, molten salt, molten metal, gravity batteries, and high-temperature FC can potentially be used in a potent form.
- Peak Shaving
  Industrial consumers can potentially shave energy from their power consumption peaks by shifting generated PV energy or stored grid energy to time frames of higher demand. This would tremendously benefit energy and financial security for such actors. ESS for this purpose needs to operate once or a few predictable times a day. Unlike the load shifting application, peak shaving requires fewer attributes and is expected to contribute for a shorter period. The state of charge mostly is at 100 % and the system is discharged quickly. Due to predictable consumption peaks, the response time of the ESS does not need to be fast. The power rating and energy capacity are highly user-dependent, but the whole system needs to be easily siteable. The radar charts in the middle part of Figure 27 show the available characteristics of different storage technologies to serve peak shaving features. As can be seen in the radar chart, energy capacity, and density are two major technical requirements, whereas siteability and technical maturity decide what kind of technology can be implemented in a particular case. Energy cost is not a significant factor here, as peak shaving is an urgent problem and can alleviate grid congestion in a big way. The most engaging technologies for this task are seen to be high-temperature FC and Li-ion batteries. It is important to note that

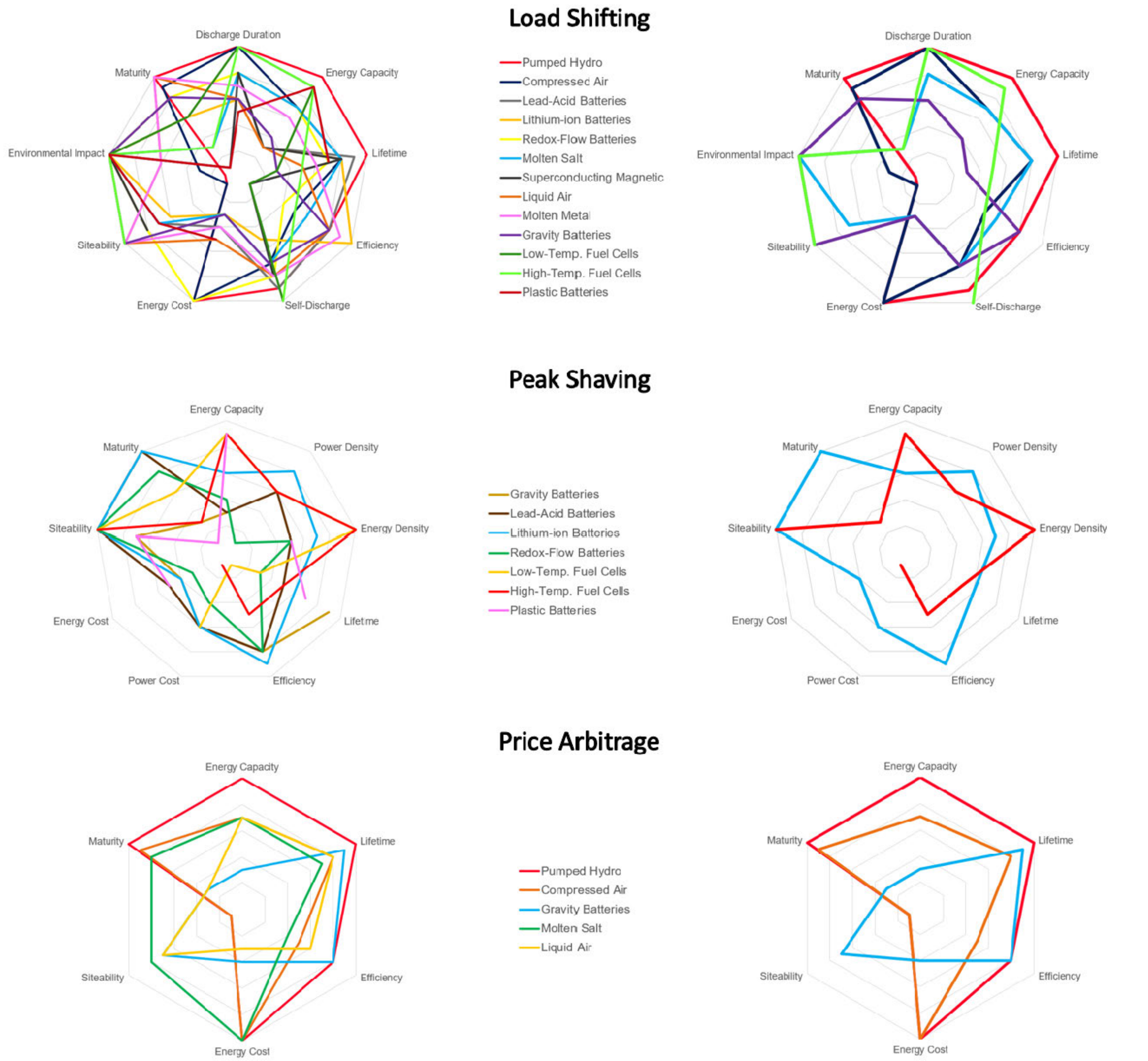

FIGURE 27. Radar charts suggesting most promising technology for energy management applications.

some characteristics between FC and Li-ion batteries are not exactly complementary and serve different objectives under given circumstances. However, H_2 FC may become more profitable for high energy capacities in the future.

- Price Arbitrage
  Price arbitrage is an economic motivation to buy energy at cheap prices and sell it at higher prices. Therefore, in the radar chart, fewer attributes have been considered, since they bear different significance compared to the former two application areas. Economic considerations are absolutely secondary for this purpose, however, siteability of a particular technology depends on its availability in the location of interest. ESS need to have low energy storage costs and high round-trip efficiency to be worthwhile. Typically, there is only one cycle per day and most requirements are similar to load shifting. The most potential contenders are within PHS, CAES, and gravity batteries, as seen in the bottom part of the radar chart in Figure 27. Especially PHS is dominating price arbitrage as it is the only ESS with stronger efficiency and energy cost. The siteability attribute in particular is a positive gain for gravity batteries, especially if it continues to flourish as a technology in the coming years. As can be seen in this particular case, a lot of emerging technologies are waiting to dominate this

particular application, since the physical footprint and even cost is not a concern, and these technologies can be benefited from the economy of scale.

b: ANCILLARY SERVICES

Similar to the energy management feature, the ancillary service-related applications are focused on in this section.

- Primary Frequency Control and Voltage Support
  The applications primary frequency control and voltage support have comparable requirements, especially a quick response time and high cycling. Voltage Support has the requirement for the quickest response time. The energy capacity is not too important for both applications. Both applications require a high cyclability with a state of charge of around 50% as there are many events with low energy requirements that have the characteristics of short pulses. Compared to energy management applications, there are fewer possible energy storage systems that fit these requirements. Five ESS have strong characteristics for primary frequency support and voltage support. Especially flywheels and supercapacitors are well-fitting systems for this purpose (see the top charts of Figure 28). In Japan, SMES does provide power for ancillary services [191]. Li-ion batteries are more commonly used technologies and are also used for frequency regulation and voltage support.
- Secondary Frequency Control
  While primary frequency control stabilizes the frequency after the occurrence of a contingency, secondary frequency control makes the frequency recover to a non-critical frequency window. Therefore, compared to primary frequency control, the response time needs to be less quick, and the discharge time needs to be for a longer period. Especially PHS, and Li-ion batteries have strong characteristics to satisfy such needs. Even the new entrant gravity battery offers comparable traits, at least for some of the available characteristics (see the middle charts of Figure 28).
- Tertiary Frequency Control
  Tertiary frequency control is a replacement reserve for secondary frequency control. Other than previous control stages, it is not activated automatically. The response time does not need to be quick at all, more important is the storable energy capacity and discharge duration, as it supports the affected system part to keep the frequency stable. The usable ESS are comparable to those for load shifting with especially PHS having strong attributes, as seen in the bottom chart of Figure 28.

VI. IMPORTANT TAKEAWAYS AND CONCLUSION

Energy storage solutions these days are not a choice but are becoming an integral part of the energy transition amongst the utilities. There are many different applications for energy storage, where many ESS can be used for. Within this paper, six energy storage applications and 14 different technologies at different maturity stages were presented. This section summarizes some of the dominant trends observed in this space that are suitable for ESS. It also focuses on the forthcoming challenges and opportunities presented to storage solutions and their commercial viability bottlenecks.

TABLE 36. Limitation of PHS and Lithium-ion batteries.

PHS	*Li-ion batteries*
Limited geographic usability	Degradation over lifetime
Most potential sites already used	Flammability
Environmental impacts	Additional protection requirements
High capital cost	Raw material supply chain
	High costs for large capacities
	Critical disposal concerns

A. DOMINATING ENERGY STORAGE SYSTEMS AND THEIR PROSPECTS

This section discusses the two most dominant storage technology, namely- PHS and Li-ion batteries that hog the limelight as a promising technology for grid storage and the different prospects attached to them. PHS systems have been the most commonly used energy storage systems for a long time [50], [51]. As seen in the previous Section V, the characteristics of PHS for many large energy capacity storage applications are superior to those of other ESS, currently available. BESS is one of the fastest growing technologies in the sustainable energy industry [141], [142]. Li-ion batteries are the most prevalent type within BESS [142]. The costs decreased by 85 % within ten years due to material availability and technological improvements, such as power rating and energy capacity [192]. The BESS development is increasing almost exponentially with Li-ion, lead-acid, and redox-flow in that order, as the most relevant cell chemistry. BESS solutions are mainly used in ancillary services and particularly in frequency regulation. Its contribution towards energy management applications is statistically lower but has grown significantly in the past years. Yet, PHS systems, as well as Li-ion batteries, come up with certain limitations which require deliberation. A few of those limitations are listed in Table 36.

The age-old PHS concept is reaching saturation due to the lack of new sites where the technology can be harnessed. However, some redemption is around the corner by startups like Rheenergise. It utilizes a "high-tech" fluid which is 2.5x denser compared to water, in the code name R-19. The high density essentially reduces the need for a high head of water storage for performing the discharge action and still maintains the same efficiency of a dam which would be 2.5 times taller [193]. The upfront civil construction expenses (deemed 65% of the total cost of the project) are claimed to be substantially low through this technology. The first demonstrator for the concept is underway and shows great promise for natural scalability, where curtailed RES can be put to use and the high-density PHS solution can be tested in lower-height mountains [194]. Ocean battery technology also explained in Section IV offers the promise of bridging the siteability concerns in a constructive way.

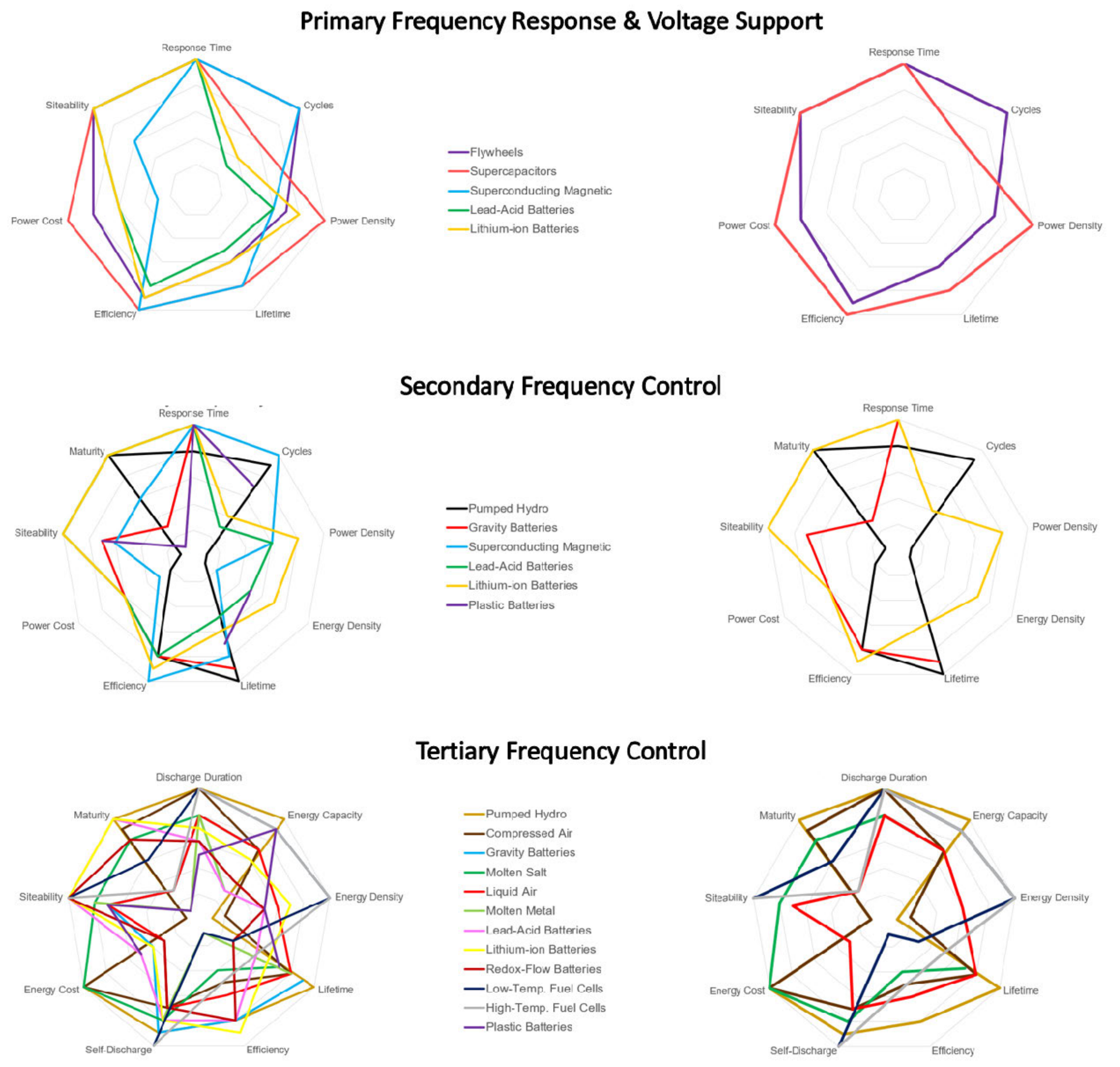

FIGURE 28. Radar charts suggesting most promising technology for ancillary service applications.

Li-ion Batteries have come of age, dealing with fire risks due to thermal run runaway concerns. The thermal characteristics are undergoing significant research progress with better cell chemistry, quick heat dissipation techniques, active cell balancing, and a continuous thermal monitoring system. Tesla is supporting a research group claiming to develop Lithium-, nickel- and manganese-based battery chemistry with a potential lifetime of 100 years at higher energy density [195].

Notwithstanding the developments happening with PHS and Li-ion batteries for retaining their competitive advantage and market dominance, other technologies mentioned in this paper are certainly going to claim the top spot in the coming years with a scale of innovation, market outreach as well as diversification in application domains.

B. GLOBAL OUTLOOK TOWARDS RECENT DEVELOPMENTS OF ENERGY STORAGE APPLICATIONS

More than 95% of electrical energy storage capacity worldwide is stored within PHS systems in 2022, followed by electrochemical, thermal, other mechanical, and electrical or electromagnetic ESS [50]. Between 2022 and 2030, a compound annual growth rate of 11 % of energy storage is expected, BESS even at a higher growth rate of 14 % [196]. Energy infrastructure developments in the Asia Pacific and North America significantly boost the demand for energy storage. Within Europe, the United Kingdom, the United States, and India, electrochemical energy storage is likely to grow more rapidly, in the Middle East, Africa, and Central and South America, thermal energy storage demand might grow in the long demand. Especially the growing popularity of battery eV in Europe is aiding the development of on-grid battery storage [196].

Load shifting is the most vital energy storage application with the biggest expected growth. As a result, the electricity demand is expected to rise, from which variable and unpredictable energy sources will play an ever more significant role. The total energy demand, and especially the use of VRE sources, might grow in the future, resulting in higher demand for load shifting through energy storage technologies [197]. Thus, there is a need for higher capacity ESS. Vehicle-to-grid initiatives can also assist widely in load shifting by bringing in a fleet of eV at the charging network to offer reverse power to the grid, helping momentary alleviating momentary overloads.

Also, energy trading through price arbitrage in power systems with more variable, uncertain, and distributed energy supply [16] might play an essential role in the future. In 2021 nearly 60 % of installed utility-scale storage capacity in the United States was used for price arbitrage, compared to 17 % in 2019 [29]. An example of massive energy trading potential is the purchase of electrical energy of the United Kingdom from Belgium suppliers for almost 10,000 British Pounds (more than 50x of the typical price - average price is about 178 British pounds) in July 2022 [198] "to keep the lights on".

Peak shavings and additional storage capacity substantially owned by industrial consumers are also increasing. Besides saving money through shaving power consumption peaks, UPS is vital in industrial processes with high power requirements, such as melting metals, to produce parts for different products requiring a lot of electricity [199]. Energy supply disturbances are expected to happen more frequently but heavily affect those productions. Thus, own ESS are expected to be more important in the future.

Within quick response ancillary services, such as primary frequency control and voltage support, there are already two strong ESS flywheels and supercapacitors. Especially the amount of those systems might grow due to increased electrification, and more variable and unpredictable energy supply, as mentioned previously [16].

To fulfill the requirements of energy storage applications, hybrid ESS may be promoted more by exploiting mutual strengths and weaknesses. For example, for frequency regulation, it is possible to use different ESS for the different control levels (e.g., supercapacitors for primary frequency control, and batteries for secondary frequency control).

The ancillary services are historically offered by third parties to the TSO and this is also partly driven by country regulations, where the TSOs do not own storage systems. Therefore DSOs with generation capacities are stepping up to this responsibility, thus offering more modularized storage solutions, which operate at lower voltages, at the distribution level, thus participating in stabilizing demand side response. The distribution grid operator Vattenfall has installed a 5 MW, 20 MWh Li-ion battery, from BMW car batteries in the Swedish city of Uppsala, in order to help peak shaving and decongest the Swedish TSO, Svenska Kraftnät in the absence of its (the latter's) grid expansion plans [200]. This was just the start of such technology demonstrations in 2020-21. China utilized 800 MWh redox flow batteries, integrated into the grid at 200 MW capacity, lasting 4 straight hours [201] in 2022. There are many grid storage projects across the globe available here.

C. EMERGING TRENDS AND CONCLUSIONS

Storage is already a relevant grid operation, planning, and maintenance solution. Grid reinforcement and release interventions are going to be more common all around the world, wherever RES has a major role to play in the generation mix. Many emerging solutions will become mainstream in the coming decades due to their promise of scalability, the economy of operation, and technical viability. The International Energy Agency projects that most of the reductions in global CO_2 emissions between now and the year 2030 would come from technologies readily available today, and more futuristic ideas towards this objective will become mainstream by 2050 [202]. Some of the key takeaways the authors predict regarding the technology solutions and application areas are as follows:

1) Most of the energy storage markets will experience high growth in the coming years, thanks to the scores of volatile VRE sources. High capacity long-duration energy storage will continue to be explored by the utilities, as the most dominating PHS and Li-ion battery solutions, alone cannot cater to the ever-growing needs for their respective limitations mentioned in the paper.
2) For ancillary services, flywheels, and supercapacitors have the most applicable characteristics. Li-ion batteries are suitable for frequency regulation, especially for secondary frequency control.
3) Li-ion batteries will see much improvement, especially in energy density, and costs. The higher availability of grid storage can be facilitated by the second life of a battery pool coming from the eV fleet.
4) H_2 storage can offer viable alternatives to PHS and Li-ion technologies, towards load shifting and price arbitrage applications by different fuel cell provisions
5) Gravity batteries show tremendous promise as they are more site independent than other technologies. They profit from the advantages of the dominating mechanical potential ESS and address the disadvantages of PHS, namely siteabiliy and scalability. This is widely promoted by a series of funding from venture capitalists and open markets.
6) Thermal storage, including compressed air, have the potential for large-scale storage. Many different technologies are on the verge of a breakthrough, and there is massive research and development within this sector. Compressed air, molten salt, liquid air, and molten metal are promising technologies for storing large amounts of energy.

7) Hybrid storage solutions will become more common where multiple technologies can coexist such as super-capacitors and batteries for frequency regulation or battery plants with different types of batteries.

NOMENCLATURE

°C	Degrees Celsius.
%	Percents.
η	Efficiency.
$\triangle T$	Change in temperature.
ν	Volume.
ρ	Density of water.
CO_2	Carbon dioxide.
H_2	Hydrogen.
H_2O	Water.
AC	Alternating current.
Al-ion	Aluminum-ion.
ALKEL	Alkaline electrolyser.
BESS	Battery energy storage systems.
C	Capacity.
CAES	Compressed air energy storage.
CSP	Concentrating solar power.
DC	Direct current.
e.g.	example given.
EES	Electrical and electromagnetic energy storage.
ENTSO-E	European Network of Transmission System Operators for electricity.
ESS	Energy storage system.
eV	Electric vehicles.
FACTS	Flexible AC transmission system.
FC	Fuel cells.
G	Gravitational constant.
H	Inertial constant.
h	Height.
HV	High voltage.
I	Current.
I	Inertia.
IBR	Inverter-based resources.
IGBT	Insulated-gate bipolar transistor.
IGCT	Integrated gate-commutated thyristor.
K	Rotational kinetic energy.
L	Inductance.
l	Liter.
LAES	Liquid air energy storage.
LFDD	Low frequency demand disconnection.
Li-ion	Lithium-ion.
m	Mass.
m	Meters.
MCFC	Molten carbonate FC.
MESS	Mechanical energy storage systems.
n.d.	No
n.p.	No place of publication known.
O	Oxygen.
P2G	Power-to-gas.
P2P	Power-to-power.
PEMEL	Proton-exchange membrane electrolyser.
PEMFC	Proton-exchange membrane FC.
PHS	Pumped hydro storage.
PQ	Power Quality.
PV	Photovoltaic.
q	Quantity of transferred heat.
RES	Renewable energy sources.
RHFC	Regenerative hydrogen fuel cell.
RoCoF	Rate of change of frequency.
rpm	Revolutions per minute.
S	Apparent power.
s	Seconds.
SMES	Superconducting magnetic energy storage.
SOEL	Solid-oxide electrolyser.
SOFC	Solid-oxide FC.
T	Tons.
T&D	Transmission and distribution.
TES	Thermal energy storage.
TWEST	Traveling wave energy storage technology.
UPS	Uninterruptible power supply/source.
V	Voltage.
v	Velocity.
V2G	Vehicle-to-grid.
VAR	Volt Ampere Reactive.
VRE	Variable renewable energy.

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