Hybrid Energy Storage: The Key to a Stable, Clean Power Future

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1.0 Introduction

The transition to a cleaner energy future has accelerated the integration of renewable energy (RE) sources into existing power grids worldwide. This shift offers significant environmental benefits and supports decarbonisation goals. However, it also introduces challenges that must be addressed to maintain system reliability and stability.

As wind and solar generation increases, power systems face growing issues including:

- Frequency fluctuations caused by rapid supply-demand imbalances
- Voltage instability particularly in weak grid sections
- Grid congestion resulting from geographical mismatches between generation and load centres
- Curtailment of clean energy resources during periods of oversupply.

These challenges stem from the fundamental intermittency of renewable energy resources. Wind turbines and solar panels generate electricity based on environmental conditions, not grid requirements. This creates critical timing mismatches between generation and consumption patterns, which conventional grid operations struggle to accommodate.

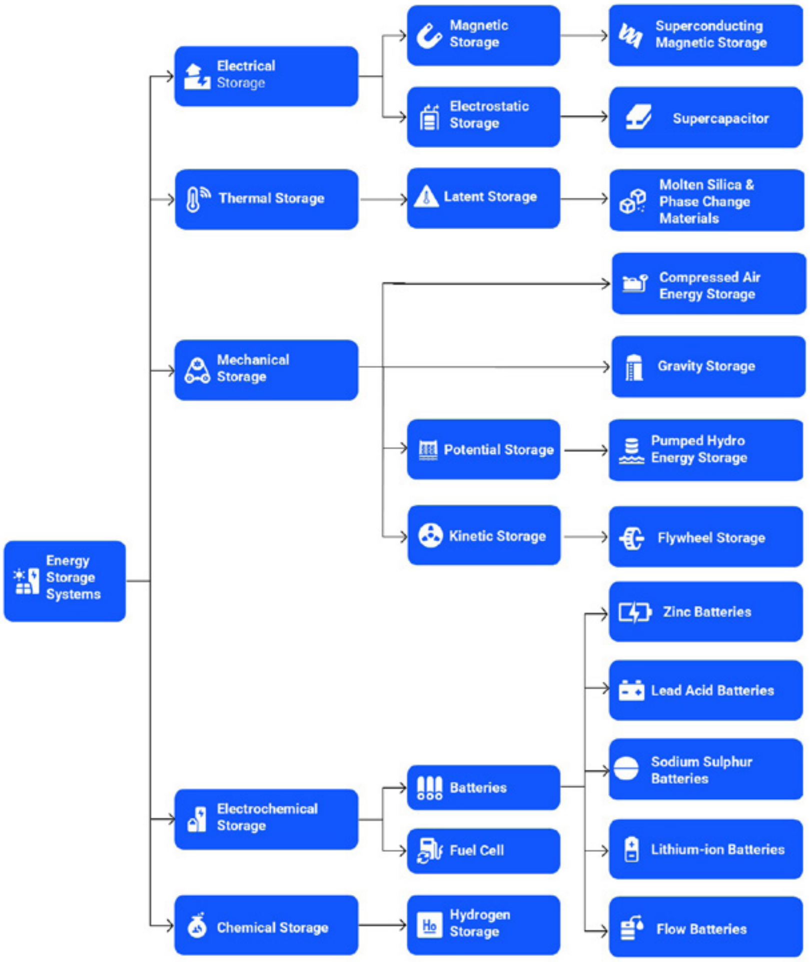
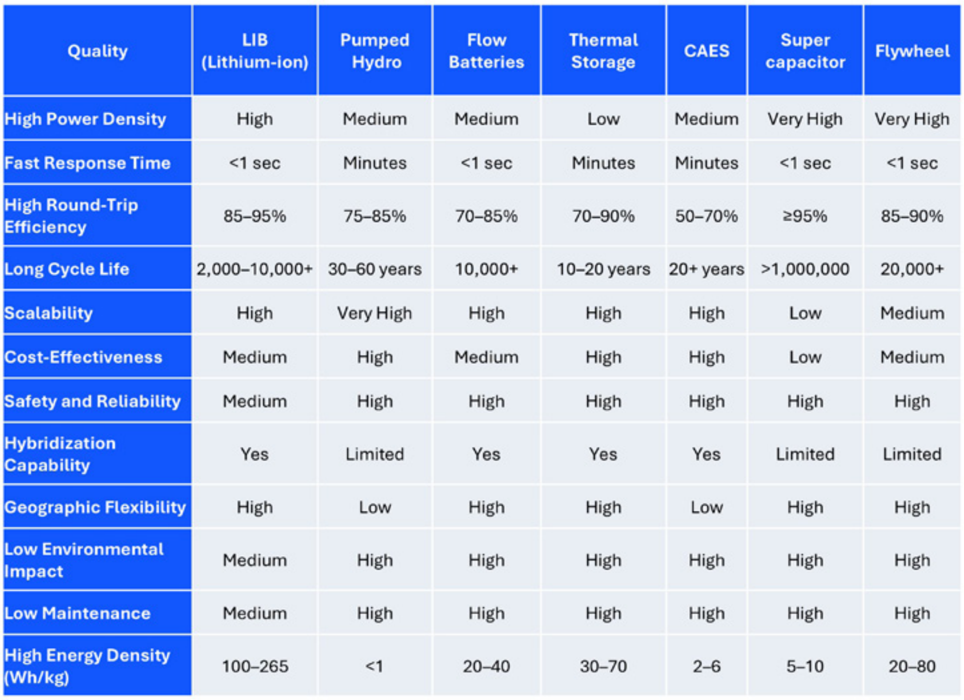


Figure 1: Types of ESS.

Energy storage systems (ESSs) have evolved over decades and emerged as crucial solutions to these challenges. They are available in various forms, including electrochemical, chemical, mechanical, and electrical storage systems, as illustrated in Figure 1.

For frequency regulation, energy storage systems provide critical grid balancing services, though their response capabilities vary by technology type. Inverter-based systems (such as lithium-ion batteries) can respond within milliseconds to grid deviations, supplying or absorbing power to correct imbalances between generation and demand. In contrast, synchronous generator-based storage technologies typically respond within seconds to minutes but offer valuable system inertia that enhances grid stability. For voltage support, the power conversion systems (Bidirectional Inverters) in battery storage installations inject or absorb reactive power to maintain voltage levels within acceptable ranges. This capability is provided by the inverter technology rather than the battery itself, similar to how standalone static var compensators and synchronous generators provide voltage control through field excitation adjustment.

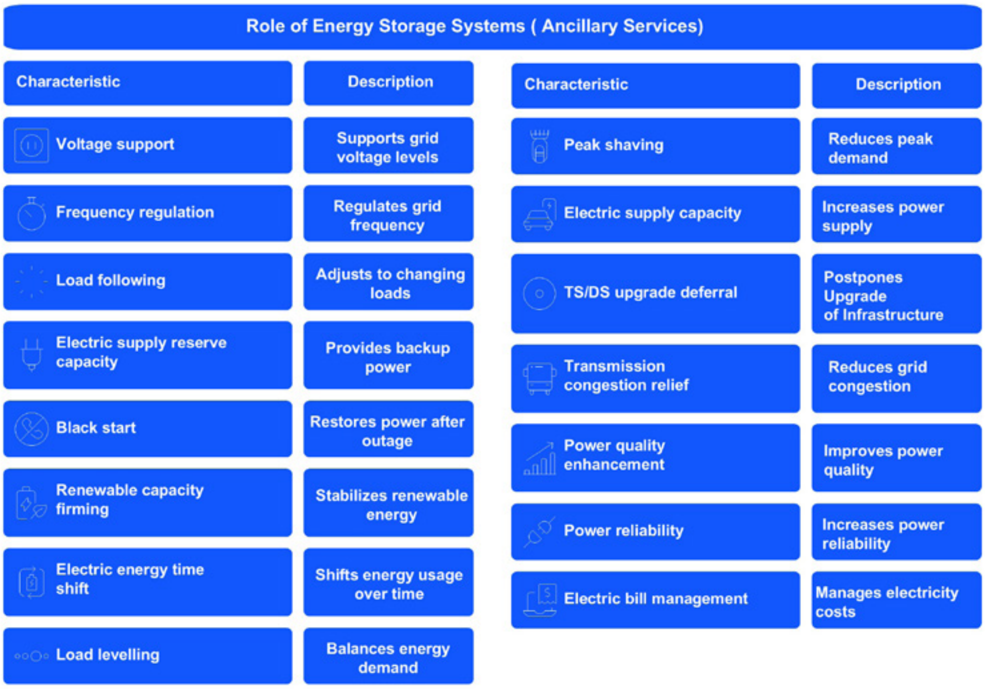
Energy storage systems also support system restoration by providing initial power during grid recovery following blackouts. However, most storage technologies have limited energy discharge duration, making them suitable for initial restoration phases while conventional generators (gas turbines, conventional hydro, or thermal plants) handle sustained system recovery. The choice of black-start resources varies by system requirements and available infrastructure. Additionally, storage systems provide spinning reserve functionality, with inverter-based technologies offering rapid power injection while backup generators start up. This enables conventional generators to operate at optimal efficiency without maintaining costly idle capacity for contingency response.



Quality	LIB (Lithium-ion)	Pumped Hydro	Flow Batteries	Thermal Storage	CAES	Super capacitor	Flywheel
High Power Density	High	Medium	Medium	Low	Medium	Very High	Very High
Fast Response Time	<1 sec	Minutes	<1 sec	Minutes	Minutes	<1 sec	<1 sec
High Round-Trip Efficiency	85–95%	75–85%	70–85%	70–90%	50–70%	≥95%	85–90%
Long Cycle Life	2,000–10,000+	30–60 years	10,000+	10–20 years	20+ years	>1,000,000	20,000+
Scalability	High	Very High	High	High	High	Low	Medium
Cost-Effectiveness	Medium	High	Medium	High	High	Low	Medium
Safety and Reliability	Medium	High	High	High	High	High	High
Hybridization Capability	Yes	Limited	Yes	Yes	Yes	Limited	Limited
Geographic Flexibility	High	Low	High	High	Low	High	High
Low Environmental Impact	Medium	High	High	High	High	High	High
Low Maintenance	Medium	High	High	High	High	High	High
High Energy Density (Wh/kg)	100–265	<1	20–40	30–70	2–6	5–10	20–80

Table 1: Qualities of different ESSs.

Beyond these ancillary services, storage systems facilitate energy management applications such as peak shaving, where behind-the-meter storage reduces peak demand on the power system by utilising stored energy during high-demand periods (without reducing total energy consumption, just shifting the source of supply). Energy arbitrage allows storage operators to purchase electricity during low-price periods and discharge during high-price periods, capturing value from temporal price differences. Additionally, storage systems enable transmission deferral by reducing peak loads on constrained grid elements, potentially postponing costly infrastructure upgrades. Figure 2 illustrates the different types of services offered by ESSs.



Role of Energy Storage Systems (Ancillary Services)

Characteristic	Description	Characteristic	Description
Voltage support	Supports grid voltage levels	Peak shaving	Reduces peak demand
Frequency regulation	Regulates grid frequency	Electric supply capacity	Increases power supply
Load following	Adjusts to changing loads	TS/DS upgrade deferral	Postpones Upgrade of Infrastructure
Electric supply reserve capacity	Provides backup power	Transmission congestion relief	Reduces grid congestion
Black start	Restores power after outage	Power quality enhancement	Improves power quality
Renewable capacity firming	Stabilizes renewable energy	Power reliability	Increases power reliability
Electric energy time shift	Shifts energy usage over time	Electric bill management	Manages electricity costs
Load levelling	Balances energy demand		

Figure 2: Services offered by ESSs.

2.0 The Need for Hybrid Storage Solutions

The energy landscape is rapidly evolving with several major developments occurring simultaneously. Large-scale power systems are expanding, renewable energy sources are being integrated into existing grids and electric vehicles are creating new demand patterns. This diverse set of requirements presents a significant technical challenge: no single storage technology can effectively support all these diverse applications while maintaining optimal efficiency and performance. Individual storage technologies face inherent limitations, making them insufficient for modern grid demands.

Consider a modern city's transportation system. Just as no single mode of transport can efficiently meet all travel needs, no single energy storage technology can fully address all grid requirements effectively. Long-duration technologies like compressed air energy storage (CAES) or pumped hydro energy storage (PHES) excel at sustained energy delivery over hours or days, while lithium-ion batteries offer quick, responsive service for immediate power needs and frequency regulation. The system works best when these technologies complement each other - similarly, hybrid energy storage systems (HESSs) leverage multiple technologies to optimise grid performance. This is where HESSs demonstrate their transformative potential. By integrating complementary technologies, hybrid systems provide a comprehensive energy management solution.

3.0 Lithium-Ion Batteries (LIB)-Supercapacitor

LIB furnish ancillary services such as frequency and voltage regulation, alongside rapid power injection/absorption during grid perturbations. Although LIB can technically address transient high-power demands, this operational mode necessitates system oversizing and precipitates accelerated electrochemical degradation due to high-current cycling.

To eliminate these limitations, Hybrid Energy Storage Systems, integrating LIB and supercapacitors (SCs), present a viable architectural refinement. Supercapacitors, characterised by their high-power density and rapid charge/discharge kinetics, can effectively buffer short-duration, high-power transients, thereby reducing the operational stress on the battery subsystem and prolonging its service life. This hybridised topology enhances performance in applications demanding fast frequency response and exhibiting over 1,000,000 duty cycles. However, the incorporation of SCs introduces augmented system capital expenditure and increased system design complexity. These hybrid LIB-SC are still in research stage and extensive studies are being conducted to optimise various factors such as load profiles, cycling regimes, thermal management strategies, and battery aging characteristics.

4.0 Lithium-Ion Batteries (LIB)-Hydrogen storage (H2)

LIB with hydrogen storage (Hybrid LIB-H2 storage) systems offers a comprehensive energy storage solution that combines the advantages of both technologies to overcome standalone system limitations. These hybrid systems merge hydrogen's high energy density and long-duration storage capabilities with batteries' rapid response and efficient energy conversion characteristics. The technology utilises hydrogen as an energy carrier, stored in various forms including compressed gas, liquid hydrogen, or solid-state materials. Recent advances in solid-state storage materials have achieved up to 8 wt.% capacity under moderate conditions.

The system has diverse applications across sectors:

- In renewable energy microgrids, where excess solar energy is converted to hydrogen for later use while batteries manage immediate power needs.
- In grid-scale applications, where the combination enhances reliability while reducing costs.

However, despite its advantages, the technology faces several challenges, including high initial costs, complex system design requirements, and efficiency losses during energy conversion. Ongoing research in advanced materials and electrochemical processes continues to address these limitations, driving further advancements in hybrid hydrogen-battery storage systems. The projected capital cost reductions of up to 80% for electrolyser by 2050, as outlined in IRENA's 1.5°C pathway scenarios [1], will enhance the economic viability of hybrid lithium-ion battery-hydrogen (LIB-H2) storage systems in regions where hydrogen can be generated at a lower cost.

Notable implementations include the Remote Area Power Supply (RAPS) system by UNSW Sydney's Hydrogen Storage and Energy Group, demonstrating its effectiveness in delivering sustainable power to remote communities. [2]

Case Study: The Calistoga Resiliency Centre (CRC), Napa County, California represents the world's largest utility-scale Hybrid LIB-H2 storage integrating 293 MWh of lithium-ion battery storage (B-VAULT™ DC) with green hydrogen fuel cells (H-VAULT™) for long duration applications. Designed to deliver 8.5 MW instantaneous power with 48-hour continuous discharge capability, the system operates in islanded mode, leveraging hydrogen electrolysis and fuel cell stacks to sustain the Calistoga microgrid.

The LIB subsystem provides grid-forming inertia (0.5–2 Hz response time) and black start functionality, while the hydrogen chain (electrolyser→storage→fuel cell) enables multi-day energy autonomy using renewable-sourced H2. Energy Vault's VaultOS™ Energy Management System orchestrates real-time power allocation between subsystems via predictive load forecasting and state-of-charge optimisation algorithms.

5.0 Lithium-Ion Batteries (LIB)-Flywheel Storage

LIB-Flywheel Hybrid Energy Storage Systems represent an innovative integration that combines batteries' high energy density with flywheels' high power density capabilities. Flywheel energy storage systems (FESSs) are particularly well-suited for high-cycle applications due to their exceptional durability and low maintenance requirements. Modern flywheels utilise high-strength composite materials for the rotor, enabling rotational speeds of up to 20,000 revolutions per minute within vacuum-sealed chambers to minimise aerodynamic drag. Magnetic bearings are employed to support the rotor, effectively eliminating mechanical friction and wear. These design advancements contribute to significantly extended operational lifespans, with current-generation flywheels capable of sustaining over 200,000 full-depth charge-discharge cycles, far exceeding most LIB storage technologies in high-frequency cycling performance.

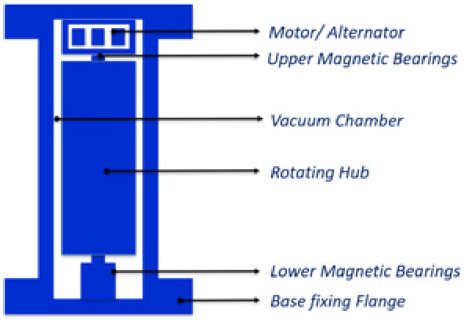


Figure 3: Flywheel design

The LIB-Flywheel Hybrid Energy Storage architecture offers multiple advantages, including:

- Extended battery lifespan through reduced cycling stress,
- Improved efficiency by maintaining optimal battery state-of-charge, and
- Enhanced cost optimisation through lower maintenance requirements.

Field deployments confirm the value of pairing LIBs with flywheels for grid frequency control and renewable integration, such as wind farms. ABB has provided several 500 kW PowerStoreTM flywheel units, managed by the MGC 600 microgrid controller [3], which tracks power flows across sources and rapidly counters surges from renewables or brief generation dips. In Italy, transmission system operators reported up to 50% reduction in battery ageing through flywheel integration. QuinteQ Energy has demonstrated practical applications of their hybrid energy storage technology with ultra-fast, lightweight carbon rotor that is 100 % magnetically levitated and reaching speeds of 22,500 RPM

Case Study: SJ and SMEC have been engaged to lead the decarbonisation of one of Indonesia's major coal mining facilities, which was previously reliant on 13 diesel generators for its power needs. The initial design concept involves integrating solar PV systems with LIB storage, however, the operational characteristics of the mine present unique technical challenges. The plant's core processes involve the operation of high-power inductive loads such as conveyor belt motors and crushers, which require large inrush currents during startup.

These sudden high-power demands exceed the instantaneous power delivery capabilities of the LIB's Power Conversion System (PCS), which is typically optimised for steady-state and moderately dynamic loads. One approach to address this limitation—using LIB alone—would be to significantly oversize the PCS and battery system to handle the transient peaks, but this leads to increased capital costs and underutilised capacity during normal operation.

To address these issues more effectively, SJ and SMEC are currently exploring the integration of a FESS in parallel with the LIB. Flywheels are well-suited for short-duration power spikes due to their rapid response time and high-power density. Preliminary simulations indicate that incorporating FESS can enhance overall system stability, reduce PCS sizing requirements for the LIB, and improve system efficiency, all while lowering total system cost compared to using LIB alone.

6.0 Lithium-Ion Batteries (LIB)-Thermal Energy storage

The integration of lithium-ion batteries with thermal energy storage (TES) systems creates a hybrid solution that combines the fast response time of lithium-ion technology with TES's long duration energy storage capabilities. While LIB dominate in applications demanding high energy density and rapid response, TES systems present distinct advantages relative to LIB, particularly for large-scale, long-duration thermal management applications. TES offers superior scalability and cost-effectiveness for bulk energy storage in comparison to LIB, by utilising readily available materials like phase change materials or sand, often boasting significantly longer lifespans and enhanced safety due to the absence of flammable components and thermal runaway risks. Furthermore, certain TES configurations allow for a decoupling of power and energy capacity, providing design flexibility, and some technologies can operate at wider temperature ranges, facilitating integration with industrial processes.

Current thermal energy storage products are only able to store and release the heat. Some of the notable products include Energy Nest's Thermal Battery™ System [4], Finland's sand-based TES prototype [5], and Ice Energy's Ice Bear System for commercial building cooling [6].

Case Study: SJ has entered into a research collaboration agreement with Higher Dimension Materials (HDM), USA, to co-develop a long-duration thermal energy storage (TES) system integrated with lithium-ion batteries (LIB). HDM contributes its proprietary technology [5], including advanced shielding layers for molten silicon crucibles and engineered silica-based thermal storage media, designed to significantly reduce heat loss, one of the primary challenges faced by conventional thermal storage systems. Molten silicon, with its exceptionally high heat of fusion, can absorb or release substantial amounts of energy during phase transitions at a melting point of approximately 1,415 °C. Given this high operating temperature, effective thermal insulation is critical to achieving high round-trip efficiency. SJ is responsible for developing the thermal-to-electrical energy conversion technologies and the overall system integration from a future Power-to-Heat-to-Power (P2H2P) product development standpoint. In this hybrid configuration, the LIB plays a vital role by providing rapid-response electrical output, compensating for the slower thermal-to-electric conversion process, which typically occurs over several minutes to hours. The integrated system is particularly suited for applications requiring both thermal and electrical outputs, such as industrial parks where cost-effective steam and renewable electricity are in high demand.

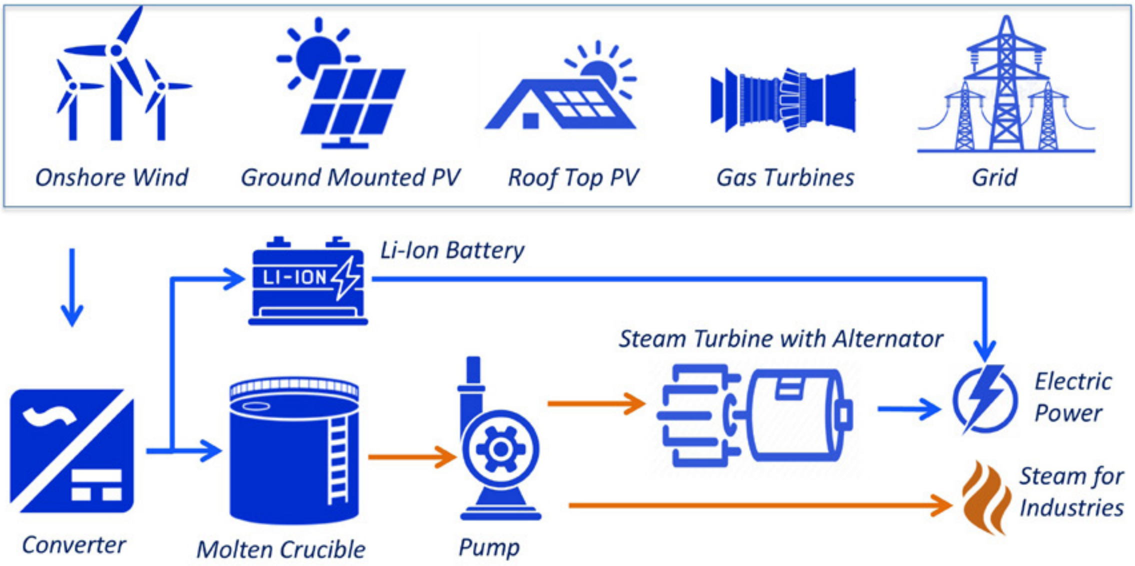


Figure 4: Integrated Thermal Storage

7.0 Lithium-Ion Batteries (LIB)-Pumped Hydro Storage

Lithium-Ion Batteries -Pumped Hydro Energy Storage Systems (LIB-PHES) integrate the long-duration storage capabilities of pumped hydro with the rapid response and high energy density characteristics of lithium-ion batteries to deliver a highly flexible and efficient energy solution.

This hybrid system operates by pumping water between reservoirs during periods of low electricity demand, effectively storing energy over long durations. Meanwhile, batteries manage immediate power needs and short-term fluctuations due to their rapid response and high energy density. By integrating these two technologies, LIB-PHES offers operational flexibility, cost-effectiveness through pumped hydro's lower lifetime costs, enhanced renewable energy integration, and an extended system lifespan, pumped hydro infrastructure can last up to 100 years, significantly longer than the typical 20-year lifespan of battery systems.

Beyond energy storage, PHES systems play a vital role in enhancing grid stability and resilience. They provide essential grid support services including voltage control, frequency regulation, and system restart capabilities [7]. Voltage control is achieved both rapidly, through absorption or injection of reactive power while operating in generation, pumping, or synchronous condenser modes, and more slowly by adjusting the generating output voltage via tap-changers on transformers. Frequency control is delivered across primary, secondary, and contingency layers.

Fixed-speed PHES systems offer physical inertia to resist frequency changes, while variable-speed systems provide synthetic inertia and rapid power output ramping to arrest frequency incidents. Integration with Automatic Generation Control (AGC) enables precise secondary frequency regulation, and contingency frequency control is provided on multiple timescales, from seconds to minutes, enhancing overall system strength. For system restart, PHES's low start-up power demand supports reliable black-start functionality and extended grid recovery following outages. While PHES systems inherently provide comprehensive grid services including black-start capability through their standard DC systems (traditionally using lead-acid batteries), the integration of LIB represents an evolution in station service technology.

As lithium-ion technology matures with improved energy density, longer cycle life, and declining costs, it is increasingly being considered to replace conventional lead-acid systems in hydro environments. However, the transition requires careful consideration of thermal management, fire suppression requirements, and technology maturity factors that are critical in hydro infrastructure applications.

Case Study: SJ and SMEC Indonesia have been engaged to design and develop a fast-switching LIB–Hydroelectric Power Plant (HEPP) system at the Balambano HEPP, a 140 MW facility located on the Larona River in South Sulawesi, Indonesia. This plant primarily supplies electricity to an industrial mining operation. The proposed LIB system will replace the existing Emergency Diesel Generator (EDG) currently used to support station services (SS) during black start scenarios, in the event both operational hydro units are unavailable. The integration of a 500-kWh commercial-scale LIB will significantly reduce black start response time and eliminate the operational and maintenance costs associated with diesel generators and its emissions.

8.0 Compressed Air-Thermal Energy Storage

Compressed Air Energy Storage (CAES) combined with Thermal Energy Storage (TES) represents an innovative hybrid solution that enhances large-scale energy storage capabilities. The system operates by compressing air during low demand periods to pressure up to 100 bar and storing it in pressurised containers or underground reservoirs, while simultaneously capturing and storing the compression-generated heat in thermal storage media like molten salts or phase change materials. When the stored energy is needed, this compressed air is used to generate power in a turbine while simultaneously recovering the heat from the thermal storage improving overall efficiency and eliminating the need for external fuel sources [8].

Engineered silica-based materials offer a cost-effective and environmentally benign solution for TES, presenting excellent integration potential with Adiabatic -CAES. Their high heat capacity, coupled with suitable operating temperatures and widespread availability, positions them as a compelling material choice for CAES applications.

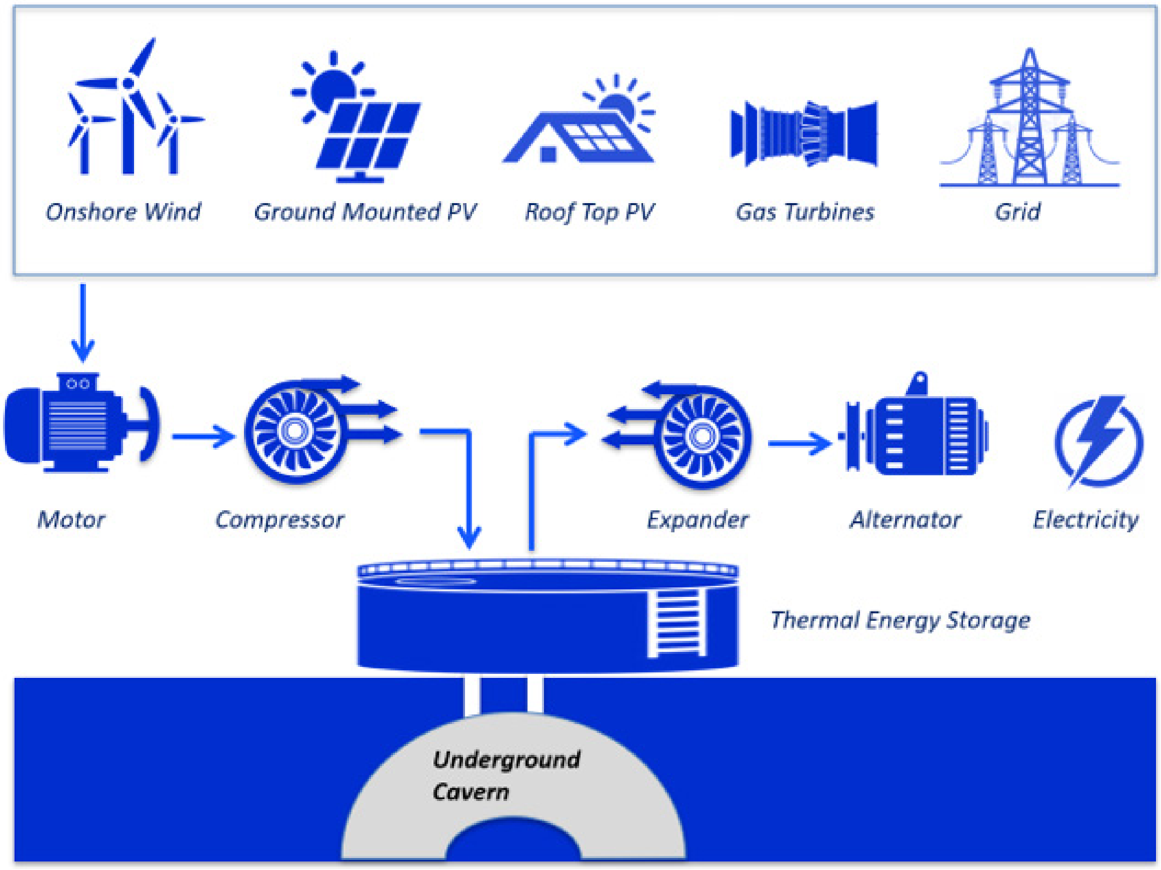


Figure 5: Integrated Compressed Air Storage

The technology comes in various forms, including Adiabatic CAES (A-CAES), which achieves zero emissions by reusing stored heat, and Isothermal CAES, which maintains constant temperature during operation.

Case Study: Germany's Huntorf Plant, the world's first commercial CAES facility in which the turbine output is 290 MW, and the total underground cavern volume is 310 000 m³ with operational pressure of 43 bar, whereas ADELE Project incorporating advanced thermal storage compresses air up to 100 bar reaching temperature of 600 °C, which presents a challenge of high temperature and high-pressure cyclical stresses in rotating components. While the system offers benefits like high energy capacity, improved efficiency, and effective renewable energy integration, it faces challenges including thermal management complexity, high infrastructure costs, and geographic limitations.

9.0 Lithium-ion-Vanadium Redox Flow Batteries (VFRB)

Hybrid lithium-ion (LIB) and vanadium redox flow battery (VRB) systems represent a cutting-edge energy storage solution that synergises LIBs' high-power density and rapid response with VRBs' long-duration energy capacity and cycle stability. This integration reduces costs of energy storage by leveraging VRBs' high energy capacity and LIBs for peak power demands, while extending system lifespans (>25 years for VRBs, 30,000+ cycles) [9].

VRFBs store energy in externally placed liquid electrolytes in large tanks and inherently prevent thermal runaway and propagation due to use of aqueous and non-flammable chemistry. Even direct mixing of electrolytes from anolyte and catholyte causes a mild temperature increase, not an explosion. This intrinsic safety due to separated storage/conversion and non-flammable electrolytes is a key advantage over other electrochemical batteries. Due to the relatively large relative atomic mass of vanadium, the maximum energy density of a vanadium redox battery is ~40 Wh/kg, which is comparatively lower than the energy density of a lithium battery of 150- 300 Wh/kg. However, the ability to customise VRB designs for multi-story buildings and underground installations has shown that VRBs can achieve a comparable footprint to lithium batteries.

Innovations like Nitrogen/Bismuth-doped graphene electrodes boost VRB efficiency by 70%, and advanced energy management systems (EMS) optimise state-of-charge balancing, cutting LIB cycling by 30% in off-grid solar applications. Challenges remain, such as VRB parasitic losses (3–10% energy consumed by pumps) and vanadium's cost dominance (~50% of VRB expenses for a 5 hour system), driving research into zinc-bromine hybrids and AI-driven EMS. However, VRB remains the only proven and commercially available flow battery technology to date, unlike newer chemistries.

Case study: SJ is engaged in a research collaboration with VFlowTech, a leading developer of Vanadium Redox Flow Battery (VRFB) technology in Singapore, to design and implement an innovative underground Hybrid Energy Storage System (HESS). This initiative builds on VFlowTech' s prior success in demonstrating an above-ground HESS at Jurong Island in partnership with Advario [10], where existing oil storage tanks were repurposed for VRFB electrolyte containment. Leveraging insights from that deployment, the collaboration now advances toward a fully underground 2.5 MWh HESS to address Singapore's land constraints and maximise spatial efficiency.

The proposed system configuration includes:

- Two 40-foot or four 20-foot containerised electrolyte tanks for VRFB energy storage.
- One 40-foot container accommodating the VRFB power stacks, microgrid Power Conversion System (PCS), and hybrid controller; and
- One 20-foot container housing a lithium-ion battery system with its dedicated PCS.

This integrated underground design enables high-capacity, flexible, and space-efficient energy storage for urban environments. This creates an opportunity for land-constrained countries like Singapore to accommodate more BESS in underground spaces.

10. Conclusion

In conclusion, hybrid energy storage systems (HESSs) are pivotal in addressing the challenges posed by the integration of renewable energy sources into power grids. By combining different storage technologies, such as batteries with supercapacitors, hydrogen, flywheels, thermal energy storage, and others, HESSs offer comprehensive solutions to issues like intermittency, grid stability, and energy management.

Despite facing challenges such as increased complexity and higher initial costs, these systems provide enhanced efficiency, reliability, and cost-effectiveness. As the energy landscape continues to evolve, the development and deployment of HESSs will be crucial for achieving sustainable energy goals and ensuring a reliable transition to a cleaner energy future.

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