On behalf of:

Federal Ministry
for the Environment, Climate Action,
Nature Conservation and Nuclear Safety

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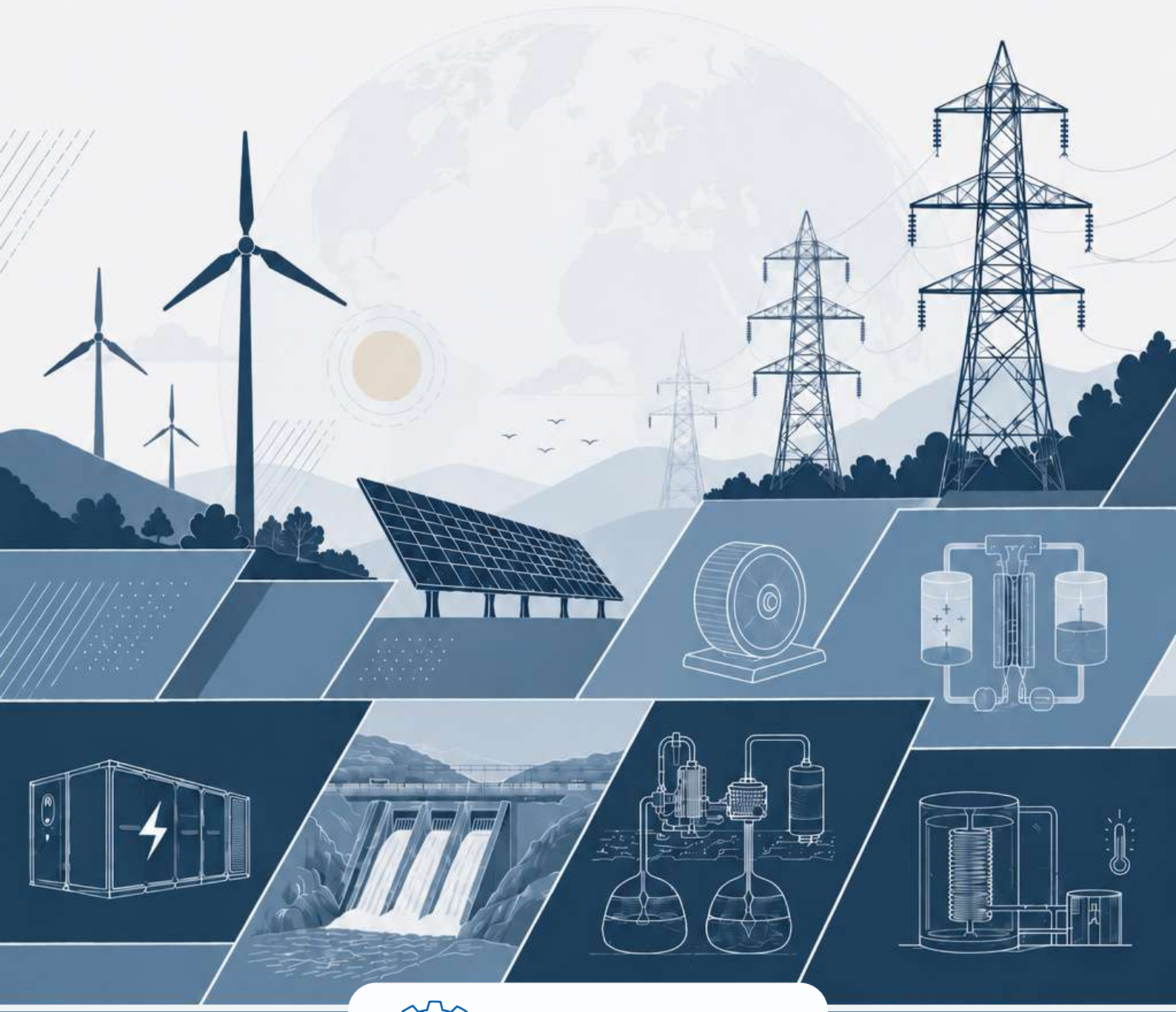
IKI INTERNATIONAL CLIMATE INITIATIVE

सत्यमेव जयते

नवीन एवं
नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
NEW AND
RENEWABLE ENERGY

Global Energy Storage Systems:

A Critical Technical Review



IIT Bombay

giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

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Global Energy Storage Systems:

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by

Grid Integration Lab
IIT Bombay

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Foreword

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FOREWORD

At the COP30 conference held in Belém, Brazil, in 2025, the global climate agenda further reinforced the need to accelerate implementation of clean energy transitions while ensuring secure, reliable, and resilient energy systems. Renewable energy deployment has continued to expand rapidly across the world, with global installed solar photovoltaic capacity reaching around 3,050 GW and wind power capacity around 1,350 GW by May 2026. The increasing penetration of variable renewable energy is fundamentally changing the operational requirements of power systems. Variability in generation, increasing ramping requirements, renewable energy curtailment, network congestion, and reduced system inertia are creating a growing need for flexibility, balancing reserves, and fast-acting grid-support services. Energy storage is therefore becoming an increasingly important component of stable operation of future power systems. Storage can provide services across multiple timescales from sub-second scale frequency and stability support, to minute- and hour-scale balancing and ramping, and to long-duration energy shifting for adequacy and resilience. With different technologies offering distinct response characteristics, duration, efficiency, scalability, and operating capabilities, no single storage technology can efficiently address all system requirements. This warrants a technology agnostic and capability-based approach to energy storage planning and deployment, supported by appropriate technical standards, grid codes, market mechanisms, and regulatory frameworks.

International cooperation and exchange of global experience are important for understanding the evolving role of energy storage in renewable-rich power systems. German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) through International Climate Initiative (IKI), in cooperation with Ministry of New and Renewable Energy (MNRE), provides an important platform under Energy Storage for Renewable Energy Integration in India (StoREin) project for exchange of experience and knowhow. Global experiences on storage technologies, applications, system integration, markets, and regulatory practices can provide valuable insights for countries transitioning towards higher shares of renewable energy.

Indian Institute of Technology Bombay
Office of the Director

Indian Institute of Technology (IIT) Bombay is committed to playing a constructive role in advancing reliable, sustainable energy transition. This specific report, *"Global Energy Storage Systems: A Critical Technical Review"*, prepared by the Grid Integration Lab, Department of Energy Science and Engineering, IIT Bombay, presents a comprehensive technical review of the global energy storage landscape. The report examines energy storage technologies, grid applications, gird integration, modelling and interoperability, economics and market participation, along with lessons from operating projects and programmes across the world. It further highlights the need for capability-based planning, appropriate technical standards, and enabling market and regulatory frameworks for effective integration of energy storage into future power systems.

I would like to congratulate the authors, all the stakeholders involved, the reviewers, and the supporting organisations contributing to the successful preparation of this report.

[Shireesh Kedare]

Acronyms

A-CAES	Adiabatic Compressed Air Energy Storage
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
APeC	Asia Pacific excluding China
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
BMS	Battery Management Systems
BoS	Balance of System
BSUoS	Balancing Services Use of System
BTM	Behind-the-Meter
C&I	Commercial and Industrial
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
CAPEX	Capital Cost
CEI	Cathode Electrolyte Interface
D-CEAS	Diabatic Compressed Air Energy Storage
DER	Distributed Energy Resource
DFIG	Doubly Fed Induction Generator
DG	Distributed Generators
DoD	Depth of Discharge
DOE	Department of Energy
EBA	European Battery Alliance
EC	European Commission
ECES	Electrochemical Energy Storage
EDLC	Electric Double-Layer Capacitor
EFR	Enhanced Frequency Response
EMS	Energy Management System
EMT	Electromagnetic Transient
EPC	Engineering, Procurement and Construction
ESR	Equivalent Series Resistance
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FBESS	Flow Battery Energy Storage Systems
FC	Full Conversion
FCAS	Frequency Control Ancillary Services
FERC	Federal Energy Regulatory Commission
FESS	Flywheel Energy Storage System
FTM	Front-of-the-meter
GESS	Gravitational Energy Storage Systems
GFL	Grid Following
GFM	Grid Forming
GSC	Grid Side Converter
GSSF	Grid Scale Storage Fund
I-CEAS	Isothermal Compressed Air Energy Storage
IBR	Inverter Based Resources
IRA	Inflation Reduction Act
ISO	Independent System Operator
LA	Lead-acid
LCA	Life Cycle Assessment

LCO	Lithium Cobalt Oxide
LCOS	Levelised Cost of Storage
LDES	Long Duration Energy Storage
LFP	Lithium Iron Phosphate
LHESS	Latent Heat Energy Storage System
LMO	Lithium Manganese Oxide
LTO	Lithium Titranium Oxide
MES	Mechanical Energy Storage
MISO	Midcontinent Independent System Operator
MSC	Machine Side Converter
NCA	Nickel Cobalt Alluminium Oxide
NEM	National Electricity Market
NMC	Nickle Manganese Cobalt Oxide
NYISO	New York Independent System Operator
NYSERDA	New York's New York State Energy Research and Development Authority
Ofgem	The Office of Gas and Electricity Markets
OPEX	Operating Expenditure
PBFB	Polysulphide Bromide Flow Batteries
PCS	Power Conversion System
PHS	Pumped Hydro Storage
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PMSG	Permanent Magnet Synchronous Generator
POI	Point of Interconnection
PTESS	Pumped Thermal Energy Storage Systems
PV	Photovoltaic
RE	Renewable Energy
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
RTE	Round Trip Efficiency
RTO	Regional Transmission Organisations
RTS	Rooftop Solar
RUL	Remaining Useful Life
SAVPP	South Australia Virtual Power Plant
SEI	Solid Electrolyte Interphase
SEI	Solid Electrolyte Interface
SESS	Supercapacitor Energy Storage System
SET	Strategic Energy Technology
SHESS	Sensible Heat Energy Storage Systems
SLB	Second Life Battery
SMES	Superconducting Magnetic Energy Storage
SoC	State of Charge
SoH	State of Health
SSFP	Smart Systems and Flexibility Plan
TCES	Thermochemical Energy Storage Systems
TESS	Thermal Energy Storage Systems
TRL	Technology Readiness Level
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VPP	Virtual Power Plant
VRFB	Vanadium Redox Flow Battery
VSC	Voltage Source Converter
WTG	Wind Turbine Generators
ZBFB	Zinc Bromide Flow Batteries

Abstract

The rapid transition towards Renewable Energy (RE) dominated power systems has fundamentally transformed the operational requirements of electricity grids. High penetration of variable RE is increasing net load variability, ramping requirement, congestion, curtailment of RE, frequency and voltage stability challenges across transmission and distribution networks. Moreover, RE driven displacement of synchronous generator is reducing inherent inertia, ramping reserves, increased net load variability and altering fault behaviour, thereby increasing the need for balancing reserves and fast-acting control and explicitly defined stability services. In this context, energy storage systems are no longer optional balancing assets, rather their role is becoming increasingly critical for secure, stable, flexible, and resilient grid operation under high renewable penetration.

This report presents a detailed technical review of energy storage with emphasis on how energy storage is evolving into a multi-service, digitally managed resource helping the power system manage higher share of RE resources. This report analyses energy storage technology and system perspectives with real-world deployment learnings and case study insights. The report covers storage technology landscapes, grid applications, power electronic interface and control strategies, modelling and interoperability requirements, digitalisation and cybersecurity considerations, and evidence from operating projects and programs. The analysis shows that storage value is increasingly determined not only by the storage medium, but by system integration, including control design, verified dynamic performance, digital monitoring and automation, and regulatory alignment.

One of the findings is that no single storage technology can efficiently address all the grid requirements for RE uptake. Energy storage requirements span multiple timescales, from sub-second response for frequency and stability support, to minute- and hour-scale flexibility for ramping and balancing, to long-duration storage capability that contributes to adequacy and resilience during prolonged periods of low RE or extreme events. Least-cost and high-reliability outcomes, therefore, require a capability-driven portfolio approach. Energy storage should be planned, accredited, and procured using measurable attributes such as response speed, duration, ramping capability, efficiency under realistic duty cycles, deliverability at constrained network locations, and availability during defined system stress periods.

The report further concludes that energy storage economics and bankability increasingly depend on multi-service revenue stacking. Energy arbitrage alone is often insufficient to support investment at scale, particularly as storage penetration increases and price spreads compress. Projects deliver higher system value and stronger commercial viability when they can combine energy shifting with ancillary services such as frequency regulation, operating reserves, voltage support, and congestion relief, and where relevant, with capacity or availability payments tied to reliability performance. Enabling stacking requires market rules that define service compatibility, prioritisation during contingencies, and settlement methods that prevent double counting of the same physical capability.

Energy storage and other converter-interfaced resources are increasingly expected to deliver fast frequency response, synchronous synthetic inertia behaviour as applicable, dynamic reactive power support, fault ride-through performance, and, in some systems, grid-forming behaviour that supports stable operation in weak grid conditions. Achieving these outcomes reliably requires standardised grid codes with measurable performance definitions, validated dynamic models, consistent commissioning and compliance testing, and clear operator procedures for converter-dominant system dynamics.

Accurate modelling and simulation are therefore foundational. Planning and interconnection assessment must reflect both steady-state and dynamic behaviour, using RMS approaches for broad planning and EMT approaches where detailed, fast dynamics and control interactions are the subject. Standardised modelling practices, transparent and realistic study assumptions, and verified model libraries reduce uncertainty for developers and operators, reduce connection delays, and improve reliability outcomes.

Digitalisation emerges as a decisive factor for both operational performance and economic viability. Digital energy management systems, forecasting, analytics, and automated control enable storage to respond efficiently to market signals and operator requirements while managing degradation, thermal constraints, and safety limits. Predictive maintenance improves the availability and reliability contribution. At the same time, cybersecurity becomes an essential infrastructure practice, requiring secure communications, access control, event logging, and compliance standards to protect system integrity.

Based on the findings of this study, this report recommends technology neutral, capability based frameworks that explicitly recognize short and long duration and stability oriented services where needed; market reforms and procurement mechanisms that enable multi service operation with robust measurement and verification; standardized grid codes, performance supported by validated models and commissioning tests; targeted demonstrations to de risk emerging long duration and stability relevant configurations; and mandatory digital monitoring, interoperability standards, and cybersecurity compliance for grid scale assets. The strategic roadmap prioritises the near-term standardisation of modelling and interconnection requirements, the medium-term scaling of long-duration and stability-capable deployments through bankable contracting tied to stress period performance, and the long-term evolution toward interoperable, digitally coordinated storage fleets that provide real-time system services under strong governance and operator oversight.

In summary, the decisive challenge for next-generation power systems is not whether energy storage is needed, but how quickly policy, markets, standards, modelling discipline, and operational practice can evolve to integrate storage as a verified, multi-service, digitally managed infrastructure platform. A capability-centric approach grounded in dynamic performance validation, robust governance, and digital control offers a credible pathway to reduce curtailment, improve reliability, maintain stability in converter-dominant grids, and deliver least-cost decarbonisation at scale.

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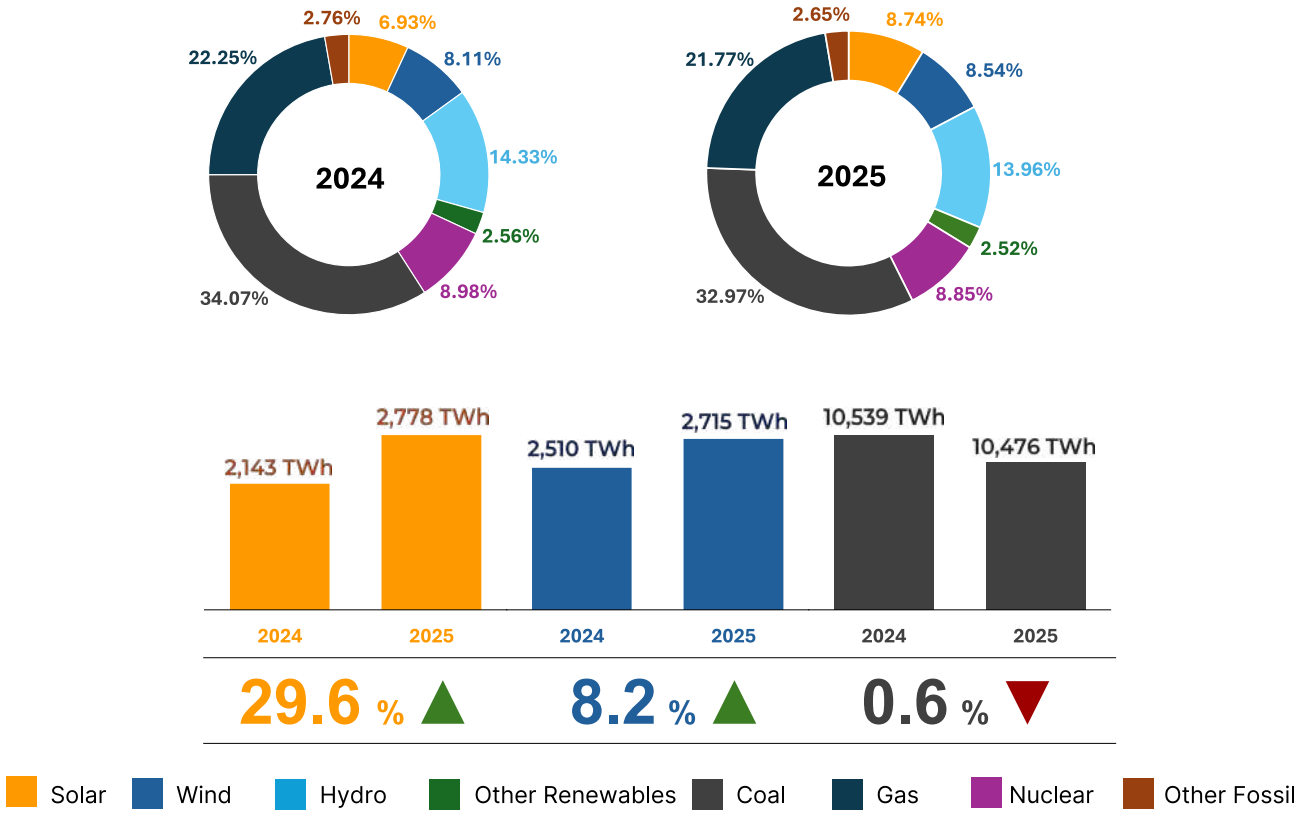
Executive Summary

Global Context and Need for Energy Storage

The global energy system is undergoing a structural transition driven by climate change, increased Renewable Energy (RE) deployment, and increasing electricity demand. The power sector occupies a central position in this transition because it is both a major source of global CO_2 emissions and the primary energy carrier for decarbonising transport, buildings, industry, and other end-use sectors through electrification. From January 2015 till February 2026, power industry alone accounted for 26 percent of global CO_2 emissions, indicating that power sector decarbonisation is essential for achieving wider climate objectives[1]. However, decarbonisation of electricity system must be supported by sufficient operational flexibility, as future low carbon power systems will be shaped by variable RE generation, decentralised resources, and climate induced reliability risks.

The global electricity mix is shifting rapidly towards RE generation as shown in Figure E1, led by solar PV and wind based generation technologies. Solar generation increased from approximately 2,143 TWh in 2024 to 2,778 TWh in 2025, representing the highest absolute growth among major electricity technologies. Wind generation also increased from around 2,510 TWh to 2,715 TWh during the same period. In contrast, coal generation declined marginally from approximately 10,539 TWh to 10,476 TWh, with its share falling below one third of global electricity generation[2]. This divergence indicates a transition from a fossil dominated, dispatchable generation structure towards a RE rich system.

Figure E1 : Global electricity generation mix



Data Source: Ember

1 "Country/Territory Inventory," Climate TRACE.
2 Ember, "Electricity Data Explorer," Ember Energy.

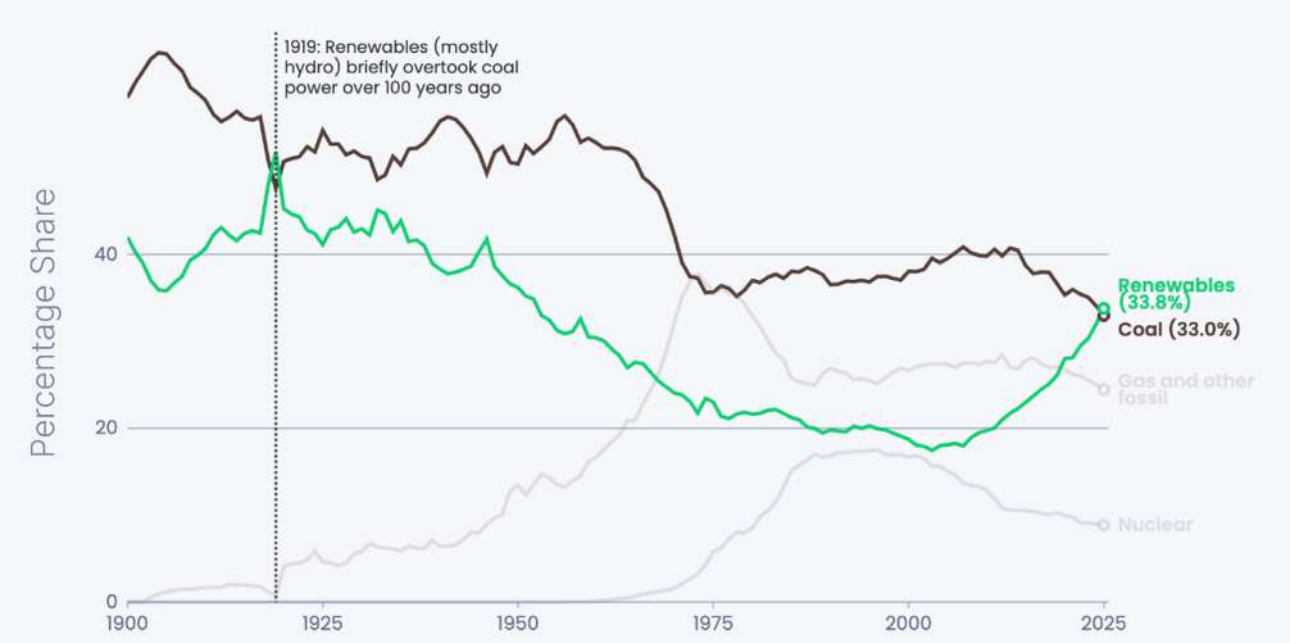
☀ KEY INSIGHT

Solar and wind generation increased by nearly 30% and 8% respectively between 2024 and 2025, while coal generation declined by 0.6%, indicating that global power-system planning is shifting from fossil fuel based dispatch management to RE flexibility management.

Large scale RE deployment is currently sufficient to alter system operation across major power markets. Approximately 2,392 GW of solar PV capacity was installed globally as of 2025[3], with deployment dominated by China, followed by the United States and India. Wind capacity also continued to expand, reaching approximately 1,346 GW by December 2025[4], with China leading the deployment, followed by United States, Germany, and India. This concentration has direct power system operational implications, as large volumes of solar PV and wind are being added over short planning cycles in systems that must manage variability, forecast error, network constraints, and reduced system inertia.

In 2025, RE accounted for 33.8 percent of global electricity generation, slightly exceeding coal at 33.0 percent for the first time in more than a century as shown in Figure E2[5]. This marks a structural inflection point in global electricity supply. This transition is primarily driven by rapid solar PV and wind deployment. As variable RE becomes a larger share of supply, system reliability increasingly depends on resources that can shift energy across time, provide operating reserves, manage steep ramps, reduce curtailment, and support frequency and voltage stability.

Figure E2 : RE surpassing global coal power generation



Source: Ember

3 IRENA, "Renewable Capacity Statistics 2026," International Renewable Energy Agency, Abu Dhabi, 2026.
4 World Wind Energy Association, World Wind Energy Report 2025, WWEA, Bonn, Germany, 2026.
5 N. Fulghum, W. Suarez, K. Altieri, and K. Rangelova, Global Electricity Review 2026, Ember, Apr. 21, 2026.

The technical need for Energy Storage System (ESS) arises from the operating characteristics of the fastest growing RE resources. Electricity generated from Solar PV and wind is intermittent and variable, weather dependent, and non-synchronous. Solar PV introduces variable generation patterns, midday net load reduction, steep evening ramps, and overvoltages & unbalance issues in distribution network. Wind generation introduces short term fluctuations and forecast uncertainty, increasing the need for balancing capability and operating reserves. As RE resources increase in the generation mix, power system operation shifts from dispatch led to flexibility led scheduling. ESS address this shift by operating as controllable, bidirectional sources that can store energy during surplus generation and supply during high demand, low RE output. The main technical drivers for ESS in RE rich systems are summarised in Table E1.

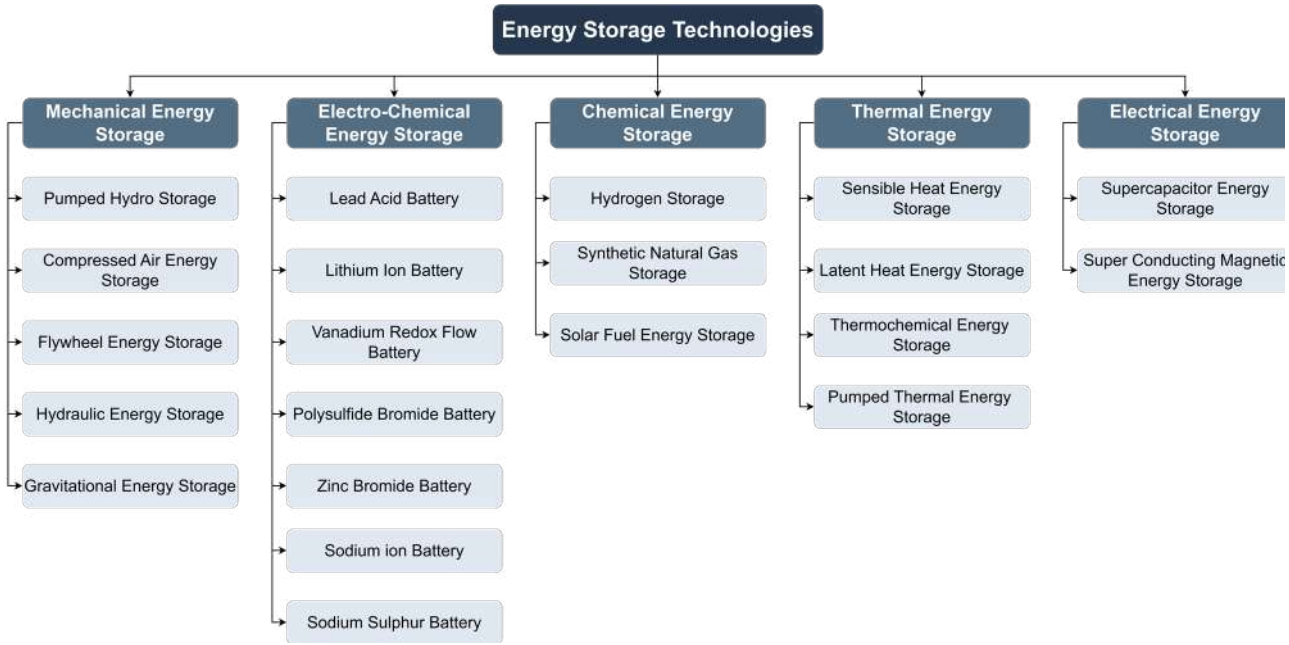
Table E1 : Grid-integration challenges and ESS functionalities

RE integration challenge	Power-system impact	ESS functions
Intermittency and variability	Increased net-load ramps, high forecast error, reserve requirements, generation dispatch uncertainty	Load balancing, energy shifting, ramping support, operating reserves, peak sharing, etc.
Non-synchronous generation	Reduced inertia, lower fault current contribution, higher RoCoF, frequency and voltage stability concerns, oscillations	Fast frequency response, synthetic inertia provision, dynamic voltage support
Power-quality impacts	Harmonics, voltage fluctuations, voltage sag, flicker, feeder voltage increase	Reactive power support, active filtering, local charging and discharging
Renewable energy curtailment	Lost RE generation due to congestion, oversupply, or price-driven dispatch	Charge surplus energy and discharge during higher-value periods
Duck/ Camel curve increase	Midday net-load depression and steep evening ramping requirement	Midday charging and evening discharge
Grid strength	Low grid strength	Helps in enhancing grid strength

Energy Storage Technology Landscape

ESS form a diverse global portfolio with different storage mechanisms, response characteristics, discharge durations, efficiency ranges, maturity levels, and system applications. As shown in Figure E3, ESS can be broadly classified into electrochemical, mechanical, chemical, thermal, and electrical ESS. This classification is important because each technology addresses different grid support requirements. Short duration technologies are generally suited for fast response, improving power quality, and frequency support, while medium and long duration technologies are more relevant for energy shifting, peak management, capacity adequacy, and seasonal balancing. Therefore, the global ESS transition is not based on a single dominant technology but on aligning technology characteristics required by the power system.

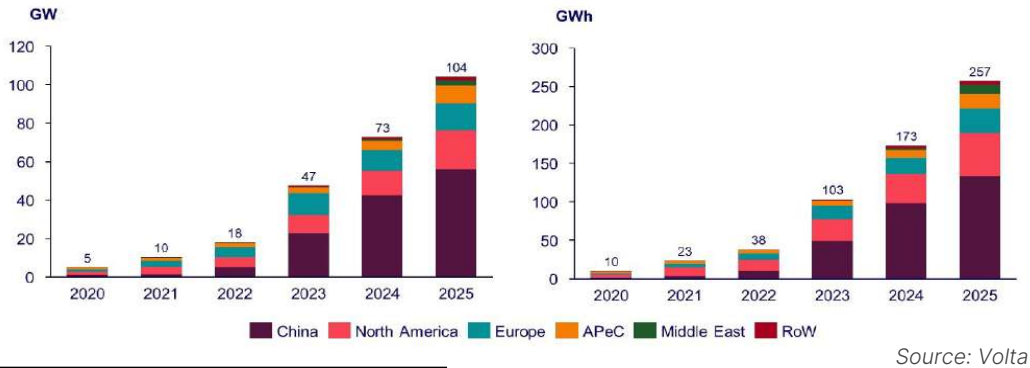
Figure E3 : Classification of energy storage technologies



Electrochemical Energy Storage (ECES) systems have become the fastest evolving storage class as they combine modularity, fast response, high controllability, and cost reductions. Battery costs declined by nearly 80 percent between 2010 and 2025[6], while energy density, cycle life, manufacturing scale, and battery management capability improved substantially. This has enabled battery storage to expand from small scale applications to electric mobility, utility scale grid storage, Behind-the-Meter (BTM) systems, RE integration, and ancillary service provision. Battery Energy Storage Systems (BESS) store energy either within electrode materials like conventional BESS, or in externally circulated electrolytes like flow battery. This distinction is important because conventional batteries are compact and efficient, whereas flow batteries provide better scalability for long duration stationary applications.

Global BESS deployment has significantly accelerated between 2020 and 2025, with China accounting for more than half of global capacity additions, as shown in Figure E4[7]. Sectoral deployment has shifted towards utility scale systems, which account for more than 80 percent of global capacity additions, as shown in Figure E5[7]. This confirms that BESS is no longer limited to distributed or backup applications but is becoming grid level asset for RE integration, peak management, capacity support, and ancillary services.

Figure E4 : Global deployment of BESS by geography



Source: Volta Foundation

6 Ember, How Cheap Is Battery Storage?, Ember Climate, London, U.K., 2025.

7 "The Battery Report 2025." Volta Foundation, 24 January 2026.

Figure E5 : Yearly sector wise BESS installations



Source: Volta Foundation

☀ KEY INSIGHT

Global BESS deployment is becoming utility-scale and regionally concentrated, with China leading more than half of additions and utility-scale systems contributing over 80% of new global capacity.

Lithium-ion BESS dominate current ECES deployment as they provide high efficiency, fast power response, modular construction, strong compatibility with power electronic control, and declining costs and mature supply chains. However, lithium-ion batteries are not a uniform technology. Chemistry selection heavily affects energy density, cycle life, safety, cost, depth of discharge, and supply-chain exposure as shown in Table E2.

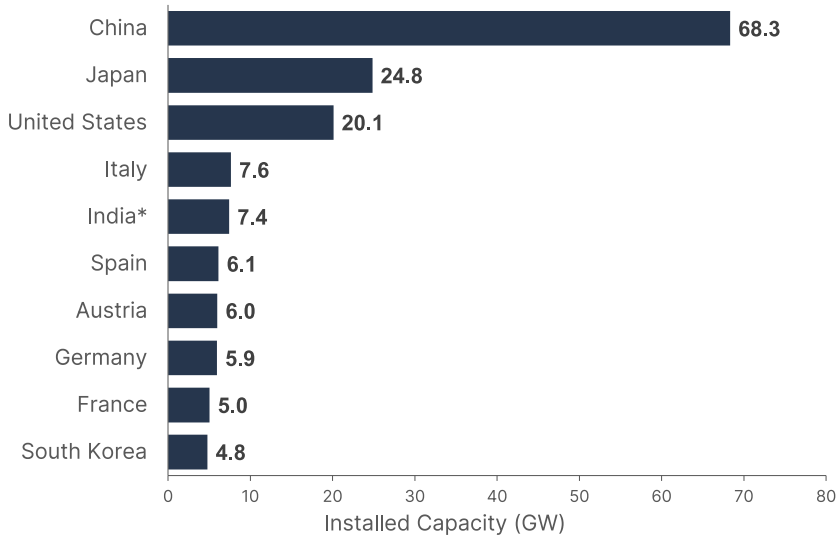
Table E2 : Comparison of major electrochemical storage technologies

Technology	Energy density (Wh/kg)	Cycle life (Cycles)	Round-trip efficiency (%)	Depth of discharge (%)	Global application
Lead-acid	30–75	250–500	75–85	40–50	Backup applications, UPS, telecom, low-cost standby storage
Li-ion LFP	90–200	3,000–8,000	85–95	80–90	Utility-scale BESS, stationary storage, RE integration
Li-ion NMC	150–240	1,500–2,000	80–95	80–90	EVs, high-energy battery packs, selected stationary storage
Li-ion NCA	200–260	1,500–2,000	90–95	80–90	High-energy EV and compact storage applications
Li-ion LTO	60–120	10,000–30,000	85–90	80–90	High-power, high-cycle, fast-response applications

Technology	Energy density (Wh/kg)	Cycle life (Cycles)	Round-trip efficiency (%)	Depth of discharge (%)	Global application
Sodium-ion	90–170	5,000–10,000	85–90	80–90	Cost-sensitive stationary storage, cold-climate use, short-range mobility
Vanadium Redox Flow	25–50	15,000–20,000	60–85	100	LDES and high-cycling grid applications
Zinc-bromide flow	30–80	1,500–6,000	65–90	100	RE shifting, microgrids, industrial backup
Polysulphide bromide flow	25–50	10,000–20,000	60–75	100	Niche flow battery applications with frequent cycling
Sodium-sulphur	150–240	2,500–4,500	80–90	80–100	Utility-scale load levelling, RE smoothing, congestion management

Non ECES technologies are essential for completing the global ESS portfolio as they address services that BESS cannot always provide economically at scale. Mechanical energy storage systems is important for bulk and long duration applications. Pumped Hydro Storage (PHS) remains the dominant global storage technology, accounting for about 95 percent of grid connected storage capacity. As of March 2026, global PHS capacity reached 196.17 GW, led by China with 68.3 GW, Japan with 24.8 GW, and the United States with 20.1 GW, as shown in Figure E6[8]. PHS provides 70 to 85 percent round trip efficiency, 50 to 80 years of service life, and 4 to 16 hours of discharge duration, making it suitable for load balancing, renewable energy shifting, reserves, black start, voltage support, and system stability. Its main constraints include site availability, long development timelines, environmental permitting, and high upfront civil infrastructure cost.

Figure E6 : Top 10 countries by operating PHS capacity (GW)



**Sardar Sarovar PHS (1.2 GW) & Kadana PHS (0.240 GW) are not operational in pumping mode*

Data as of March 2026

Data Source: Global Energy Monitor

8 Global Energy Monitor, "Global Hydropower Tracker," Global Energy Monitor.

☀ KEY INSIGHT

PHS remains the dominant and most mature global storage technology, with around 196 GW operating capacity as of March 2026 and about 95% of total grid-connected storage capacity.

Thermal and thermochemical systems support heating, cooling, industrial processes, concentrated solar power, district energy, and sector coupling, with sensible heat, latent heat, thermochemical storage, and pumped thermal storage addressing different temperature ranges, storage durations, and conversion pathways. Hydrogen storage provides the main chemical route for multi day and seasonal balancing through compressed storage, liquid hydrogen, material based storage, and underground salt caverns. This makes it relevant for RE buffering, industrial decarbonisation, heavy duty transport, and long duration adequacy. Electrical storage technologies such as supercapacitors and Super Conducting Magnetic Energy Storage (SMES) serve the fastest response segment, where the priority is not bulk energy storage but power quality, voltage support, fast frequency response, synthetic inertia, and transient stability. The comparison of these technologies is summarised in Table E3.

Table E3 : Comparison of different mechanical, thermal, thermochemical, chemical and electrical ESS

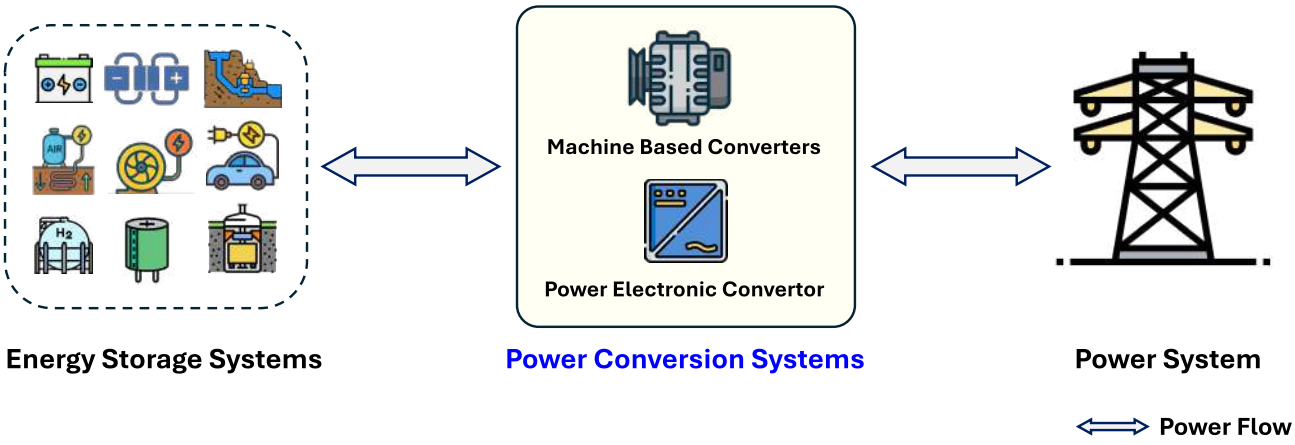
Technology	Energy density (Wh/kg)	Cycle life / asset life	Round-trip efficiency	Discharge duration	Primary role
Pumped Hydro storage	0.2–2	50–80 years	70–85%	4–16 hours	Bulk storage, RE shifting, reserves, black start
Compressed Air Energy storage	30–60	>15,000 cycles	40–70%	24+ hours	Long-duration storage, firm capacity
Flywheel storage	50–300	>100,000 cycles	80–85%	Seconds to 1 hours	Frequency regulation, power quality
Gravity storage	0.5–5	>100,000 cycles	80–90%	4–50 hours	Long-duration mechanical storage
Sensible heat storage	40–110	>10,000 cycles	50–90%	1–24 hours	District heating, CSP, industrial heat
Latent heat storage	Up to 500	>1,000 cycles	60–80%	Minutes to few hours	PCM cooling, compact thermal storage
Thermochemical storage	100–250	>1,000 cycles	60–80%	Hours to months	Seasonal heat storage, sector coupling
Pumped thermal storage	0.05–0.3	10,000–30,000+ cycles	50–70%	2–10 hours	Carnot batteries, long-duration electricity storage
Hydrogen storage	≈300	20–40 years	>60%	Multi-day to seasonal	Seasonal storage, RE buffering

Technology	Energy density (Wh/kg)	Cycle life / asset life	Round-trip efficiency	Discharge duration	Primary role
Supercapacitor Energy storage	1–10	>10^5 cycles	93%	Milliseconds to seconds	Power quality, fast frequency response
SMES	0.5–10	>10^5 cycles	90–95%	Milliseconds to seconds	Transient stability, voltage support

Power Conversion Systems and Control of Energy Storage Systems

Power Conversion System (PCS) governs how the ESS exchanges active and reactive power with the network. The PCS forms the electrical interface between the ESS and the grid, regulating voltage, current, frequency, power flow, dynamic response, harmonic behaviour, fault response, and ensure grid code compliance. As shown in Figure E7, the PCS enables bidirectional power exchange between the ESS and the power system. In this context, the PCS is not only a conversion stage but also the control layer that defines the operational capability of ESS in RE dominated systems.

Figure E7 : Interconnection of ESS with power system



ESS interfaces can be broadly classified into converter based, machine based, and hybrid electromechanical systems. Converter based systems, including BESS, fuel cell systems, supercapacitors, and several converter coupled storage technologies, provide fast and flexible control. Such systems have limited fault current contribution because their response depends on semiconductor switch ratings and control algorithms. Machine based systems, such as PHS and conventional CAES, interface through synchronous or induction machines and inherently contribute rotating inertia and short circuit current provision. Hybrid configurations, such as variable speed PHS, combine machine dynamics with power electronic controllability. This distinction is important as future grids require both fast response and stability services provided by synchronous machines.

☀ KEY INSIGHT

The system value of ESS is increasingly determined by the PCS, as converter architecture and control mode primarily define response speed, grid-code compliance, fault behaviour, and other grid support services.

For converter based ESS, control architecture is organised hierarchically. Primary local control operates at millisecond to second time scales and manages converter level response during disturbances. Secondary control operates over seconds to minutes time window and provides voltage and frequency support during normal operation. Tertiary control operates over minutes to hours time window and determines charge-discharge scheduling based on system demand, RE generation, and economic objectives.

One of the critical control distinction for modern converter interfaced ESS is between grid following and grid forming capability. Grid following control is widely used in existing commercial ESS because it provides accurate active and reactive power control in strong grids. However, it depends on an external voltage reference and can become less stable under weak grid conditions. Grid forming control allows the ESS PCS to establish voltage magnitude and frequency at its terminals, enabling operation in weak grids, islanded systems, black start conditions, and low inertia networks. The difference in service capability is summarised in Table E4, based on the comparison of Grid following and Grid forming control modes.

Table E4 : Comparison of GFL and GFM control capabilities

Service / function	Grid-following ESS	Grid-forming ESS
Energy arbitrage	Proven and widely deployed	Demonstrated and deployed
Frequency regulation	Accurate and fast	Accurate and fast, with weak-grid stability support
Capacity market participation	Reliable participation	Reliable participation with resilience contribution
Black start	Requires external voltage reference	Can independently energise grid
Virtual inertia	Limited capability	Fast virtual inertia provision
Weak-grid support	Performance degrades	Suitable for low short-circuit-ratio systems
Islanding capability	Not suitable	Supports islanding and resynchronisation with grid

Overall, PCS and its control strategy are decisive in transforming ESS from an energy shifting asset into a grid support resource. Machine based storage contributes inertia and short circuit strength inherently, while converter based ESS depends on control design to provide equivalent or enhanced stability services. Grid following control remains suitable for strong grid applications requiring precise power injection, whereas grid forming control is increasingly important for weak grids, islanded operation, black start, synthetic inertia, and high renewable systems. Hence, future ESS deployment must evaluate storage medium, PCS architecture, and control mode together, as grid stability increasingly depends on interaction of ESS with grid.

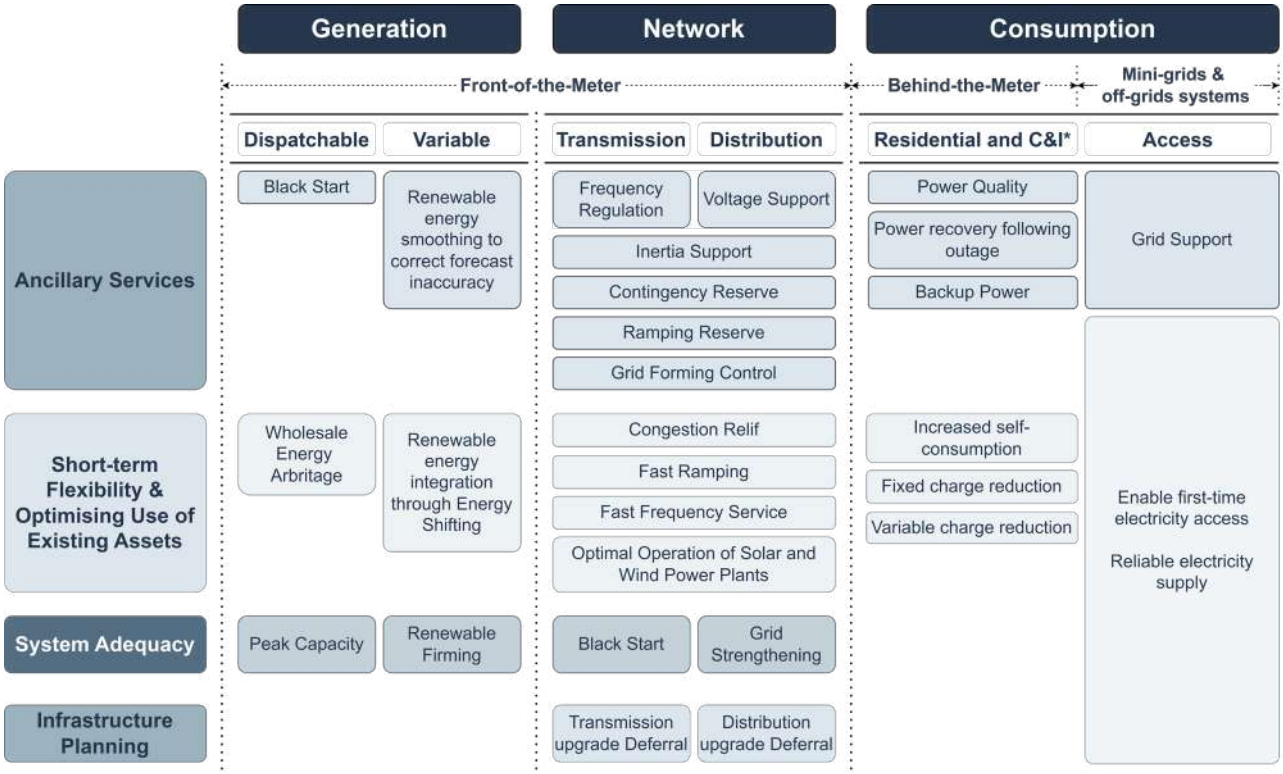
☀ KEY INSIGHT

Under weak-grid conditions, grid forming ESS provides faster voltage recovery and improved damping compared to grid-following ESS, making it critical for RE-dominated and low-inertia power systems.

Application of Energy Storage Systems

As shown in Figure E8, ESS applications extend across generation, transmission, distribution, and end use segments, including energy arbitrage, RE firming, frequency regulation, voltage support, congestion relief, black start, transmission and distribution deferral, backup power, and demand side optimisation. The value of ESS depends on its connection, response time, charging and discharging duration, and provision of multiple grid support services.

Figure E8 : ESS location in power system and representative applications



*Commercial and Industrial

At the transmission level, ESS supports bulk reliability and stability through energy shifting, fast frequency response, inertial support, voltage support, congestion relief, long duration adequacy, and black start. Technologies such as PHS, CAES, flow batteries, hydrogen, thermal storage, and multi hour BESS are more relevant for sustained energy and adequacy services, while BESS, flywheels, supercapacitors, are better suited for fast dynamic support. On the other hand, at distribution level, ESS enables higher distributed RE penetration by managing voltage rise, feeder congestion, transformer loading, local peak demand, and backup requirements. Value stacking is one of the main operational and economic principle for ESS applications. A single ESS can combine fast services such as frequency response, solar PV generation smoothing, and voltage support with slower services such as peak shaving, energy arbitrage, congestion relief, and network deferral, provided that converter capacity, SoC, degradation limits, and service priority rules are respected.

☀ KEY INSIGHT

ESS revenue is maximised when storage is planned as a location-specific and multi-service asset, not as a standalone energy-shifting device.

Table E5 : ESS application and value-stacking framework

Application layer	Main services	Best-fit technologies	Core value
Transmission network	Energy shifting, frequency response, reserves, voltage support, congestion relief, black start, adequacy	PHS, CAES, BESS, flow batteries, hydrogen, flywheels	System reliability, stability, RE integration
Fast dynamic support	Frequency response, synthetic inertia, dynamic reactive power response, power quality	BESS, flywheels, supercapacitors, SMES	Stability support in low-inertia grids
Long-duration adequacy	Multi-hour, multi-day, seasonal balancing	PHS, CAES, flow batteries, hydrogen, thermal storage	Firm capacity and RE shortfall management
Distribution network	Voltage regulation, feeder congestion relief, DER hosting, peak reduction	BESS, community storage	Local flexibility and deferred network upgrades
BTM storage	Electricity bill savings, PV self-consumption, backup power, demand-charge reduction	Residential and C&I BESS	Customer resilience and cost reduction

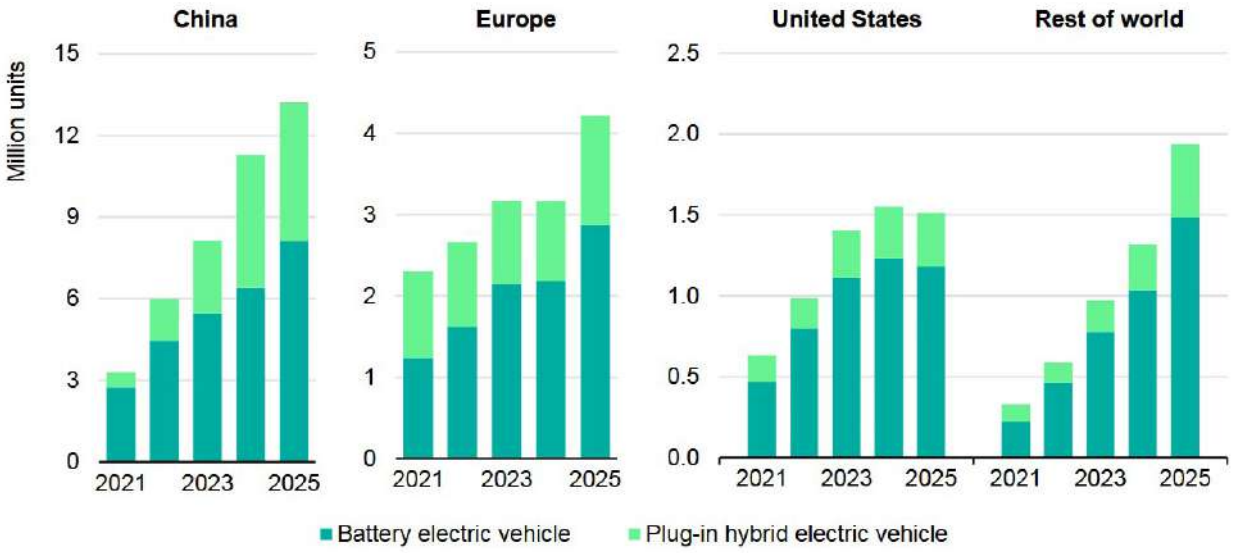
Electric Vehicle as Mobile Battery Energy Storage Systems

Electric Vehicles (EV) are becoming a globally significant distributed and mobile storage resource as EV adoption is expanding rapidly across the world, and EVs account for more than 70% of global BESS deployment. EV battery deployment reached 1.2 TWh in 2025, representing an increase of nearly 30% from 2024 and more than sevenfold growth compared with 2020[9]. As shown in Figure E9[10], this growth remains concentrated in China, Europe, and the United States, with China alone accounting for more than 12 million electric car sales in 2024, exceeding total global EV sales just two years earlier. This trend indicates that EVs are no longer only a transport decarbonisation pathway, they represent a rapidly expanding pool of mobile battery capacity that can interact with homes, buildings, distribution networks, and electricity markets through controlled charging and bidirectional power exchange.

Vehicle-to-X (V2X) applications convert EVs from passive charging loads into controllable energy resources. Vehicle-to-Grid (V2G) enables aggregated EVs to exchange power with the grid through residential, commercial, and public charging points, supporting frequency regulation, voltage support, congestion mitigation, peak load reduction, RE firming, and energy market participation. Vehicle-to-Home (V2H) and Vehicle-to-Building (V2B) extend this value to homes and buildings by improving resilience, increasing rooftop PV utilisation, and reducing peak electricity costs. However, large scale V2X adoption depends on bidirectional chargers, communication protocols, cybersecurity, user participation, battery warranty clarity, market remuneration, and controlled operation to avoid excessive battery degradation.

9 International Energy Agency, “Global EV Outlook 2026,” report, 2026.
10 International Energy Agency, “Global Energy Review 2026,” report, 2026.

Figure E9 : Global growth of electric car sales



Source: IEA

Hybrid and Multi-Use Energy Storage Systems

Hybrid and multi-use ESS are emerging globally because RE rich power systems require both fast response and sustained energy delivery. BESS, flywheels, supercapacitors, and SMES are better suited for high power, short duration services such as frequency regulation, voltage support, oscillation damping, and power smoothing. On the other hand, PHS, CAES, hydrogen, and thermal storage are more suitable for long duration shifting, adequacy, and seasonal balancing. As shown in Figure E10[11], this distinction between short duration and long duration flexibility highlights the complementary capability of different storage technologies across power system services. The implication is that future ESS portfolios will combine technologies rather than rely on a single storage asset.

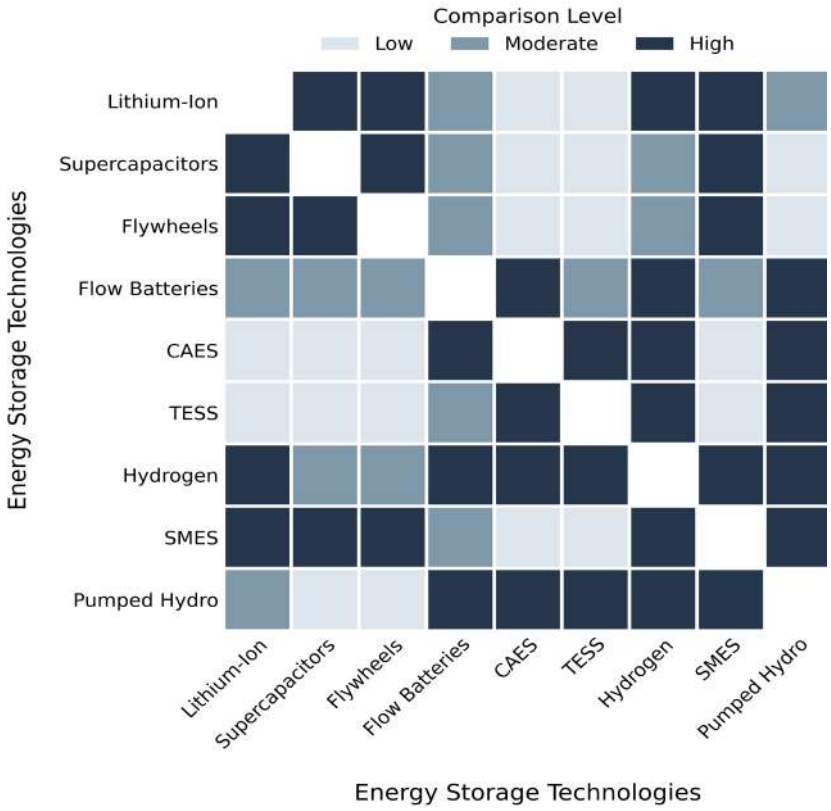
Long duration and sector coupled storage are becoming increasingly important as grids move beyond intraday balancing towards multi day, seasonal, and cross sector flexibility. Power system events span time scales from seconds to weeks, while ESS technologies occupy different discharge duration ranges. This supports the global trend towards hybrid portfolios in which BESS provides short duration grid services, PHP and CAES provide bulk energy shifting, hydrogen supports seasonal and cross sector storage, and thermal systems link electricity with heat, cooling, and industrial applications.

☀ KEY INSIGHT

Hybrid ESS development reflects a global shift from single-technology storage projects toward portfolios that combine fast-response technology with long-duration storage for multi-timescale flexibility.

11 Z. Fang, J. K. H. Shek, and W. Sun, "A review of grid-connected hybrid energy storage systems: Sizing configurations, control strategies, and future directions," J. Energy Storage, vol. 118, no. 116226, p. 116226, 2025.

Figure E10 : Comparative capability matrix of energy storage technologies across power system services and duration requirements



Data Source: A. M. Adeyinka et al.; 2025

Standards, Interoperability, and Safety Framework for ESS

Global ESS deployment is rapidly moving from project specific integration towards standardised, certifiable, and interoperable grid infrastructure. As ESS is increasingly connected at both transmission and distribution levels, standards are required to define interconnection performance, communication interfaces, cybersecurity requirements, model validation, safety testing, and installation approval. ESS connected at distribution level are governed through frameworks such as IEEE 1547, while transmission connected converter based ESS are addressed through IEEE 2800, which defines performance expectations for frequency response, voltage control, ride through capability, reactive current injection, and stability under low short circuit ratio conditions. National grid codes are also incorporating ESS as active grid resources rather than passive loads or generation substitutes. This reflects a global trend in which ESS must demonstrate not only energy delivery capability but also predictable behaviour during disturbances, compliance with grid code requirements, and validated dynamic performance, as summarised in Table E6.

☀ KEY INSIGHT

Global ESS deployment is shifting from technology-led installation to standards-led integration, where grid-code compliance, interoperability, cybersecurity, model validation, and safety certification determine whether storage can operate as reliable power-system infrastructure.

Table E6 : Key standards and their relevance for ESS deployment

Standard / framework	Main relevance for ESS
IEEE 1547 series	Distribution-level DER and ESS interconnection, voltage and frequency ride-through, anti-islanding, required grid support functionalities
IEEE 2800-2022	Transmission-level converter-based ESS performance, fault ride-through, reactive current injection, frequency and voltage response
IEC 61850, DNP3, Modbus, OpenADR, IEEE 2030.5	Communication, interoperability, SCADA integration, DER aggregation, dispatch signals, state-of-charge and operating data exchange
NERC CIP, IEEE 1547.3, IEC 62443, UL 2900	Cybersecurity, access control, secure communication, firmware integrity, monitoring, incident response
UL 9540, UL 9540A, UL 1973, UL 1741, NFPA 855, IEC 62933	ESS safety, thermal runaway testing, battery module certification, PCS certification, fire protection, installation approval

Global ESS Deployment, Policy Pathways, and Market Mechanisms

Global ESS deployment has moved from pilot scale adoption to policy driven and market integrated scale up, and major regions have announced large ESS targets as summarised in Table E7. These targets indicate that ESS is now treated as a core flexibility resource for RE integration, capacity adequacy, ancillary services, and grid resilience. The global policy direction is converging towards removal of double charging, clearer regulatory classification of storage, access to energy and ancillary service markets, and targeted support for long duration storage through capacity payments, tax credits, auctions, grants, and revenue stabilisation mechanisms.

Table E7 : ESS targets announced by major countries

Country	Key developments
United States	Cumulative 50 GW of storage by 2044 by nine states[12]
European nations	200 GW by 2030 and 500 GW by 2050[13]
China	180 GW of ESS by 2027[14]
Australia	43 GW by 2040[15]
India	73.93 GW (PHS and BESS) by 2032[16]

12 International Energy Agency, United States 2024: Energy Policy Review, IEA, Paris, France, 2024.

13 European Commission, Directorate-General for Energy, "Key facts on energy storage," European Commission.

14 The State Council of the People's Republic of China, "China accelerates development of new-type energy storage," The State Council Information Office, Sep. 12, 2025.

15 Australian Government Department of Industry, Science and Resources, "National Battery Strategy: Introduction," Australian Government.

16 Central Electricity Authority, National Electricity Plan (Volume I): Generation, Ministry of Power, Government of India, New Delhi, India, May 2023.

Regional pathways differ according to system structure, RE penetration, and market design, as summarised in Table E8. Global ESS deployment is no longer constrained only by technology cost. The major factors are policy clarity, market participation rights, bankable revenue streams, grid service valuation, and LDES support. Markets that explicitly recognise storage as both supply and demand, allow value stacking, and provide mechanisms for capacity, ancillary services, and flexibility procurement are better positioned to scale storage as core power system infrastructure.

Table E8 : Major ESS initiatives across the world

Region	Dominant pathway	Main storage driver
China	National targets, RE-storage mandates, shared storage, market participation reforms	RE integration and increased grid flexibility
United States	FERC market reforms, IRA tax credits, state mandates, DOE long-duration programmes	Market access, investment incentives, capacity and ancillary services
United Kingdom	Flexibility markets, eliminating double charging, frequency response procurement, LDES cap-and-floor model	Fast response, balancing services, long-duration reliability
European Union	Defining storage legally, market access rules exists, BESS lifecycle regulation	Harmonised regulation, energy security, flexibility and sustainability
Australia	Five-minute settlement, advanced converter funding, capacity investment schemes, state storage targets	High-RE grid operation, FCAS, inertia, system strength

Economic Assessment of ESS

The economic viability of ESS cannot be assessed through upfront capital cost alone because storage value depends on several factors like charging and discharging timing, cycling frequency, degradation behaviour, service mix, market access, and regulatory treatment. ESS operates as a multi service flexibility resource rather than a conventional generation asset, so project viability depends on both lifecycle cost recovery and the ability to monetise services such as energy arbitrage, peak shaving, RE firming, capacity adequacy, ancillary services, T&D deferral, resilience, and behind the meter bill management. A robust economic assessment must therefore combine cost metrics with value based evaluation, including system benefits, dispatch modelling, revenue stacking, financing assumptions, and project level feasibility.

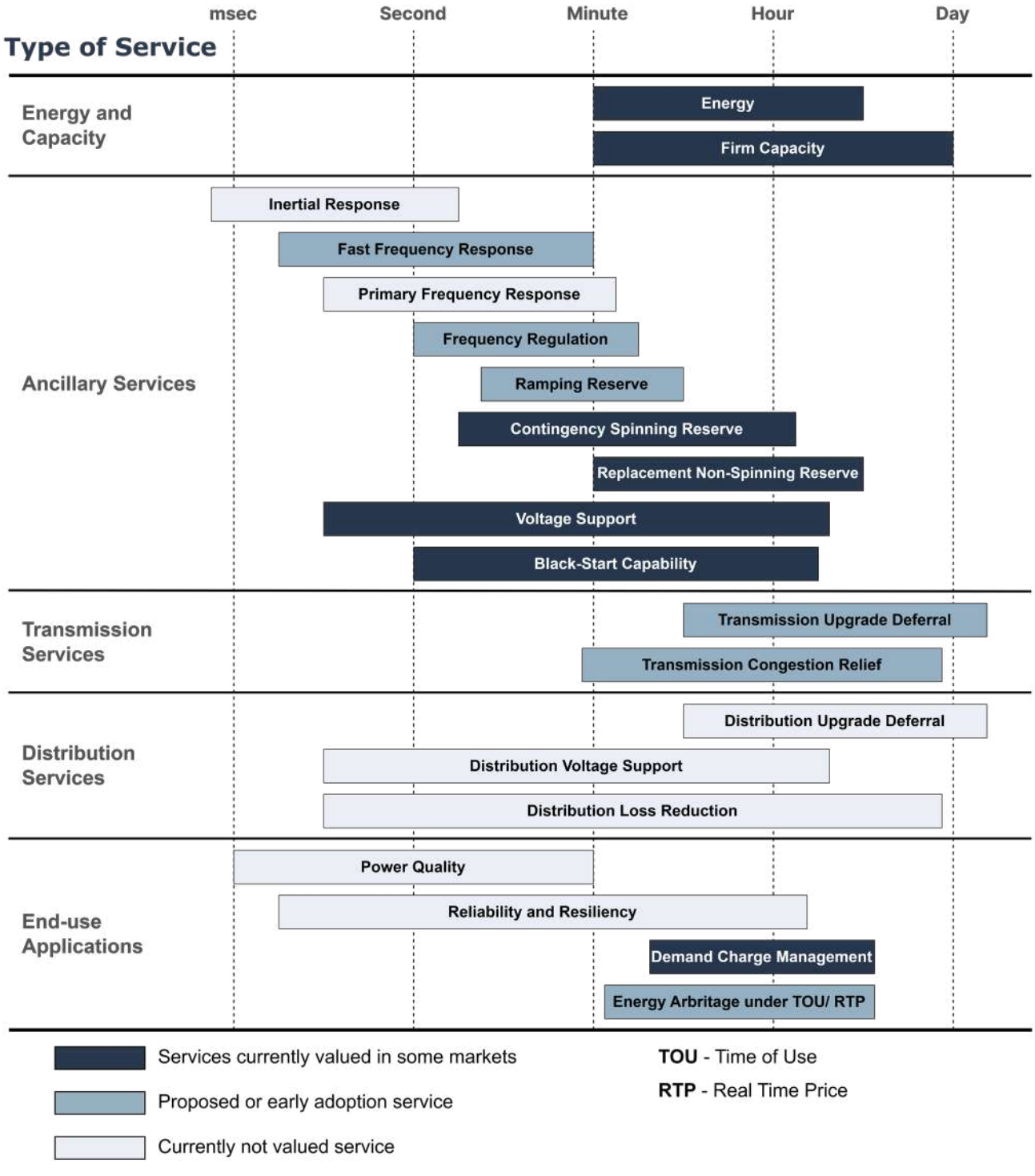
Levelised Cost of Energy Storage (LCOS) is useful for technology screening because it estimates lifetime cost per unit of discharged energy, but it is not sufficient as a standalone decision metric. It does not capture market revenues, avoided network costs, capacity contribution, ancillary service payments, or economic benefit of value stacking. The revenue landscape shown in Figure E11[17], highlights that ESS services span milliseconds to days, covering different type of grid support services and end use applications. This confirms that storage economics are both service specific and market specific. ECES is typically aligned with fast ancillary services, mechanical and chemical storage are more relevant for bulk and long duration services, and thermal storage is more closely linked with behind the meter and demand side applications.

17 Clean Energy Ministerial, Exploring the Value of Electricity Storage: A Comprehensive International Overview, White Paper, 2025.

☀ KEY INSIGHT

LCOS enables cost benchmarking, but ESS financial viability depends on value stacking across energy, capacity, ancillary, network, and customer-side services.

Figure E11 : Revenue Streams from ESS

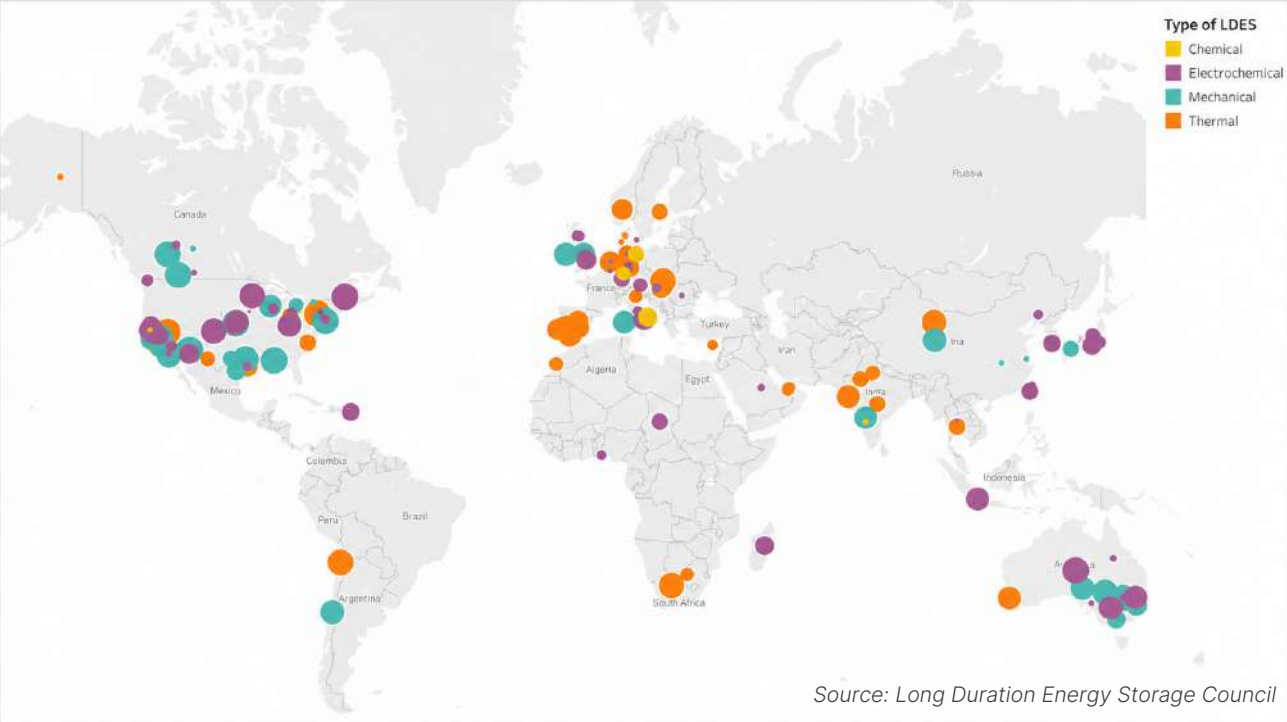


Key Challenges, Research Directions, and Roadmap to 2050

The next stage of global ESS deployment will be shaped by technology advancement, financial viability, safety, market design, and supply chain resilience. Key constraints include lithium ion degradation and thermal safety, non-uniform availability of Li-ion reserve and monopoly, limited field validation for emerging chemistries, site and permitting constraints for PHS and CAES, low round trip efficiency for hydrogen, interconnection delays, unclear long duration revenue mechanisms, and concentrated critical mineral supply chains. Research and policy priorities should therefore focus on degradation aware control, reliable SOH and remaining useful life estimation, validated safety models, duration specific capacity accreditation, long duration revenue mechanisms, recycling, SLBs, and battery passports.

The 2050 roadmap requires storage portfolios segmented by duration and system service. Short duration technologies such as lithium ion batteries, flywheels, and supercapacitors are aligned with short term balancing, frequency control, ramping, power quality, and daily shifting, while flow batteries, CAES, PHS, thermal storage, gravity storage, and hydrogen are required for inter day, multi day, and seasonal adequacy. The early global deployment of long duration storage projects shown in Figure E12 indicates that these technologies are moving from planning to initial implementation, although maturity and financial viability remain uneven across technologies and regions.

Figure E12 : Early global adoption of LDES projects worldwide



Source: Long Duration Energy Storage Council

☼ KEY INSIGHT

The 2050 ESS roadmap is expected to be duration-segmented, combining fast-response storage for grid stability with long-duration technologies for adequacy, resilience, and seasonal balancing.

Key Findings

- RE resources crossed a global inflection point in 2025, reaching 33.8% of global electricity generation and slightly exceeding coal at 33.0%, making storage essential for flexibility, ramping, curtailment reduction, and grid stability.
- Solar PV is now a major driver of ESS demand, with global solar generation increasing from approximately 2,143 TWh in 2024 to 2,778 TWh in 2025, while around 627 GW of new solar PV capacity was added globally in 2025.
- PHS remains the backbone of global bulk storage, accounting for about 95% of grid-connected storage capacity, with global operating PHS capacity reaching 196.17 GW by March 2026.
- Global BESS deployment is becoming utility-scale and regionally concentrated, with China accounting for more than 50% of global BESS capacity additions and utility-scale systems contributing over 80% of new global BESS capacity.
- Lithium-ion battery manufacturing is highly concentrated, with global production increasing from approximately 1.6 TWh in 2024 to 2.3 TWh in 2025, while China accounted for about 86% of global Li-ion battery production.
- ESS policy targets are scaling rapidly across major regions, with China targeting 180 GW of ESS by 2027, European national plans indicating around 45 GW by 2030, the United States announcing more than 50 GW of future storage capacity, and Australia projecting 43 GW by 2040.
- EVs are emerging as a major distributed storage resource, with global electric car sales exceeding 21 million in 2025.
- SLBs can become an important circular economy pathway, since retired EV batteries typically retain about 70–80% of nominal capacity and can be repurposed for stationary storage before recycling.
- ESS value depends on service stacking and market access. ESS financial viability cannot be judged by LCOS alone as it depends on combining energy, capacity, ancillary service, network, resilience, and customer-side revenues within technical and regulatory limits.
- Grid-forming control, safety standards, and lifecycle sustainability are becoming decisive for large-scale ESS deployment. Future ESS growth will require advanced PCS control, standardised interconnection and certification, recycling, second-life use, and critical-mineral diversification.

01

CHAPTER 1

INTRODUCTION



Pexels

Summary

- Establishes the global context for ESS by linking climate change, power sector emissions, renewable energy growth, and increasing power system flexibility requirements.
- Highlights the rapid global expansion of solar PV and wind, including their impact on the electricity mix, net load variability, reserve requirements, curtailment, and duck curve behaviour.
- Discuss the key technical drivers for ESS in renewable rich grids, including intermittency, non-synchronous generation, reduced inertia, voltage rise, power quality impacts, and congestion related curtailment.
- Positions ESS as a controllable flexibility resource capable of energy shifting, fast frequency response, voltage support, curtailment reduction, and improved renewable integration.





Pexels

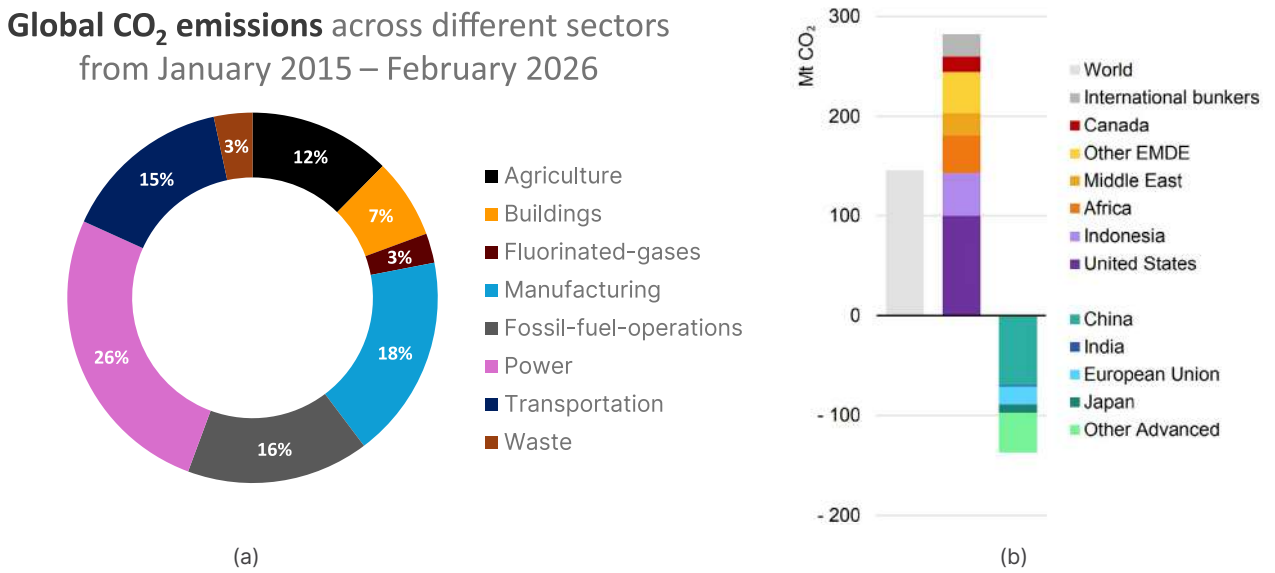
1.1 Background

The global energy system is undergoing a structural transition while operating under escalating climate and environmental challenges. Continious increase in global warming has intensified both frequency and severity of extreme events, particularly heat waves, amplifying risks associated with droughts, storms, wildfires, and hydrological variability[1]. Climate-related factors directly affect power system planning and operation through (i) higher and more volatile cooling load driven peak demand, (ii) reduced efficiency and available capacity of thermal generation and transmission network assets during extreme heat, (iii) increased outage probability and more complex system restoration under compound events, and (iv) greater uncertainty in electricity demand and Renewable Energy (RE) generation profiles. In parallel, air pollution in many regions is closely linked to emissions from fossil fuel combustion. Therefore, decarbonising electricity supply and end-use sectors can also improve public health and air quality. This creates an additional societal benefit for faster decarbonisation[2].

1.1.1 Emissions Profile and Primary Drivers

The climate emergency is primarily driven by persistently high greenhouse gas emissions, largely from energy production and energy use sectors. The sectoral breakdown of global CO_2 emissions in major energy sectors from January 2015 to February 2026, highlights the sectors that account for the high share of emissions as shown in Figure 1[3]. It is observed that the power industry accounts for 26 percent of global CO_2 emissions, indicating that power sector decarbonisation is necessary but not sufficient. Along with this, CO_2 emissions increased by 0.4 percent globally which the slowest rate since 2021[4]. Deep decarbonisation therefore requires coordinated strategies beyond electricity generation, including electrification of transport and buildings, industrial fuel switching, and lifecycle emissions management across fuel supply and industrial processes.

Figure 1 Global CO2 emissions, (a) Share of emissions from different energy sectors, (b) Global share of emissions in 2025



(a) (b)

Data Source: Climate TRACE *Source: IEA*

1 International Energy Agency, World Energy Outlook 2025, IEA, Paris, France, 2025.
2 H. Lehtomäki, S. Rao, and O. Hänninen, "Phasing out fossil fuels would save millions of lives worldwide," BMJ (Clinical Research Ed.), vol. 383, p. 2774, 2023.
3 "Country/Territory Inventory," Climate TRACE.
4 International Energy Agency, "Global Energy Review 2026," 2026.

From an energy transition perspective, the power sector is critical because electricity is both a major emission source and the primary enabler of cross-sector decarbonisation through electrification. This dual role requires a reliable, scalable, and cost-efficient low-carbon electricity supply with sufficient operational flexibility to manage rising variability and uncertainty in supply and demand.

1.1.2 Current Energy Supply and Electricity Mix

The global electricity generation mix in 2024-2025 reflects an accelerating transition towards RE sources, led by strong growth in solar and wind. As shown in Figure 2, solar based energy generation increased from approximately 2,143 TWh in 2024 to 2,778 TWh in 2025, representing the highest absolute growth among all technologies. Wind generation also expanded, rising from around 2,510 TWh to 2,715 TWh over the same period. These trends are driven by cost reductions, policy support, and large scale capacity additions, particularly in emerging markets. As a result, variable RE is playing an increasingly significant role in incremental generation and influencing system dynamics[5].

At the same time, energy generation from conventional energy resources specially coal based power plants is reducing. Coal generation decreased marginally from approximately 10,539 TWh in 2024 to 10,476 TWh in 2025, with its share falling below one third of global electricity generation. While the reduction is modest in absolute terms, it reflects a shift in long standing generation patterns. Gas and other fossil fuels continue to contribute substantially, although their relative growth is slower compared to RE. This divergence between expanding RE generation and gradually declining fossil based generation highlights the transitional nature of the current energy mix.

Long term perspective on this energy transition can be shown from Figure 2, illustrating the evolution of the global electricity mix from 2000 to 2025[4]. Fossil fuels, particularly coal, have historically dominated generation, but their share is gradually declining as RE technologies scale. The rapid rise of wind and solar has contributed to a more diversified and lower carbon energy mix, while hydro and nuclear have remained relatively stable. This structural transformation is characterised by increasing variability and decentralisation, underscoring the need for enhanced system flexibility through energy storage, grid modernisation, and advanced operational strategies.

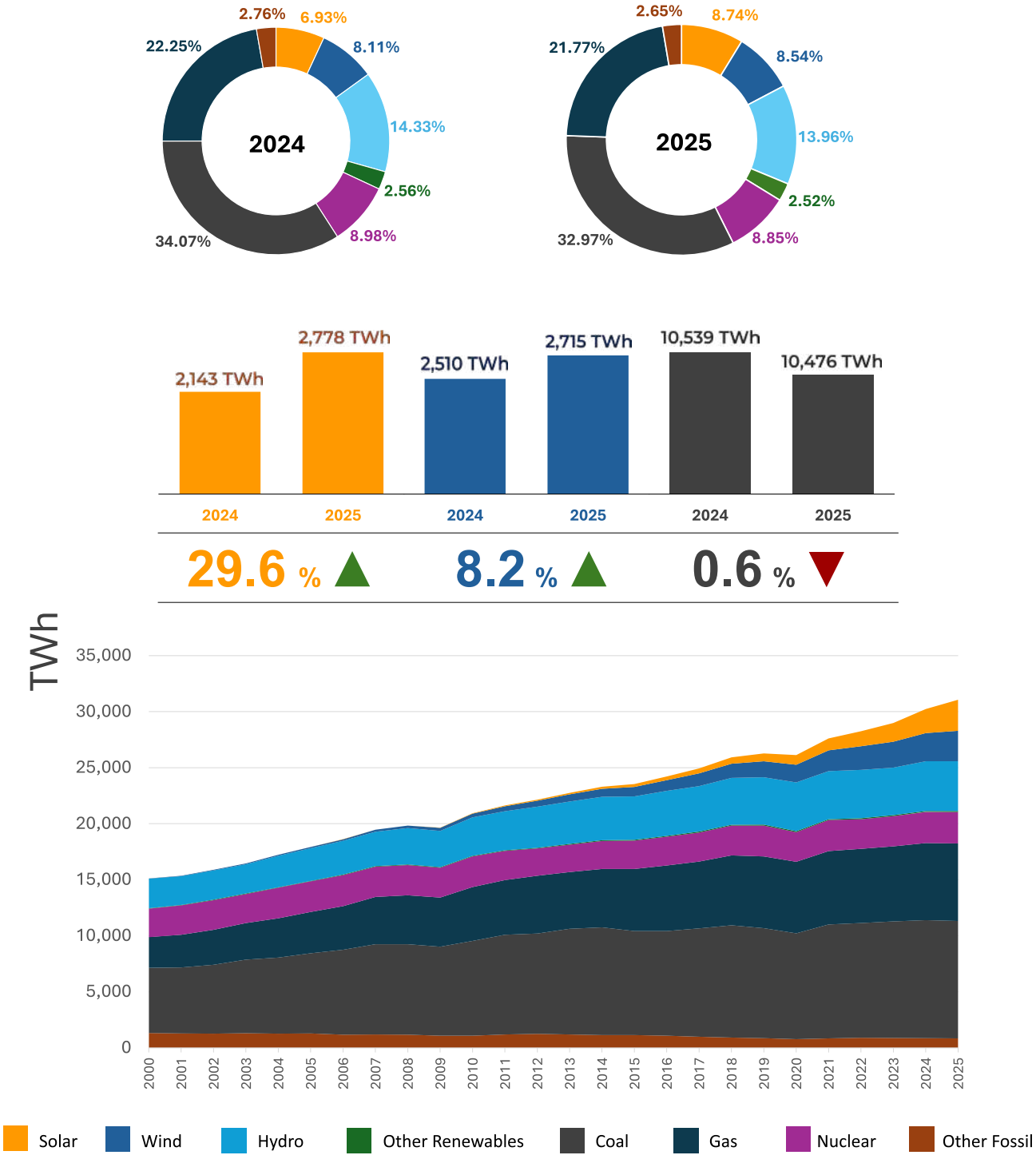
From a system operation perspective, the increasing share of Variable RE is altering net load profiles, leading to steeper ramping requirements and reduced system inertia due to the displacement of synchronous generation. This is evident in regions with high solar Photovoltaic (PV) penetration, where midday generation surpluses and evening demand peaks create pronounced duck curve effects. Increased variability and forecast uncertainty also raise the need for real time balancing resources, fast frequency response, and enhanced reserve margins. The declining share of dispatchable thermal generation constrains conventional flexibility, necessitating a transition towards Inverter Based Resources (IBR) capable of providing advanced grid support functions. These dynamics reinforce the importance of advanced control strategies, grid forming technologies, and integrated flexibility solutions to maintain stability and reliability in high RE riched power systems.

5 Ember, “Electricity Data Explorer,” Ember Energy.



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Figure 2 Global electricity generation mix and trends by source

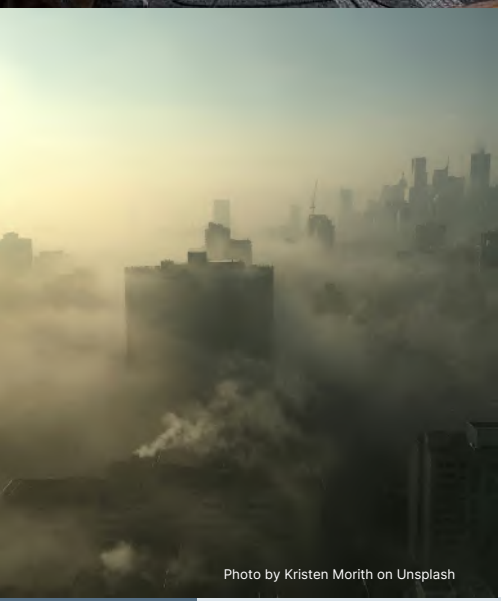


Data Source: Ember

Other RE generation: Bioenergy, geothermal, tidal and wave generation.
Other fossil generation: Generation from oil and petroleum products, as well as manufactured gases and waste.
Legends are same throughout all the plots


Pexels


Pexels


Photo by Kristen Morith on Unsplash

1.1.3 Climate-Impact Signals Relevant to Energy Systems

Climate-driven impacts such as heatwave, air quality degradation, cryosphere loss, and wildfires increasingly stress electricity systems by raising peak demand, derating assets, and increasing reliability risks. Some of the major risks are highlighted below:

- **Extreme heat and peak demand stress:** Record or near record global temperatures and frequent heatwaves have direct implications for power systems through surge in energy demands, equipment deratings, and elevated forced outage risk during peak load periods. Heat related demand growth is particularly consequential because it increases reliance on peaking and flexibility resources, increases network congestion, and reduces operating margins when multiple assets are simultaneously utilised[6].
- **Air quality degradation:** Severe urban air pollution occurrences, are often amplified by adverse meteorological conditions and high atmospheric temperature. It intersect with energy systems through increased public health related risks and intensified policy pressure to reduce combustion related emissions. Global health evidence indicates that ambient air pollution contributes to millions of premature deaths per year, directly linking air quality outcomes to energy transition policies and long term investment decisions[7].
- **Cryosphere decline and hydropower uncertainty:** Sustained cryosphere decline, including accelerated glacier melting loss is assessed to affect seasonal water availability, hydropower inflows, and multi sector risk profiles. These changes have potential implications for both energy adequacy and operational scheduling under altered hydrological conditions[8].
- **Wildfire risk and transmission network exposure:** Wildfire and smoke impacts across multiple regions can directly threaten transmission corridors and substations and can necessitate preventive operational measures under high risk conditions. These impacts are consistent with the broader documented increase in extreme event severity and frequency under continued warming and changing land and atmosphere interactions[5].

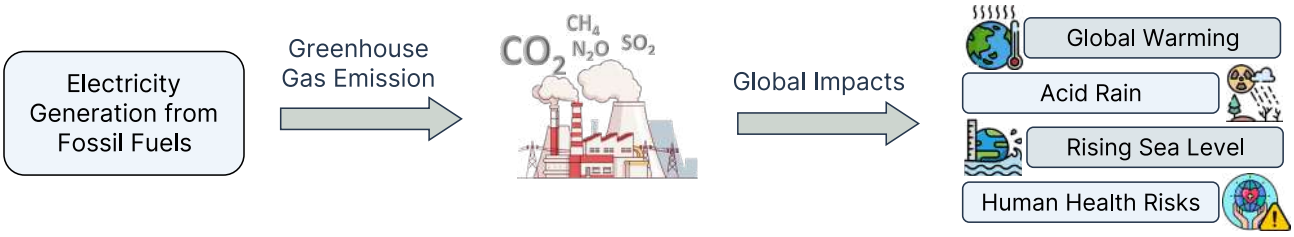
6 World Meteorological Organization, State of the Global Climate 2024 (WMO-No. 1368), WMO, Geneva, Switzerland, 2025.

7 World Health Organization, Ambient (Outdoor) Air Quality and Health, WHO, Geneva, Switzerland.

8 International Centre for Integrated Mountain Development, HI-WISE Report: Climate Risks and Adaptation in the Hindu Kush Himalaya Region, ICIMOD, Kathmandu, Nepal.

Taken together, these climate impact signals highlight the close linkage between fossil fuel based electricity generation, greenhouse gas emissions, and downstream environmental and societal impacts, as illustrated in Figure 3. Emissions from power generation contribute directly to global warming and related outcomes such as air quality deterioration, sea level rise, and human health risks, which in turn feed back into electricity systems through higher demand, asset stress, and increased operational risk.

Figure 3 Linkage from fossil fuel based electricity generation to global warming impacts

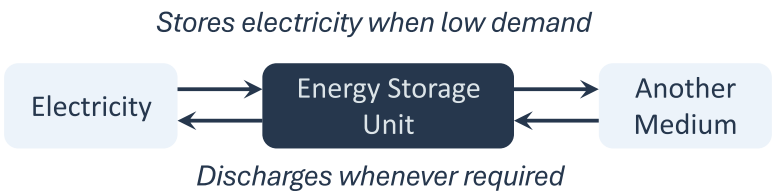


This linkage emphasises the need for power systems to simultaneously reduce emissions and enhance resilience, reinforcing RE generation. Hence, energy storage plays a key resource for providing controllable flexibility and resilience, while supporting power sector decarbonisation and electrification.

1.2 Historical Evolution of Energy Storage Systems

Energy Storage Systems (ESS) have evolved over more than a century in response to changing power system requirements and technological advancements. Historically, the primary motivation for storage deployment was not RE integration, but rather load balancing, reserve provision, and operational flexibility within vertically integrated power systems. As shown in Figure 4 the role of ESS is to store electrical energy in another medium during periods of low demand and convert it back into electricity during periods of high demand.

Figure 4 Functioning of energy storage systems



The earliest large scale grid connected energy storage deployments were based on mechanical technologies, most notably Pumped Hydro Storage (PHS) plants. PHS has been in use since the late nineteenth century, with widespread utility scale deployment during the twentieth century to address growing demand and load variability[9]. Owing to its large energy capacity, long discharge duration, and mature technology, PHS is well suited for bulk energy shifting and system balancing. As a result, PHS has historically dominated global grid scale storage capacity, accounting for nearly

9 U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Pumped Storage Hydropower, U.S. DOE, Washington, DC, USA.


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KEY INSIGHT

PHS established ESS as a bulk load-balancing resource, but advances in battery storage and market reforms have shifted ESS toward dispatchable, multi-service grid assets for RE integration, capacity support, and advanced ancillary service provision, making BESS as the fastest growing ESS technology.

all installed capacity in the mid-2010s and continuing to represent over 90 percent of total grid connected storage capacity despite recent growth in alternative technologies[10].

A second major phase in the evolution of energy storage emerged with advances in electrochemical technologies, particularly lithium ion batteries. While batteries have existed for over a century, the commercial introduction of lithium ion technology in 1991 marked a key inflection point due to higher energy density, longer cycle life, and scalable manufacturing[11]. Initially used in consumer electronics, lithium ion batteries later expanded into stationary applications as system integration improved. Advances in battery management systems, thermal control, and grid connected power electronics enabled reliable operation of complete battery energy storage systems rather than standalone battery cells[12].

In parallel, technologies such as Compressed Air Energy Storage (CAES) were explored for long duration applications but remain limited by site specific geology, long development time lines, and system complexity. This reflects a broader pattern in ESS deployment, where large scale adoption is driven more by deployability, standardisation, and risk reduction. By the mid-2010s, ESS shifted from isolated assets to recognised multi service grid resources, supported by clearer definitions and regulatory recognition. Authorities formally defined ESS as a distinct system function involving energy deferral and reconversion, separate from generation and load, enabling more consistent evaluation in planning studies[13]. This clarity, along with market reforms allowing participation in energy, capacity, and ancillary services, accelerated the transition of ESS from experimental deployments to mainstream grid infrastructure[14].

10 World Bank, Energy Sector Management Assistance Program, Pumped Storage Hydropower: Benefits, Challenges, and the Role of the Public Sector, World Bank, Washington, DC, USA, 2022.

11 The Royal Swedish Academy of Sciences, The Nobel Prize in Chemistry 2019 – Press Release, Nobel Prize Outreach AB, Stockholm, Sweden, 2019.

12 U.S. Department of Energy, Quadrennial Technology Review 2015: Chapter 3 – Enabling Modernization of the Electric Power System: Technology Assessments – Electric Energy Storage, U.S. DOE, Washington, DC, USA, 2015.

13 Eurostat, Electricity Production, Consumption and Market Overview, European Commission, Luxembourg.

14 Federal Energy Regulatory Commission, Order No. 841: Electric Storage Participation in Markets Operated by RTOs and ISOs, Feb. 2018.

1.3 Need of Energy Storage in RE Integrated Power System

Rapid growth of RE resources, mainly solar PV and Wind Turbine Generators (WTG), has shifted power system operation from dispatch led to flexibility led scheduling. As RE penetration increases, system reliability highly depends on balancing short term variability, managing energy shifting needs, and maintaining frequency and voltage stability with reduced synchronous generation. In this context, ESS act as multi time-scale flexibility resources, providing energy shifting, operating reserves, and fast dynamic support.

1.3.1 RE Resources Portfolio

Major RE resources, as depicted in Figure 5 highlights an important system level distinction. All RE technologies do not contribute the same type or degree of operational flexibility. Hydro power and geothermal resources can be dispatchable within water availability and steam cycle constraints, whereas solar PV and wind generation are inherently variable and non-synchronous in nature. Green hydrogen is viewed as a cross sector energy carrier rather than a direct electricity supply source, with electrolysis functioning as a controllable load and storage enabling long duration energy balancing. Biomass based generation is dispatchable within fuel supply and sustainability constraints and can provide firm capacity and limited operational flexibility on grid integration.

Figure 5 Renewable energy resources



Solar PV and WTGs are most common source of RE generation. Higher share of these technologies increases the need for non-generation flexibility resources, including ESS, demand response, interconnection, and grid enhancing technologies, because the marginal RE MWh is not controllable in the same manner as conventional generation. ESS are therefore positioned as controllable converter interfaced assets that can operate alternately as generation during discharging and as load during charging, enabling reduction of operational constraint violations[15].

1.3.2 Scale of RE Growth Driving Flexibility Requirements

The pace of global solar PV growth shown in Figure 6 indicate that solar energy is increasingly becoming a dominant energy source across multiple regions, with deployment concentrated in a limited number of major markets[16]. Around 629 GW of solar PV capacity was installed globally in 2025, and its total installed capacity reached 3,056 GWs till May 2026[17]. As of 2025, country-level capacity additions were dominated by China, with 1063 GW installed, followed by the United States

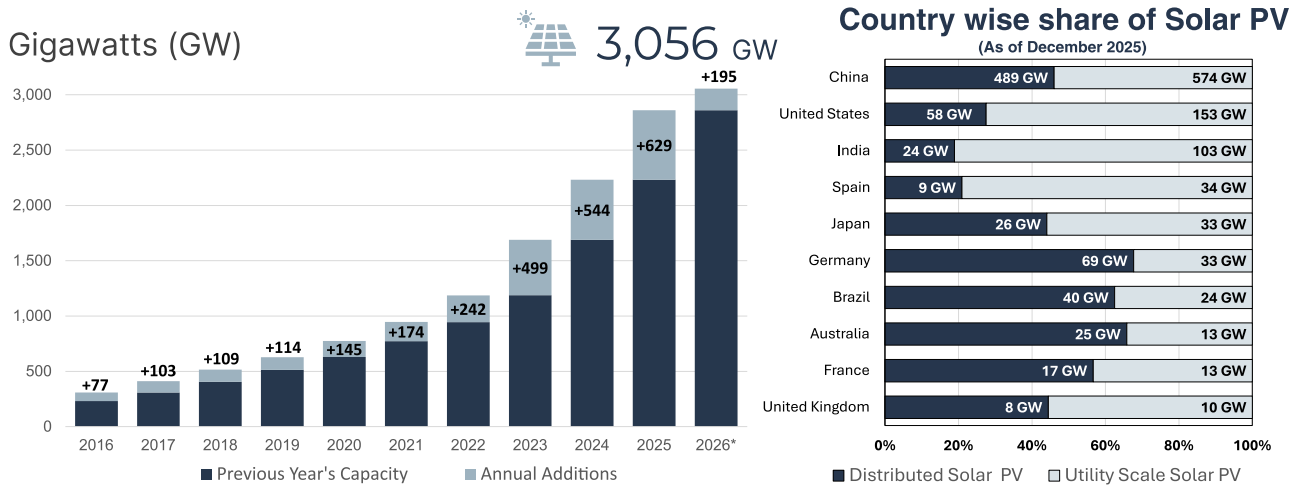
15 National Renewable Energy Laboratory, Operational Impacts of Variable Renewable Generation and Flexibility Needs (Balancing, Reserves, and Ramping), NREL, Golden, CO, USA, technical report series, 2019–2024.

16 IEA PVPS Task 1 Strategic PV Analysis and Outreach, Snapshot of Global PV Market 2025, International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), April 2025.

17 Ember, "Wind and Solar Capacity Data Explorer," Ember Energy.

at 221 GW and India at 127 GW[18]. When capacity additions of this magnitude occur over short planning cycles, power systems are required accommodate substantial incremental volumes of low marginal cost energy. The output of this energy is governed by solar irradiance and prevailing weather conditions rather than direct operator dispatch.

Figure 6 Global solar PV installations



Data Source: Ember **Data till May 2026* *Data Source: Global Energy Monitor*

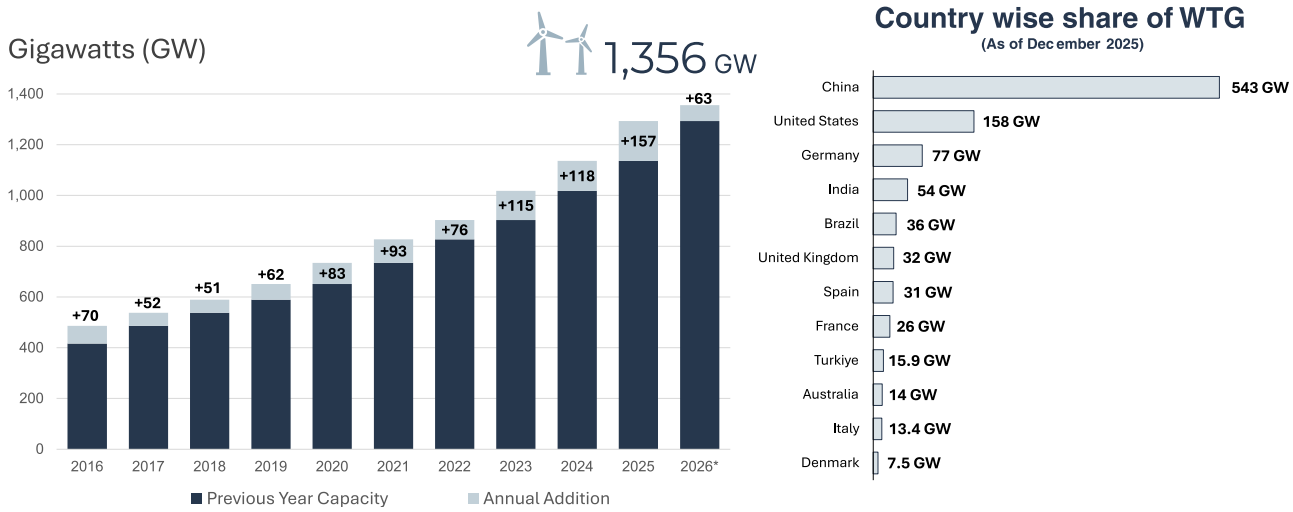
Similarly, the WTG deployment trajectory shown in Figure 7 indicates sustained global capacity growth, reaching approximately 1,356 GW by May 2026[19], with WTG installations concentrated in a limited number of major markets, including China, the United States, Germany, and India[18]. This concentration has operational implications, as wind generation is weakly correlated with electricity demand and subject to short-term forecasting and ramping uncertainty, increasing the need for additional operating reserves and faster regulation capability to maintain system balance and reliability.

18 Global Energy Monitor, Global Wind and Solar 2025: The G7 Gap

19 World Wind Energy Association, World Wind Energy Report 2025, WWEA, Bonn, Germany, 2025.



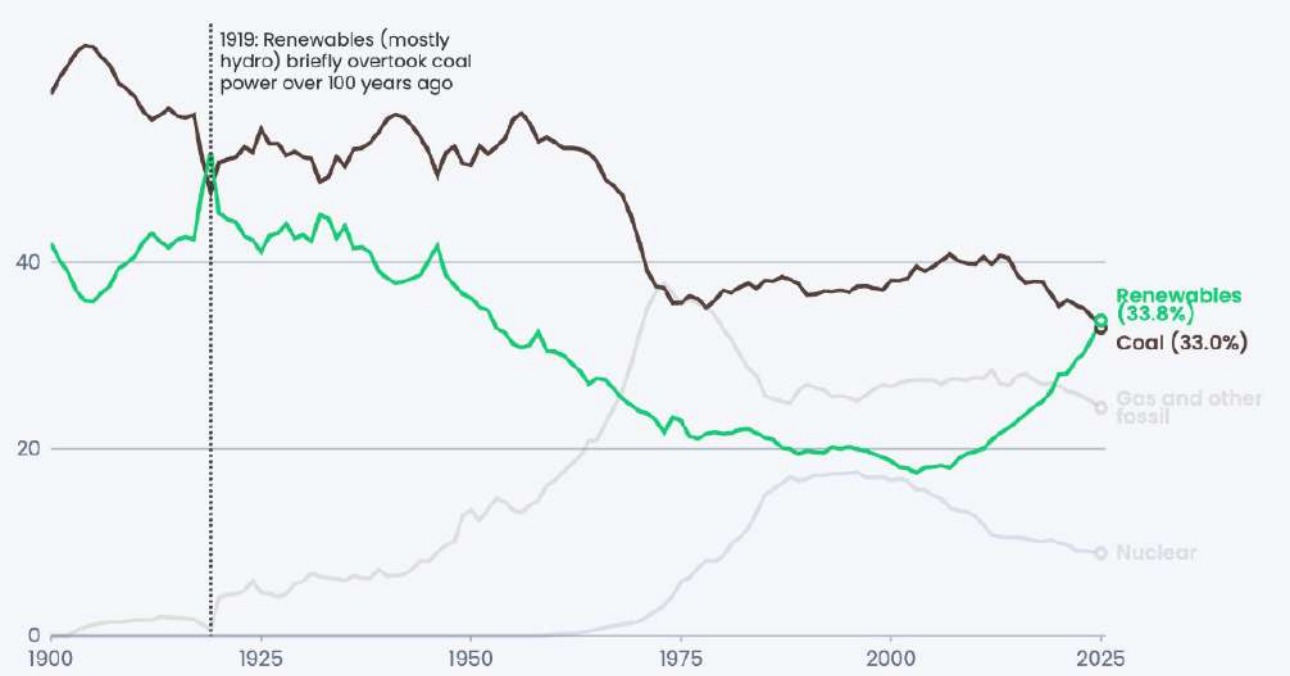
Figure 7 Global wind installations



Data Source: Ember **Data till May 2026* *Data Source: Global Energy Monitor*

With the increase in expansion of solar PV and wind, the global electricity mix has reached a critical inflection point, with RE surpassing coal for the first time in over a century. In 2025, RE accounted for 33.8 percent of global generation, slightly ahead of coal at 33.0 percent, reflecting the accelerating impact of variable renewable deployment. This transition has been driven primarily by WTG and solar PV, whose combined share has more than tripled over the past decade, while coal's contribution has steadily declined. The growing share of variable RE resources not only reshapes generation patterns but also increases the need for system flexibility to manage variability and intermittency. As illustrated in Figure 8[20] , this structural shift highlights the central role of RE growth in driving future flexibility requirements.

Figure 8 RE surpassing global coal power generation



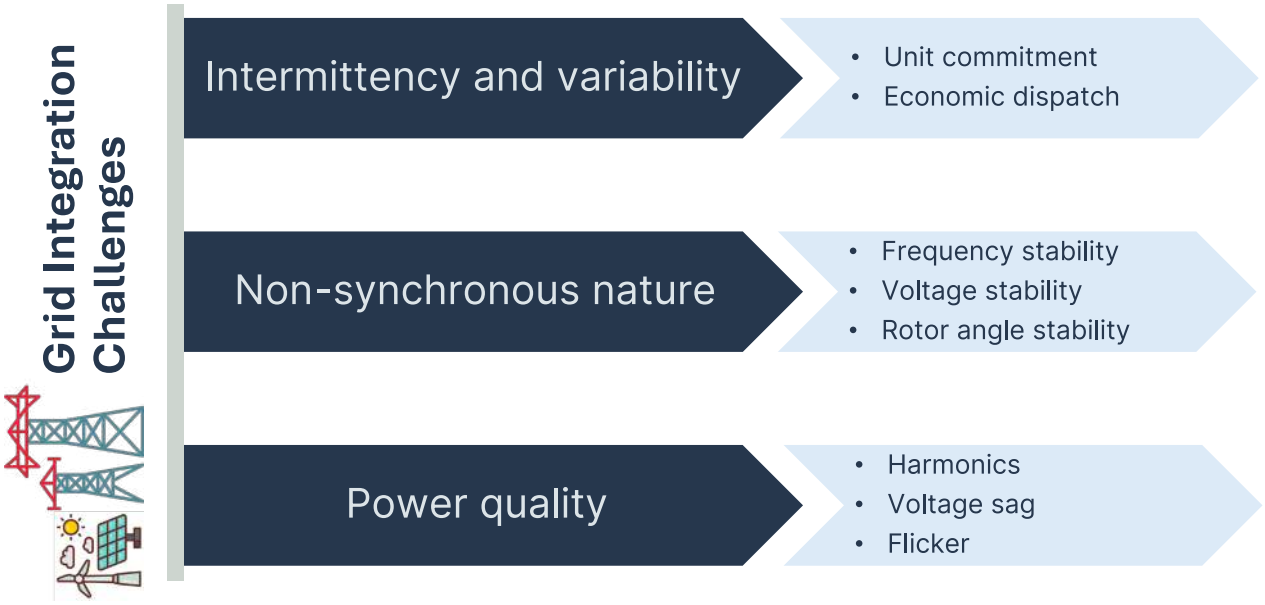
Source: Ember

20 N. Fulghum, W. Suarez, K. Altieri, and K. Rangelova, Global Electricity Review 2026, Ember, Apr. 21, 2026.

1.3.3 Technical Drivers for Energy Storage System Deployment

The three major gird integration challenges drivers as highlighted in Figure 9, namely intermittency and variability, non-synchronous resource characteristics, and power quality impacts, each of which maps directly to a corresponding family of ESS services.

Figure 9 Grid integration challenges due to RE resources



- **Intermittency and variability, scheduling and balancing impacts:** Rising variability in RE generation increases the need for flexible unit commitment, intraday redispatch, and short-term operating reserves. ESS mitigates these impacts through energy shifting and bidirectional power control, reducing net load ramps, peak capacity requirements, and cycling stress on thermal units while supporting regulation and more efficient system dispatch[21].
- **Non synchronous nature, stability impacts:** As synchronous generation declines, system inertia and fault current reduce, adversely affecting frequency and voltage stability, and rotor angle stability. ESS can provide fast frequency response, inertia like control behaviour, and dynamic voltage support, thereby improving stability margins in IBR dominated power systems[22].
- **Power quality impacts:** High levels of RE generation can increase harmonic distortion and voltage fluctuations, particularly in distribution networks. ESS equipped with appropriate control functions, such as reactive power support and active filtering, can mitigate these effects by locally injecting or absorbing real and reactive power, thereby improving power quality and reducing network stress[23].

21 S. Impram, S. Varbak Nese, and B. Oral, "Challenges of renewable energy penetration on power system flexibility: A survey," Energy Strat. Rev., vol. 31, no. 100539, p. 100539, 2020.

22 Power System Operation Corporation Limited (POSOCO) and Grid Integration Lab, IIT Bombay, Report on Assessment of Inertia in Indian Power System, IIT Bombay, Mumbai, India.

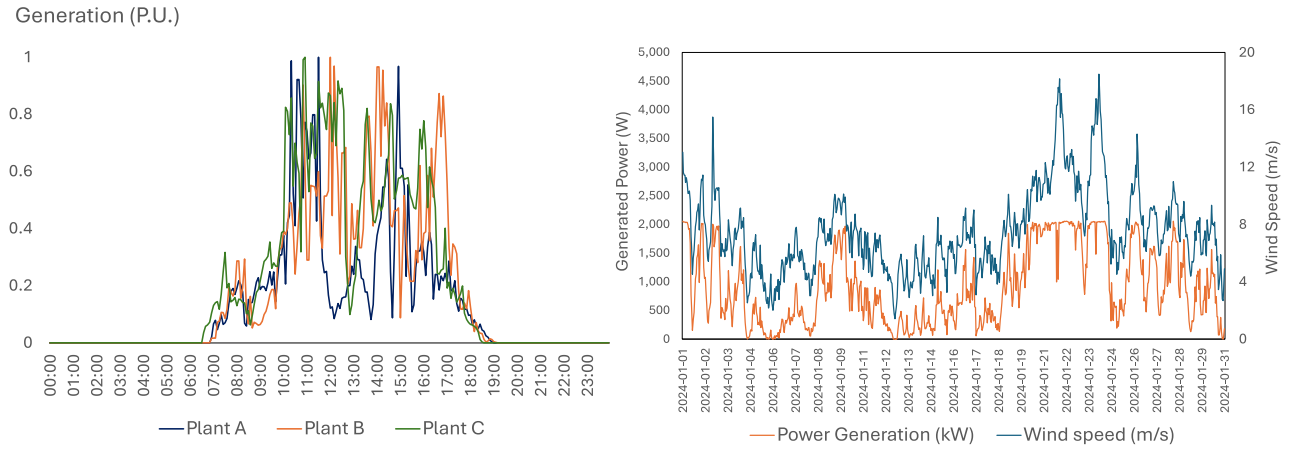
23 H. Eroğlu, E. Cuce, P. Mert Cuce, F. Gul, and A. Iskenderoğlu, "Harmonic problems in renewable and sustainable energy systems: A comprehensive review," Sustain. Energy Technol. Assessments, vol. 48, no. 101566, p. 101566, 2021.

1.3.4 Variability in Solar PV and Wind Power Generation

Solar PV generation exhibits pronounced variability across daily and sub-daily timescales due to its dependence on solar irradiance, cloud cover, and atmospheric conditions. As illustrated in Figure 10 (a), PV output follows a strong diurnal pattern, with zero generation at night, steep ramps during morning and evening transitions, and short-term fluctuations during daylight hours. This inherent variability poses operational challenges for power systems, including net load ramping, reserve allocation, and voltage management, particularly at high PV penetration levels.

Wind output examples further illustrate pronounced fluctuations over operational timescales as shown in Figure 10 (b) and highlight that variations in wind speed translate directly into power ramps that require active balancing actions. In practical system operation, this necessitates maintaining sufficient ramping capability and operating reserves to address both forecast error and real time variability. ESS provide this capability with rapid response characteristics and, in many operating contexts, lower mechanical wear and operational stress compared to frequent cycling of conventional generation units[24].

Figure 10 Variability in electricity generated from solar PV and WTG



(a) Solar PV Generation

(b) WTG Generation

Data Source: GIL Data

Data Source: Kelmarsh Wind Power Data, Zenodo

1.3.5 Frequency and Voltage Impacts with High RE Penetration

High penetration of RE has a significant impact on power system frequency dynamics. As illustrated in Figure 48[25], increasing RE penetration reduces system inertia and results in higher Rates of Change of Frequency (RoCoF) following disturbances. Lower inertia shortens the time available for primary frequency response and increases the risk of frequency deviations, thereby placing greater demands on fast-acting control resources to maintain system stability.

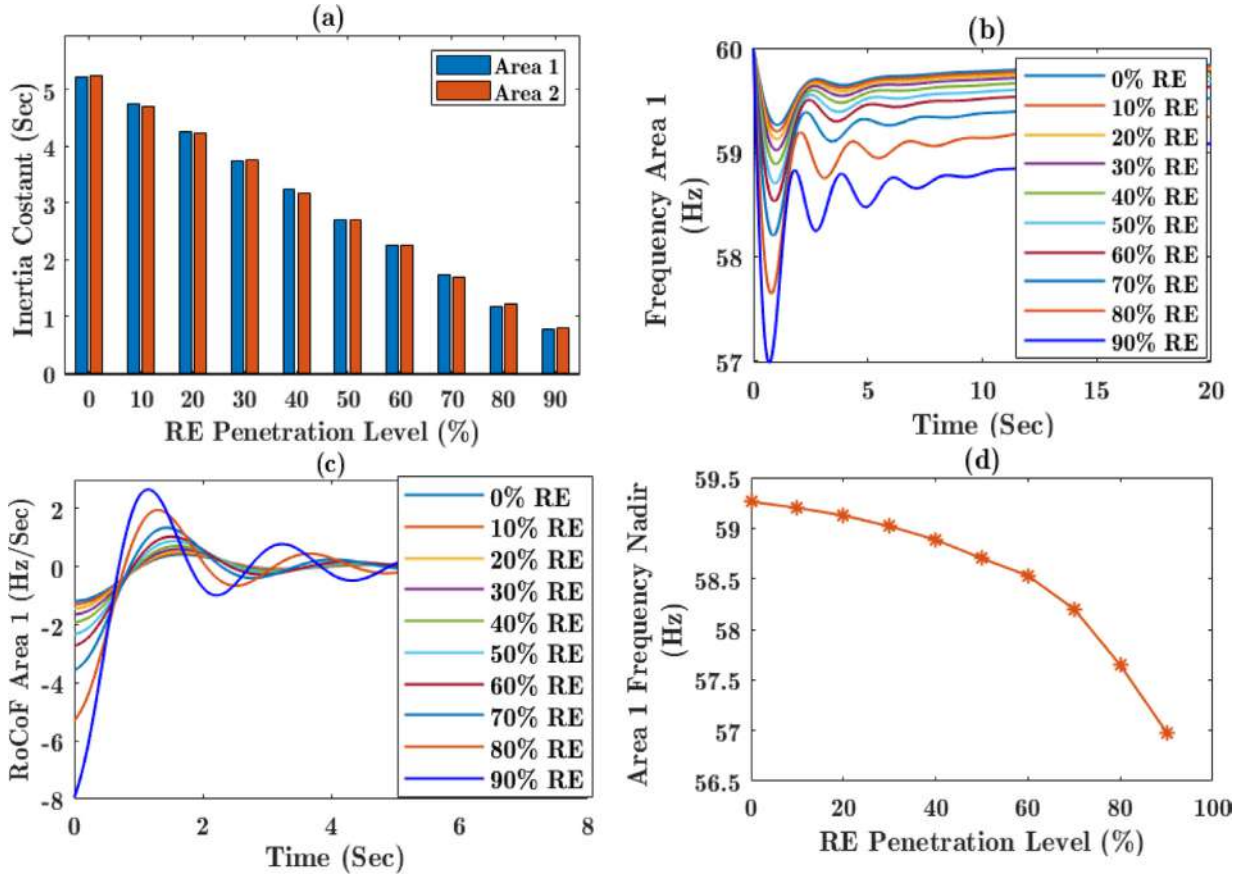
The operational implication is that system disturbances, such as generation trips or large load steps, produce faster and deeper frequency deviations in low inertia systems, thereby reducing the time

24 J. Reilly, R. Poudel, V. Krishnan, B. Anderson, J. Rane, I. Baring-Gould, and C. Clark, Hybrid Distributed Wind and Battery Energy Storage Systems, National Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-5000-77662, June 2022.

25 Saha, Sajeeb, M. I. Saleem, and T. K. Roy. "Impact of high penetration of renewable energy sources on grid frequency behaviour." International Journal of Electrical Power & Energy Systems, 2023.

available for primary frequency response. ESS can respond on timescales ranging from micro-seconds to seconds, providing rapid active power injection or consumption. When appropriately controlled and adequately sized, ESS can improve frequency nadir and reduce exposure to high RoCoF, thereby enhancing frequency stability in low inertia power systems.

Figure 11 Impact on system frequency due to high RE penetration

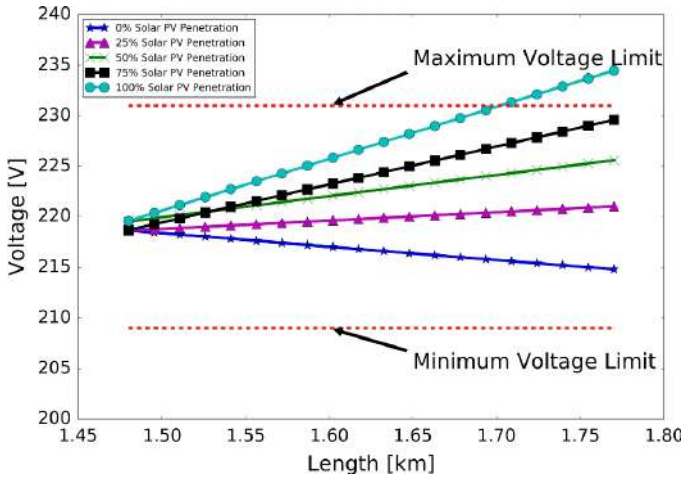


Source: S. Saha et al.; 2023

Rooftop Solar (RTS) PV installations in low voltage distribution networks are rapidly increasing across the globe. During peak solar generation hours and low demand periods, frequent over-voltage issues are observed due to significant increase in reverse power flow, resulting in tripping of RTS PV inverter. Figure 12[26] shows the increase in feeder voltage as solar PV penetration rises along with distance from the substation, which is indicative of distribution voltage rise mechanisms under reverse power flow conditions. As solar PV generation increases at electrically remote nodes, feeder impedance can cause voltage magnitudes to rise during export conditions, potentially leading to upper voltage limit violations. ESS mitigate this effect by locally consuming surplus solar PV energy through charging during periods of high irradiance and by providing reactive power support, subject to converter capability and applicable interconnection rules. This functionality effectively transforms a voltage constraint into a dispatchable flexibility resource, while simultaneously reducing curtailment risk for Behind-the-Meter (BTM) and distribution-connected solar PV installations.

26 T. Alquthami, R. Sreerama Kumar, and A. A. Shaikh, "Mitigation of voltage rise due to high solar PV penetration in saudi distribution network," Electrical Engineering, vol. 102, no. 2, pp. 881–890, Jan. 2020.

Figure 12 Impact on bus voltage due to high RE penetration

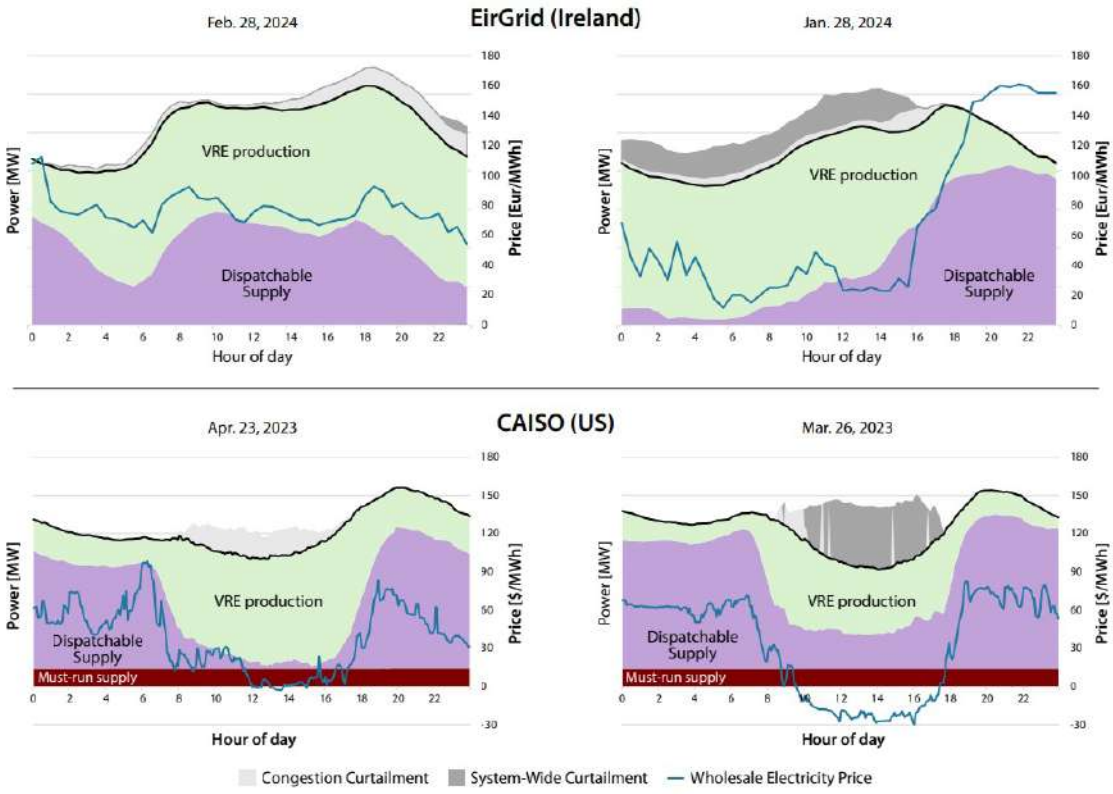


Source: T. Alquthami et al.; 2020

1.3.6 RE Curtailment Challenges

Curtailment refers to the intentional reduction of generation below available output due to system constraints such as network limitations, system strength considerations, minimum conventional generation requirements, or market-based dispatch outcomes. As illustrated in Figure 13[27], the principal drivers of curtailment are grouped into three categories, namely network congestion, system-wide oversupply, and wholesale price signals that constrain economic dispatch.

Figure 13 Congestion vs. system-wide curtailment dispatch stacks



NREL

27 Global Power System Transformation Consortium, What Is Power System Curtailment?, Global PST Consortium.

- **Congestion and local constraints:** Curtailment occurs when transmission or distribution constraints limit the delivery of available RE generation. ESS can alleviate congestion by charging behind constrained interfaces and discharging when constraints ease, effectively providing time-domain transmission capacity through energy shifting.
- **System wide oversupply conditions:** During periods of high solar or wind generation periods, surplus energy is generated due to must-run generation requirements, limited export capability, and minimum stable generation levels of conventional units. ESS charge this surplus generation and subsequently discharge it during periods of higher demand, thereby reducing forced curtailment.
- **Wholesale price driven curtailment:** High RE output can depress wholesale electricity prices, leading to curtailment when prices fall below operational thresholds or dispatch incentives become unfavourable. ESS mitigates this effect by charging during low-price periods and discharging during higher-value intervals, thereby improving system economics and reducing curtailment.

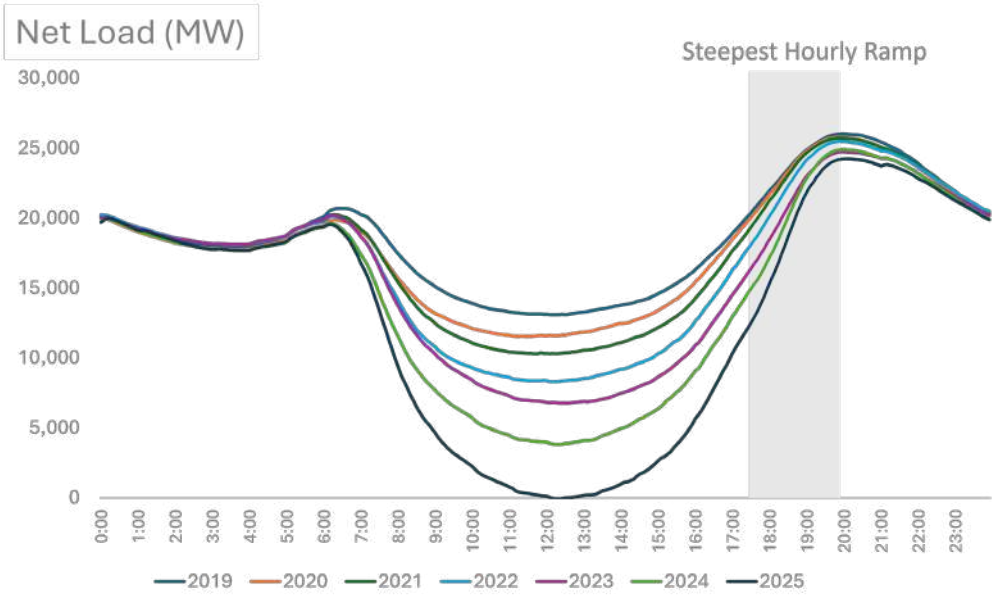
1.3.7 Duck Curve Issue

The duck curve shown in Figure 14 is a common operational pattern in power systems with high solar PV penetration, defined by the net load profile as shown in below equation.

$$P_{\text{net}}(t) = P_{\text{load}}(t) - P_{\text{RE}}(t)$$

High midday PV output reduces net load and creates steep upward ramps in the late afternoon and evening as PV generation declines while demand remains high. The key operational challenge lies not only in depth of midday trough but also in the ramping capability required from dispatchable and flexible resources to maintain system balance and reserves[28].

Figure 14 Duck Curve observed in CAISO



Data Source: CAISO

28 California Independent System Operator, What the Duck Curve Tells Us About Managing a Green Grid, CAISO Fast Facts, Folsom, CA, USA.

ESS mitigate the duck curve through two complementary actions, first through charging during midday surplus solar PV to raise net load and reduce reverse power flow and discharging during late afternoon and evening ramps to ease ramping needs and reduce dependency on fast start conventional plants. Through this dual role, ESS address curtailment, adequacy, and ramping challenges, making them a highly effective flexibility resource for reshaping PV driven net load profiles.

1.4 Scope and Structure of the Report

This report presents a global technical review of ESS, with emphasis on the role of different storage technologies within modern power systems undergoing rapid electrification and increasing penetration of RE resources. The section below clarifies (i) the technical and geographic scope of the analysis, and (ii) the organizational structure of the report, which is designed to support evidence based decision making by government agencies, utilities, regulators, and industry stakeholders.

1.4.1 Scope of the Report

The scope of the reported in classified into technical, geographical and policy, and temporal aspects as described below:

1.4.1.1 Technical Scope

The report examines ESS technologies and their system value from a power system perspective, spanning the following themes.

- **System drivers and grid context:** Climate and energy transition drivers, present energy supply mix, growth of wind and solar PV generation, operational challenges introduced by variable RE energy, and the resulting need for flexibility and ESS in power systems.
- **ESS functional roles and services:** Energy shifting and arbitrage, peak shaving, flexibility and balancing, frequency and voltage support, synthetic or virtual inertia, reserves, congestion management, black start and resilience services, and Behind-the-Meter (BTM) applications.
- **Technology landscape and classification:** Classification of ESS technologies by storage medium and energy conversion pathway, including mechanical, electrochemical, electrical, thermal, and chemical systems, together with representative technology variants and operating principles.
- **Performance characterization:** A consistent set of technical parameters and metrics used to compare ESS across use cases, including power and energy ratings, duration, ramping and response capability, efficiency, degradation and lifetime characteristics, and key operational constraints.
- **Planning and economic evaluation at a high level:** Translation of technical parameters into practical implementation and system value, technology screening across short, medium, and long duration classes, and evaluation perspectives commonly applied in planning, including system value, reliability value, and cost competitiveness.

Note: Detailed techno-economic modelling, market simulation, and project level financial valuation is out of scope unless explicitly introduced later in the report structure.

1.4.1.2 Geographic and Policy Scope

The report adopts a global orientation, comparing regional deployment patterns, grid conditions, and policy approaches across major electricity markets. Country or regional discussions are used to illustrate representative system conditions, such as high variable RE energy penetration, rapidly growing demand, or transmission constrained systems. Any jurisdiction specific content is presented for illustrative purposes and should not be interpreted as prescriptive regulatory guidance.

1.4.1.3 Temporal Scope

The report draws on multiple datasets and aligns trend discussions with the time ranges explicitly shown in figures and tables. References to recent developments are limited to periods supported by the cited datasets and the curated evidence base.

1.4.2 Structure of Report

The report is structured to provide a systematic global review of Energy Storage Systems, beginning with the need for storage in renewable-rich power systems and progressing toward technology assessment, applications, economics, sustainability, case studies, and future roadmaps.

Chapter 1 introduces the global energy transition context and the technical need for ESS. It links RE growth with variability, curtailment, reduced inertia, congestion, voltage rise, and duck-curve ramping. The chapter positions ESS as a multi-timescale flexibility resource for secure grid operation.

Chapter 2 presents the technology landscape of ESS. It classifies storage into electrochemical, mechanical, chemical, thermal, thermochemical, and electrical categories. Technologies such as Li-ion, sodium-ion, flow batteries, pumped hydro, CAES, hydrogen, thermal storage, supercapacitors, and SMES are compared using response time, duration, efficiency, cycle life, maturity, and scalability. The chapter establishes that ESS selection must be application-specific rather than technology-specific.

Chapter 3 focuses on Power Conversion Systems and control strategies. It explains converter-based, machine-based, and hybrid interfaces for active power, reactive power, fault response, inertia contribution, and grid-code compliance. The chapter highlights grid-forming ESS for weak grids, black start, voltage recovery, synthetic inertia support, and low-inertia operation.

Chapter 4 reviews ESS applications across transmission, distribution, and BTM domains. It covers energy shifting, frequency regulation, voltage support, congestion relief, long-duration adequacy, black start, DER hosting, peak shaving, PV smoothing, and value stacking. It also introduces component-level, plant-level, RMS, and EMT modelling for planning and stability studies.

Chapter 5 examines Electric Vehicles (EVs) as mobile energy storage systems. It reviews global EV adoption, Li-ion battery requirements, pack architecture, charging infrastructure, degradation, and battery-health impacts. The chapter also discusses V2G, V2H, V2B, V2L, and V2V as pathways for using EV fleets as distributed flexibility resources.

Chapter 6 discusses hybrid and multi-use ESS for multi-timescale flexibility. It explains how batteries, flywheels, supercapacitors, hydrogen, pumped hydro, and thermal storage can be combined to allocate fast response and sustained energy delivery. The chapter also covers sector coupling, community storage, and global hybrid ESS projects.

Chapter 7 presents the standards framework for ESS interconnection, communication, cybersecurity, testing, and safety certification. It covers key standards such as IEEE 1547, IEEE 2800, IEC 61850, DNP3, OpenADR, NERC CIP, IEC 62443, UL 9540, UL 9540A, NFPA 855, and IEC 62933. The chapter establishes standards as essential for safe, interoperable, and bankable ESS deployment.

Chapter 8 analyses global ESS deployment strategies, incentives, and market pathways. It compares China, the United States, the United Kingdom, the European Union, and Australia. The chapter focuses on policy targets, tax credits, auctions, grants, capacity mechanisms, ancillary service markets, long-duration storage support, and regulatory reforms.

Chapter 9 presents the economic assessment of ESS through cost, valuation, LCOS, and revenue-stacking frameworks. It focuses on ESS viability which depends on dispatch timing, utilisation, degradation, financing, market access, and service monetisation. The chapter highlights value stacking as central to project bankability.

Chapter 10 examines sustainability, recycling, and circular economy issues across the ESS lifecycle. It covers lifecycle emissions, second-life batteries, SOH-based screening, repurposing workflows, recycling pathways, critical minerals, battery passports, and producer responsibility. The chapter shows that ESS assessment must include material security and end-of-life governance.

Chapter 11 presents global ESS case studies across for majorty types of energy storage technologies. It draws practical lessons from these storage technologies and their operation in RE-riched power systems. The chapter demonstrates real-world grid-service delivery and value stacking.

Chapter 12 synthesises major challenges and research directions for ESS. It covers technology-specific barriers, market limitations, interconnection delays, revenue uncertainty, weak long-duration valuation, and critical-mineral risks. The chapter identifies research needs in lifetime prediction, degradation-aware dispatch, safety validation, interoperability, resilience valuation, recycling, and aggregation.

Chapter 13 presents the future outlook and roadmap to 2050. It explains the shift from short-duration flexibility toward inter-day, multi-day, and seasonal storage under high RE penetration. The chapter highlights long-duration technologies, AI/ML-enabled diagnostics, advanced BMS, digital traceability, battery passports, circularity, and global collaboration.

Chapter 14 concludes the report by consolidating the technical, economic, policy, and sustainability findings. It positions ESS as a multi-timescale and multi-service infrastructure asset. The chapter presents key insights, policy recommendations, industry and academic priorities, and a roadmap for integrating ESS into reliable, secure, and decarbonised power systems.



Image by Sebastian Ganso from Pixabay



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02

CHAPTER 2

ENERGY STORAGE TECHNOLOGIES

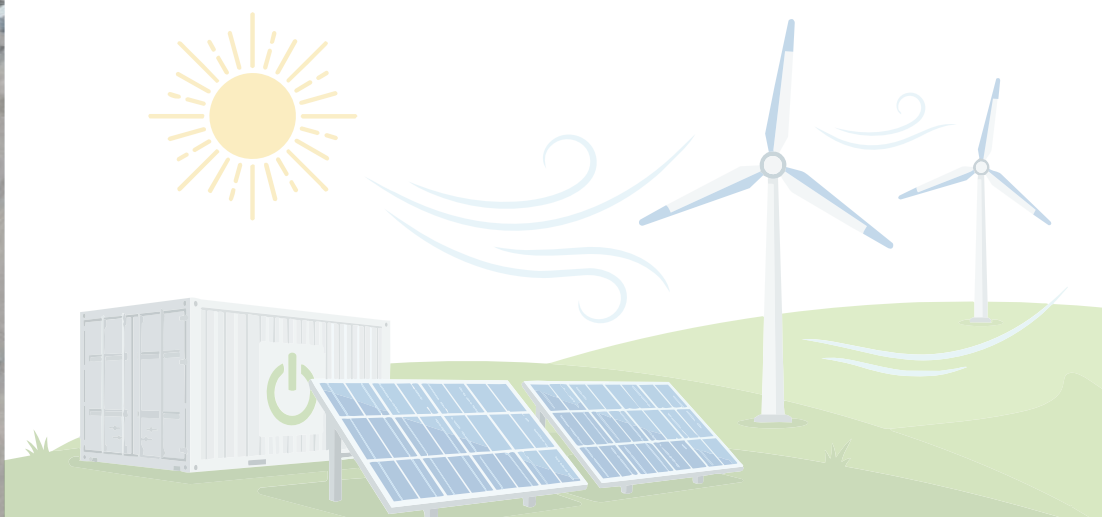


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Summary

- Presents a technology wide classification of Energy Storage Systems, covering electrochemical, mechanical, chemical, thermal, thermochemical, and electrical storage technologies.
- Compares major ESS technologies using technical parameters, maturity, scalability, and application suitability.
- Highlights the global dominance of lithium ion BESS, while examining sodium ion, flow batteries, PHS, CAES, gravity storage, hydrogen, thermal storage, supercapacitors, and SMES as complementary technologies.
- Establishes that future storage deployment will be application specific, with different technologies serving short duration grid support, medium duration energy shifting, long duration adequacy, seasonal storage, and sector coupled applications.





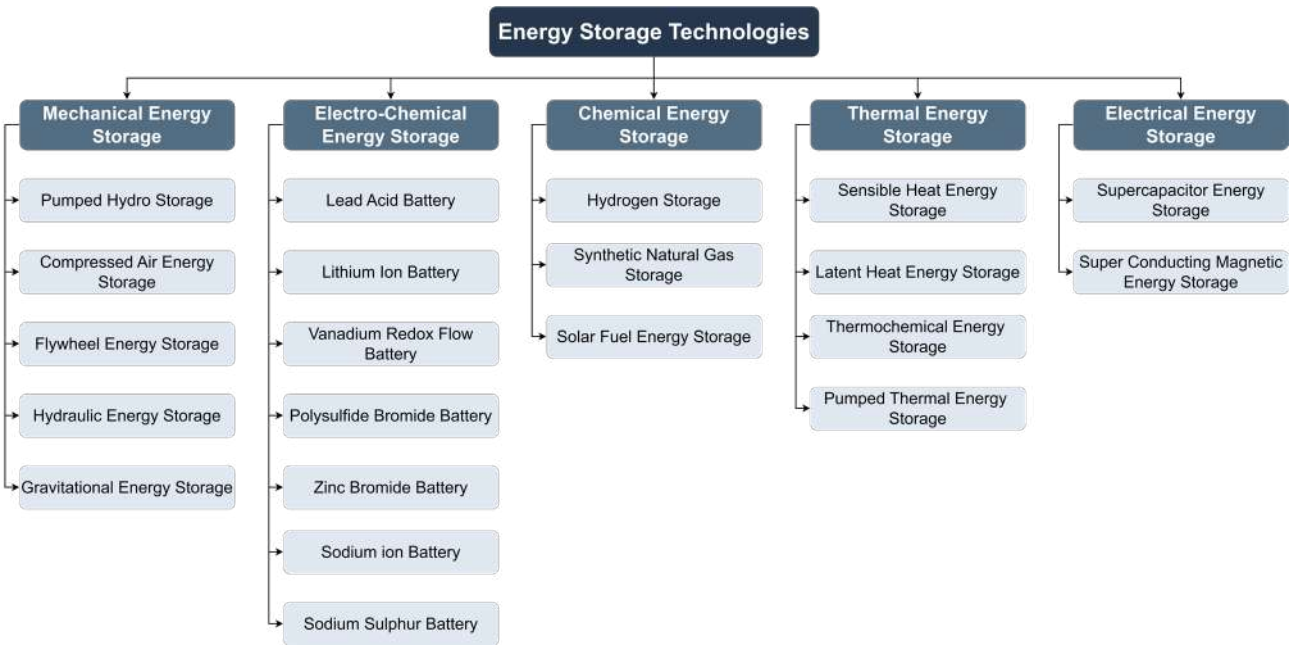
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2.1 Energy Storage System Landscape

The ESS landscape encompasses a broad and continuously evolving set of technologies that differ fundamentally in physical storage principles, response characteristics, energy and power ratings, efficiency, technology maturity, and suitability for specific grid and end-use applications. A clear and consistent classification framework is therefore essential. It helps position storage technologies according to how energy is stored, such as electrochemical, mechanical, chemical, thermal, or electrical forms. It also considers how stored energy is converted back to electricity. Finally, it classifies technologies by service timescale, ranging from sub-second power quality support to multi-hour and seasonal energy shifting.

Such a structured taxonomy enables the consistent comparison of technology capabilities, identification of appropriate use cases across generation, transmission, distribution, and all other end-use domains, and an informed assessment of trade-offs among cost, performance, scalability, and system integration complexity. The classification presented in Figure 15 provides a comprehensive and technology-agnostic overview of the global energy storage landscape, serving as a foundational reference for subsequent detailed discussions of individual storage technologies, their operating characteristics, and their roles within modern power systems.

Figure 15 Classification of energy storage technologies



Technology Readiness Levels (TRLs) of ESS vary significantly across categories. Mature technologies such as PHS and lithium ion batteries are deployed at large commercial scales, whereas others, including electrical storage, flow batteries, and thermochemical storage, are at demonstration or early commercialisation stages. Emerging technologies such as gravity based and advanced thermal storage solutions continue to progress towards higher TRLs as pilot deployments scale globally. A detailed assessment of the evolution of ESS technologies over the past five years, based on TRL levels, is presented in Appendix A.

2.2 Technical Parameters for Energy Storage Systems

Technical characterisation of ESS is essential for assessing their suitability for grid and end use applications, comparing technologies consistently, and designing control, protection, and market participation strategies. Key parameters across storage technologies define power capability, energy duration, conversion efficiency, and performance degradation over time and should be interpreted in a technology agnostic manner for system level planning and operational analysis. Table 1 summarises the key technical parameters relevant across energy storage technologies and their system level interpretation[29,30].

Table 1 Technical parameters of energy storage systems

Parameter	Definition	Units
Power rating	The maximum instantaneous electrical power that an ESS can charge from or discharge to the grid or connected load under specified operating conditions.	W, kW, MW
Energy capacity	The total amount of usable electrical energy that ESS can store and subsequently deliver over time under specified operating conditions.	Wh, kWh, MWh
Energy-to-Power (E/P) ratio	The ratio of ESS's usable energy capacity to its rated power, representing the duration for which the system can continuously discharge at rated power under specified operating conditions.	hour
State of Charge (SoC)	The degree to which an ESS is charged relative to the maximum possible amount of energy that can be stored by the system. $$SOC = \frac{E_{\text{stored}}}{E_{\text{rated}}} \times 100\%$$	%
Depth of Discharge (DoD)	The percentage of ESS's usable capacity that has been discharged from a fully charged state during a given operating cycle. $$DOD = 1 - SOC$$	%
Round-Trip efficiency (RTE)	The ratio of the total electrical energy delivered by an ESS during discharge to the total electrical energy consumed during charging, accounting for all conversion and parasitic losses, over a predetermined charging–discharging cycle under specified continuous operating conditions, expressed as a percentage. $$RTE = \frac{E_{\text{discharge}}}{E_{\text{charge}}} \times 100\%$$	%

29 International Electrotechnical Commission, IEC 62933-1:2024, Electrical Energy Storage (EES) Systems – Part 1: Vocabulary, Ed. 2.0, IEC, Geneva, Switzerland, May 2024.

30 "IEEE Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure," in IEEE Std 2030.2-2015, vol., no., pp.1-138, 30 June 2015.

Parameter	Definition	Units
Response time	The time interval between a control or dispatch command and the moment an ESS begins delivering power at its point of connection, determined by the characteristics of the storage technology and its interconnection.	msec to minutes
C-Rate	It is defined as the rate at which the device is charged or discharged relative to its rated energy capacity, where a 1C rate corresponds to charging or discharging the full rated capacity in one hour under ideal conditions.	$hour^{-1}$
Ramp rate	The rate at which the power output of ESS changes over time, typically expressed as the change in instantaneous power per unit time, and reflecting the dynamic capability of the source to increase or decrease output.	MW/s
Cycle life	The number of complete charge-discharge cycles an ESS can undergo before its usable capacity or performance degrades to a specified end-of-life criterion, beyond which it is no longer suitable for the intended application.	cycles
Calendar life	The duration of time an ESS can remain in service under specified operating and environmental conditions before its usable capacity or performance degrades to a defined end-of-life criterion, independent of cycling.	years
Internal resistance	The effective electrical resistance within an energy storage device that opposes the flow of current during charging and discharging, causing voltage drop and power losses.	mΩ
State of Health (SoH)	The overall condition of EES, determined from measurements that indicate its actual performance relative to its rated performance, and reflecting the degree of degradation over time.	%
Operating temperature range	The specified range of ambient or internal temperatures within which an ESS can operate safely while maintaining acceptable performance and reliability.	°C
Self-Discharge rate	The phenomenon by which an ESS loses stored energy over time through internal processes or auxiliary paths other than intentional discharge through the primary point of connection.	%/day

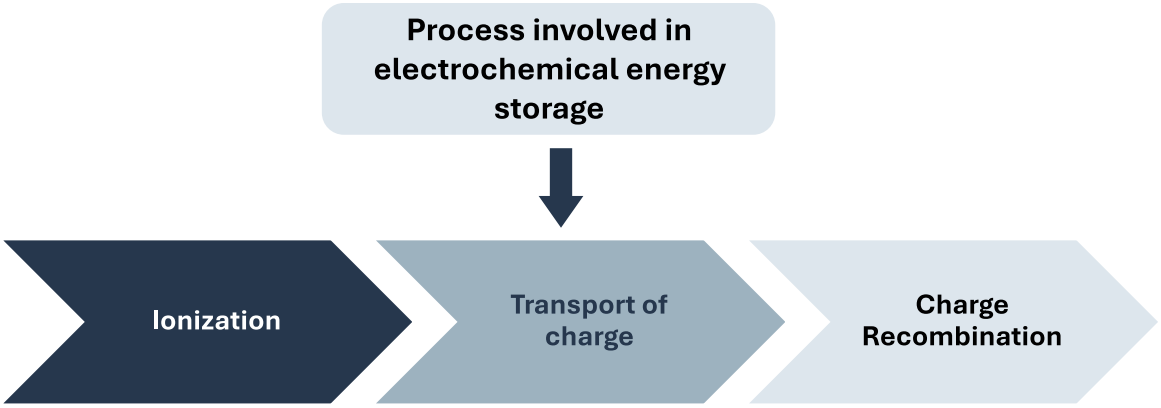


2.3 Electro-Chemical Energy Storage Systems

Electrochemical Energy Storage (ECES) systems, particularly battery based technologies, represent the most widely deployed form of energy storage across both the power sector and the transport sector. Over the period from 2010 to 2025, average battery costs declined by nearly 80 percent, while key performance indicators such as energy density and cycle life improved substantially[31]. These trends have driven large scale adoption of ECES in stationary grid applications as well as in electric mobility.

The fundamental operation of ECES involves three primary processes that includes charge ionization, its transport and recombination, as illustrated in Figure 16. ECES systems are broadly categorized into two main types: (a) Battery Energy Storage Systems (BESS) and (b) Flow Battery Energy Storage Systems (FBESS). In BESS configurations, electrical energy is stored directly within the electrode materials, which typically comprise an anode, a cathode, and an electrolyte that facilitates ionic transport between electrodes during charge and discharge. In contrast, in FBESS architectures, energy is stored in liquid electrolytes held in external tanks. These electrolytes are circulated through the flow battery stack, where electrochemical redox reactions at the electrodes generate electrical power. This section provides a detailed discussion of the major ECES technologies, highlighting their operating principles, performance characteristics, and relevance for grid and end use applications.

Figure 16 Operational procedure of ECES

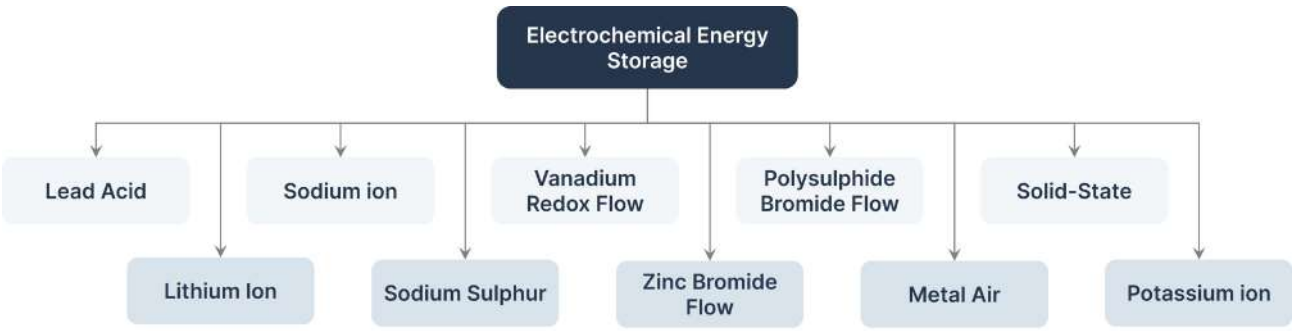


2.3.1 Overview and Classification

ECES systems encompass a broad family of technologies that convert chemical potential into electrical energy through reversible redox reactions. These systems differ primarily in electrode materials, electrolyte composition, cell configuration, and underlying charge storage mechanisms, which collectively determine performance characteristics, cost structure, and suitability for specific grid and end use applications. Figure 17 presents the classification of ECES technologies, providing a structured overview of the principal technology families and their distinguishing features.

31 Ember, How Cheap Is Battery Storage?, Ember Climate, London, U.K., 2025.

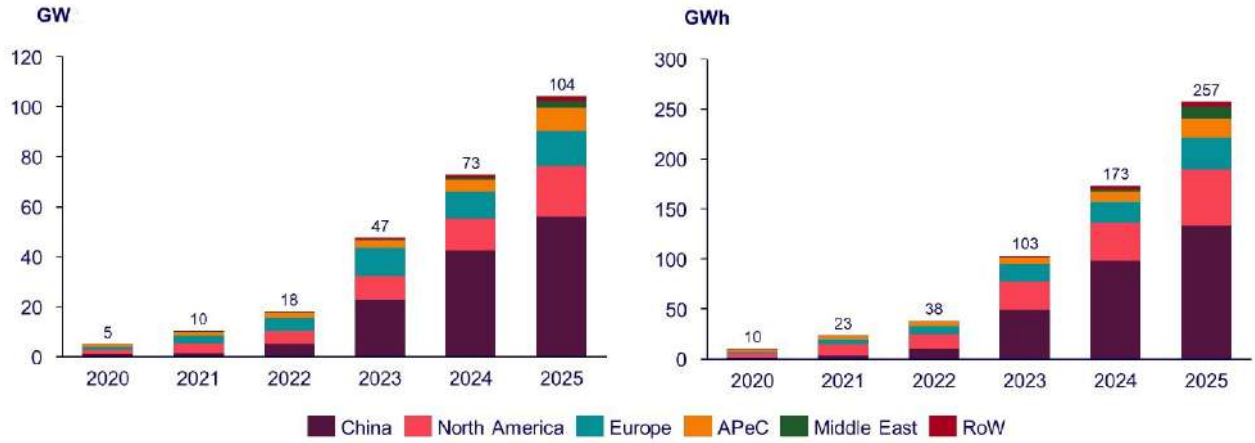
Figure 17 Classification of electrochemical energy storage systems



2.3.2 Global BESS Deployment

The rapid growth and regional distribution of global BESS deployments in both power (GW) and energy (GWh) from 2020 to 2025 is shown in Figure 18[32]. China dominates installations, accounting for more than half of global capacity additions, driven by strong policy support and large scale deployments. North America consistently holds the second position, particularly in GWh terms, indicating a preference for longer duration storage systems. Europe shows steady growth but remains behind North America in energy capacity, while Asia Pacific excluding China (APeC) contributes moderately to overall expansion. Notably, the Middle East, led by Saudi Arabia, has emerged as a fast growing market in recent years, reflecting increased investment in grid scale storage to support energy transition objectives.

Figure 18 Global deployment of BESS by geography



Source: Volta Foundation

In parallel, segmentation of BESS deployments by application indicates a clear shift towards utility scale dominance, as illustrated in the Figure 19[30]. Although commercial and industrial (C&I) and residential installations continue to grow in absolute terms, their relative share has declined, falling to single digit percentages in both GW and GWh by 2025. This trend reflects increasing investor preference for large scale projects, driven by improved technology maturity, stronger revenue visibility, and better access to financing. Utility scale systems account for over 80 percent of global capacity additions, highlighting their central role in several grid level applications.

32 "The Battery Report 2025." Volta Foundation, 24 January 2026.

Figure 19 Yearly sector wise BESS installations



Source: Volta Foundation

2.3.3 Lead Acid Battery

Lead-acid (LA) batteries represent one of the most mature and historically significant ECES technologies, tracing their origins to Gaston Planté's pioneering work in 1859. As the world's first rechargeable battery system, LA chemistry laid the foundation for modern ECES and has remained commercially relevant for over a century and a half. The robustness of the design, simplicity of manufacturing, and low cost have contributed to widespread adoption across automotive, industrial, telecommunications, and stationary ESS applications[33]. Over the decades, continuous evolution in materials engineering such as the development of pasted-plate electrodes, sealed valve-regulated constructions, advanced grid alloys, and improved separator technologies have enhanced performance, reliability, and operational safety. Although more recent chemistries such as lithium-ion now dominate high-performance energy storage markets, LA batteries continue to play a crucial role wherever cost-effectiveness, established recycling infrastructure, and compatibility with existing electrical architectures are primary considerations. So LA remain relevant for distributed energy applications, where affordability and reliability strongly influence technology adoption.

2.3.3.1 Working Principle

The operation of LA battery is governed by reversible electrochemical reactions between metallic lead (Pb), lead dioxide (PbO_2), and sulphuric acid (H_2SO_4). These reactions occur within an aqueous electrolyte, enabling the conversion between electrical energy and chemical potential energy. During discharge, stored chemical energy is converted into electrical energy as electrons flow through the external circuit, while the charging process reverses these reactions to restore the electrodes to their active states. The architecture of typical LA battery is shown in Figure 20[34].

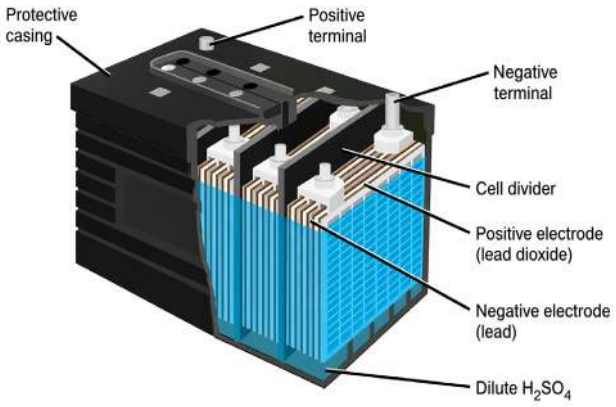
A defining characteristic of LA chemistry is that both electrodes converge to the same reaction product, lead sulphate ($PbSO_4$), during discharge. This symmetric reaction pathway simplifies cell manufacturing, enhances system robustness, and supports cost-effective recycling. The electrolyte, a mixture of sulfuric acid and water, plays an active role in the electrochemical process, with

33 P. Kurzweil, "Gaston Planté and his invention of the lead–acid battery—The genesis of the first practical rechargeable battery," J. Power Sources, vol. 195, no. 14, pp. 4424–4434, 2010.

34 F. H. Acasuso, "A life cycle analysis of storage batteries for photovoltaic water pumping systems in Sub-Saharan remote areas," Master's thesis, Energy Futures Lab, Imperial College London, London, U.K., Sep. 2021.

acid concentration varying during charge and discharge as sulphate ions transfer between the electrolyte and electrodes. This behaviour enables SoC estimation via electrolyte specific gravity measurements, providing a distinctive diagnostic advantage of LA battery systems[35].

Figure 20 Architecture of lead acid aattery

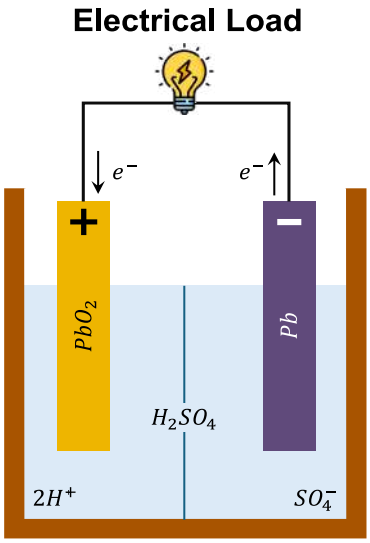


Source: F. H. Acasuso et al.; 2021

2.3.3.2 Chemistry and Operation

A typical LA battery consists of a porous lead negative plate, a lead dioxide positive plate, and an aqueous sulphuric acid electrolyte, with porous separators that permit ionic transport while preventing electrical short circuiting[36]. The operation of LA batteries is depicted in Figure 21.

Figure 21 Internal structure of lead acid battery



During discharge, the battery converts stored chemical energy into electrical energy delivered to the external circuit. Sulphate ions (SO_4^{2-}) from the electrolyte combine with the active material at both electrodes, resulting in the formation of lead sulphate. At the same time, sulphuric acid is consumed and water is produced, leading to a reduction in electrolyte acid concentration and a

35 G. J. May, A. Davidson, and B. Monahov, “Lead batteries for utility energy storage: A review,” J. Energy Storage, vol. 15, pp. 145–157, 2018.

36 Department of Materials Science and Metallurgy, "Lead-Acid Batteries," Dissemination of IT for the Promotion of Materials Science (DoITPoMS), University of Cambridge, Cambridge, U.K.

corresponding decrease in specific gravity. These coupled electrochemical and electrolyte changes are characteristic of LA battery discharge behaviour and underpin diagnostic methods based on electrolyte properties. During charging, the applied external power reverses the discharge reactions. Lead sulphate formed during discharge is electrochemically reduced back to metallic lead at the negative electrode, releasing sulphate ions back into the electrolyte and restoring the active material for subsequent discharge cycles. The charging and discharging equations are mentioned below[36]:

- Charging Reaction (Positive electrode): $\mathrm{PbO_2 + H_2SO_4 + 2H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O}$
- Charging Reaction (Negative electrode): $\mathrm{Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-}$
- Discharging Reaction (Positive electrode): $\mathrm{PbSO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^-}$
- Discharging Reaction (Negative electrode): $\mathrm{PbSO_4 + H^+ + 2e^- \rightarrow Pb + HSO_4^-}$

2.3.3.3 Advantages and Disadvantages

LA batteries represent a mature and widely deployed ECES technology, particularly in applications where proven reliability, well understood operating behaviour, and established end of life management pathways are key decision criteria. A major advantage of LA technology is the existence of a highly developed circular value chain. In the United States, LA batteries are reported to be recycled at rates of approximately 99 percent annually, supported by mature collection mechanisms, disposal restrictions, and economic incentives such as refundable core charges[37]. LA battery design also facilitates recovery of major material components at high rates, and this closed loop model is frequently cited as a benchmark for circularity within ECES[38].

From a system perspective, LA solutions can offer relatively low upfront capital cost and benefit from a long operational history in standby and mission critical applications. However, assessments by national laboratories indicate that LA systems are generally constrained by shorter cycle life and are therefore better aligned with capacity oriented or standby use cases rather than high throughput cycling applications[39]. Additional limitations include relatively low gravimetric and volumetric energy density compared with lithium ion technologies, sensitivity to deep cycling, and a stronger dependence of lifetime on operating regime[37]. These characteristics restricts the suitability of LA batteries for intensive grid support services or frequent cycling duties.

37 Battery Council International, “Battery Facts and Applications, Battery Council International”, Washington, DC, USA.
38 Battery Council International, “How a Lead Battery Is Recycled, Battery Council International”, Washington, DC, USA.
39 K. Mongird, V. Fotedar, V. Viswanathan, V. Koritarov, P. Balducci, B. Hadjerioua, and J. Alam, Energy Storage Technology and Cost Characterization Report, Pacific Northwest National Laboratory, Richland, WA, USA, Tech. Rep. PNNL-28866, Jul. 2019.



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2.3.3.4 Performance parameters

For LA batteries, performance should be specified using parameters that directly influence performance and lifecycle cost. Key parameters include rated energy capacity, rated power, allowable charge and discharge current limits, and discharge time are summarised in Table 2.

Table 2 Performance parameters of lead acid battery

Parameters	Operating Range
Cell Voltage (V)	1.75 - 2.4
Cycle Life	250-500
Energy Density (Wh/kg)	30-75
Round-Trip-Efficiency	75% - 85%
C Rate	0.1C - 0.5C (Advanced designs may handle peak discharge rates in the range of 5 C– 10 C for short duration of time)
Discharge Time	Second - Hours
Depth of Discharge	50% - 55%

2.3.3.5 Applications

LA batteries are well established in applications where reliability, proven maintenance practices, and predictable operating behaviour are prioritized over high energy density or intensive cycling capability. Common applications include automotive starting functions, telecommunications backup systems, industrial standby power supplies, and uninterrupted power supply installations serving critical loads[37]. For stationary power system applications, LA deployments are more frequently aligned with capacity provision and backup objectives rather than frequent deep cycling services, reflecting inherent limitations in cycle life and degradation behaviour.

In RE integrated systems, LA batteries have been deployed in small scale storage roles where duty cycles are carefully controlled, and depth of discharge is managed to preserve operational lifetime. In contrast, modern large scale grid deployments that require frequent cycling, high energy throughput, and compact physical footprints increasingly favour advanced electrochemical chemistries, which offer superior cycle life and higher gravimetric and volumetric energy density relative to LA technology[40].

2.3.3.6 Global Deployment

For grid storage applications, the global installed base of lead acid technology remains small relative to PHS and the rapid growth of lithium ion systems in recent deployments. Few global deployments are listed in Table 17[41].

40 International Energy Agency, Batteries and Secure Energy Transitions, IEA, Paris, France, World Energy Outlook Special Report, Apr. 2024.

41 Grid Integration Laboratory Research

Table 3 Potential global deployment of lead acid battery

Site / Project	City / Region	Country	Capacity (Power/Energy)	Commissioning Year
M5BAT	Aachen	Germany	5MW/7.52 MWh	2016
Energy Buffer Unit – Alt Daber	Brandenburg	Germany	2MWh	2014
Notrees Wind Storage project	Texas	USA	36MW/24MWh	2012
Chino Battery Energy Storage System	Chino	USA	10MW/40MWh	1988
BEWAG Berlin	Berlin	Germany	17 MW / 14 MWh	1986

Early LA battery ESS successfully demonstrated grid-support functions such as peak shaving, RE integration, and frequency regulation, establishing the technical feasibility of ECES. However, their deployment remained limited due to low cycle life, poor efficiency, high maintenance requirements, and constraints in handling high-power, high-cycling applications. Consequently, lithium-ion batteries are replacing lead-acid systems because they offer higher efficiency, longer lifespan, greater energy and power density, and significantly lower lifecycle costs.

2.3.4 Lithium Ion Battery

Lithium ion batteries have emerged as the dominant ECES technology for both transport electrification and stationary power system applications. This position is primarily attributable to high energy density, high round-trip efficiency, strong power capability, and rapid controllability enabled by power electronic interfaces and advanced Battery Management Systems (BMS). Continued scale-up of manufacturing, standardization of cell formats and pack architectures, and sustained innovation in cathode and anode materials have driven substantial cost reductions and performance improvements. These developments have enabled lithium ion systems to expand from early adoption in consumer electronics to widespread deployment in electric vehicles and grid-connected storage at utility scale[40]. In stationary power system applications, lithium ion based BESS are increasingly deployed to provide fast frequency response, regulation services, peak management, RE smoothing, and reliability oriented services[42].

2.3.4.1 Working Principle and Operation

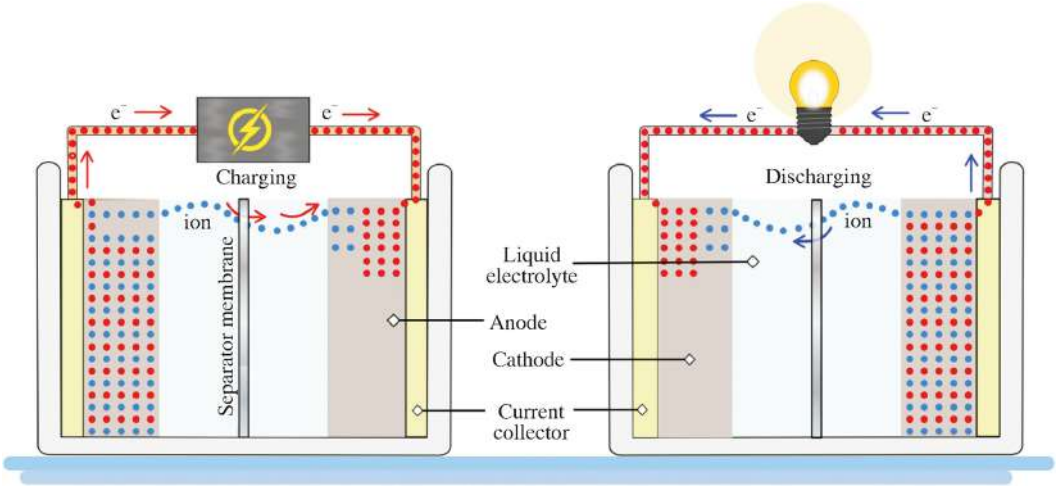
Lithium ion batteries have become the dominant rechargeable ECES technology for portable electronics, electric mobility, and for stationary BESS. This dominance is primarily driven by a favourable combination of high energy density, high round trip efficiency, high cycle life and modular scalability at the cell, module, and pack levels[40]. From a power system perspective, the fast electrochemical response of lithium ion cells and their precise controllability through power

42 S. B. Wali et al., "Grid-connected lithium-ion battery energy storage system towards sustainable energy: A patent landscape analysis and technology updates," J. Energy Storage, vol. 77, no. 109986, p. 109986, 2024.

electronic converters make them well suited for energy shifting applications and advanced grid support services provision. At the same time, continued advances in electrode materials, electrolytes, and cell engineering are steadily improving energy density, cycle life, and safety characteristics, further reinforcing their suitability for large scale deployment[43].

A lithium ion cell consists of four essential functional elements: an anode, a cathode, an ion conducting electrolyte, and a porous separator positioned between the electrodes. The separator provides physical isolation between the anode and cathode to prevent internal short circuiting, while allowing lithium ions to migrate through electrolyte filled pores. Electrons are blocked from passing internally and are therefore forced to flow through the external circuit, enabling useful electrical work to be delivered to the load. In commercial lithium ion cells, the cathode typically comprises a lithium metal oxide or lithium iron phosphate based material, the anode is most commonly graphitic carbon, and the electrolyte consists of a lithium salt dissolved in organic solvents to provide ionic conductivity between electrodes. The coupled transport of lithium ions through the electrolyte and separator, and electrons through the external circuit during charging and discharging, is illustrated in Figure 22[44]. The charging and discharging process are explained below.

Figure 22 Lithium ion cell operation



Source: J. Mitali et al.; 2017

Charging Process

During charging, an external power source applies a voltage above the cell open-circuit voltage, driving non-spontaneous electrochemical reactions. Lithium ions migrate from the cathode through the electrolyte to the anode, while electrons flow through the external circuit to maintain charge neutrality. At the anode, lithium ions intercalate into the graphite structure. This reversible intercalation and deintercalation of lithium ions between electrode materials constitutes the fundamental operating principle of lithium ion batteries[45].

A commonly used simplified half-cell representation is employed to illustrate this mechanism without invoking detailed reaction kinetics. For a generic layered oxide cathode $LiMO_2$ and a graphite anode, the charging reactions can be expressed as follows[45].

43 N. Nitta, F. Wu, J. T. Lee, and G. Yushin, "Li-ion battery materials: present and future," Mater. Today (Kidlington), vol. 18, no. 5, pp. 252–264, 2015.

44 J. Mitali, S. Dhinakaran, and A. A. Mohamad, "Energy storage systems: a review," Energy Storage and Saving, vol. 1, no. 3, pp. 166–216, 2022.

45 M. Yekini Suberu, M. Wazir Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," Renew. Sustain. Energy Rev., vol. 35, pp. 499–514, 2014.

- Cathode during charging: $\mathrm{LiMO_2} \rightarrow \mathrm{Li_{(1-x)}MO_2} + x\mathrm{Li^+} + xe^-$
- Anode during charge: $\mathrm{C_6} + x\mathrm{Li^+} + xe^- \rightarrow \mathrm{Li_xC_6}$
- Overall, during charge: $\mathrm{LiMO_2} + \mathrm{C_6} \rightarrow \mathrm{Li_{1-x}MO_2} + \mathrm{Li_xC_6}$

These expressions capture the direction of lithium ion transfer from the cathode to the anode during charging and are widely used for system level explanation of lithium ion cell operation. The parameter x represents the fraction of lithium transferred and is directly related to the SoC of the cell.

Discharge Process

During discharge, the cell is connected to an external electrical load, and the electrochemical system relaxes toward a lower energy state. Lithium previously stored in the anode host structure is released as lithium ions, which migrate through the electrolyte back toward the cathode, while electrons flow through the external circuit from anode to cathode and deliver electrical energy to the load. The electrochemical reactions proceed in the reverse direction of the charging process[45].

- Anode reaction during discharge: $\mathrm{Li_xC_6} \rightarrow \mathrm{C_6} + x\mathrm{Li^+} + xe^-$
- Cathode reaction during discharge: $\mathrm{Li_{1-x}MO_2} + x\mathrm{Li^+} + xe^- \rightarrow \mathrm{LiMO_2}$
- Overall reaction during discharge: $\mathrm{Li_{1-x}MO_2} + \mathrm{Li_xC_6} \rightarrow \mathrm{LiMO_2} + \mathrm{C_6}$

During discharge, lithium ions migrate from the anode to the cathode through the electrolyte, while electrons flow through the external circuit to the load, delivering electrical power. This process reverses charging, with ionic transport occurring within the cell and electronic transport through the external circuit providing the output current. Ion transport is driven by concentration gradients and the internal electric field, while electron flow constitutes the delivered current[43].

Roles of electrolyte and separator in operation and safety

The electrolyte must provide high ionic conductivity and remain electrochemically stable over the cell operating voltage while supporting stable electrode–electrolyte interfaces. Commercial lithium ion electrolytes typically use lithium salts such as $LiPF_6$ in organic carbonate solvents, which offer high ionic conductivity but introduce flammability and safety risks. Consequently, electrolyte selection, cell design, and protection strategies are critical for high-energy lithium ion applications[46]. The separator is a safety-critical component that electrically isolates the anode and cathode while allowing lithium ion transport. Failure or thermal degradation of the separator can cause internal short circuits and initiate thermal runaway, making separator material properties, thermal shut down behaviour, and mechanical robustness essential to lithium ion battery safety[47].

2.3.4.2 Lithium Ion Cell Chemistries

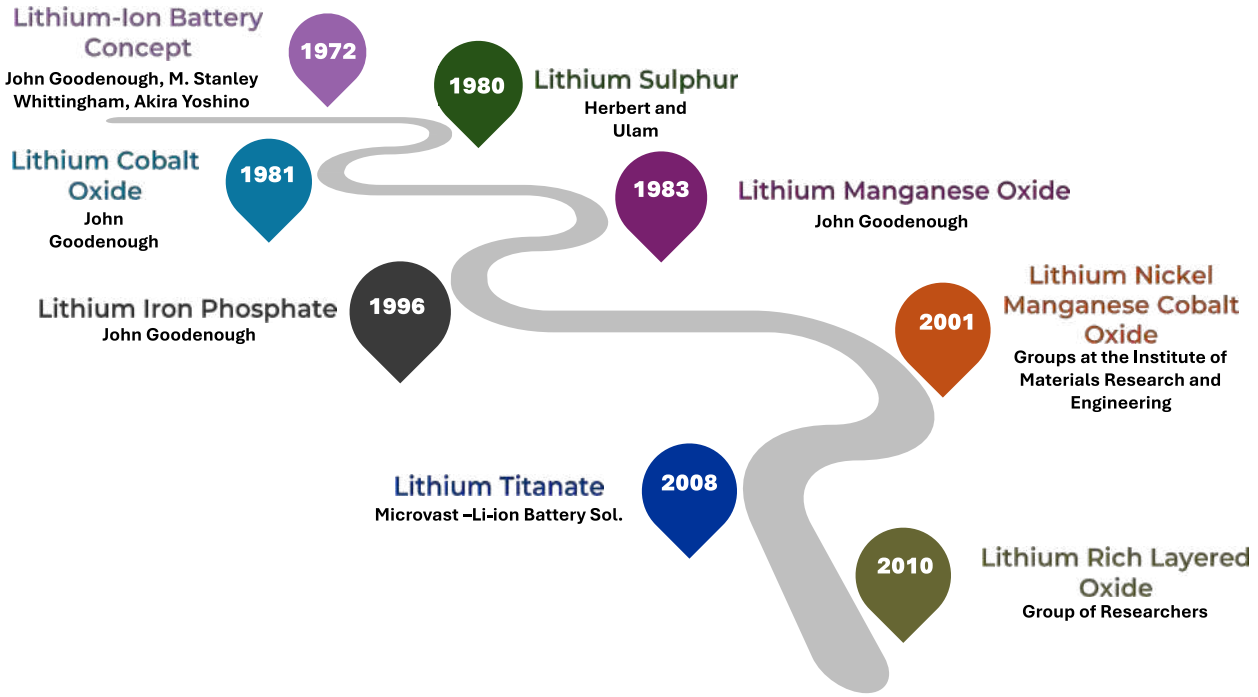
Lithium ion batteries are best viewed as a configurable electrochemical platform, as performance, safety, cost, and lifetime depend on the selected cathode, anode, and electrolyte system[40]. Cell chemistry refers to this specific material combination and determines key attributes such as voltage, energy density, power capability, thermal stability, and degradation behaviour. Commercial lithium ion cells typically employ a lithium metal oxide or phosphate cathode, a graphitic carbon anode, and a non-aqueous lithium salt electrolyte, with lithium ion transport enabling reversible energy storage

46 Christopher J. Orendorff, “The role of separators in lithium-ion cell safety,” The Electrochemical Society Interface, vol. 21, no. 2, pp. 61–65, Summer 2012.

47 A. Hahn, M. Ruf, S. Doose, and A. Kwade, “Enhancing lithium-ion battery safety: A comparative study of separator performance under mechanical abuse,” Future Batteries, vol. 6, no. 100064, p. 100064, 2025.

and delivery[48]. The development of lithium ion batteries is driven by advances in intercalation chemistry and stable high voltage cathodes, enabling safe and reversible lithium storage with improved energy density and cycle life. Key milestones are summarised below and aligned with the timeline in Figure 23, which highlights major material and system level innovations.

Figure 23 Historical evolution of lithium ion battery chemistries



Timeline narrative

- **1970s Intercalation concept:** M. Stanley Whittingham demonstrated reversible lithium intercalation using titanium disulphide as a cathode and lithium metal as an anode, establishing the principle of lithium ion storage in layered host structures. This work laid the scientific foundation for lithium ion batteries by enabling rechargeable operation through reversible ion insertion without severe structural degradation[49].
- **1980 High voltage oxide cathode:** John B. Goodenough and collaborators identified lithium cobalt oxide as a high-voltage cathode, enabling substantially higher operating voltage and energy density than earlier intercalation systems. This work established layered transition metal oxides as the dominant cathode family in lithium ion batteries and remains central to modern cell chemistries.
- **1985 to early 1990s practical lithium ion cell:** Akira Yoshino developed a lithium ion cell using a carbon-based anode and an intercalation cathode, eliminating metallic lithium. This design improved safety and cycle life and enabled the first commercially viable lithium ion batteries, introduced by Sony in 1991[50].

48 L. Yun et al., "Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles," Resour. Conserv. Recycl., vol. 136, pp. 198–208, 2018.

49 M. S. Whittingham, "The origins of the lithium battery," Nobel Lecture, Nobel Prize in Chemistry, Stockholm, Sweden, Dec. 8, 2019.

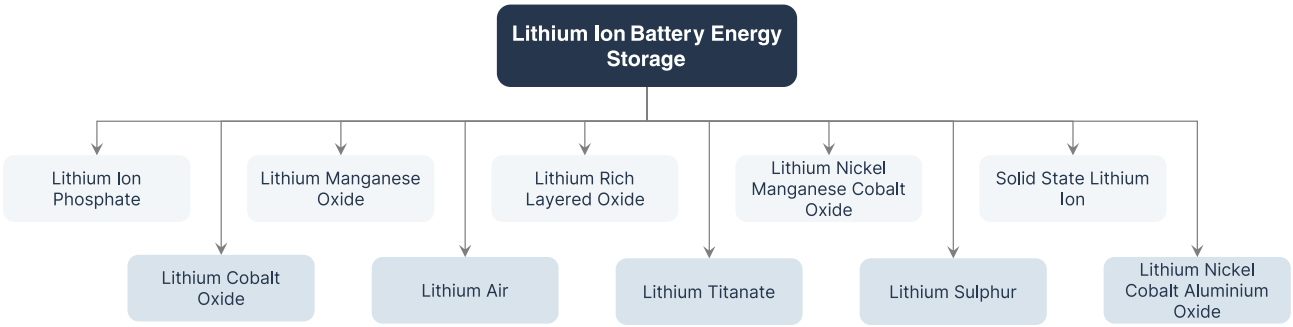
50 R. Krishnan, V. Packirisamy, D. Palani, and R. Ariyamuthu, "Historical perspective in technological advances in lithium-ion battery development," JCIS Open, vol. 21, no. 100163, p. 100163, 2026.

- **1990s to 2000s chemistry diversification:** To address limitations in cost, safety, and power capability, additional cathode families such as manganese spinels and phosphate-based materials, including lithium iron phosphate, were developed. These chemistries expanded lithium ion battery applications beyond consumer electronics to power tools, electric mobility, and early stationary storage[50].
- **2010s onward advanced materials and high nickel systems:** Recent development has focused on nickel-rich layered oxides, lithium-rich materials, silicon composite anodes, and solid-state electrolytes to increase energy density, reduce cobalt use, and improve safety, thermal stability, and sustainability for large-scale and grid-connected applications[50].

In 2019, the Nobel Prize in Chemistry was awarded to John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino for developing lithium ion batteries. The award recognised their contributions to intercalation chemistry, high voltage cathodes, and practical lithium ion cell designs that enabled modern rechargeable batteries[50].

Lithium ion battery chemistries are best classified by cathode and anode families, as these materials determine key characteristics such as voltage, energy density, thermal behaviour, safety, and lifecycle performance. The electrolyte plays a supporting role by influencing ionic conductivity, electrochemical stability, and operating temperature, without fundamentally altering the primary performance limits set by the electrodes[50]. The detailed classification of lithium ion battery chemistries based on cathode and anode combinations is presented in Figure 24.

Figure 24 Lithium ion battery chemistries



The cathode and anode families used in the manufacturing of Li-ion cells are described below:

Cathode Families:

- **Layered transition metal oxides:** This cathode family includes lithium cobalt oxide, lithium nickel manganese cobalt oxides, and lithium nickel cobalt aluminium oxides. These materials provide high operating voltage and energy density, supporting widespread use in electric mobility and high-energy stationary storage. Composition tuning balances energy density, thermal stability, cost, and degradation, with higher-nickel variants offering greater energy density but requiring stricter thermal and lifetime management[51].
- **Spinel oxides:** Lithium manganese oxide spinel cathodes offer three-dimensional lithium diffusion, providing good power capability at relatively low cost and making them suitable for high-rate applications. However, at elevated temperatures and high depth of discharge, they can experience capacity fade due to manganese dissolution and structural degradation[51].

51 A. K. Koech, G. Mwandila, F. Mulolani, and P. Mwaanga, "Lithium-ion battery fundamentals and exploration of cathode materials: A review," S. Afr. J. Chem. Eng., vol. 50, pp. 321–339, 2024.

- **Phosphate polyanion cathodes:** Lithium iron phosphate is a phosphate polyanion cathode with high thermal stability, long cycle life, and strong safety characteristics. Although its energy density is lower than layered oxides, its robust and stable behaviour makes it well suited for large battery packs and stationary energy storage applications where safety and longevity are prioritised[51].

Anode Families:

- **Graphite and carbonaceous anodes:** Graphite is the dominant anode material in lithium ion cells due to its high coulombic efficiency, mature manufacturing processes, and favourable energy density. Performance and safety depend on the formation and stability of the solid electrolyte interphase at the anode surface. Carbon-based anodes were also critical in enabling practical pairing with high-voltage cathodes and supporting the transition to scalable commercial lithium ion cells[52].
- **Silicon composite anodes:** Silicon-based anodes are pursued for their high theoretical capacity and potential to increase energy density when blended with graphite. However, large volume changes during cycling lead to mechanical and interfacial instability, accelerating degradation. As a result, commercial deployment is typically limited to silicon–graphite composite anodes rather than full silicon designs[53].
- **Lithium titanate anodes:** Lithium titanate anodes operate at a higher potential than graphite, reducing lithium plating risk and improving safety during fast charging. This enables high power capability and long cycle life; however, the elevated anode potential lowers cell voltage and energy density, limiting suitability for energy-constrained applications despite strong power and durability performance[54].

Lithium ion cell chemistry strongly influences material composition and supply chain exposure. Cathode selection drives the use of critical materials such as cobalt, nickel, manganese, and iron, while overall cell design also determines requirements for aluminium, copper, and graphite, affecting cost volatility, sustainability, recycling value, and geopolitical supply risk[45]. Figure 25 compares material composition across major lithium ion chemistries, illustrating how chemistry choice shapes material demand profiles.

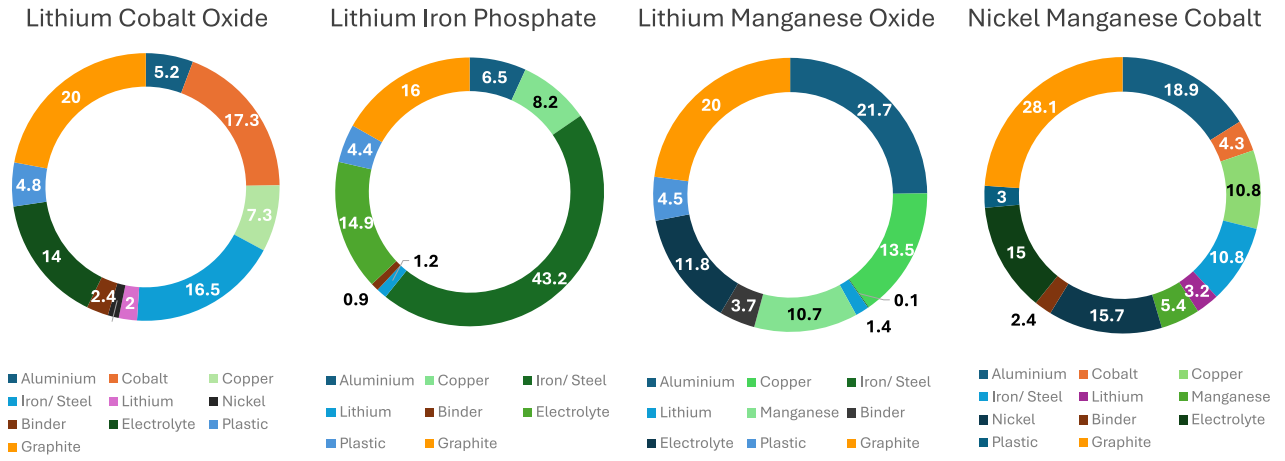
52 J. Asenbauer, T. Eisenmann, M. Kuenzel, A. Kazzazi, Z. Chen, and D. Bresser, "The success story of graphite as a lithium-ion anode material – fundamentals, remaining challenges, and recent developments including silicon (oxide) composites," Sustain. Energy Fuels, vol. 4, no. 11, pp. 5387–5416, 2020.

53 Z. Chen et al., "A comprehensive review of various carbonaceous materials for anodes in lithium-ion batteries," Dalton Trans., vol. 53, no. 11, pp. 4900–4921, 2024.

54 L. Youjie, R. Li, Y. Yang, and Z. Li, "Lithium titanate anode for high-performance lithium-ion batteries using octadecylamine and folic acid-functionalized graphene oxide for fabrication of ultrathin lithium titanate nanoflakes and modification of binder," New J. Chem., vol. 42, no. 18, pp. 15097–15104, 2018.


Gnoeee, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

Figure 25 Chemical composition of different lithium ion batteries



Data Source: Liu Yun et al.; 2018

2.3.4.3 Performance Matrices

Lithium ion batteries are characterized using a set of performance metrics that jointly capture energy capability, power capability, efficiency, lifetime, safety margin, and suitability for a given duty cycle. Table 4 summarises key performance parameters of different chemistries of lithium ion batteries[55].

Table 4 Performance matrices comparison of different lithium ion chemistries

Parameter	LFP	NMC	NCA	LMO	LTO
Nominal cell voltage (V)	3.2	3.6	3.6	3.7 - 3.8	2.3 - 2.4
Energy density (Wh/kg)	90-200	150 - 240	200 to 260	100- 150	60 - 120
C Rate	0.25 - 4	1 - 2	0.5 to 1	1 to 2	3 to 10
Cycle life	3,000 - 8,000*	1,500 - 2,000#	1,500 - 2,000	1,000 - 2,000	10,000 - 30,000
Round trip efficiency (%)	85 - 95	80 - 95	90 - 95	85 - 95	85 - 90
Depth of discharge (%)	80 - 90	80 - 90	80-90	80 - 90	80 - 90

**Most advanced LFP have cycle life: 10,000+*

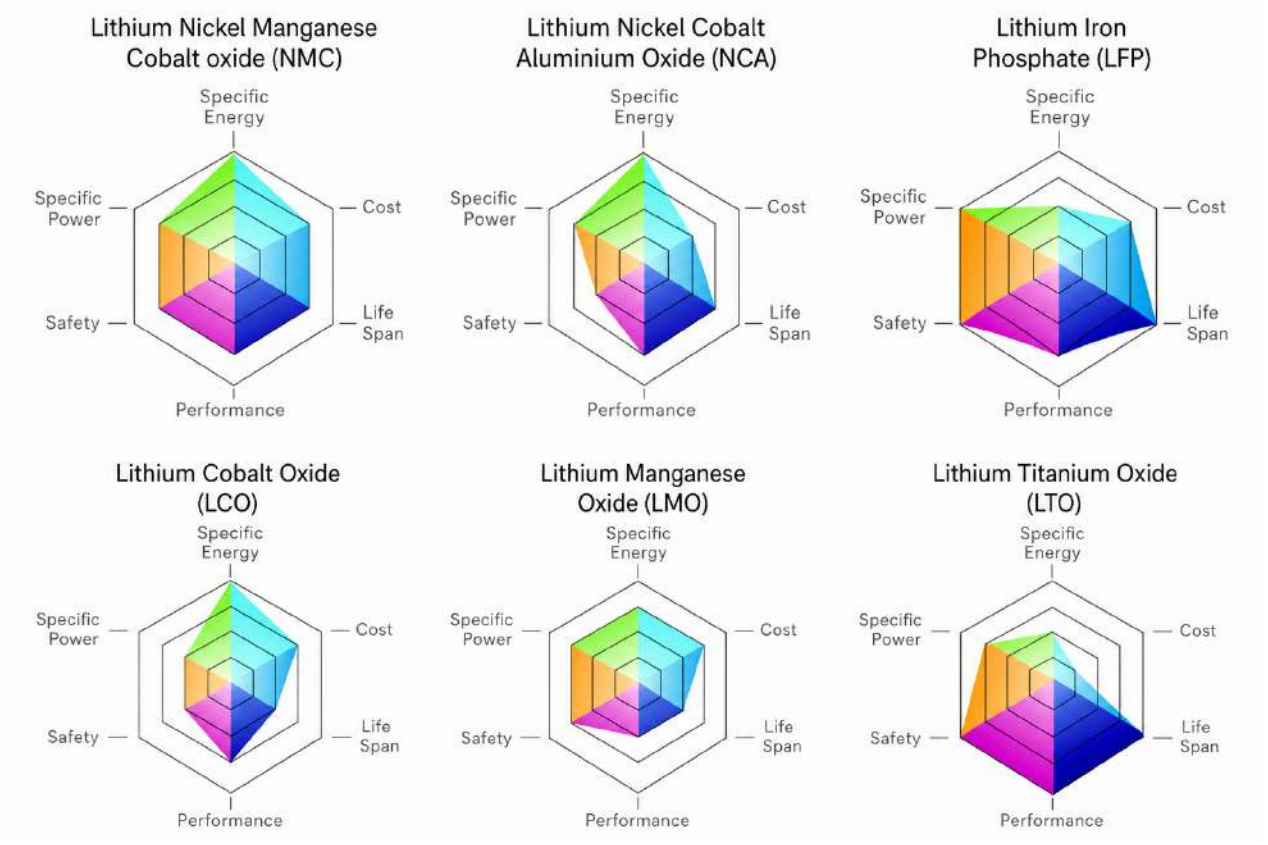
#Till 80% SOH

The values reported in Table 4 correspond to representative ranges observed in widely deployed lithium-ion battery technologies. These parameters are not absolute and may evolve with advancements in cell chemistry, electrode materials, manufacturing processes, and battery management strategies driven by continuous research and development efforts.

55 GIL Research

LMO based systems offer good power capability but have experienced declining adoption in modern electric vehicles due to lower achievable energy density and limitations in calendar life. As a result, these chemistries now more commonly appear in blended cathode formulations rather than as standalone deployments in contemporary applications. Figure 26[56] presents a comparative visualization of normalized performance metrics across major lithium ion chemistries, including LFP, NMC, NCA, LMO, and LTO. The figure compares specific energy, power capability, cycle life, thermal stability, and cost sensitivity on a normalized basis to highlight relative strengths and trade-offs among chemistries rather than absolute values.

Figure 26 Radar chart comparing normalised metrics across LFP, NMC, NCA, LMO, and LTO



Source: Elements

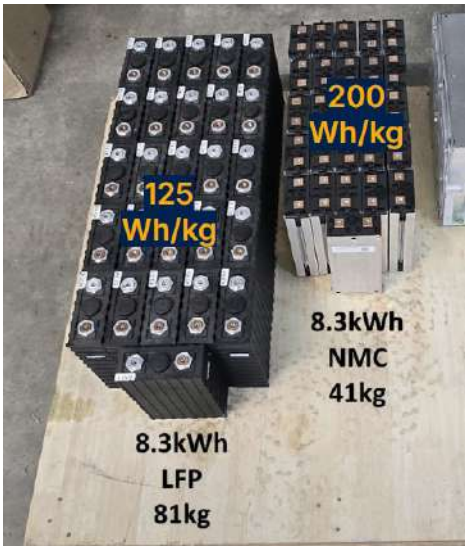
2.3.4.4 Form Factor and Chemistry Trade-offs in Lithium Ion Batteries

Battery design involves a fundamental trade-off between energy density and other critical parameters such as safety, cost, and cycle life. As illustrated in Figure 27[32], different lithium ion chemistries and form factors can deliver the same energy capacity with significantly different mass and performance characteristics. For example, an equivalent energy capacity of approximately 8.3 kWh can be achieved using a lighter NMC or NCA based pack due to higher energy density, whereas an LFP based pack requires greater mass but offers advantages in safety, cost, and longer cycle life. This demonstrates that higher energy density does not necessarily translate to superior overall system performance, particularly when safety and lifecycle considerations are prioritised. The selection of chemistry and form factor is therefore application dependent. High energy density chemistries such as NMC and NCA are typically preferred in electric vehicle applications, where weight and volume constraints are critical. In contrast, LFP batteries are widely adopted in stationary storage and heavy duty applications, where space constraints are less restrictive and priorities shift

56 Visual Capitalist, "The Six Major Types of Lithium-Ion Batteries."

towards cost effectiveness, thermal stability, and longer operational life. This trade off highlights the importance of aligning battery design choices with end use requirements rather than optimising a single performance metric.

Figure 27 Form Factors of LFP and NMC batteries



Source: Battery Report 2025

2.3.4.5 Applications

Lithium ion batteries are the most widely deployed ECES technology in stationary power systems and electric mobility due to several advantages. They are deployed across grid-scale installations, BTM systems, and electric vehicles, with adoption driven by their ability to deliver controllable power, operate over diverse duty cycles, and integrate with advanced control and Energy Management Systems (EMS) under stringent grid and safety requirements. The applications of Lithium ion BESS in power systems are described below[57]:

- **Transmission level applications:** At the transmission level, lithium ion battery energy storage systems support system stability and operational flexibility in power systems with high RE penetration. Key applications include frequency regulation and fast frequency response, where sub-second power injection helps contain frequency deviations and reduces reliance on synchronous generation. Lithium ion systems also support congestion management, transmission deferral, and black start by absorbing excess generation, supplying power during peak loading conditions, and enabling system restoration[58].
- **Distribution level applications:** At the distribution level, lithium ion batteries are deployed to manage voltage, mitigate reverse power flow from rooftop solar, and reduce peak loading on feeders and substations. Fast converter-based reactive power control enables effective voltage regulation and power quality improvement[59]. These batteries can also defer network upgrades by shaving peak demand, typically operating under predictable daily

57 T. Chen et al., "Applications of lithium-ion batteries in grid-scale energy storage systems," Trans. Tianjin Univ., vol. 26, no. 3, pp. 208–217, 2020.

58 G. De Carne et al., "The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions," Electric Power Syst. Res., vol. 236, no. 110963, p. 110963, 2024.

59 N. G. Chatzigeorgiou, S. Theocharides, G. Makrides, and G. E. Georghiou, "A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector," J. Energy Storage, vol. 86, no. 111192, p. 111192, 2024.

charge–discharge cycles, and may offer economic advantages over conventional network reinforcement in suitable scenarios[60,61].

- **BTM applications:** BTM lithium ion batteries are widely deployed in residential, commercial, and industrial settings to increase self-consumption of onsite generation, reduce demand charges, and enhance outage resilience. When paired with rooftop solar, they enable energy time shifting and peak tariff reduction. For critical facilities, lithium ion batteries increasingly replace or complement traditional backup systems due to fast response, high efficiency, low maintenance requirements, and compact, modular design[61].
- **Electric mobility applications:** In the transport sector, lithium ion batteries are the core energy storage technology for electric vehicles across two-wheelers, passenger cars, buses, and commercial vehicles, enabling practical driving range and performance. Ongoing advances in cell chemistry and pack design continue to reduce costs and extend service life. Beyond propulsion, electric vehicle batteries are increasingly treated as distributed energy resources, with Vehicle-to-Grid (V2G), and Vehicle-to-Home (V2H) concepts enabling bidirectional power exchange for services such as peak shaving, frequency support, and backup supply, subject to appropriate control and market frameworks[62].
- **Microgrids and isolated systems:** Lithium ion batteries play a central role in microgrids and isolated power systems by enabling high RE penetration while maintaining reliability and power quality. They provide short-term balancing, replace spinning reserve, and support seamless transitions between grid-connected and islanded operation, making them well suited for converter-dominated and weak grid environments. In remote applications, lithium ion batteries paired with solar, or wind generation reduce diesel fuel consumption, emissions, and operating costs while improving supply reliability compared to diesel-only systems[59].

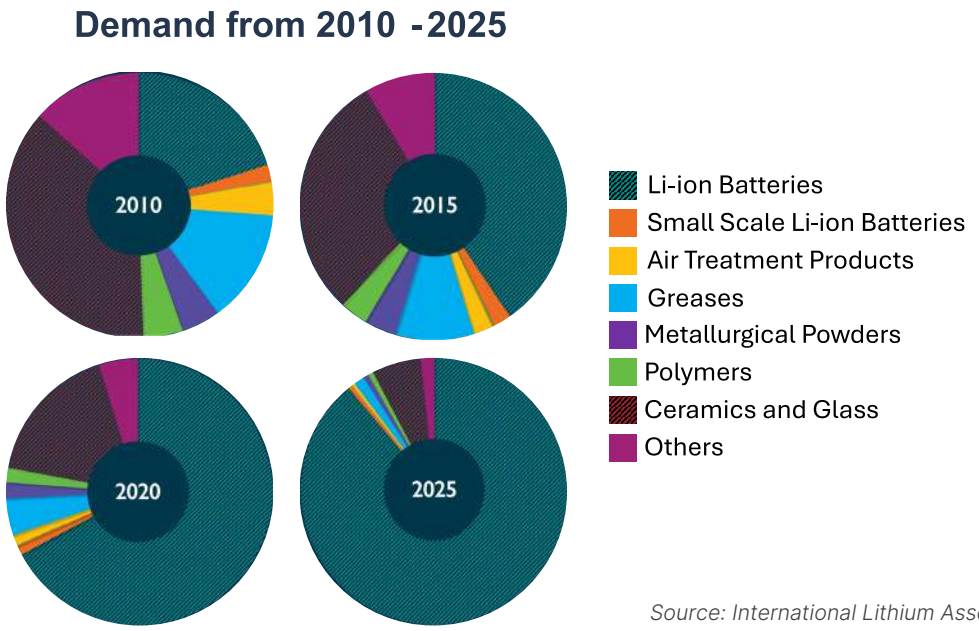
2.3.4.6 Global Lithium Ion Battery Market

The global lithium ion battery market is shifting from portable electronics toward electric mobility and stationary energy storage, accompanied by rapid expansion of cathode material supply chains and declining system costs. Lithium ion batteries lead the market due to high energy density, efficiency, modular manufacturability, and compatibility with power electronics, enabling cost-effective deployment across transport and grid applications, as illustrated in Figure 28[63]. This growth is driving increased lithium demand, as lithium remains essential to most cathode chemistries and electrolytes despite ongoing efforts to manage cost, safety, and supply risk.

60 "Battery Energy Storage and Operational Use-Cases at the electricity distribution network level," IEEE Smart Grid.
61 M. Stecca, L. Ramirez Elizondo, T. Batista Soeiro, P. Bauer, and P. Palensky, "A comprehensive review of the integration of battery energy storage systems into distribution networks," IEEE Open J. Ind. Electron. Soc., pp. 1–1, 2020.
62 "Global EV outlook 2025: Expanding sales in diverse markets," International Energy Agency, Paris, France, 2025.
63 Project Blue, "Lithium 2040 The Element Shaping Our Future", International Lithium Association, London, 2025.


AI Image

Figure 28 Global demand mix of lithium from 2010 to 2025

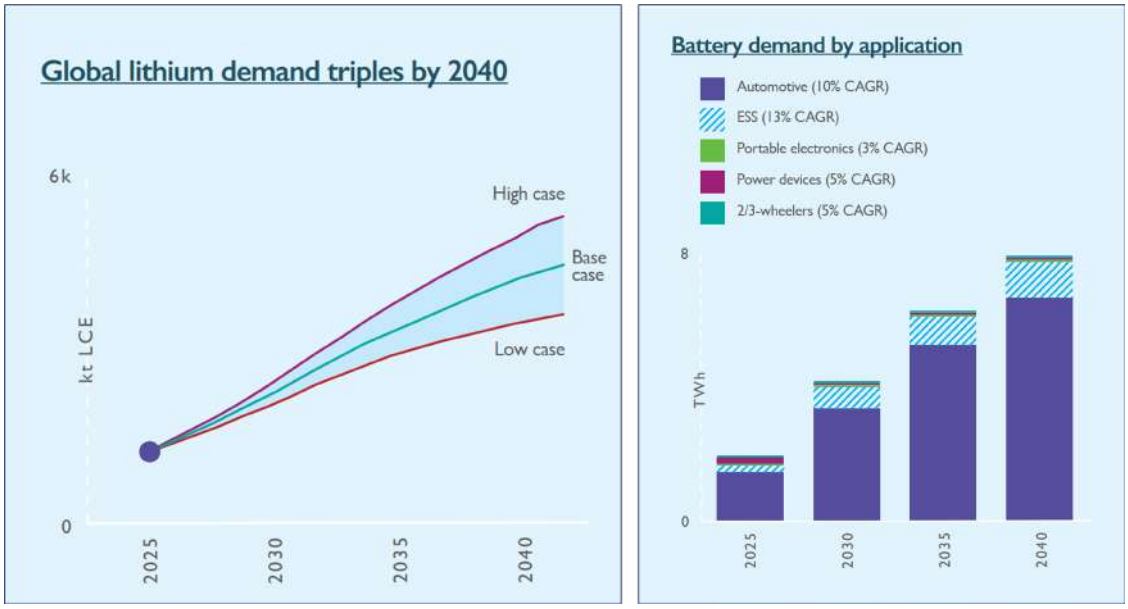


Source: International Lithium Association

Forward-looking scenarios project multi-fold growth in lithium demand to 2040, driven primarily by expanding lithium ion battery deployment. One outlook estimates global demand increasing from approximately 1.3 Mt LCE to 3.6–5.2 Mt LCE by 2040, depending on scenario assumptions, as shown in Figure 29[63]. This growth is supported by rising electric vehicle adoption, increasing battery pack sizes, and expanded deployment of stationary energy storage for RE integration and grid balancing.

Battery demand growth varies by application. EVs are expected to remain the largest source of demand through 2040, while stationary energy storage exhibits the fastest growth due to increasing flexibility requirements in RE-rich power systems. Portable electronics decline in relative importance as vehicle and stationary deployments scale, with EV penetration projected to increase substantially and account for a majority of passenger car sales by 2040.

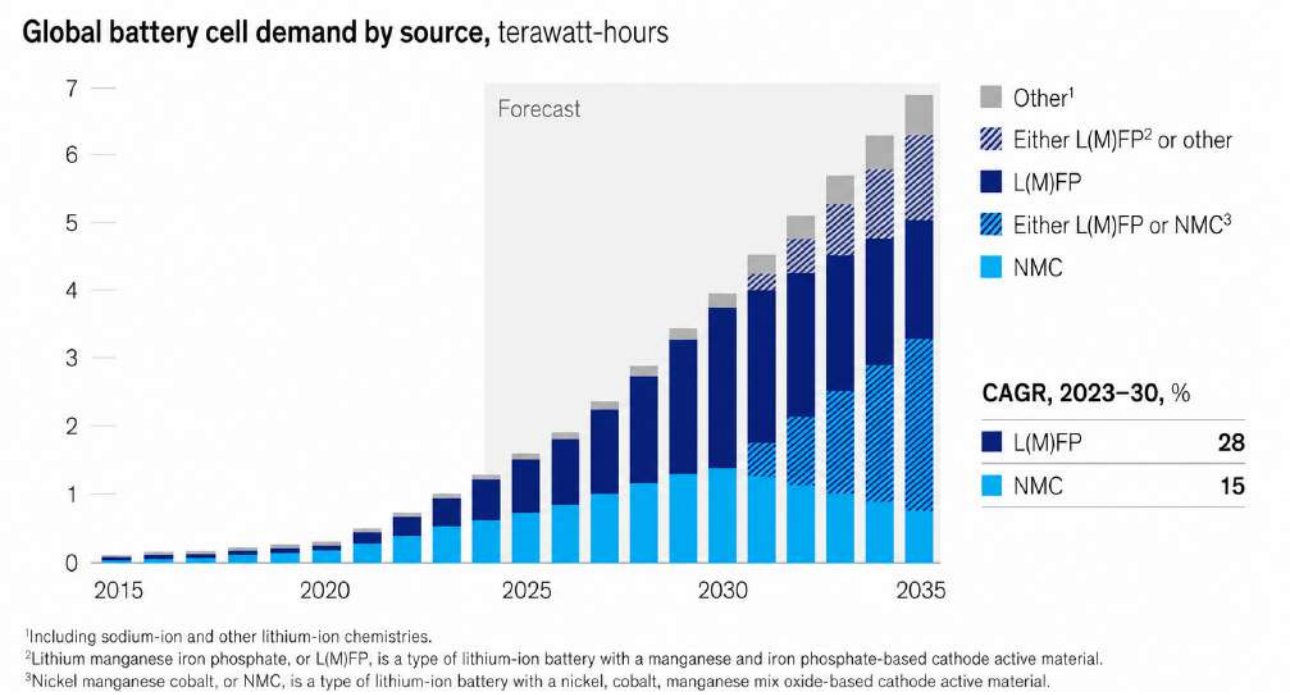
Figure 29 Projected lithium demand by 2040



Source: International Lithium Association

The market is also shifting in its choice of lithium ion chemistries, as chemistry selection affects cost, safety, cycle life, and critical mineral use. As shown in Figure 30, iron based cathodes such as lithium iron phosphate have been widely adopted due to low cost and strong safety performance, particularly in stationary ESS applications[64]. This shift has upstream implications for lithium precursor demand, as different cathode families prefer different conversion pathways, making refining and chemical conversion capacity a strategic supply chain constraint. Cost and deployment dynamics continue to reinforce the market leadership of lithium ion batteries. As seen from Figure 31[20] adoption at utility scale ESS and in electric mobility has been enabled by sustained cost reductions driven by manufacturing scale up, learning effects, and progressive optimization of global supply chains. Long run assessments of battery markets document substantial declines in battery pack prices over time and highlight their central role in reducing total cost of ownership for electric vehicles and lowering levelised cost metrics for stationary ESS.

Figure 30 Global battery cell demand by chemistry

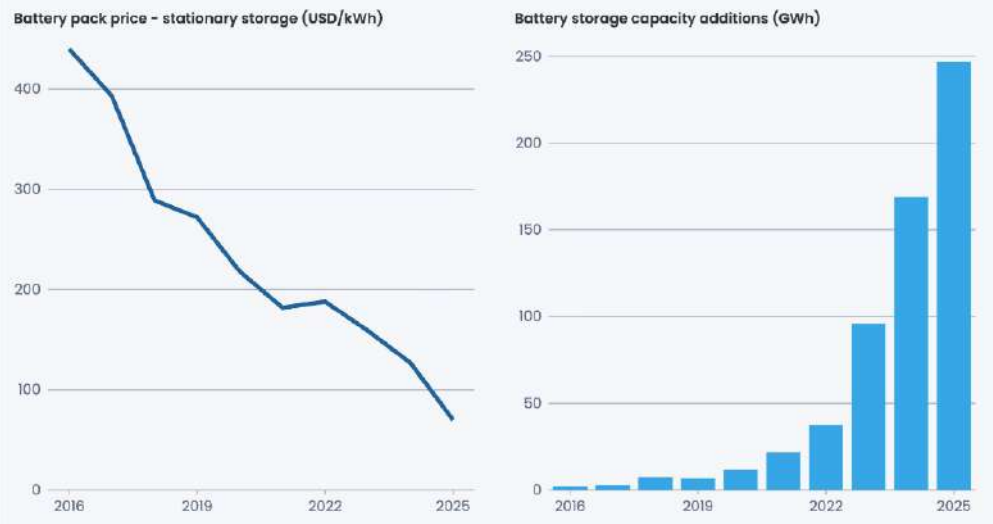


Source: McKinsey Battery Insights

64 McKinsey and Company, The Battery Chemistries Powering the Future of Electric Vehicles, McKinsey Battery Insights.



Figure 31 Global gross battery storage capacity additions and total installed electricity storage project costs per kWh



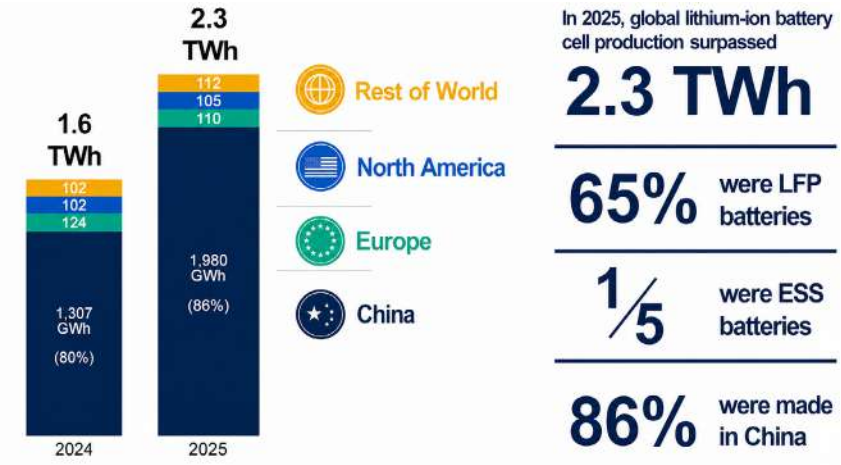
Source: Ember

2.3.4.7 Global Lithium ion Battery Production

Global lithium ion battery production has expanded rapidly, reflecting strong growth in electric mobility and stationary energy storage applications. As shown in Figure 32[32], total production surpassed 2.3 TWh in 2025, increasing from approximately 1.6 TWh in 2024. This growth is driven by manufacturing scale up, improvements in cell chemistry, and increasing deployment across multiple sectors. LFP chemistry accounted for around 65 percent of total production, indicating a shift towards cost effective and resource abundant battery technologies, particularly for energy storage applications.

The global production landscape remains highly concentrated, with China accounting for approximately 86 percent of total manufacturing. While North America and Europe are expanding giga factory capacities, they continue to rely on imports, particularly for ESS applications. The data also indicates emerging market dynamics, including overcapacity in segments such as LFP and ESS cells, contributing to price reductions and increased competitiveness. The industry structure remains relatively concentrated, with a few major manufacturers controlling a significant share of output.

Figure 32 Lithium ion battery production summary in 2025

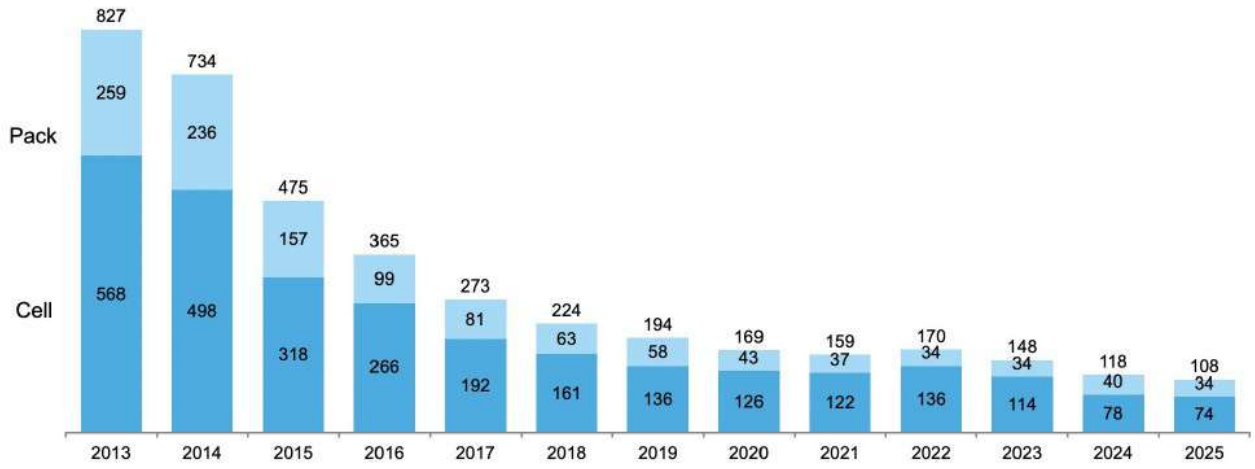


Source: Battery Report 2025

2.3.4.8 Global Average Selling Price of Lithium ion Cell and Pack

Cell and pack prices reached historic lows in 2025 as shown in Figure 33[32], driven by advancements in cell chemistry and manufacturing processes that offset moderate increases in raw material costs. ESS pack prices were among the lowest at around 70 $/kWh, while average battery electric vehicle (BEV) pack prices fell to just below 100 $/kWh. Among chemistries, LFP packs were more cost competitive at approximately 81 $/kWh compared to NMC packs at 128 $/kWh. Regionally, China recorded the lowest pack prices at around 84 $/kWh, reflecting widespread adoption of LFP technology, whereas Europe reported the highest prices at about 131 $/kWh, followed by North America at approximately 120 $/kWh.

Figure 33 Reduction in global average selling price of Li-ion battery cell and pack



Source: Battery Report 2025

2.3.4.9 Value Chain

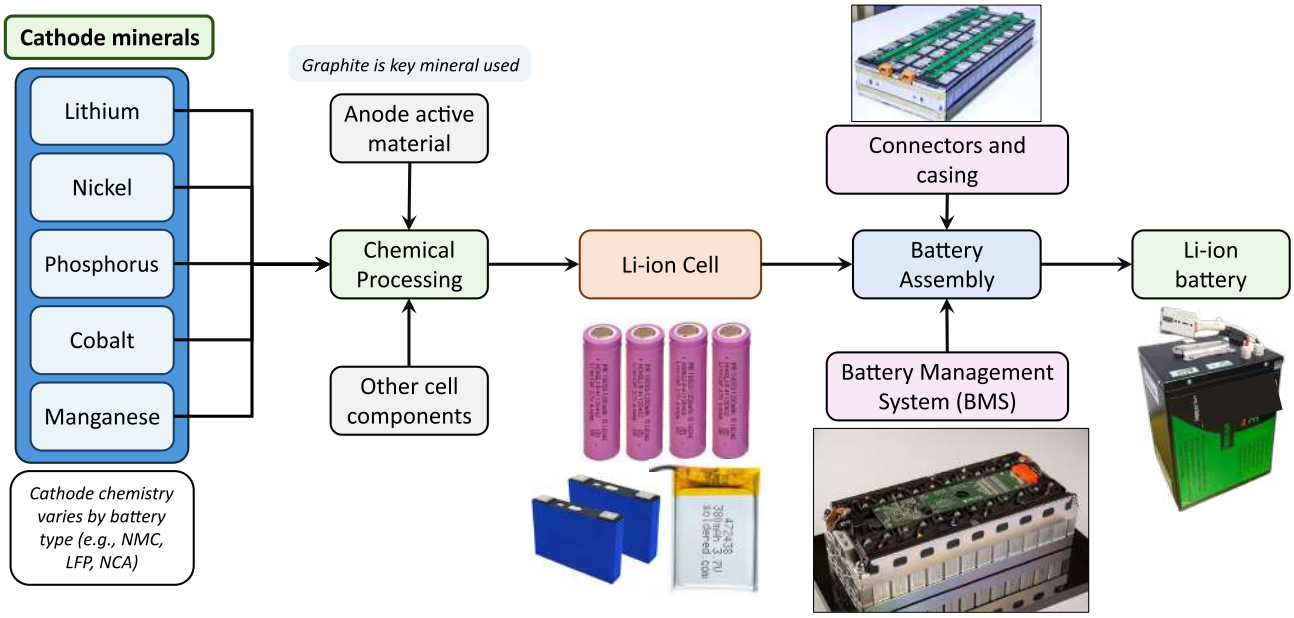
The lithium ion BESS value chain spans mineral extraction, material refining, cell and pack manufacturing, and system integration through to operation and end-of-life recovery. Scalable and secure supply chains require coordinated capacity across all stages, as constraints in any segment, such as refining, materials production, or cell manufacturing, can limit deployment despite strong downstream demand.

A technically rigorous framing of the value chain therefore treats the battery not as a single discrete product, but as an entire industrial system. As shown in Figure 34, mined and refined commodities are transformed into engineered electrochemical components, which are then assembled into qualified cells, modules, and packs, and ultimately integrated into grid connected systems that must satisfy safety, reliability, and performance requirements over a multiyear service life[65].

- **Upstream extraction and concentration of battery minerals:** Lithium ion BESS value chain spans mineral extraction, material refining, cell and pack manufacturing, system integration, operation, and end-of-life recovery. Scalable and secure supply chains require coordinated capacity across all stages, as constraints in any segment, such as refining, materials production, or cell manufacturing, can limit deployment despite strong downstream demand.

65 D. Warrior, A. Tyagi, and R. Jain, How Can India Indigenise Lithium-Ion Battery Manufacturing? Formulating Strategies across the Value Chain, Council on Energy, Environment and Water (CEEW), New Delhi, India, Issue Brief, Feb. 2023.

Figure 34 Value chain of lithium ion BESS



- **Midstream refining and active material production:** Midstream processing converts mined materials into battery-grade salts, precursors, and engineered electrode materials. This includes lithium refining, production of nickel, cobalt, and manganese intermediates, synthesis of cathode and anode materials, and electrolyte preparation. Material quality is critical at this stage, as impurities and variability directly affect cell yield, safety, and lifetime. Supply chain analyses indicate that battery scale-up requires coordinated investment across extraction, processing, materials production, and manufacturing, rather than cell assembly alone.
- **Downstream cell manufacturing processes:** Downstream manufacturing converts engineered materials into electrochemical cells through tightly controlled, capital-intensive processes, including electrode coating, cell assembly, electrolyte filling, and formation cycling. Formation and aging are critical for establishing the solid electrolyte interphase and screening early defects. These steps strongly influence yield, cost, and performance, making cell manufacturing both quality and capital intensive and a common source of supply bottlenecks during periods of rapid demand growth.
- **Pack and system integration:** Pack and system integration includes cell sorting, module and pack assembly, thermal management, electrical interconnection, and integration of sensing and protection hardware. The battery management system provides safety-critical functions such as monitoring, state estimation, balancing, and protection, while communicating with higher-level controllers. For grid applications, integration also includes power conversion, protection coordination, and supervisory control to deliver services such as peak shaving, frequency response, and voltage support. System-level design choices, including thermal systems, interconnects, enclosures, and controls, significantly affect cost, performance, and safety even when cell chemistry is unchanged.
- **Deployment, operations, and asset management:** Deployment and operations include project engineering, installation, commissioning, and long-term asset management. For BESS, value is realised only if contracted power and energy services are delivered reliably while controlling degradation. This requires effective management of SoC, temperature, and ramp rates, along with maintenance of auxiliary and safety systems. At this stage, battery

operation directly interfaces with power system and market requirements while respecting cell- and system-level operating limits.

- **End of life management and recycling:** End-of-life management closes the value chain through collection, evaluation for second-life use, and recycling to recover materials and reduce reliance on primary supply. Recycling is increasingly viewed as strategic for supply resilience and sustainability as battery retirements grow. It can provide a secondary supply of critical materials for midstream processing, subject to process maturity, economics, and recovered material quality.

The BESS value chain involves a diverse set of Original Equipment Manufacturers (OEMs) and specialised suppliers across segments, from raw material extraction and processing to cell manufacturing, system integration, and end of life management. Each stage is characterised by a distinct ecosystem of technology providers, reflecting differences in technical expertise, capital intensity, and regional supply chain dynamics. A detailed segment wise mapping of key OEMs across the value chain is provided in Appendix B.

2.3.4.10 Global Lithium and Critical Mineral Availability

Global availability of lithium and other battery critical minerals reflects constraints across geology, mining, refining, and downstream material production. While resource endowment is necessary, near- to medium-term supply is more often constrained by project lead times, permitting, processing capacity, and geographic concentration. Together, these factors increase exposure to policy, trade, and logistical risks within battery supply chains[66]. Comparative assessments show that midstream and downstream segments are more geographically concentrated than mining, particularly in lithium, cobalt, and graphite refining, as well as cathode, anode, cell, and battery system production. This concentration creates structural supply security risks even when upstream extraction is diversified, highlighting the need for coordinated capacity development across the full value chain[67].

From a system planning perspective, availability of lithium, nickel, cobalt, and graphite should be assessed using indicators such as mine production, refining capacity, reserves, and supply concentration. Supply adequacy also depends on the conversion of mined material into battery-grade chemicals, which requires specialised refining processes and strict quality control. As shown in Figure 35[67], refining and downstream battery manufacturing are highly geographically concentrated, particularly in China, making effective availability more dependent on midstream and downstream capacity than on mining alone[67]. Rapid clean energy deployment further tightens critical mineral availability, as lithium, nickel, cobalt, graphite, and related materials must scale quickly to meet decarbonisation pathways[66]. Scenario analyses indicate that announced projects may be insufficient under more ambitious targets, while recent assessments point to weakening investment and slower exploration growth, increasing the risk of supply bottlenecks later in the decade. As a result, mineral availability is dynamic and shaped by investment cycles, project execution, and demand growth from EVs and stationary ESS. Chemistry selection influences mineral exposure through nickel, cobalt, and graphite intensity, while recycling and circularity can enhance supply resilience by partially offsetting primary supply, subject to collection rates, processing scale, and end-of-life volumes.

66 International Energy Agency, Global Critical Minerals Outlook 2025, IEA, Paris, France, 2025.

67 International Energy Agency, Global Supply Chains of EV Batteries, Paris, France, 2022.

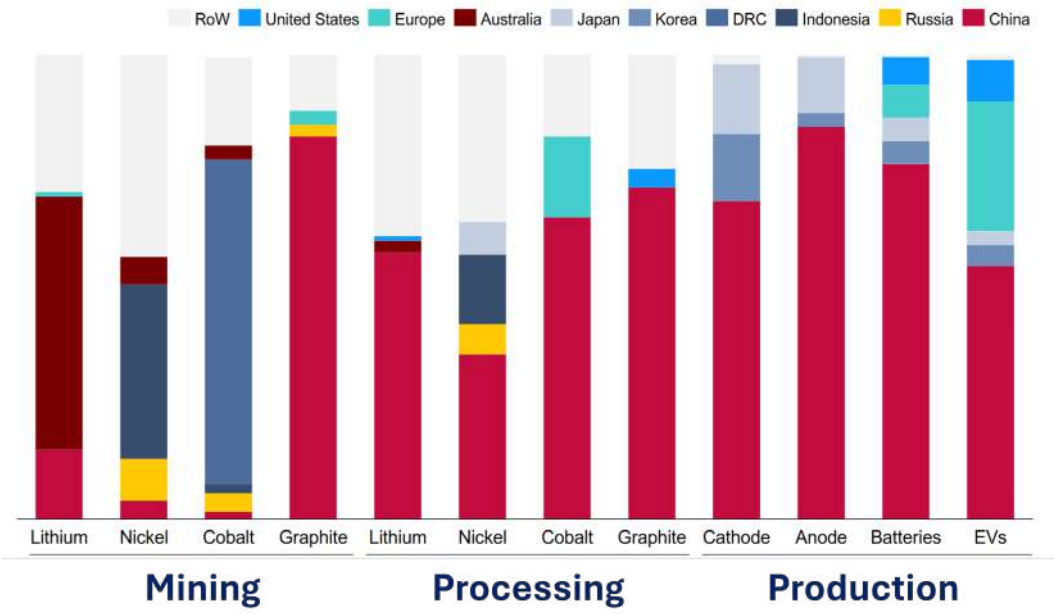


Photo by MiningWatch Portugal on Unsplash

☀ KEY INSIGHT

Critical mineral risk is driven more by concentrated refining and battery manufacturing than by mining alone, making supply-chain diversification and recycling essential for Li-ion BESS scale-up.

Figure 35 Critical mineral used in lithium ion BESS value chain across the world



Source: IEA

2.3.4.11 Global Lithium Supply Chain

Global lithium ion BESS supply chains form an integrated value network spanning critical minerals, refining, active materials, cell manufacturing, and end use in transport and stationary ESS[40]. Strategic risk arises from uneven capacity distribution, with refining, materials processing, and cell manufacturing highly concentrated despite more diversified mining. This concentration increases exposure to trade, policy, and sustainability constraints and is reflected in supply chain competitiveness assessments, as shown from Table 5[68] which show China leading across multiple stages, followed by countries such as Canada and the United States with more segmented capabilities.

China's position in the battery supply chain highlights areas of strong control as well as potential points for competitive entry as shown from Figure 36[69]. It has dominated across most segments, particularly in LFP battery products, while other regions retain strengths in other selected chemistries, including parts of the NMC ecosystem. Flow-based analysis further shows that supply dependence is driven more by processing and conversion stages than by mining alone. This is critical for BESS stakeholders, as procurement risk is often shaped by chemical conversion and precursor bottlenecks under conditions of rapid demand growth.

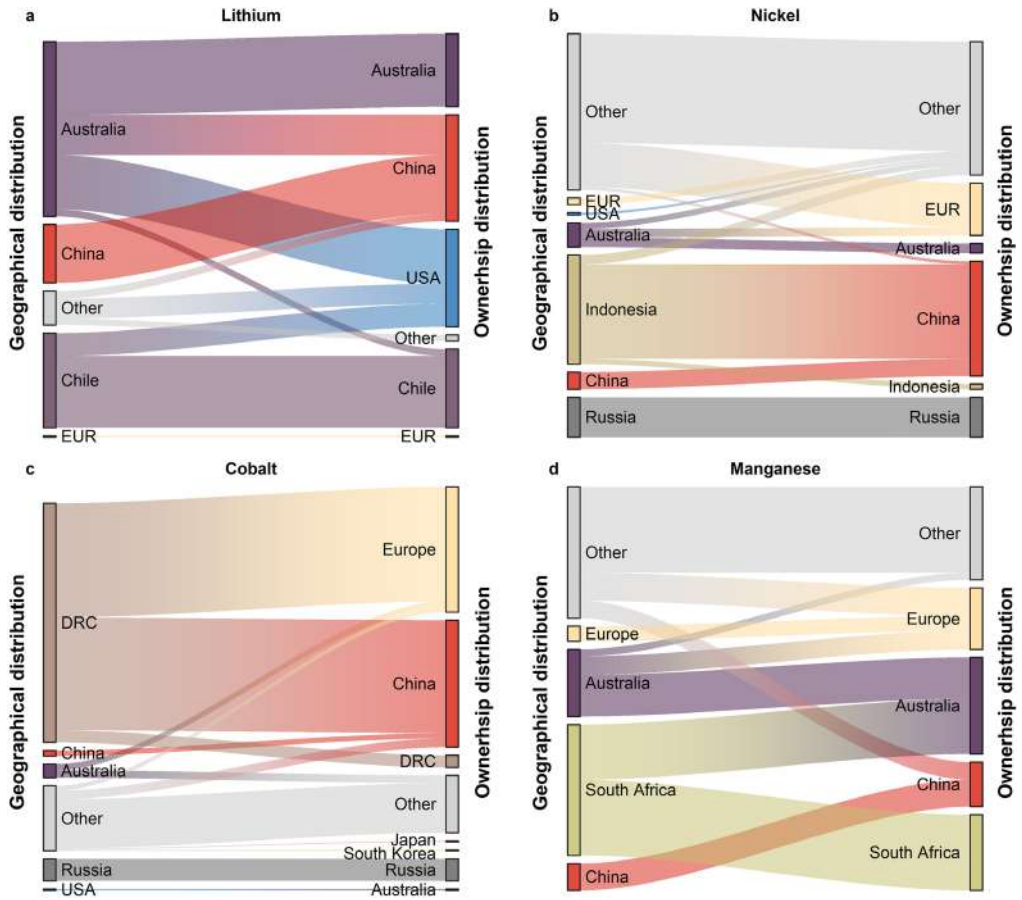
68 BloombergNEF, "China regains number one spot in BloombergNEF's global Lithium-Ion battery supply chain ranking," BloombergNEF, May 22, 2025.

69 T. Greitemeier, A. Kampker, J. Tübke, and S. Lux, "China's hold on the lithium ion battery supply chain: Prospects for competitive growth and sovereign control," Journal of Power Sources Advances, vol. 32, p. 100173, 2025.

Table 5 Global lithium battery supply chain ranking till 2024

Country	Rank		Country	Rank	
China	1	▲ 1	United Kingdom	12	=
Canada	2	▼ 1	Indonesia	13	▲ 4
United States	3	▲ 1	India	14	▲ 2
Germany	4	=	Poland	15	▼ 1
South Korea	5	▲ 1	Brazil	16	▲ 5
Australia	6	▲ 3	Chile	17	▼ 4
Sweden	7	=	Czech Republic	17	▲ 1
Norway	8	=	Vietnam	19	=
Japan	9	▲ 2	South Africa	20	▲ 2
France	10	=	Hungary	21	▼ 7
Finland	11	▼ 6	Thailand	22	▲ 1
Turkey	23	▲ 3	Philippines	27	=
Argentina	24	▲ 1	Morocco	28	=
Mexico	25	▼ 5	Democratic Republic of Congo (DRC)	29	=
Slovakia	26	▼ 2	Bolivia	30	=

Figure 36 Linking upstream minerals to downstream battery value chain stages by region



Source: Tim Greitemeier et al.; 2025

A concise country and region snapshot is provided in Table 6. The objective is not to be exhaustive, but to highlight dominant comparative advantages across key supply chain nodes, supported by at least one quantitative indicator from authoritative sources[69,70].

Table 6 Comparative analysis of country wise strength of minerals mining

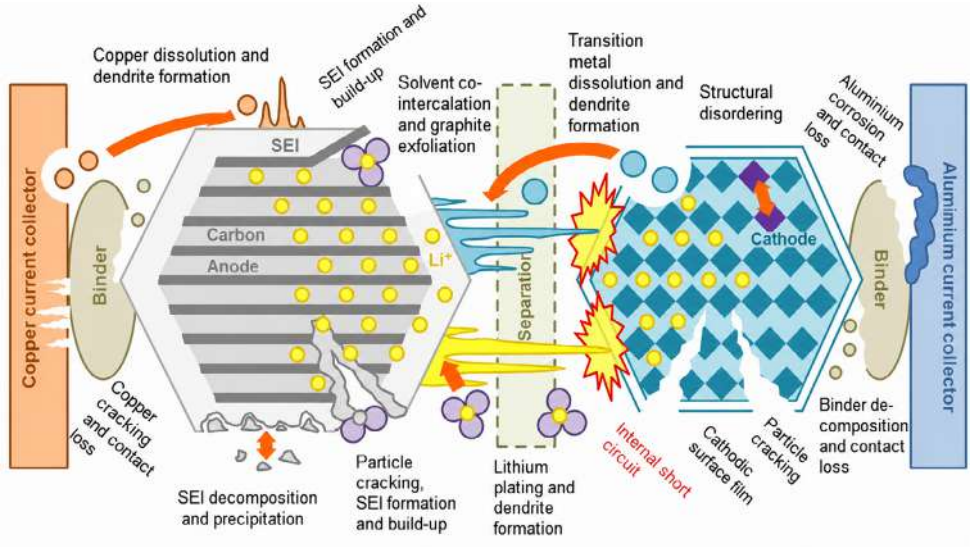
Country/ Region	Supply chain	Country strength
China	Processing, cathode/ anode materials, large-scale cell manufacturing	▶ 75% of global Li-ion battery production ▶ 70% cathode and approx. 85% anode capacity ▶ >50% of lithium, cobalt, graphite processing ▶ >98% dominance in LFP related segments
Europe	EV assembly and expanding cell manufacturing	▶ >25% of global EV assembly ▶ Limited upstream and midstream footprint ▶ 20% share of cobalt processing
United States	EV production with policy-driven supply chain expansion	▶ 10% of global EV production ▶ 7% of battery manufacturing capacity ▶ Future growth driven by industrial policy
Japan	Advanced materials and component manufacturing	▶ 14% of global cathode material production ▶ 11% of anode material production
Korea	Cathode materials and downstream manufacturing	▶ 15% share of global cathode production ▶ Strong integration with cell manufacturing
Australia	Lithium mining and upstream resources	▶ Major global lithium producer ▶ Strong position in upstream mining and exports
DRC	Cobalt mining	▶ Highly concentrated global cobalt supply ▶ Critical dependency highlighted in trade flows
Indonesia	Nickel mining with growing processing investment	▶ 40% of global nickel production ▶ Increasing downstream processing capacity

70 S. Carrara, S. Bobba, S. Blagoeva, D. Alves Dias, P. Cavalli, A. Georgitzikis, K. Grohol, M. Iuliu, A. Kuzov, L. Latunussa, C. Lyons, L. Malano, G. Maury, T. Prior, A. Somers, J. Telsnig, T. Veeh, C. Wittmer, D. Black, C. Pennington, and D. Christou, Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU – A Foresight Study, European Commission, Joint Research Centre, JRC Science for Policy Report, EUR 31437 EN, 2023.

2.3.4.12 Degradation Mechanism in Lithium ion Battery

Lithium ion battery degradation arises from a combination of electrochemical side reactions, mechanical damage, and transport limitations. These processes lead to capacity fade, internal resistance increase, and non-uniform aging at both electrode and cell levels. Degradation is commonly classified into three modes: (1) loss of lithium, (2) loss of active material, and (3) internal impedance rise. Each mode can result from multiple interacting mechanisms involving the anode, cathode, electrolyte, separator, and current collectors[71]. These interactions are illustrated in Figure 37[72] that links individual degradation mechanisms to their combined effects on cell performance.

Figure 37 Degradation mechanism in lithium ion cell



Source: M. M. Kabir et al.; 2017

- **Anode degradation:** Solid Electrolyte Interphase (SEI) growth results from electrolyte reduction at low anode potentials and is accelerated by high temperature, high SoC, and repeated cycling. This leads to loss of cyclable lithium, increased interfacial resistance, and reduced rate capability, manifested as capacity fade and resistance increase. Lithium plating is closely linked to SEI behaviour, as degraded interfacial transport promotes plating, which further increases irreversible lithium loss.
- **Cathode degradation:** Cathode degradation involves structural changes, microcracking, transition metal dissolution, surface reconstruction, and, in some chemistries, oxygen release at high potentials. Electrolyte oxidation at the cathode interface further accelerates degradation, leading to loss of active material, increased impedance, and depletion of lithium inventory.

The cause-effect pathway of battery ageing is described in Figure 38[73]. Here, operating conditions such as SoC, temperature, cycling intensity, and current act as stress factors that initiate internal degradation mechanisms, including SEI or Cathode Electrolyte Interface (CEI) growth, lithium plating, particle cracking, and material dissolution. These mechanisms collectively lead to key degradation

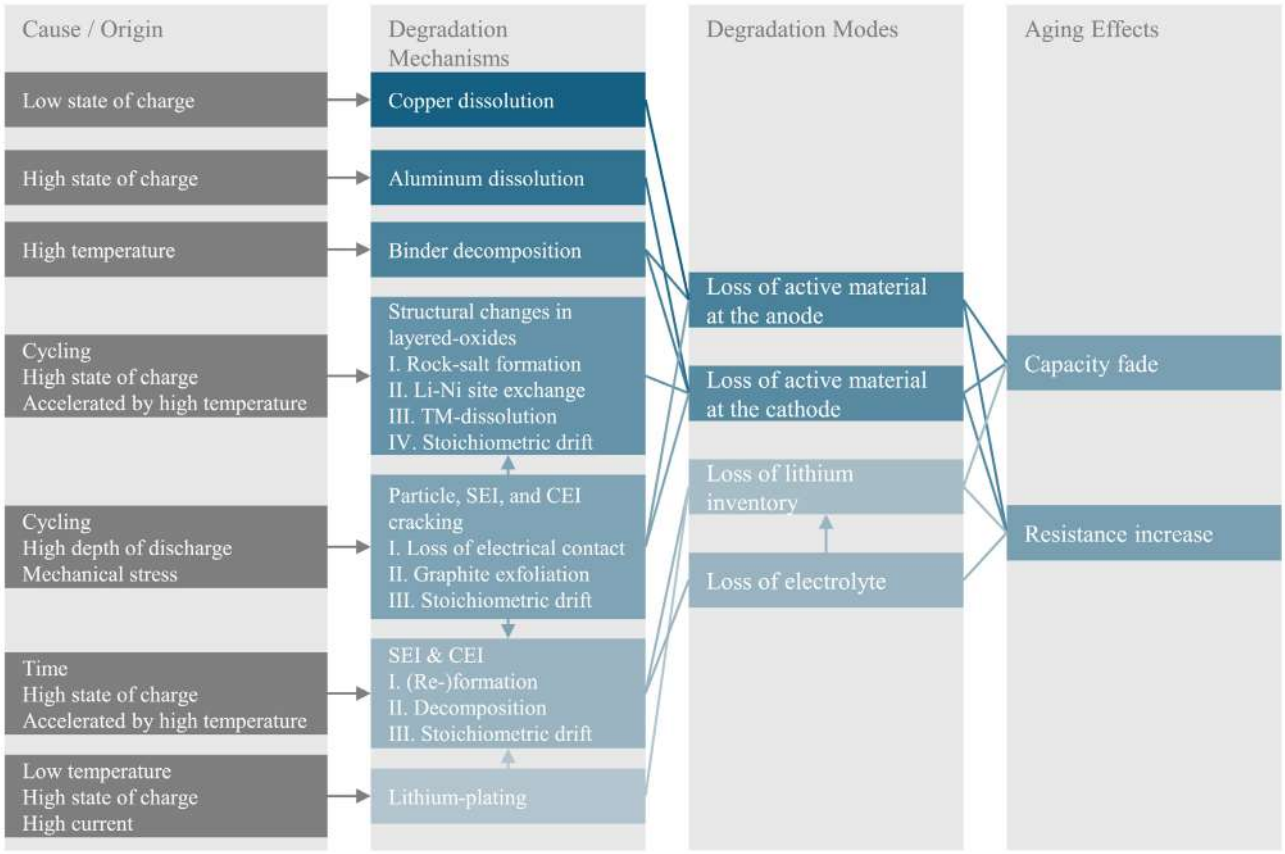
71 J. S. Edge et al., "Lithium ion battery degradation: what you need to know," Phys. Chem. Chem. Phys., vol. 23, no. 14, pp. 8200–8221, 2021.

72 M. M. Kabir and D. E. Demirocak, "Degradation mechanisms in Li-ion batteries: a state-of-the-art review: Degradation Mechanisms in Li-ion Batteries: A State-of-the-Art Review," Int. J. Energy Res., vol. 41, no. 14, pp. 1963–1986, 2017.

73 M. Fischer et al., "How degradation of lithium-ion batteries impacts capacity fade and resistance increase: A systematic, correlative analysis," J. Power Sources, vol. 656, no. 237921, p. 237921, 2025.

modes such as loss of active material, loss of lithium inventory, and electrolyte depletion. Over time, these effects manifest as observable performance degradation, primarily in the form of capacity fade and increased internal resistance. Since both outcomes originate from the same underlying processes, they are strongly correlated, enabling resistance to be used as a rapid indicator of capacity degradation. This relationship highlights the importance of understanding degradation pathways for accurate battery modelling, diagnostics, and SoH estimation.

Figure 38 Overview of lithium ion battery degradation pathways



Source: M. Fischer et at.; 2025



Photo by Homa Appliances on Unsplash

2.3.4.13 Global Deployment of Lithium ion BESS

Lithium ion batteries are most preferred ESS for majority of the countries in the world. Few major country wise deployment of lithium ion BESS is mentioned in Table 7[74]

Table 7 Global Deployment of lithium ion BESS plant

Project Name	Location	Capacity	Commissioning year
United States			
Gateway Energy Storage	San Diego, California	250 MW/ 250 MWh	2020
Dynegy Vistra Moss Landing	Moss Landing, California	Phase I: 300 MW/1,200 MWh Phase II: 100 MW/ 400 MWh Phase III: 350 MW/ 1,400 MWh	2023
Stanton BESS	Orange Country, California	68.8 MW/275.2 MWh	2023
Edwards Sanborn Storage	Kern Country, California	875 MW/3,287 MWh	2024
Gemini Storage	Nevada	380 MW / 1,416 MWh	2024
Crimson BESS	California	350 MW/ 1,400 MWh	2022
Desert Peak Energy Storage	Palm Springs, California	700 MW/ 2,800 MWh	2023
Reid Gardner BESS	Moapa, Nevada	220 MW/440 MWh	2023
Atrisco Solar & Energy Storage	Bernalillo Country, New Mexico	300 MW/1,200 MWh	2024
Papago Storage facility	Tonopah, Arizona	300 MW / 1,200 MWh	2025
Tanzanite Storage	Athens, Texas	265.8 MW / 531.6 MWh	2025
Bellefield Solar & Storage	Kern County, California	500MW/2000 MWh	2025
FPL Manatee Energy Storage Center	Manatee, Florida	409 MW/900 MWh	2021
China			
Huadian Xinjiang Kashgar project	Xinjiang	500 MW / 2000 MWh	2025
Zhangbei Renewable Project	Jiayuguan	500 MW / 1000 MWh	2025
Tongliao Conch Energy Storage Power Station	Naiman Banner	500 MW / 2000 MWh	2025

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Project Name	Location	Capacity	Commissioning year
Baotang BESS	Foshan	300 MW / 600 MWh	2024
Baoku Energy Storage Power Station	Qinghai Baoku	224.5 MW / 889 MWh	2024
Kizilsu Kirghiz Autonomous Prefecture	Xinjiang	300 MW / 1,200 MWh	2024
United Kingdom			
Wilton International Battery Storage	Teesside	400 MW / 1,300 MWh	2026
Coalburn 1 BESS	Scotland	500 MW / 1,000 MWh	2026
Thurrock Storage	Essex	300 MW / 600 MWh	2025
Lakeside BESS	North Yorkshire	100 MW / 200 MWh	2024
Pillswood BESS	East Yorkshire	98 MW/ 196 MWh	2022
Australia			
Neoen Collie Battery	Western Australia	560 MW / 2,240 MWh	2025
Synergy Collie Battery	Western Australia	500 MW / 2,000 MWh	2026
Western Downs Battery	Queensland	540 MW / 1,080 MWh	2025
Waratah Super Battery	New South Wales	850 MW / 1,680 MWh	2025
Hornsdale Power Reserve	South Australia	150 MW / 193.5 MWh	2020
Victorian Big Battery	Victoria	300 MW / 450 MWh	2021
Ireland			
Aghada 2 BESS	Country Cork	15 MW / 300 MWh	2024
Lumcloon BESS	Offaly	100 MW / 78.5 MWh	2021
Shannonbridge BESS	Offaly	63.2 MW / 180 MWh	2026
Poolbeg Energy Hub	Dublin	75 MW / 150 MWh	2023
Canada			
Oneida Energy Storage	Ontario	250 MW / 1,000 MWh	2025
WaterCharger BESS	Alberta	180 MW/360 MWh	2024
Hagersville	Ontario	300 MW / 1,200 MWh	2026
WindCharger Battery Storage	Alberta	10 MW / 20 MWh	2020

Project Name	Location	Capacity	Commissioning year
Germany			
Eco Power Three BESS	Saxony-Anhalt	300 MW / 740 MWh	2026
Kupferzell Netzbooster BESS	Kupferzell	250 MW/ 250 MWh	2025
Hamm BESS	Hamm	140 MW / 150 MWh	2024
Alfeld BESS	Lower Saxony	137.5 MW / 282 MWh	2026
Lingen Megabattery	Lingen	45 MW / 49 MWh	2023
Neurath BESS	North Rhine-Westphalia	80 MW / 84 MWh	2025
Spain			
Romeral BESS	Cuenca	30 MW / 60 MWh	2026
Olmedilla BESS	Cuenca	30 MW / 60 MWh	2026
Andévalo BESS	Huelva	28.8 MW / 50 MWh	2026
Revilla-Vallejera BESS	Castile and León	25 MW / 50 MWh	2025
Puertollano BESS	Ciudad Real	5 MW / 20 MWh	2022
France			
Cheviré BESS	Nantes Saint-Nazaire Harbour	100 MW / 200 MWh	2025
Amarenco-Claudia BESS	Gironde	105 MW / 98 MWh	2023
Dunkirk BESS	Dunkirk	61 MW / 61 MW	2021
Grandpuits BESS	Grandpuits	43 MW / 43 MWh	2023
Netherlands			
Project Pollux	Vlissingen	30 MW / 68 MWh	2023
Project Castor	Vlissingen-Oost	30 MW / 63 MWh	2023
RWE Eemshaven BESS	Eemshaven	35 MW / 41 MWh	2025
Italy			
Udine BESS	Friuli	201 MW / 800 MWh	2024
Trino BESS (Phase I)	Piedmont	208 MW / 832 MWh	2024
Catania Solar BESS	Sicily	13.75 MW / 50 MWh	2026

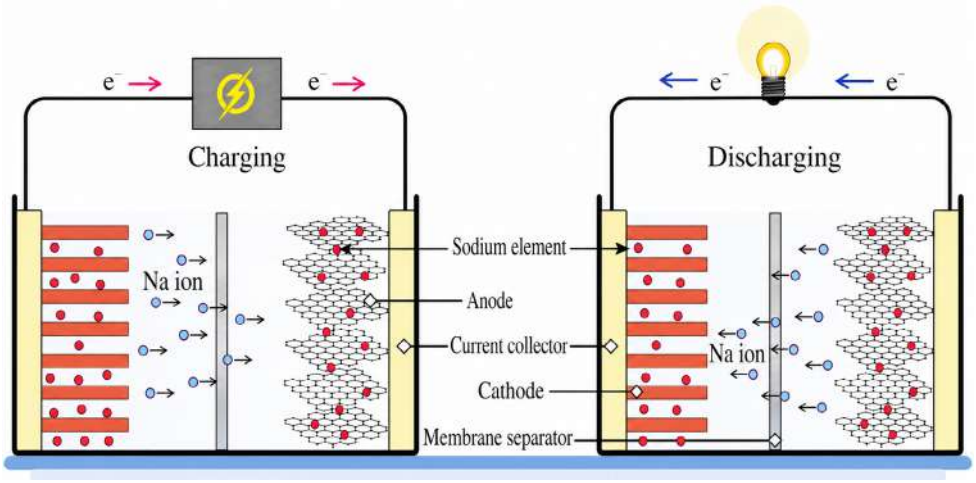
2.3.5 Sodium Ion Batteries

Sodium ion batteries are rechargeable ECES devices that use sodium ions as the charge carrying species and operate through reversible sodium ion insertion and extraction in electrode host materials. Interest in sodium ion batteries has increased due to sodium abundance, reduced dependence on geographically concentrated critical minerals, and their suitability for cost sensitive stationary storage where high energy density is not the primary requirement. A key similarity with lithium ion batteries is the shared intercalation based operating principle, which allows partial use of existing manufacturing approaches; however, differences in sodium ion size, mass, and redox potential lead to distinct cell designs and performance trade-offs[75].

2.3.5.1 Working Principle

A sodium ion battery cell consists of a positive electrode, a negative electrode, an electrolyte that enables sodium ion transport, and a separator that prevents internal short circuits while allowing ionic conduction. During operation, sodium ions move through the electrolyte and separator, while electrons flow through the external circuit, with charge transfer occurring at the electrode–electrolyte interfaces. This operating principle as illustrated in Figure 39[44], which shows sodium ion movement between electrodes and electron flow through the external circuit during charging and discharging.

Figure 39 Operation of sodium ion battery



Source: J. Mitali et al.; 2017

During charging, an external power source drives electrons into the negative electrode. To maintain charge balance, sodium ions migrate through the electrolyte from the positive electrode to the negative electrode and are stored within the anode host material. In most commercial sodium ion designs, the anode is hard carbon rather than graphite, because sodium insertion into graphite is thermodynamically and kinetically unfavourable compared to lithium insertion[76].

During discharging, the anode releases sodium ions into the electrolyte, and these ions migrate toward the cathode where they are inserted into the cathode host structure. At the same time, electrons flow through the external circuit and deliver electrical energy to the load. The overall

75 K. Deshmukh et al., "Sodium-ion batteries: state-of-the-art technologies and future prospects," J. Mater. Sci., vol. 60, no. 8, pp. 3609–3633, 2025.

76 P. Phogat, S. Rawat, S. Dey, and M. Wan, "Advancements and challenges in sodium-ion batteries: A comprehensive review of materials, mechanisms, and future directions for sustainable energy storage," J. Alloys Compd., vol. 1020, no. 179544, p. 179544, 2025.

operating principle is similar to lithium ion batteries, but performance differs because sodium ions are larger and heavier, which affects diffusion kinetics, mechanical strain, interphase formation, and cell voltage characteristics[76].

2.3.5.2 Cell Chemistries and Operation

Sodium ion battery performance and manufacturability are mainly determined by the choice of cathode structure, anode material, electrolyte, and separator. Although the overall system architecture is similar to lithium ion batteries, sodium ion chemistry requires different host materials because sodium insertion thermodynamics, diffusion behaviour, and associated volume changes differ from those of lithium. Cathode materials for sodium ion batteries are commonly grouped into four main categories based on crystal structure and sodium storage mechanism[76].

- **Layered transition metal oxides:** Layered oxides can offer relatively high energy density but often face stability challenges at higher operating voltages. Compositional tuning is usually required to balance capacity, structural stability, and cost. Examples include $NaCoO_2$ and mixed transition metal layered oxides, which provide good energy density but may exhibit limited long term stability under repeated cycling.
- **Polyanionic compounds:** Polyanionic cathodes such as phosphates and NASICON (Sodium Super Ionic Conductor) type structures provide rigid three dimensional frameworks that improve structural and thermal stability. For example, $Na_3V_2(PO_4)_3$ has open sodium ion pathways that support fast diffusion and high rate capability, while $NaFePO_4$ offers strong bonding and thermal robustness but can be limited by lower ionic and electronic conductivity. Voltage stabilization through inductive effects is a key advantage, although conductive additives or coatings are often required to enhance performance.
- **Prussian blue analogues:** Prussian blue analogues are open-framework materials with large interstitial sites and three-dimensional diffusion pathways, enabling fast sodium ion insertion with minimal volume change. Their low-cost synthesis and favourable environmental profile make them suitable for stationary storage, with sodium iron hexacyanoferrate offering a theoretical capacity of approximately 170 mAh per gram through transition metal redox reactions.
- **Organic cathodes:** Organic cathode materials can deliver high specific capacity and potential sustainability benefits, but they often suffer from lower operating voltage and stability challenges related to dissolution and cycling, which require careful electrolyte and electrode design.

The comparative analysis of cathode materials in Sodium ion batteries is mentioned in Table 8[76].


Pexels

Table 8 Comparative analysis of cathode materials in sodium ion batteries

Cathode Material	Energy Density (Wh/kg)	Voltage Range (V)	Cyclic Stability	Advantages	Challenges
$NaCoO_2$ (Layered Oxide)	250–300	2.5 – 4	Moderate (300–500 cycles)	High energy density, stable cycling	High cost, low stability at high voltage
$NaFePO_4$ (Polyanionic)	210–250	3 – 4.2	High (2000+ cycles)	Safe, high thermal stability, abundant material	Lower energy density, slow kinetics
$Fe[Fe(CN)_6]$ (Prussian Blue Analogue)	190–220	3 – 3.8	High (1000+ cycles)	High capacity, low cost, easy synthesis	Poor conductivity, low energy density
$Na_3V_2(PO_4)_3$ (Polyanionic)	230–270	3 – 4	Moderate (1000+ cycles)	High stability, high-rate performance	Moderate energy density, low conductivity

2.3.5.3 Performance Matrices

A structured set of parameters is commonly used to evaluate sodium ion behaviour, efficiency, and durability, including specific capacity, energy density, cycling stability, coulombic efficiency, rate capability, voltage profile, power density, internal resistance, thermal stability, and self-discharge rate. Table 22[77] summarizes the typical range of key performance matrices of sodium ion batteries.

Table 9 Performance matrices of sodium ion batteries

Parameters	Typical range
Cell Voltage (V)	2.3 - 4
Cycle Life	3000 - 5000 (Few advanced Sodium Ion battery have cycle life up to 10,000 cycles)
Energy Density (Wh/kg)	90 - 300
Round-Trip-Efficiency	60% - 85%
C Rate	0.1C - 5C
Discharge Time	Second - Hours
Depth of Discharge	80 - 90 %

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2.3.5.4 Applications

Sodium ion BESS are best suited for applications where supply chain resilience, cost control, safety margin, and temperature robustness are more important than compactness. They are commonly described as a complementary option to lithium ion batteries, with the strongest fit in use cases where cost is prioritised over energy density[76].

- **Grid-scale energy storage:** It is one of the most promising applications of sodium-ion batteries, where energy density is less critical than cost and durability. Their use of abundant sodium makes them attractive for frequency regulation, peak shaving, and large stationary installations supporting power grids.
- **RE storage system:** It benefit from sodium-ion batteries due to their good thermal stability and long cycle life. They are well-suited for storing excess solar and wind energy and delivering it during periods of intermittency, particularly in large solar parks and wind farms.
- **Low-speed and short range mobility:** Electric two-wheelers, three-wheelers, and e-rickshaws, can effectively utilize sodium-ion batteries. The moderate energy density is adequate for urban mobility, while improved safety and lower cost help reduce overall vehicle price.
- **Backup power and industrial storage:** It includes telecom towers, data centres, UPS systems, and microgrids. Sodium-ion batteries offer reliable performance over wide temperature ranges with lower fire risk, making them suitable for long-duration and safety-critical backup power solutions.

2.3.5.5 Lithium ion Vs. Sodium ion Battery

Lithium ion and sodium ion BESS are complementary rather than direct substitutes, as their respective strengths suit different operating conditions. While both rely on reversible ion storage, sodium ion batteries exhibit lower energy density and operating voltage but offer advantages in material availability and potential safety. The comparative analysis of both these technologies is depicted in Table 10[78].

Table 10 Li ion Vs. Sodium ion batteries comparison

Parameter	Sodium-Ion (Na-ion)	Lithium-Ion (Li-ion)	Comment
Raw Material Abundance	Very high (Na abundant availability globally)	Moderate (Li concentrated in few countries)	Na-ion has cost and supply chain advantage
Material Cost	Lower	Higher	Na-ion is more economical for stationary/grid-scale use
Low Temperature Tolerance	Better (operates down to −20°C)	Degrades below 0°C	Advantageous for cold climates
Safety	High (non-flammable electrolytes possible)	Risk of thermal runaway	Both can be made safe, but Na-ion avoids heat risk

78 R. Wanison et al., "Engineering aspects of sodium-ion battery: An alternative energy device for Lithium-ion batteries," J. Energy Storage, vol. 100, no. 113497, p. 113497, 2024.

Parameter	Sodium-Ion (Na-ion)	Lithium-Ion (Li-ion)	Comment
Ease of Recycling	Easier materials recovery (non-toxic metals)	Complex (Li, Co recovery is energy-intensive)	Na-ion is potentially more circular
Environmental & Social Risks	Low (no cobalt, less intensive mining)	High (cobalt, lithium extraction impacts)	Na-ion is more sustainable and ethical in sourcing

2.3.5.6 Global Deployment

The global deployment of Sodium Ion batteries is summarised in Table 11[79]

Table 11 Global deployment of sodium ion BESS plant

Project / Plant	Location	Size (MWh/MW)	Commissioning Year
China			
Datang Hubei Sodium-ion BESS	Qianjiang	100 MWh / 50 MW	2024
Baochi Hybrid Lithium + Sodium ESS	Yunnan	400 MWh / 200 MW (40 MWh Sodium Ion)	2025
Fulin Sodium-Ion BESS	Sichuan	50 MWh / 12.5 MW	2025
Xingkong Na Maliu Industrial Park Project	Sichuan	1000 MWh	2025
United States			
Peak Energy SolarTAC Pilot	Colorado	3.5 MWh	2025
DOE / Aquion Energy Test System	Santa Clara, California	0.056 MWh / 0.014 MW	2013
Europe			
Phenogy Bremen Airport Project	Germany	1 MWh / 0.4 MW	2025
Japan			
Tsu Storage Battery Plant	Tsu City, Mie	69.6 MWh / 11.4 MW	2025
Buzen Power Station (NaS)	Fukuoka	300 MWh / 50 MW	2016
NAS MODEL L24 Container System	Aichi	1.2 MWh / 0.2 MW	2024

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2.3.6 Vanadium Redox Flow Batteries

Vanadium Redox Flow Batteries (VRFB) are mature aqueous energy storage systems suited to long-duration stationary applications where safety, deep discharge capability, and high utilisation are prioritised over energy density. Energy is stored in vanadium-based liquid electrolytes contained in external tanks, while power is delivered through an electrochemical stack, allowing independent scaling of energy and power and distinguishing them from lithium ion systems[44]. From a grid planning perspective, VRFBs are valued for long asset life, frequent cycling capability, strong safety performance, and recycling potential. As shown in Figure 40, they can operate at full depth of discharge over their lifetime, tolerate wider temperature ranges, and be expanded modularly to meet changing requirements. Their non-flammable aqueous electrolyte reduces thermal runaway risk, and electrolyte recovery at end of life improves circularity, supporting their use in long-duration and daily cycling applications despite higher upfront cost and larger footprint compared to lithium ion systems[80].

Figure 40 Drivers to shift towards VRFB from lithium ion BESS

	Lithium Ion Battery	Vanadium Redox Flow Battery
Asset Life	Degrades over time, reduced capacity	Maintains full discharge capability over lifetime
Flexibility	Limited temperature tolerance	Operates well over wide temperature range
Scalability	Fixed ratio, cannot scale energy and power independently	Modular: kW and kWh scaled separately
Safety	Risk of overheating, flammable, toxic	Non-flammable, non-toxic, no explosion risk
Recycling capability	Complex, costly recycling process	Nearly 100% electrolyte recovery with low cost
Operating Cost	Higher LCOS with frequent use	Lower LCOS due to long life and daily cycling ability

2.3.6.1 Chemistry and Operation

VRFBs are aqueous systems that store energy in dissolved vanadium ions circulated between external electrolyte tanks and an electrochemical stack. Their key feature is the decoupling of energy and power, with energy set by electrolyte volume and power by stack size, making them well suited for long duration storage where discharge duration can be increased without resizing the stack[81].

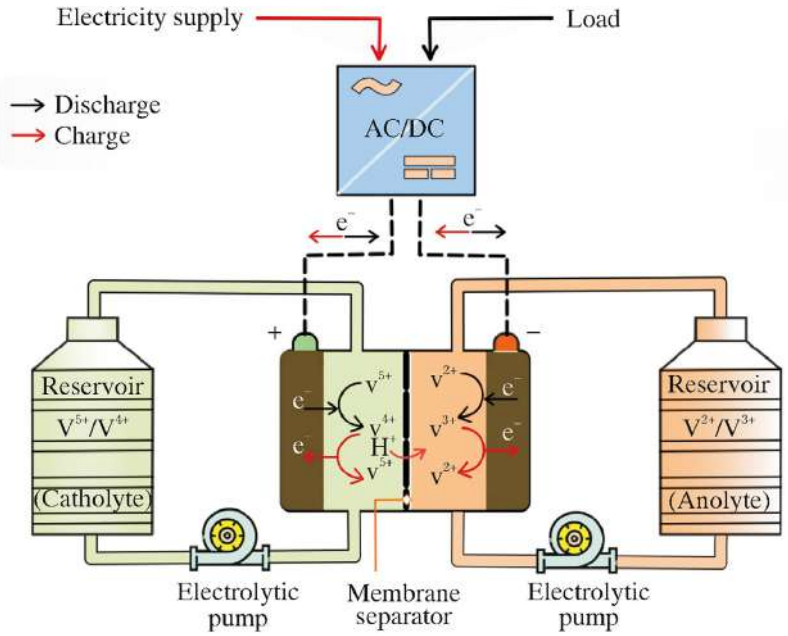
A typical VRFB system as shown in Figure 41[43], includes two electrolyte tanks, one positive and one negative, pumps and piping for electrolyte circulation, an electrochemical stack with porous

80 International Bank for Reconstruction and Development/The World Bank and PwC, "VANADIUM BATTERY STORAGE REPORT," International Bank for Reconstruction and Development/The World Bank, 2023.

81 K. J. Kim, M.-S. Park, Y.-J. Kim, J. H. Kim, S. X. Dou, and M. Skyllas-Kazacos, "A technology review of electrodes and reaction mechanisms in vanadium redox flow batteries," J. Mater. Chem. A Mater. Energy Sustain., vol. 3, no. 33, pp. 16913–16933, 2015.

electrodes separated by an ion conducting membrane, and bidirectional power electronics that connect the DC stack to the grid and AC loads. During operation, electrolytes are circulated through flow channels near the electrodes, where redox reactions occur at the electrode surfaces, while ions pass through the membrane to maintain charge balance.

Figure 41 Structure and operation of VRFB



Source: J. Mitali et al.; 2017

The standard all vanadium chemistry uses V^{2+} and V^{3+} species in the negative electrolyte and VO^{2+} and VO_2^+ species, often written as V^{4+} and V^{5+}, in the positive electrolyte. Sulphuric acid acts as the supporting electrolyte and provides protons for the positive half-cell reaction. During discharge, reduction occurs in the positive half-cell while oxidation occurs in the negative half-cell. The discharge half reactions are mentioned below[81].

- Positive half cell (reduction during discharge): $VO_2^+ + e^- + 2H^+ \leftrightarrow VO^{2+} + H_2O$
- Negative half cell (oxidation during discharge): $V^{2+} \leftrightarrow V^{3+} + e^-$
- Overall reaction: $VO^{2+} + 2H^- + V^{2+} \leftrightarrow VO_2^+ + H_2O + V^{3+}$

The reversible reaction property of the electrochemical reactions supports the long cycle life of VRFBs. Unlike intercalation batteries, degradation mechanisms such as crystal damage, lithium plating, and interphase growth are minimal because the active species remain dissolved and the electrodes primarily act as catalytic surfaces. Long-term performance is instead governed by electrolyte stability, membrane crossover, water transport, and maintenance of vanadium species balance between tanks.



2.3.6.2 Performance Matrices

Performance assessment of VRFB is compiled in Table 12[82]

Table 12 Performance parameters of VRFB

Parameters	Operating Range
Cell Voltage (V)	1.15 - 1.55
Cycle Life	15,000 - 20,000
Energy Density (Wh/kg)	25 - 50
Round-Trip-Efficiency (%)	60 - 85
C Rate	0.1C - 1C
Discharge Time	Second - Hours
Depth of Discharge	100

2.3.6.3 Applications

VRFB applications are best suited to uses that prioritise long cycle life, deep discharge capability, and long-duration storage, where larger footprint and lower energy density are acceptable. In large power systems, they support RE integration by balancing supply and demand, managing variability, and providing operating reserves and ancillary services[80]. Few major applications of VRFB are mentioned below:

- **RE integration and smoothing:** Deploying VRFBs with wind and solar PV systems for power smoothing and grid support, including centralized and distributed integration configurations in microgrids, as well as practical deployments where VRFBs absorb high frequency fluctuations in RE output to deliver a smoother power profile to the grid.
- **Peak shaving, energy arbitrage, and bill management:** Although VRFBs may not represent the lowest capital cost option, they are well suited for peak shaving and energy shifting applications where frequent daily cycling over long lifetimes reduces overall lifetime cost.
- **Ancillary services and operational flexibility:** From a grid operator perspective, fast power response is determined primarily by the power conversion system, while the electrochemical subsystem sustains power over the required duration. Through converter interfaces, VRFBs can provide ancillary services such as frequency regulation and reactive power support, as well as longer-duration services including contingency reserves, load levelling, and capacity firming.
- **Microgrids and resilience:** In grid connected microgrids, VRFBs can be deployed in both centralized and distributed configurations. Centralized coupling at the point of common coupling may require larger storage capacity to smooth aggregated RE output, while distributed coupling at individual RE sources can simplify control strategies and avoid excessive scaling of storage capacity.

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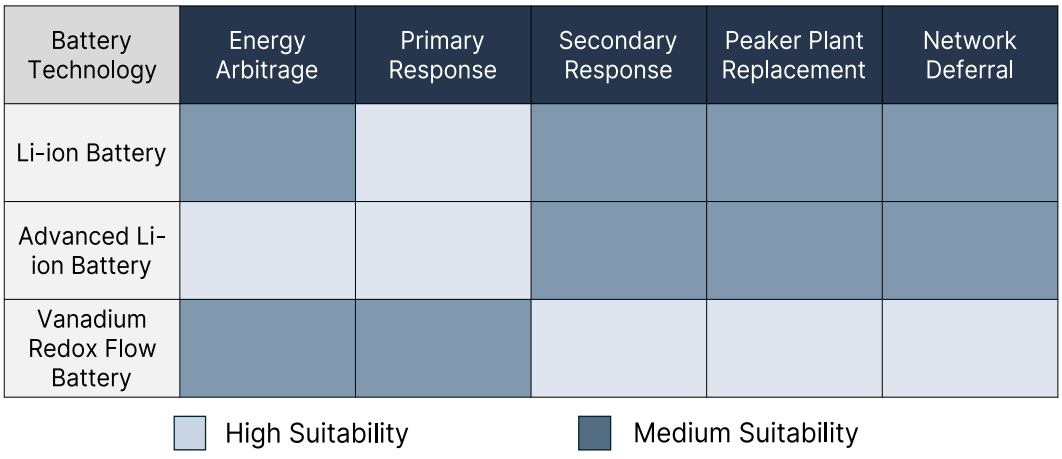
2.3.6.4 Vanadium Redox Flow Batteries Vs. Lithium ion Batteries

As shown in Table 13[83], VRFBs are well suited to high-cycle, deep-discharge, long-duration applications with high utilisation and long service life. In contrast, lithium ion batteries offer higher energy density and efficiency, making them preferable for footprint-constrained and efficiency-critical uses. This comparison highlights that VRFBs are better suited to long-duration, high-cycling applications, while lithium ion batteries are favoured where compactness and efficiency dominate. Figure 42 depicts the comparison of Li ion battery, advanced Li ion battery, and VRFB for provision of grid support services[80].

Table 13 VRFB Vs. Lithium Ion battery comparison

Parameter	Lithium ion	VRFB
Energy Density (Wh/kg)	100-300	10-50
Power Density (W/kg)	250 - 2,000	75 - 100
Round-trip efficiency (%)	90 - 95	60 - 85
Cycle Life	3,000 - 8,000	15,000 - 20,000
Depth of Discharge (%)	80 - 90	100
Reaction Time	msec	msec
Operating Temperature (°C)	-20 to 60	5 to 45
Lifespan (years)	10 - 15	20+
Safety	Moderate (Thermal runaway risk)	High (Non - flammable electrolytes)

Figure 42 Suitability of VRFB as compared to lithium ion BESS to stable grid operation



Li-ion Battery: LFP, NMC 111/532/622, LCO, NCA

Advance Li-ion Battery: NMC 811, LNMO, Lithium-Silicon, Lithium-Cobalt, Lithium-Sulphur, and many more

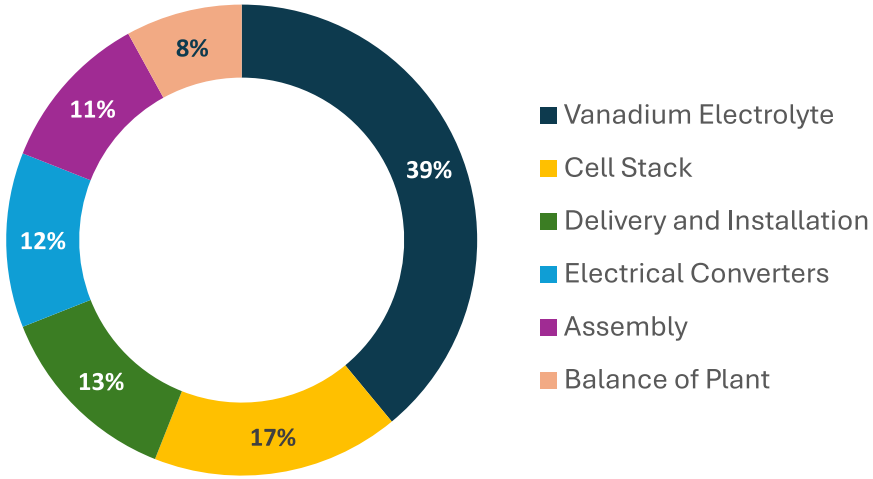
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2.3.6.5 Global Vanadium Redox Flow Batteries Market

The global market for VRFB is increasingly driven by demand for Long Duration Energy Storage (LDES), evolving system level cost structures, and the growing availability of bankable stationary storage projects with extended operational lifetimes. Unlike lithium ion batteries, where cost reductions have largely resulted from manufacturing scale and supply chain optimization at the cell level, VRFB market development is more strongly governed by electrolyte economics, stack manufacturing scale, and balance of plant standardization[84].

VRFB system costs are distributed across the electrochemical stack, vanadium electrolyte, and auxiliary components, as shown in Figure 43[80]. Competitiveness therefore depends on electrolyte cost reduction, reuse or leasing strategies, and increased system modularisation, in addition to electrochemical performance improvements. These characteristics favour VRFBs in high-utilisation, long-life applications where deep discharge and high cycling deliver high lifetime energy throughput and competitive economics[84].

Figure 43 Cost distribution in VRFB Systems



Data Source: Vanadium Battery Storage Report, World Bank Group

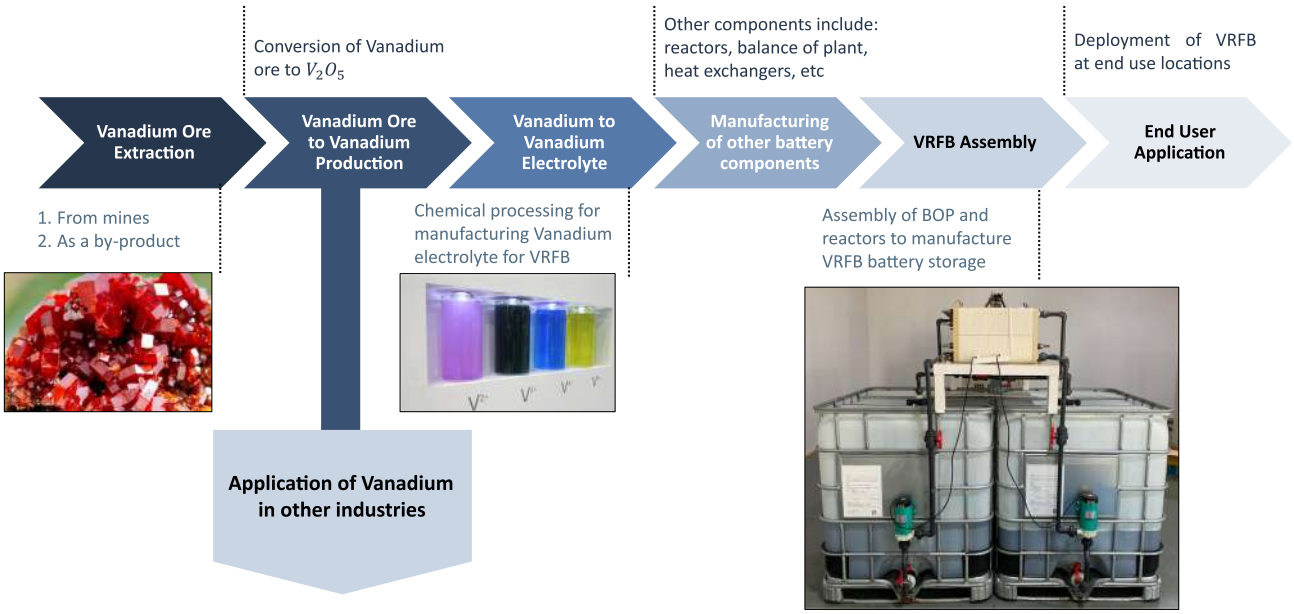
Deployment trends indicate that VRFB adoption increases as system costs decline to levels viable for stationary applications, particularly where long discharge duration and safety are prioritised. However, future costs remain sensitive to vanadium prices, electrolyte supply localisation, and manufacturing scale-up. As a result, VRFB growth is expected to concentrate on long-duration stationary applications such as RE firming, peak shifting, grid support, and industrial microgrids rather than energy-dense uses.

2.3.6.6 Value Chain

The VRFB value chain spans vanadium sourcing, electrolyte processing, stack and balance-of-plant manufacturing, system integration, and long-term operation, as shown in Figure 44. A key distinction is that the electrolyte functions both as the energy storage medium and as a high-value asset, introducing unique ownership, financing, and logistics considerations compared to solid-state batteries.

84 H. Hu et al., "Development status, challenges, and perspectives of key components and systems of all-vanadium redox flow batteries," Future Batteries, vol. 4, no. 100008, p. 100008, 2024.

Figure 44 Value chain of VRFB



Vanadium feedstock can originate from primary mining or secondary recovery, affecting supply diversity and cost stability. Downstream processing requires electrolyte purification, as impurities impact stability and long term performance. Stack manufacturing adds constraints related to membrane, electrode durability, and hydraulic design, while balance of plant components is critical for reliable and safe electrolyte circulation. Overall, VRFB value chain robustness depends on electrochemical components, established fluid handling and system integration practices.

2.3.6.7 Global Vanadium and Critical Mineral Availability

The global market for VRFBs is mainly driven by growing demand for long duration ESS, system level cost considerations, and the development of stationary ESS projects with long operating life. In contrast to lithium ion batteries, where cost reduction has been driven mainly by cell manufacturing scale, VRFB market progress depends more on electrolyte cost, stack manufacturing scale, and standardisation of balance of plant components. A defining feature of VRFB economics is that system cost is shared across the electrochemical stack, vanadium electrolyte, and auxiliary systems such as pumps, piping, and power electronics[85].

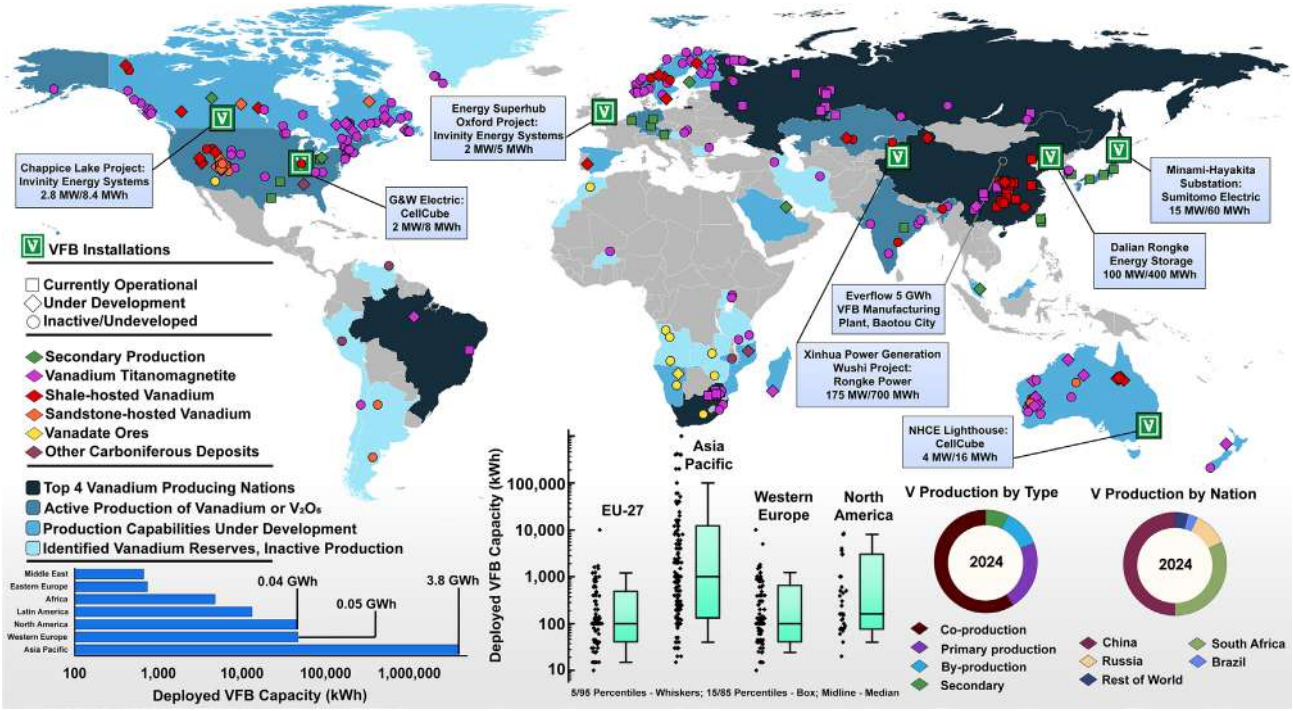
As a result, VRFBs show stronger lifetime economics in applications with high utilisation and long service life, where deep DoD operation and high cycle capability allow large lifetime energy throughput. Deployment trends indicate higher adoption as system costs move into viable ranges for stationary storage, especially where long discharge duration and safety are valued. At the same time, cost outlook remains sensitive to vanadium price variation, localisation of electrolyte supply, and the speed of manufacturing scale up. From a planning perspective, VRFB growth is therefore expected to focus on long duration stationary uses such as RE firming, peak shifting, grid support services, and industrial microgrids, rather than applications that require high energy density[86].

85 B. L. Rogers and S. Banerjee, “Mine the gap: Sourcing vanadium for the energy transition,” Joule, vol. 9, no. 11, p. 102139, 2025.

86 A. Aluko and A. Knight, “A review on vanadium redox flow battery storage systems for large-scale power systems application,” IEEE Access, vol. 11, pp. 13773–13793, 2023.

In this context, the global distribution of vanadium resources further reinforces the strategic considerations shaping VRFB deployment. World vanadium resources production as seen from Figure 45[85], is concentrated in a limited number of regions, notably China, Russia, South Africa, and Brazil, underscoring both supply concentration and geopolitical sensitivity. China currently dominates primary vanadium production, while countries such as India rely largely on secondary sources, including iron and steel slags and other industrial wastes, highlighting the importance of recovery based supply pathways. This resource geography directly influences electrolyte cost, supply chain security, and the potential for localization of VRFB value chains, which are increasingly central to long duration storage planning and investment decisions[87].

Figure 45 Global vanadium production and selected VRFB installations



Source: B. L. Rogers et al.; 2025

2.3.6.8 Vanadium Tank Contamination

In operating VRFB systems, tank contamination is best described as electrolyte imbalance or degradation that reduces usable capacity and efficiency, rather than permanent loss of active material. The main drivers include vanadium ion crossover through the membrane, water transport between tanks, impurity ingress, and shunt current effects, all of which can disturb the oxidation state balance over time. These effects appear as apparent capacity fade and a narrower operating window, even when the electrochemical stack remains structurally sound. If not managed, electrolyte imbalance can increase polarisation losses, complicate state of charge estimation, and raise operation and maintenance effort[86,88]. So, research has been focused more on monitoring and mitigation measures such as electrolyte rebalancing, improved membrane selectivity, and operating strategies that limit crossover and shunt currents. From an engineering standpoint, tank contamination is best treated as a manageable operational issue rather than a fundamental life limiting failure mechanism.

87 U.S. Geological Survey, Mineral Commodity Summaries 2025: Vanadium, U.S. Department of the Interior, U.S. Geological Survey, Reston, VA, USA, 2025.

88 W. Sharmoukh, “Redox flow batteries as energy storage systems: materials, viability, and industrial applications,” RSC Adv., vol. 15, no. 13, pp. 10106–10143, 2025.

2.3.6.9 Global Deployment

The global deployment of VRFB is summarised in Table 14[89].

Table 14 Global deployment of VRFB plant

Project / Plant	Location	Size (MWh/MW)	Commissioning year
China			
Jimusaer Solar-Storage Project	Jimusaer, Xinjiang	200 MW / 1,000 MWh	2025
Xinhua Wushi Energy Storage	Wushi, Xinjiang	175 MW / 700 MWh	2024
Dalian Peak-shaving Station (Phase I)	Dalian, Liaoning	100 MW / 400 MWh	2022
Xiangyang Solar-Storage (Phase I)	Xiangyang, Hubei	100 MW / 500 MWh	2023
Guizhou Qiandongnan Project	Guizhou	10 MW / 40 MWh	2023
Hubei Zaoyang Solar-Storage Pilot	Zaoyang, Hubei	3 MW / 12 MWh	2019
United States			
San Miguel Substation	San Diego, California	2 MW / 8 MWh	2017
SnoPUD MESA 2 Project	Snohomish, Washington	2 MW / 8 MWh	2017
Pullman Washington Project	Pullman, WA	1MW / 4 MWh	2015
Painesville Municipal Power	Painesville, Ohio	1 MW / 8 MWh	2014
Europe			
Fraunhofer ICT Pfinztal (RedoxWind)	Pfinztal, Germany	2 MW / 20 MWh	2019
CIUDEN Research Facility	Cubillos del Sil, Spain	1 MW / 8 MWh	2026
Son Orlandis Solar PV Plant	Mallorca, Spain	1.1 MW / 5.5 MWh	2025
Energy Superhub Oxford	Oxford, United Kingdom	2 MW / 5 MWh	2021
La Plagne Microgrid	La Plagne, France	0.05 MW / 0.2 MWh	2022

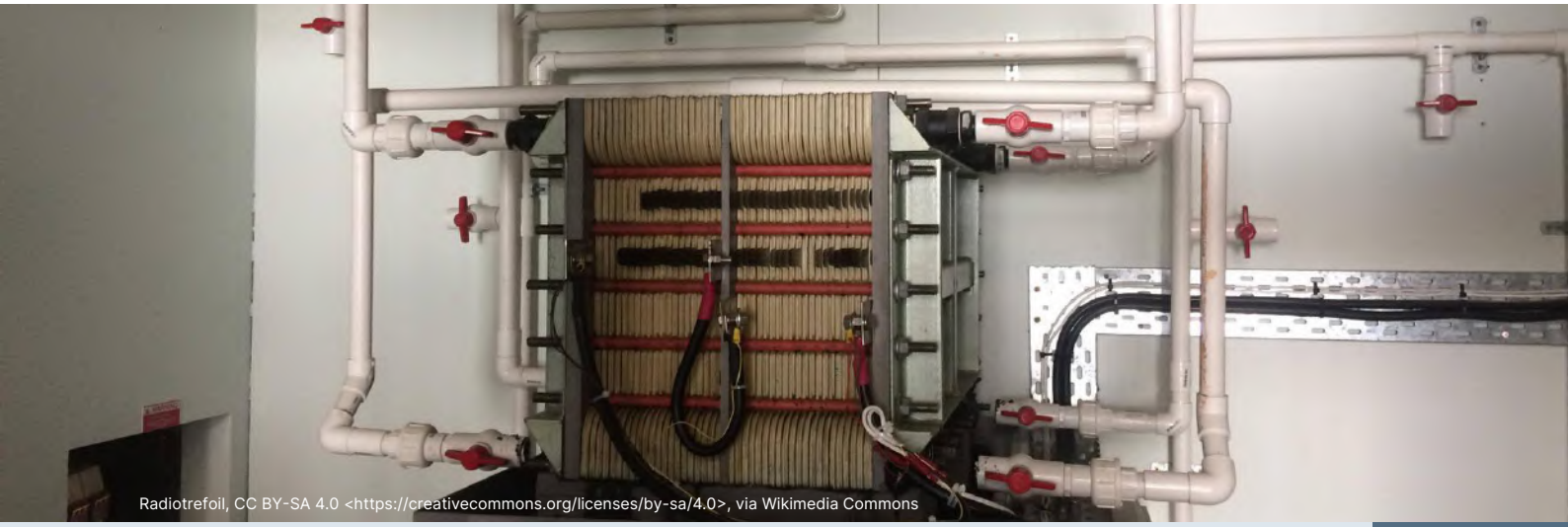
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Project / Plant	Location	Size (MWh/MW)	Commissioning year
Australia			
Spencer Energy Project	Port Pirie, South Australia	2 MW / 8 MWh	2025
Kununurra Microgrid	Kununurra, Washington	0.078 WM / 0.22 MWh	2024
Pajingo Gold Mine	Charters Towers Queensland	0.15 MW/0.4 MWh	2023
Monash University Microgrid	Melbourne, VIC	0.12 MW / 0.60 MWh	2018
Japan			
Minami-Hayakita (Phase II)	Abira, Hokkaido	17 MW / 51 MWh	2022
Minami-Hayakita (Phase I)	Abira, Hokkaido	15 MW / 60 MWh	2015
Kashiwazaki IR Energy Project	Kashiwazaki, Niigata	1 MW / 8 MWh	2024
Kurokiyama Solar Plant	Minamikyushu, Kagoshima	2 MW / 8 MWh	2025

2.3.7 Zinc-Bromide Flow Battery

Zinc Bromide Flow Batteries (ZBFB) are hybrid flow systems that combine features of flow batteries and metal electrode technologies. Energy is stored through reversible zinc metal deposition and dissolution at the negative electrode and bromine redox reactions at the positive electrode, with formation of a solid zinc phase during charging, which increases energy capacity but introduces operational challenges[44]. ZBFB systems are studied since 1970s, and since then they remain relevant due to the use of earth-abundant materials, non-flammable aqueous electrolytes, and suitability for long-duration stationary storage where safety, lifetime, and discharge duration are prioritised over footprint[90].

90 Z. Xu, J. Li, and M. Wu, “A high-rate and long-life zinc-bromine flow battery,” J. Power Sources, vol. 613, no. 234869, p. 234869, 2024.



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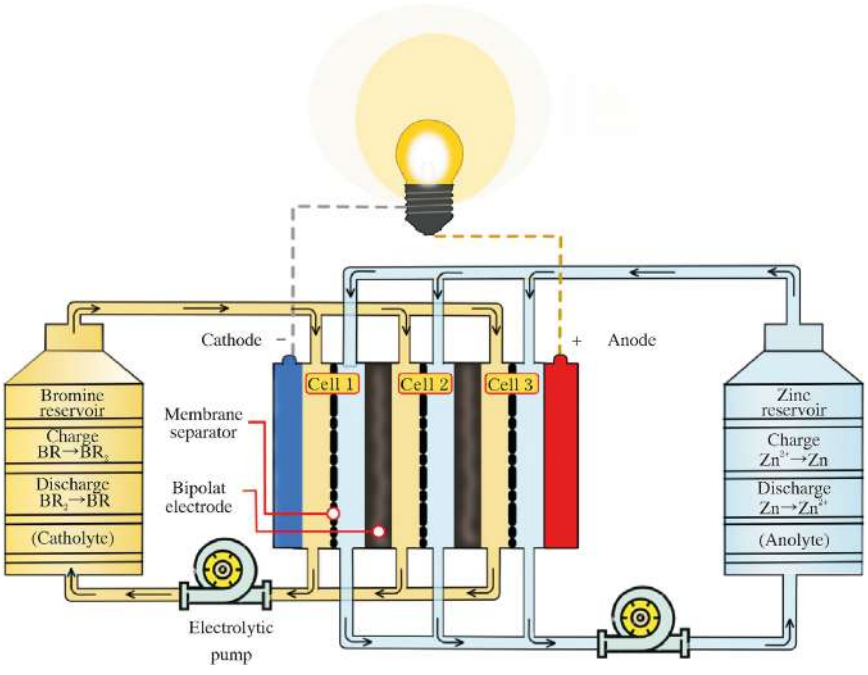
2.3.7.1 Chemistry and Operation

The electrochemical operation of a ZBFB is based on the reversible Zn^{2+} to Zn reaction at the negative electrode and the Br_2 to Br reaction at the positive electrode, both occurring in an aqueous electrolyte as shown in Figure 46[44]. During charging, zinc ions are reduced and deposited as metallic zinc on the negative electrode, while bromide ions are oxidised to molecular bromine at the positive electrode. The half-cell reactions during charging can be expressed as:

- Negative electrode (anode during discharge): $\mathrm{Zn}^{2+} + 2\mathrm{e}^- \rightleftharpoons \mathrm{Zn\,(s)}$
- Positive electrode (cathode during discharge): $2\mathrm{Br}^- \rightleftharpoons \mathrm{Br}_2 + 2\mathrm{e}^-$

During discharge, the reactions reverse, with metallic zinc dissolving into the electrolyte as Zn^{2+} ions and bromine being reduced back to bromide ions. Bromine formed during charging is usually complexed with an organic agent to create a dense, immiscible phase that is stored separately, which helps reduce self-discharge and improves safety. A distinguishing feature of ZBFB is the use of a single circulating zinc bromide electrolyte, rather than two fully separated electrolytes as in vanadium systems. Ionic separation is provided by a polymer membrane or microporous separator that restricts bromine crossover while allowing ion transport. Electrolyte circulation using pumps helps maintain uniform concentration and temperature in the cell stack[91].

Figure 46 Schematic and working of zinc bromide flow battery



Source: J. Mitali et al.; 2017

In operation, zinc bromide systems require periodic maintenance cycles, such as full discharge, to remove residual zinc deposits and limit dendrite growth. These procedures are important for sustaining performance and avoiding internal short circuits over long term operation.

91 A. Mahmood, Z. Zheng, and Y. Chen, "Zinc-bromine batteries: Challenges, prospective solutions, and future," Adv. Sci. (Weinh.), vol. 11, no. 3, p. e2305561, 2024.

2.3.7.2 Performance Matrices

The key performance matrices of ZBFB are mentioned in Table 15[92].

Table 15 Performance matrices of zinc bromide flow battery

Parameters	Operating Range
Cell Voltage (V)	1.8 - 1.85
Cycle Life	1,500 – 6,000
Energy Density (Wh/kg)	30-80
Round-Trip-Efficiency (%)	65 - 90
C Rate	0.1C - 1C
Depth of Discharge	100

2.3.7.3 Applications

ZBFB are primarily used in stationary ESS applications where safety, material availability, and long discharge duration are prioritised over compact system size. Common use cases include load levelling, peak shaving, RE integration, microgrids, and industrial backup power. In power systems with high RE penetration, zinc bromide systems are applied for solar and wind time shifting, as they can deliver multi-hour discharge and operate at deep depth of discharge. Their aqueous, non-flammable chemistry makes them suitable for installations near buildings, industrial sites, and remote communities where fire risk is a key planning consideration. ZBFB have also been demonstrated in microgrid and defence-related settings where robustness and tolerance to harsh conditions are important. However, relatively high self-discharge limits their suitability for applications requiring long standby periods without regular cycling[90].

2.3.7.4 Global Deployment

Global deployment of ZBFB as depicted in Table 16[92] shows a long record of pilot and commercial installations across North America, Europe, Asia, and Australia. Early projects mainly targeted utility scale load levelling and peak shaving, while more recent deployments focus on RE integration, microgrids, and grid support applications.

Table 16 Global deployment of zinc bromide flow battery

Project / Plant	Location	Size (MWh/MW)	Commissioning year
Paskenta Band Microgrid	California, USA	5.0 MW / 20.0 MWh	2025
Rialto Bioenergy Facility	Rialto, California, USA	0.5 MW / 2.0 MWh	2022

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Project / Plant	Location	Size (MWh/MW)	Commissioning year
Mahu 078 Well Site	Xinjiang, China	0.5 MW / 2.0 MWh	2024
Boggabri Coal Mine	Boggabri, NSW, Australia	2.0 MW / 6.3 MWh	2025
Massachusetts Grid Pilot	Massachusetts, USA	0.5 MW / 3.0 MWh	2016
Brisbane City Council Project	Brisbane, Australia	0.01 MW / 0.03 MWh	2023
Redflow Northwest Tasmania Microgrid	Tasmania, Australia	0.1 MW / 0.28 MWh	2021
Primus Power Southern African Mine Site	Amandelbult mine South Africa	0.2 MW / 1.0 MWh	2023

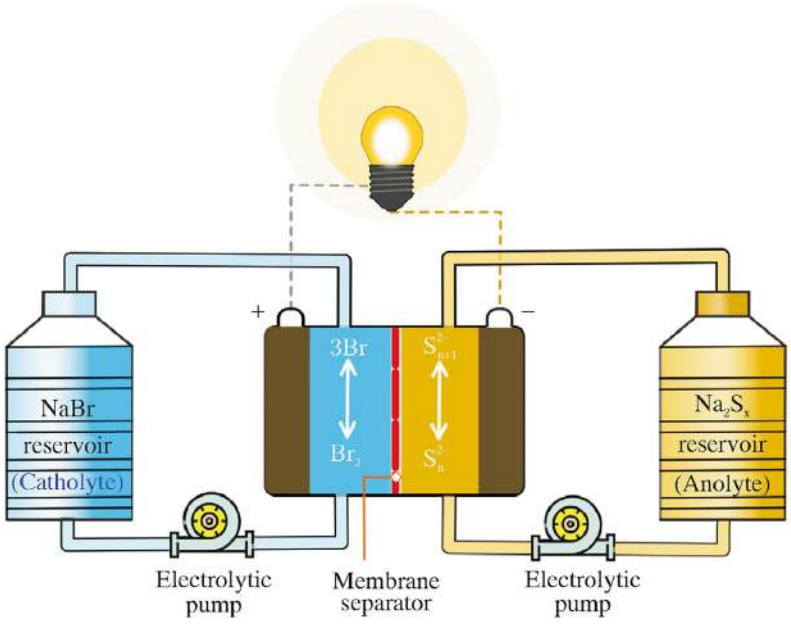
2.3.8 Polysulphide Bromide Flow Battery

Polysulphide Bromide Flow Batteries (PBFB) are aqueous redox flow systems using sodium polysulphide and sodium bromide electrolytes stored in separate tanks. As one of the earliest fully liquid flow battery chemistries, they feature fast electrochemical kinetics, simple cell design, and low cost, earth abundant materials, making them attractive for large scale stationary storage[44].

2.3.8.1 Chemistry and Operation

The electrochemical operation of a PBFB is based on reversible redox reactions between sulphur species in the negative electrolyte and bromine species in the positive electrolyte, both present in aqueous sodium-based solutions, as shown in Figure 47[44]. In this system, sodium polysulphide (Na_2S_x) serves as the negative electrolyte, while sodium bromide (NaBr) serves as the positive electrolyte.

Figure 47 Schematic and operation of polysulphide bromide battery



Source: J. Mitali et al.; 2017

During charging, bromide ions are oxidised at the positive electrode to form bromine species, while complementary redox reactions occur in the polysulphide electrolyte at the negative electrode. The corresponding half-cell reactions can be expressed in simplified form as follows[93].

- Cathode reaction: $2NaBr \rightleftharpoons 2e^- + Br_2 + 2Na^+$
- Anode reaction: $2Na^+ + (x-1)Na_2S_x + 2e^- \rightleftharpoons xNa_2S_{x-1}; \quad x = 2-4$
- Overall reaction: $2NaBr + (x-1)Na_2S_x \rightleftharpoons Br_2 + xNa_2S_{x-1}; \quad x = 2-4$

During discharge, these reactions proceed in the reverse direction, allowing electrical energy to be delivered to the external circuit. Ionic conduction between the two half-cells is enabled by a polymer membrane or separator that permits selective ion transport while limiting mixing of active species[93].

Both electrolytes are continuously circulated through the electrochemical stack using external pumps to maintain uniform concentration, temperature, and reaction conditions. Because PBFBs operate entirely with liquid phase redox couples, they avoid issues related to metal deposition and stripping, which simplifies stack design compared to hybrid systems. However, the use of bromine introduces additional requirements for containment and material compatibility due to its corrosive and toxic nature.

2.3.8.2 Performance Matrices

The performance characteristics of PBFB reflect their early generation chemistry and aqueous operation. The key performance matrices are mentioned in Table 17[94].

Table 17 Performance matrices of polysulphide bromide flow battery

Parameters	Operating Range
Cell Voltage (V)	1.6 - 1.75
Cycle Life	10,000 - 20,000
Energy Density (Wh/kg)	25 - 50
Round-Trip-Efficiency (%)	60 - 70
C Rate	0.1C - 1C
Depth of Discharge	100

2.3.8.3 Applications

PBFB have mainly been considered for grid support applications requiring fast response, such as frequency regulation, power smoothing, and short-duration load support. Their fast electrochemical kinetics and low self-discharge make them suitable for frequent cycling and high-power operation[44]. As a result, PBFB are best regarded as niche solutions within the broader flow battery landscape, suited to specific operational requirements rather than broad grid-scale deployment.

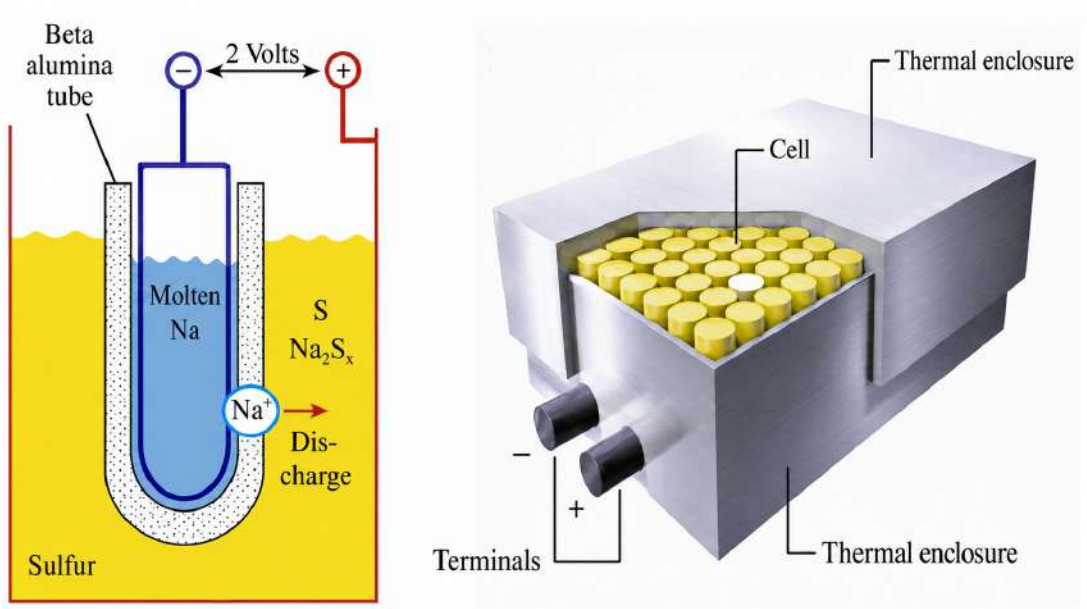
93 S. Chitvuttichot, R. Yeetsorn, and A. Tuantranont, "Investigating impact of charging parameters on discharge efficiency of sodium polysulfide-bromide flow battery," J. Energy Storage, vol. 102, no. 114070, p. 114070, 2024.

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2.3.9 Sodium Sulphur Battery

Sodium sulphur batteries are high-temperature ECES that use molten sodium as the negative electrode and molten sulphur as the positive electrode, separated by a solid ceramic electrolyte as shown in Figure 48[95]. This technology is among the earliest BESS deployed at utility scale and has been demonstrated for grid applications since the latter half of the twentieth century. Unlike room-temperature electrochemical systems, sodium sulphur batteries operate at elevated temperatures, typically around 300°C to 350°C, to maintain the electrodes in molten form and to provide sufficient ionic conductivity through the ceramic electrolyte. Despite this requirement, sodium sulphur batteries have achieved wide deployment due to their relatively high energy density, good round-trip efficiency, and suitability for long-duration stationary energy storage.

Figure 48 Schematic of sodium sulphur battery



Source: H Chen et al.; 2009

2.3.9.1 Chemistry and Operation

The electrochemical operation of a sodium sulphur battery is based on the reversible reaction between molten sodium and molten sulphur, with sodium ions transported through a solid ceramic electrolyte, commonly beta alumina. This electrolyte is electronically insulating while providing high sodium ion conductivity at elevated operating temperatures.

During discharge, sodium at the negative electrode is oxidised to sodium ions, which migrate through the beta alumina electrolyte toward the positive electrode. At the positive electrode, sodium ions react with sulphur to form sodium polysulphides, as represented by the general reaction given below[96].

- Negative electrode (anode during discharge): $\mathrm{Na} \rightarrow \mathrm{Na}^{+} + \mathrm{e}^{-}$
- Positive electrode (cathode during discharge): $\mathrm{xNa}^{+} + \mathrm{S_x} + \mathrm{xe}^{-} \rightarrow \mathrm{Na_xS}$

95 H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," Progress in Natural Science Materials International, vol. 19, no. 3, pp. 291–312, Jan. 2009.

96 N. Wang et al., "High-performance room-temperature sodium–sulfur battery enabled by electrocatalytic sodium polysulfides full conversion," Energy Environ. Sci., vol. 13, no. 2, pp. 562–570, 2020.

During charging, the reactions proceed in the reverse direction, decomposing sodium polysulphides back into elemental sodium and sulphur.

- Negative electrode (cathode during charging): $\mathrm{Na^+ + e^- \rightarrow Na}$
- Positive electrode (anode during charging): $\mathrm{Na_xS_x \rightarrow xNa + S}$

The electrochemical components are housed within a thermally insulated steel enclosure to maintain the required operating temperature and safely contain the molten materials. Electrical heating is required during start-up, after which internal resistive and electrochemical losses help sustain thermal balance during normal operation. The solid electrolyte is critical for both performance and safety, as it separates molten sodium and sulphur while permitting only sodium ion transport. Its mechanical strength and chemical stability under repeated thermal cycling are therefore key factors for long-term system reliability[95],[97].

2.3.9.2 Performances Matrices

The performance matrices of Sodium Sulphur batteries are mentioned in Table 18.

Table 18 Performance matrices of sodium sulphur battery

Parameters	Operating Range
Cell Voltage (V)	1.78-2.08
Cycle Life	2,500 – 4,500
Energy Density (Wh/kg)	150-240
Round-Trip-Efficiency (%)	80 - 90
C Rate	0.1 – 0.25C
Depth of Discharge	80 - 100

2.3.9.3 Applications

Sodium sulphur batteries are mainly used in utility scale stationary ESS applications such as load levelling, peak shaving, RE energy integration, and grid congestion management. Their high energy density and ability to deliver power over several hours make them suitable for applications that require sustained discharge durations[44].

These systems have also been applied for RE smoothing and firming, supporting higher wind and solar penetration by reducing intermittency and diurnal variation. In distribution networks, they have been used to defer infrastructure upgrades and support voltage stability during peak demand periods[96].

However, the use of molten sodium and high operating temperatures introduces safety concerns, leading to strict requirements for installation, monitoring, and maintenance. As a result, sodium sulphur batteries are generally deployed in controlled and dedicated facilities rather than in densely populated or space constrained areas.

97 European Association for Storage of Energy, Technology Description: Sodium–Sulfur (NaS) Batteries, EASE, Brussels, Belgium, 2018.

2.3.9.4 Global Deployment

Sodium sulphur batteries are among the most widely deployed non lithium stationary battery technologies, with cumulative global installations reaching several gigawatt hours over multiple decades. Commercial deployment began in the late twentieth century and expanded into large utility scale projects across Japan, Abu Dhabi, and Italy. The largest installation of sodium sulphur BESS is of 50 MW/300 MWh and is commissioned in Japan for peak shaving and balancing of solar power[98].

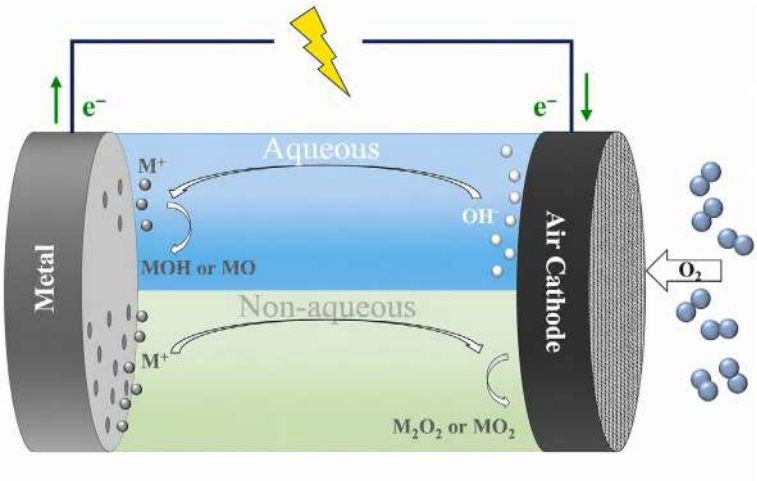
2.3.10 Emerging Battery Chemistries

Emerging battery chemistries are being developed to address limitations of existing storage technologies related to material availability, safety, operating conditions, scalability, and long-duration storage. Although most remain at early to intermediate stages of development, they are increasingly considered in system planning due to their potential role in meeting future grid requirements, diversifying supply chains, and supporting long-term sustainability.

2.3.10.1 Metal Air Battery

Metal air batteries use a metal anode and oxygen from ambient air as the cathode reactant. Because the cathode material is not stored inside the cell, these systems offer very high theoretical energy density, which makes them attractive for long duration and energy intensive applications. The schematic and functioning of metal-air battery as seen from Figure 49[99].

Figure 49 Schematic diagram of metal air battery



Source: Y E Durmus et al.; 2020

In a typical metal–air battery, the metal anode oxidises during discharge, releasing electrons to the external circuit, while oxygen from air is reduced at the cathode. These reactions occur in an aqueous or non-aqueous electrolyte depending on the metal chemistry. Common metal–air systems include zinc–air, iron–air, aluminium–air, and lithium–air batteries .

Despite high theoretical energy density, metal-air batteries face practical limitations related to air electrode durability, reaction kinetics, electrolyte management, and reversibility. Many systems

98 BEST Magazine, World's Largest Sodium-Sulphur Energy Storage System Deployed in Japan.

99 Y. E. Durmus et al., "Side by side battery technologies with lithium-ion based batteries," Adv. Energy Mater., vol. 10, no. 24, p. 2000089, 2020.

exhibit limited cycle life or require metal anode replacement, increasing system complexity. As a result, metal-air batteries are currently better suited to long-duration, low-power, or specialised applications rather than general grid-scale energy storage. The different chemistry of metal air battery is compiled in Table 19.

Table 19 Metal air battery chemistry

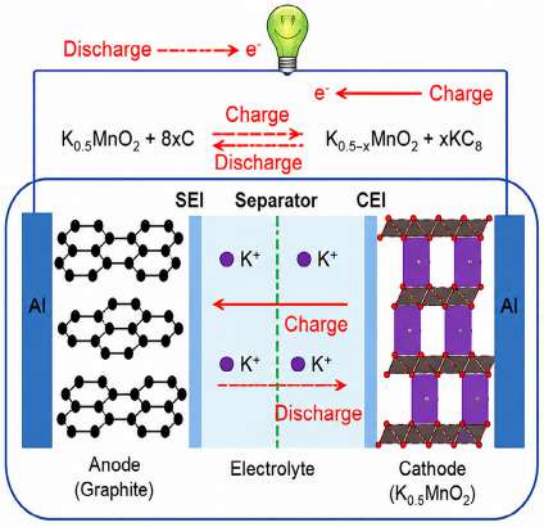
Metal–Air Chemistry	Typical Energy Density (Wh/kg)	Cycle Life	Key Advantages	Key Limitations
Zinc–air	300–400 (practical)	100–1000	Abundant materials, safety	Limited recharging capacity
Iron–air	600–1000 (theoretical)	1000+	Low cost, long-duration potential	Low power density
Aluminium–air	>1000 (theoretical)	Semi-primary	Very high energy density	Not fully rechargeable
Lithium–air	>3000 (theoretical)	<100	Extremely high energy density	Poor cycle life, stability issues

2.3.10.2 Potassium Ion Battery

Potassium ion batteries are an emerging intercalation based battery technology that operates on principles similar to lithium ion batteries but uses potassium ions as charge carriers. High natural abundance and lower cost of potassium compared to lithium make this technology attractive from a resource sustainability perspective.

Electrochemically, potassium ion batteries operate through reversible insertion and extraction of potassium ions in host electrode materials during charge and discharge as seen from [100]. Because potassium ions have a larger ionic radius than lithium ions, intercalation behaviour differs, affecting electrode stability, diffusion kinetics, and achievable energy density.

Figure 50 Schematic diagram of potassium Ion battery



Source: Q Zhang et al.; 2018

100 Q. Zhang, Z. Wang, S. Zhang, T. Zhou, J. Mao, and Z. Guo, "Cathode materials for potassium-ion batteries: Current status and perspective," Electrochem. Energy Rev., vol. 1, no. 4, pp. 625–658, 2018.

In practice, potassium ion batteries generally show lower energy density than lithium ion systems but can offer good rate capability and potentially better low temperature performance, linked to weaker solvation and faster ionic transport in some electrolyte systems. However, stable electrode materials, compatible electrolytes, and long term cycling durability are still under development, and commercial scale performance has not yet been demonstrated[100].

As shown in Table 20[101], potassium ion batteries provide advantages related to resource availability and potential cost, but they currently fall behind lithium ion systems in energy density, cycle life, and overall technology maturity. As a result, their near term relevance is expected mainly in stationary applications where mass and volume constraints are less critical.

Table 20 Comparison of potassium ion battery and lithium ion battery

Parameter	Potassium-Ion Battery	Lithium-Ion Battery (LFP)
Active ion abundance	Very high	Moderate
Energy density (Wh/kg)	100–160	90-200
Operating temperature (°C)	-60 to 50	-20 to 60
Cycle life	< 2500	3000 - 8000
Technology maturity	Early research / pilot	Commercial

2.3.10.3 Solid State Battery

Solid state batteries replace the liquid electrolyte in conventional batteries with a solid ionic conductor, which can improve safety, increase energy density, and widen the operating temperature range. They are widely considered a next generation option for addressing safety and performance limits associated with liquid electrolytes[44]. Solid electrolytes may be ceramic, polymer, or composite materials and are designed to allow fast ion transport while limiting dendrite formation. Removing flammable liquid electrolytes reduces fire and thermal runaway risk, which makes solid state batteries attractive for safety critical uses[102]. However, these batteries face major challenges related to electrode electrolyte interface resistance, mechanical stability during cycling, and scalable manufacturing. Most solid state systems are still at laboratory or pilot scale, and long term durability data under grid level operating conditions remain limited[101]. The key performance parameters and challenges associated with solid state battery technology is mentioned in Table 21[101].

Table 21 Performance attributes and challenges associated with solid state battery

Attribute	Solid State Battery
Electrolyte type	Solid ceramic / polymer
Energy density potential (Wh/kg)	300–500 (projected)
Safety	Very high
Operating temperature	Wide
Manufacturing maturity	Low
Key challenge	Interfacial resistance, scalability

101 GIL Research

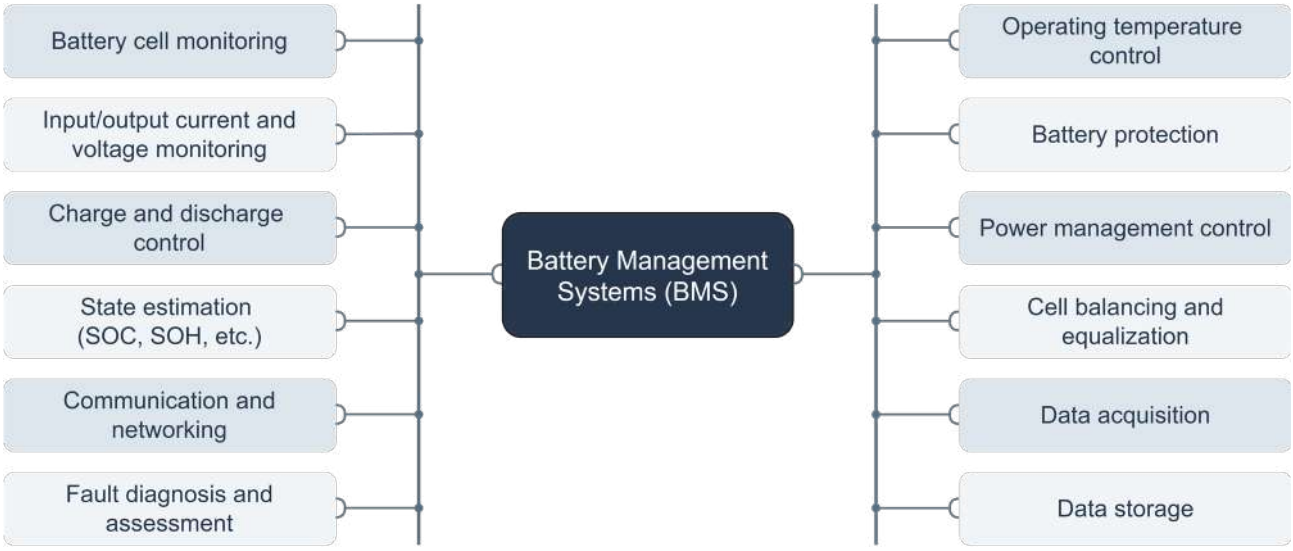
102 J. Kasemchainan and P. G. Bruce, “All-Solid-State Batteries and their Remaining Challenges: A potential route towards safer, higher performing batteries,” Johns. Matthey Technol. Rev., vol. 62, no. 2, pp. 177–180, 2018.

2.3.11 Battery Management Systems (BMS)

BMS provide the supervisory control and protection needed for safe and reliable operation of rechargeable battery packs, from portable electronics to electric mobility and grid connected BESS. At the pack level, a battery management system combines sensing, state estimation, protection logic, balancing functions, thermal supervision, and communication to keep operation within specified electrical and thermal limits while meeting required power and energy demands[103].

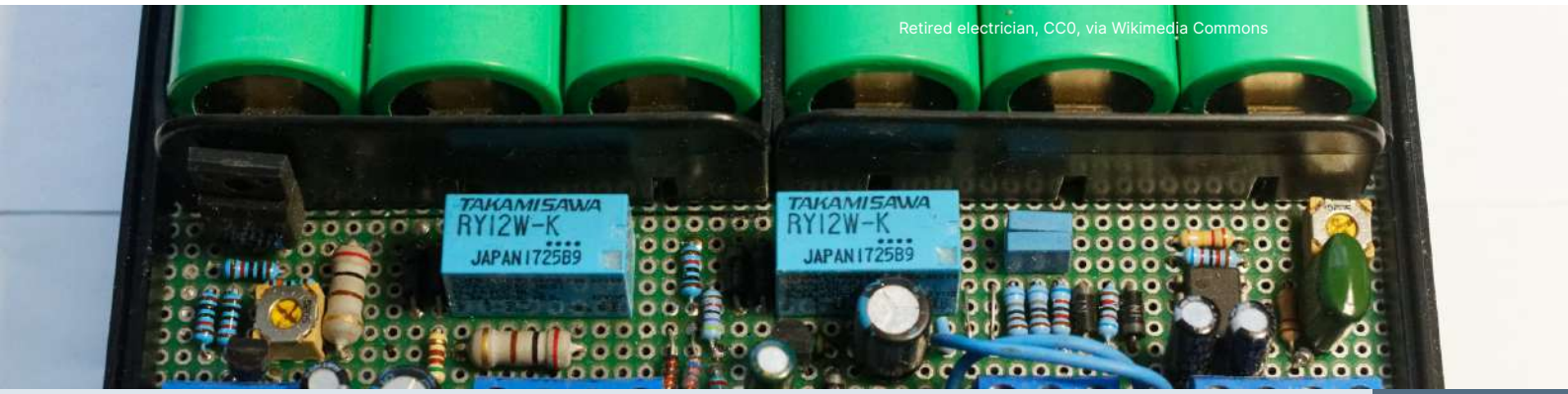
An overview of the key BMS functionalities is highlighted in Figure 51[104]. The main functional objectives are prevention of unsafe operation through protection actions, effective use of available capacity and power through accurate state estimation and balanced cell operation, and extension of battery life by limiting key stress factors such as high temperature, deep cycling, high current events, and long term cell imbalance. A practical BMS architecture can be divided into four layers. The first is a measurement layer that acquires cell and pack voltage, current, and temperature. The second is an estimation and decision layer that determines internal states such as state of charge and state of health. The third is an actuation layer that controls contactor, pre charge circuits, cell balancing hardware, and thermal components. The fourth is an external interface layer that supports diagnostics, control system integration, and compliance reporting[103].

Figure 51 Battery management system functions



103 "What Is a Battery Management System (BMS)? Why it matters, how it works, and getting started," MathWorks.

104 S. Nyamathulla and C. Dhanamjayulu, "A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations," J. Energy Storage, vol. 86, no. 111179, p. 111179, 2024.

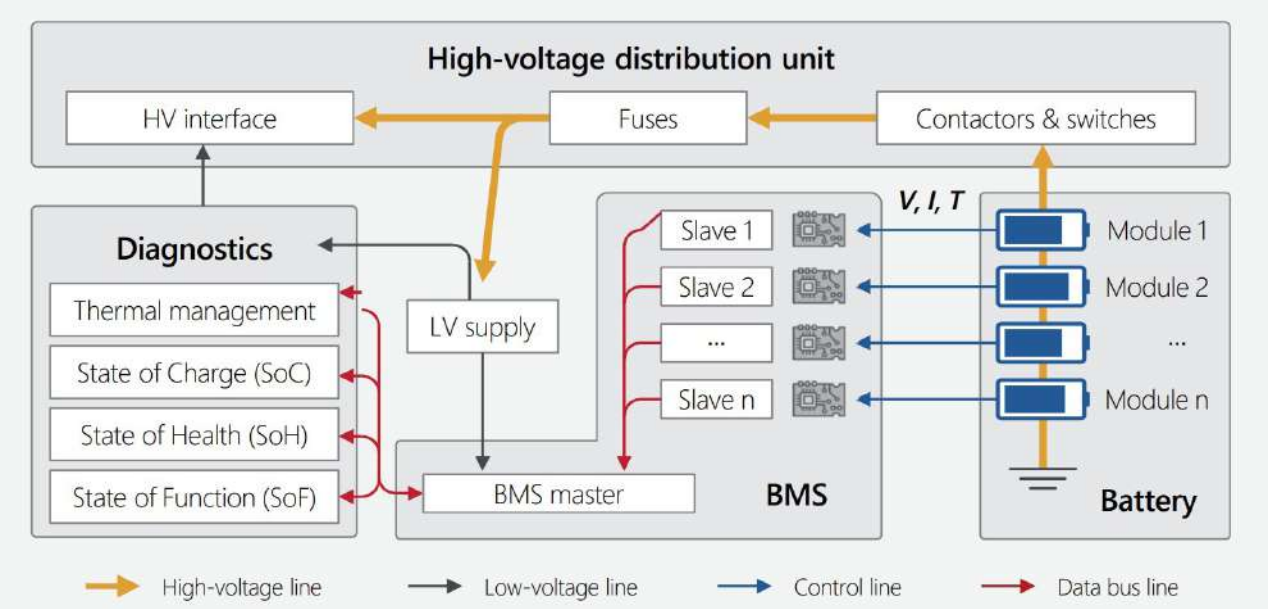


Retired electrician, CC0, via Wikimedia Commons

2.3.11.1 BMS Architecture

The detailed BMS architecture is shown in Figure 52[105]. It continuously monitors cell voltages, current, and temperatures, and initiates protection actions when limits are exceeded, including over voltage, under voltage, over current, short-circuit, and temperature-related faults. In BESS applications, it also performs supervisory functions such as power limiting based on SoC and temperature, executing grid service commands. It also logs data for warranty and traceability and continuously interfaces with EMS.

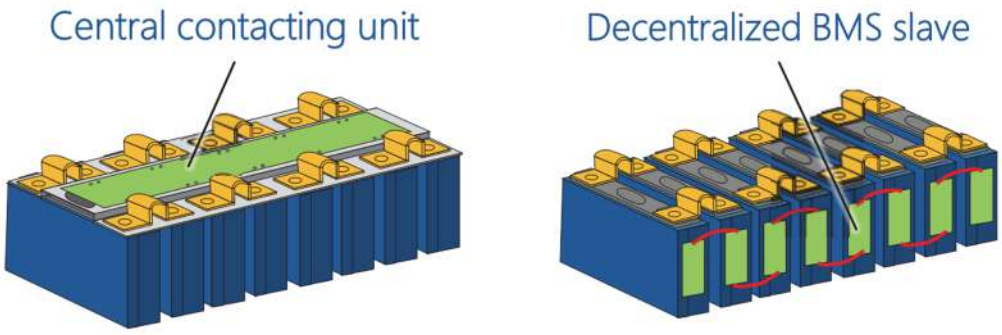
Figure 52 BMS architecture



Source: H. H Heimes et al.; 2026

As shown in Figure 53[105], BMS architectures are typically centralised, or distributed, depending on pack size, safety requirements, wiring complexity, and electromagnetic compatibility. Centralised systems are simpler but require extensive wiring. On the other hand modular or distributed designs reduce wiring, improve scalability, and enhance fault isolation at the cost of higher communication complexity. Accurate state estimation depends on high-quality voltage, current, and temperature measurements, as small errors can significantly affect SoC estimation and thermal safety performance.

Figure 53 Centralised and distributed BMS architecture



Source: H H Heimes et al.; 2026

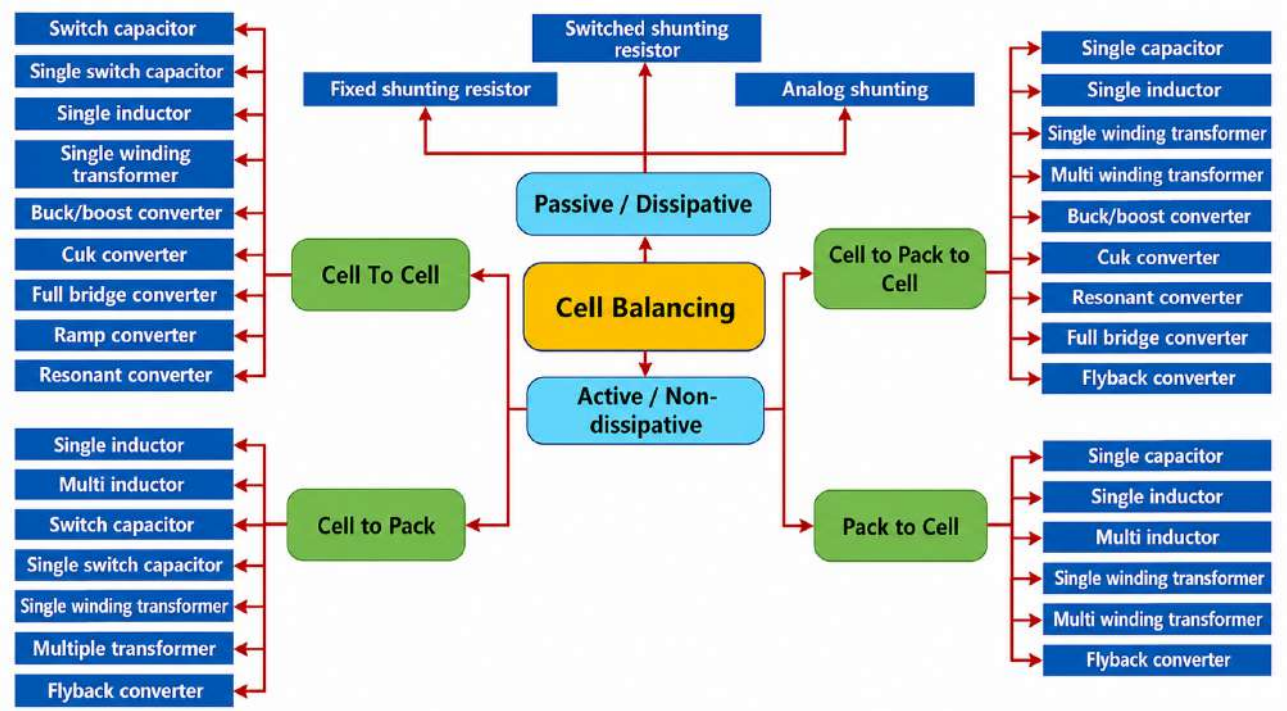
105 H. Hans Heimes et al,, "Production Process of Battery Modules and Battery Packs, 5th Edition," RWTH Aachen University and VDMA Battery Production, Feb. 2026.

2.3.11.2 Cell Balancing

Cells connected in series naturally diverge in SoC due to differences in capacity, resistance, temperature, and self-discharge. Without balancing, usable pack capacity is limited by the first cell reaching voltage limits, and divergence increases with cycling as weaker cells experience higher stress. Cell balancing aims to reduce cell-level state differences within current and thermal limits and is commonly applied near end of charge, with advanced strategies also operating during rest periods or low-power operation[106].

Passive balancing dissipates excess energy from higher-state cells through resistive paths. It is simple and low cost but reduces efficiency and can cause local heating. Active balancing transfers energy between cells using capacitive, inductive, or converter-based circuits, improving efficiency in large packs at the cost of higher complexity and expense. Different balancing techniques are illustrated in Figure 54[104].

Figure 54 Cell balancing techniques for lithium ion batteries



Source: S. Nyamathulla et al.; 2024

2.3.11.3 Thermal Management

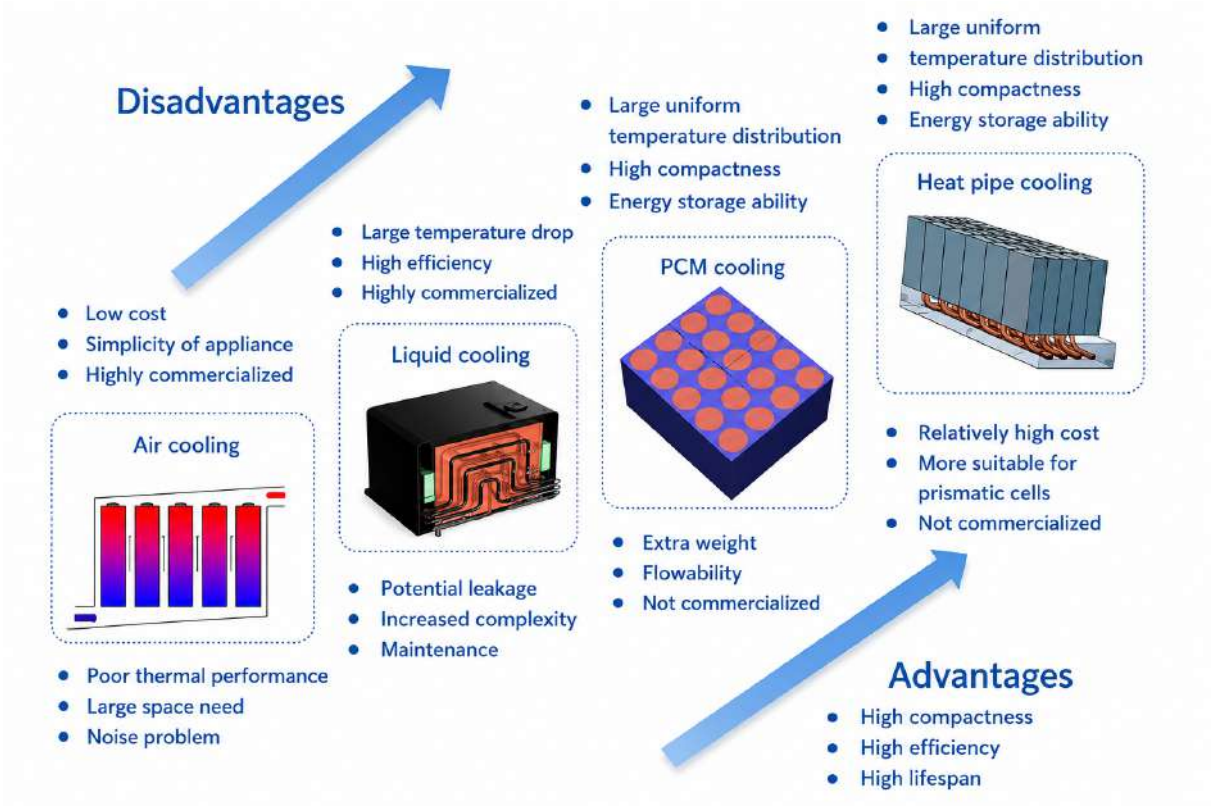
Cell temperature strongly influences power capability, safety, and degradation, with heat generated mainly from ohmic losses and electrochemical polarisation. Thermal management therefore aims to maintain temperatures within safe limits and minimise cell-to-cell temperature differences to prevent imbalance and uneven ageing[107]. Thermal control methods include air and liquid cooling, phase change materials, and heating for low-temperature operation, with selection driven by power density, packaging constraints, ambient conditions, and cost. Stationary systems prioritise reliability and maintainability, while mobility applications emphasise mass, volume, and safety[104].

106 N. Khan, C. A. Ooi, A. Alturki, M. Amir, Shreasth, and T. Alharbi, "A critical review of battery cell balancing techniques, optimal design, converter topologies, and performance evaluation for optimizing storage system in electric vehicles," Energy Rep., vol. 11, pp. 4999–5032, 2024.

107 Q. Wang, B. Jiang, B. Li, and Y. Yan, "A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles," Renew. Sustain. Energy Rev., vol. 64, pp. 106–128, 2016.

In practice, temperature-dependent current limits are enforced through control systems to ensure grid services operate within thermal constraints. Common cooling methods for lithium ion batteries are shown in Figure 55[108].

Figure 55 Battery cooling methods with advantages and disadvantages



Source: M.Shen et al.; 2019

2.3.11.4 Communication Protocols

Communication links the BMS with external controllers, chargers, converters, and diagnostic tools, enabling coordinated operation and protection. The BMS exchanges measurements, estimated states, alarms, and power limits, while receiving commands such as power setpoints and operating mode selections[103]. Protocol selection is very critical aspect for effective data communication. Protocol selection must ensure reliable and deterministic data exchange while addressing fault tolerance, cybersecurity, electromagnetic compatibility, and interoperability. In distributed battery systems, communication must remain synchronised and robust to node failures and support consistent interpretation of key states across all interfaced components.

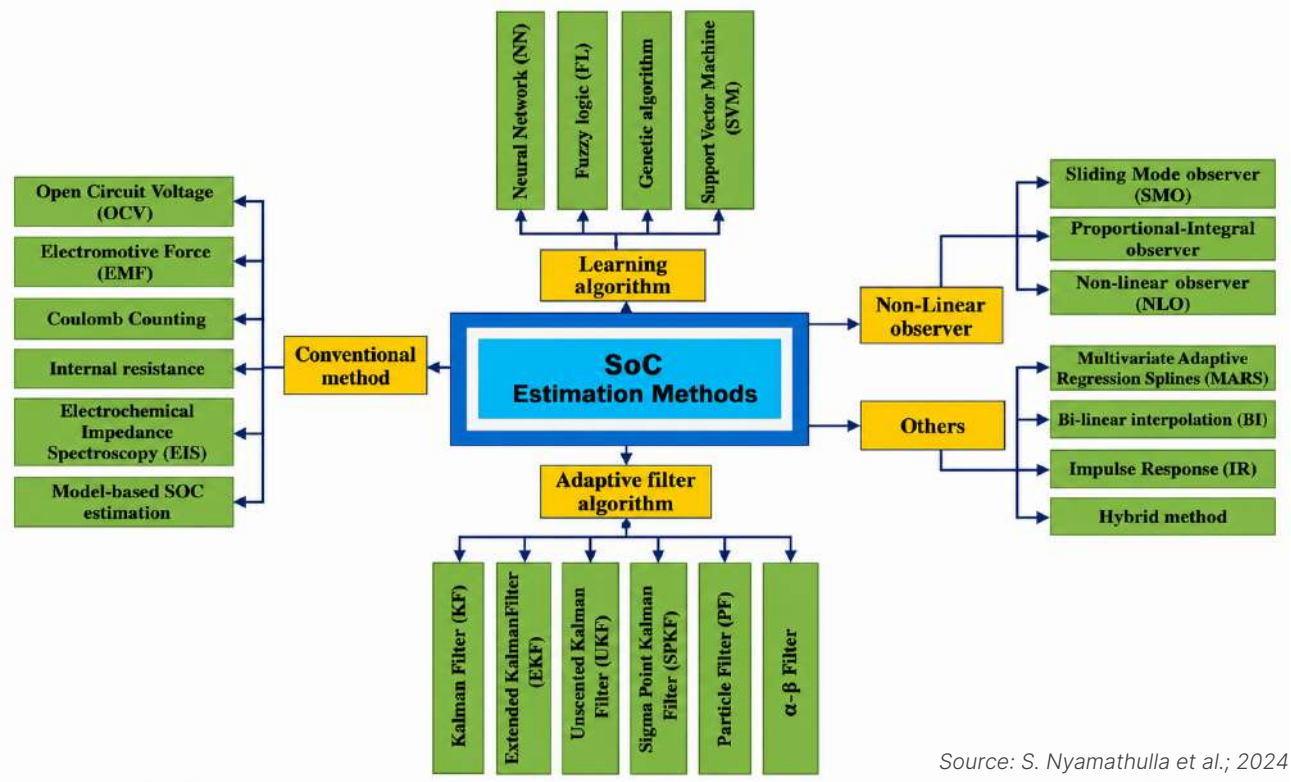
Because communication faults can be safety critical if they delay protection actions or mask abnormal conditions, BMS architectures typically employ layered safety concepts. These combine local hardware based protections at the module level with supervisory safety logic at the pack controller, ensuring that loss or degradation of communication automatically drives the system into a defined safe state.

108 M. Shen and Q. Gao, "A review on battery management system from the modeling efforts to its multiapplication and integration," International Journal of Energy Research, vol. 43, no. 10, pp. 5042–5075, Apr. 2019.

2.3.11.5 State of Charge Estimation

SoC indicates the fraction of usable capacity relative to rated capacity, while SoH describes degradation from beginning of life, typically manifested as capacity loss and resistance increase. Neither quantity is directly measurable, and both must be estimated from models and measurements, introducing uncertainty that must be considered in protection and power limit decisions. Common SoC estimation techniques are shown in Figure 56[109].

Figure 56 SoC estimation techniques



Source: S. Nyamathulla et al.; 2024

The methods to determine SoC are described below[106].

- **Open circuit voltage methods:** Open-circuit-voltage-based methods estimate SoC using a predefined relationship between open circuit voltage and capacity. Accurate application requires sufficient rest time to allow voltage relaxation and appropriate temperature compensation, which limits their direct use under dynamic operating conditions. Nevertheless, these methods remain valuable for SoC initialization and periodic calibration.
- **Ampere time integration methods:** Coulomb counting estimates SoC by integrating current over time to track charge throughput and is well suited for dynamic operating conditions. However, the method is susceptible to drift arising from current sensor bias, integration errors, and variations in effective capacity due to ageing and temperature. As a result, coulomb counting is typically complemented with correction mechanisms such as open-circuit-voltage-based recalibration or observer-based data fusion to maintain estimation accuracy over time.
- **Model based observers and filters:** Equivalent circuit models combined with observers such as Kalman filter variants enable estimation of SoC under dynamic conditions by fusing

109 J. Tao, S. Wang, W. Cao, P. Takyi-Aninakwa, C. Fernandez, and J. M. Guerrero, "A comprehensive review of state-of-charge and state-of-health estimation for lithium-ion battery energy storage systems," Ionics (Kiel), 2024.

☀ KEY INSIGHT

Accurate SoC and SoH estimation is essential for BMS reliability, since battery dispatch limits, balancing, safety margins, and usable capacity all depend on how well degradation and operating uncertainty are tracked.

current and voltage measurements with a battery model. Estimation accuracy depends on model structure, parameter identification, and adaptation to temperature and ageing effects.

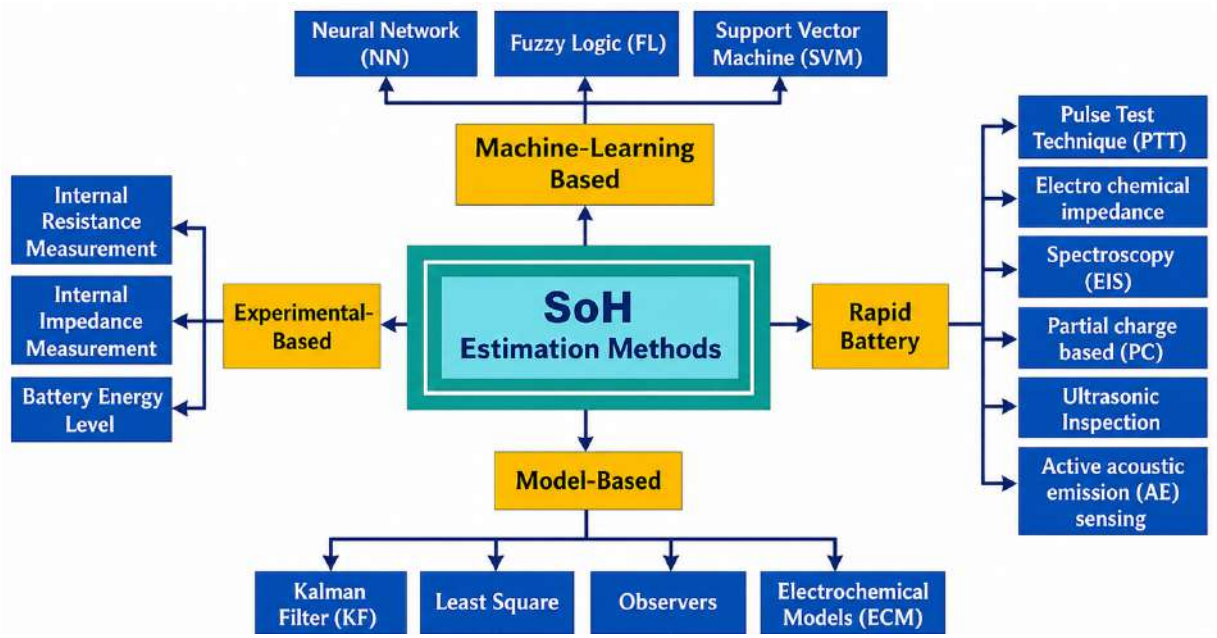
- **Data driven estimation:** Data-driven methods infer battery states by learning mappings between measured signals and internal states using training data. While these approaches can be effective when high-quality labelled datasets are available, they require careful validation across operating conditions, cell chemistries, and ageing states to avoid hidden extrapolation errors, particularly when used in safety-critical decision making.

2.3.11.6 State of Health Estimation

SoH is commonly quantified using capacity based metrics reflecting loss of cyclable lithium or active material and resistance based metrics capturing impedance growth, as shown in Figure 57[104]. Estimation methods include controlled charge discharge tests, pulse based resistance measurements, incremental capacity or differential voltage analysis, and model based approaches with online parameter updates. Since SoH affects power capability and safety margins, BMS use it to adjust current limits, DoD, and thermal constraints.

Estimation and balancing are closely linked, as cell imbalance affects SoC inference and inaccurate SoC estimates can lead to inefficient balancing. Variations in SoH across cells can further exacerbate imbalance when balancing relies solely on voltage thresholds. Advanced strategies therefore incorporate capacity information and estimation uncertainty into balancing control to preserve usable pack capacity over time.

Figure 57 SoH estimation methods

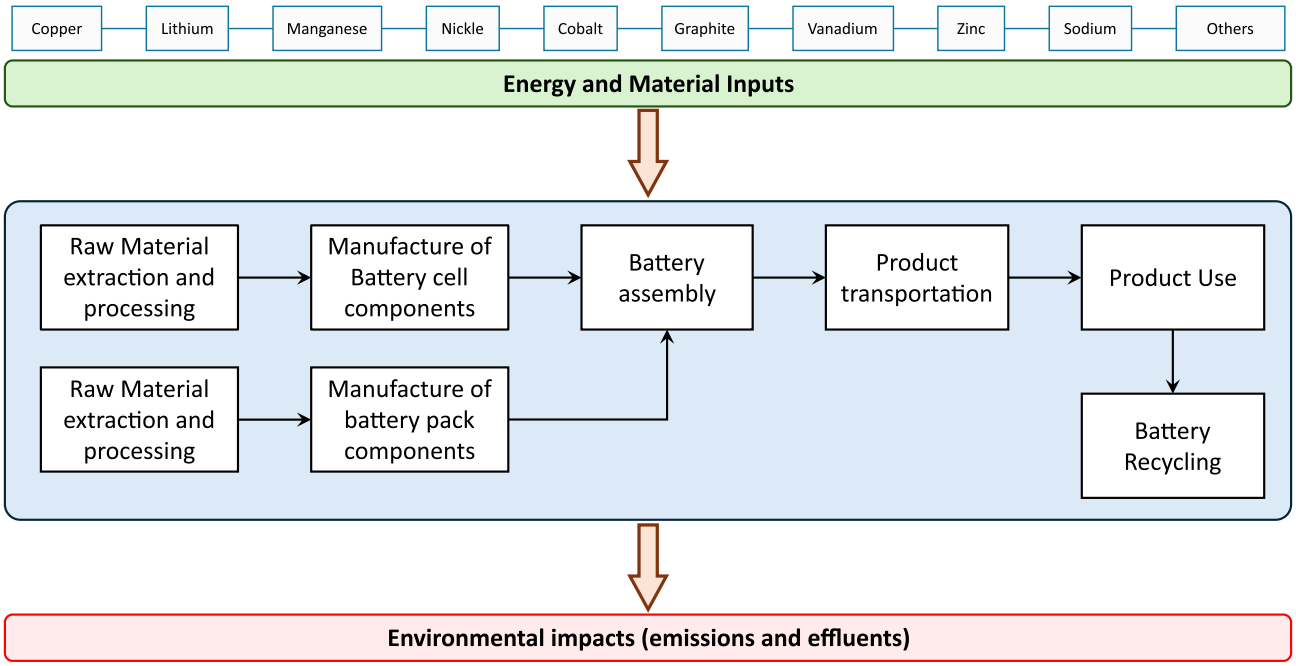


Source: S. Nyamathulla et al.; 2024

2.3.12 Life Cycle of Battery Energy Storage Systems

The lifecycle of a BESS comprises multiple interconnected stages, each contributing to energy consumption, material flows, emissions, and overall system sustainability. These is depicted in Figure 58. These stages extend beyond the operational phase to include upstream and downstream processes that have a significant influence on lifecycle performance indicators[110].

Figure 58 Generic flow diagram BESS life cycle stages



The lifecycle stages can be categorized as follows[110]:

- **Raw material extraction and processing:** Includes mining and refining of battery-grade materials such as lithium, nickel, manganese, graphite, vanadium, sodium, or sulphur depending on chemistry. This stage is typically energy-intensive and contributes substantially to greenhouse gas emissions and ecological impacts.
- **Manufacture of battery cell components:** Covers electrode fabrication, electrolyte preparation, separator production, and current collector processing. Energy consumption at this stage strongly depends on electrode coating methods, drying processes, and purity requirements.
- **Battery cell and pack assembly:** Involves cell stacking or winding, module assembly, pack integration, power electronics, and thermal management components. Manufacturing yield and quality control significantly influence lifecycle efficiency and cost.
- **Product transportation and deployment:** Accounts for logistics-related energy use and emissions, which become increasingly relevant for globally distributed supply chains.
- **Operational use phase:** Represents the primary service delivery period, where electricity is stored and dispatched. Round-trip efficiency, degradation rate, depth of discharge, and cycling frequency govern the net energy delivered over the system lifetime.

110 R. Yudhistira, D. Khatiwada, and F. Sanchez, "A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage," J. Clean. Prod., vol. 358, no. 131999, p. 131999, 2022.

- **End-of-life management and recycling:** Includes collection, dismantling, material recovery, and waste disposal. Recycling efficiency directly affects material circularity and reduces dependence on primary resource extraction.

2.3.12.1 Requirement of Evaluation Systems

Evaluation systems are required to enable evidence-based decision-making across technical, regulatory, and economic domains of battery deployment. The primary requirements are outlined below[111]:

- **Understanding system-wide impacts:** Evaluation frameworks quantify how BESS deployment affects end users, upstream supply chains such as mining and manufacturing, and downstream processes including waste management and recycling.
- **Enabling informed decision-making:** Policymakers and stakeholders use evaluation metrics to identify where technology interventions are needed, such as improving recycling efficiency, modifying product architecture, or enhancing battery performance under specific grid conditions.
- **Holistic comparison of battery technologies:** Evaluation frameworks enable consistent comparison of battery chemistries by assessing technical, environmental, social, and economic performance across the full lifecycle, rather than focusing solely on energy density or cost.
- **Alignment with sustainable development goals:** Lifecycle-based evaluation supports long-term sustainability objectives by linking battery industry practices with emissions reduction, resource efficiency, and economic viability targets.

2.3.12.2 Internal Evaluation Systems

Internal evaluation systems focus on indicators that describe the inherent properties and performance characteristics of the BESS. These indicators are generally controllable through design choices, manufacturing processes, and operational strategies[108].

Material Flow Indicators

The principal energy flow indicators are mentioned below:

- **Recycling rate**: Defined as the ratio of recycled waste batteries to total battery production within the same year. This indicator reflects material circularity and recovery efficiency.
- **Emission rate during battery production:** Represents the ratio of waste emissions generated during production stages to total battery output, capturing process efficiency and environmental burden
- **Emission rate of waste batteries:** Quantifies the proportion of non-recycled battery waste relative to total production, highlighting end-of-life management effectiveness.
- **Battery production intensity:** Measures resource utilization per unit of battery produced, linking material consumption to manufacturing output.

These indicators collectively assess how efficiently raw materials are used and recycled across the battery lifecycle.

111 Y. Yu, J. Mao, and X. Chen, "Comparative analysis of internal and external characteristics of lead-acid battery and lithium-ion battery systems based on composite flow analysis," Sci. Total Environ., vol. 746, no. 140763, p. 140763, 2020.

Energy Flow Indicators

The principal energy flow indicators are mentioned below:

- **Energy density:** Defined as the electrical energy delivered per unit mass of battery, influencing transportation, installation footprint, and material efficiency.
- **Energy consumption for battery production:** Represents the energy required to manufacture one unit mass of battery, serving as a key input to lifecycle energy efficiency analysis.

These metrics enable assessment of the energy return on investment across different battery chemistries and manufacturing routes.

Value Flow Indicators

The main value flow indicators include:

- **Price of primary minerals:** Economic value per unit mass of critical raw materials, reflecting resource scarcity and supply risk.
- **Price of secondary minerals and materials:** Captures the economic contribution of non-critical materials used in battery manufacturing.
- **Battery price:** Expressed as cost per unit of stored electrical energy, serving as a key metric for market competitiveness.
- **Cost of waste treatment:** Represents economic expenditure required for environmental remediation and disposal of battery waste.

These indicators support cost-benefit analysis and financial planning for battery deployment.

External Influence Indicators

External influence indicators capture the broader societal and economic impacts of battery systems that extend beyond the physical boundaries of the battery itself. The main external influence indicators are mentioned below108:

Social Influence Indicators

- **Total service output (electricity delivered):** Defined as the total electrical energy supplied over the lifetime of the battery system. This metric represents the societal value of energy services delivered and supports assessment of contribution to energy access and reliability.

Economic Influence Indicators

- **Net economic output:** Defined as the difference between economic outputs and inputs associated with the battery system. This indicator evaluates long-term financial viability and informs investment decisions and economic planning.

Comprehensive evaluation systems integrate internal and external indicators to deliver a multi-dimensional assessment of BESS. These systems are essential for identifying performance trade-offs across chemistries, guiding technology selection for specific grid applications, and informing regulatory frameworks and incentive mechanisms. They also support the sustainable scaling of battery energy storage infrastructure by linking technical performance with environmental and economic outcomes, making them a core element of responsible and resilient deployment[108].

2.4 Mechanical Energy Storage Systems

Mechanical Energy Storage (MES) refers to a class of ESS in which electrical energy is converted into mechanical form during charging and reconverted into electrical energy during discharge. Energy is stored as gravitational potential, kinetic, pressure, or elastic energy, depending on the storage mechanism. MES technologies represent some of the most mature large-scale ESS and are widely deployed in bulk power systems.

In modern grids with high penetration of wind and solar PV, MES addresses operational challenges including generation-demand mismatch, reduced system inertia, increased frequency and voltage regulation requirements, and long-duration energy shifting. Owing to high power ratings, long service life, and demonstrated reliability, mechanical storage technologies particularly PHS account for the majority of global installed energy storage capacity and remain well suited for large-scale, long-duration applications.

MES systems are based on established physical principles and mature engineering components such as turbines, compressors, rotating machinery, and hydraulic systems. This technological maturity supports high durability and grid-scale applicability. However, deployment is often constrained by geographical and infrastructural conditions. MES technologies are classified according to the form of mechanical energy used for storage. This classification provides a structured framework for evaluating operating principles, performance characteristics, and grid integration considerations.

- **Gravitational potential energy storage:** This category includes technologies that store energy by elevating a mass within the Earth's gravitational field. Energy is recovered when the mass descends under controlled conditions, driving a turbine coupled to a generator. PSH is the most established and widely deployed technology in this category and accounts for the majority of global installed energy storage capacity. Emerging gravity-based storage concepts using solid masses operate on the same fundamental physical principle.
- **Pressure-based (compressed gas) energy storage:** In pressure-based systems, electrical energy is used to compress a gas mostly air, which is then stored in pressurised vessels or underground caverns. During discharge, the compressed gas expands through a turbine or expander to generate electrical power. Compressed Air Energy Storage (CAES) systems are the principal technology in this category and are classified according to their thermal management strategy, including diabatic, adiabatic, and near-isothermal configurations.
- **Rotational kinetic energy storage:** These systems store energy in the form of high-speed rotational motion. Electrical energy is converted into kinetic energy by through rotating mass, typically a flywheel, to high angular velocity. During discharge, rotational speed decreases and the stored kinetic energy is converted back into electrical energy through an electromechanical interface.



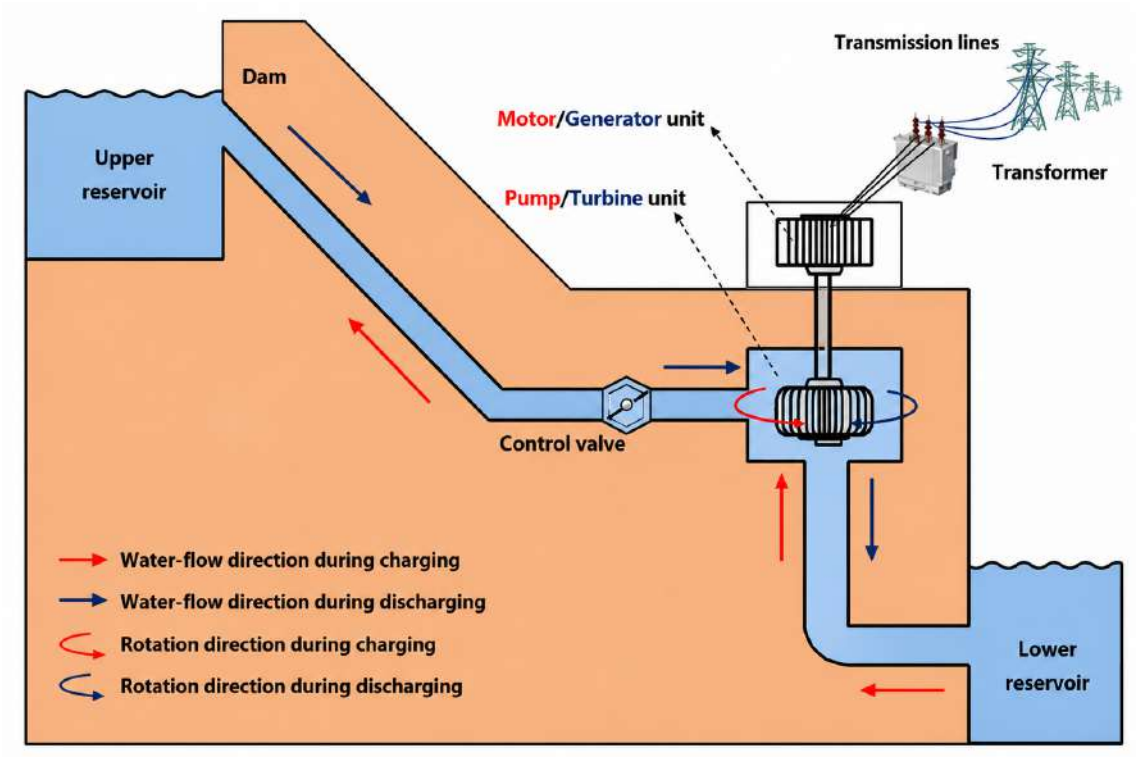
Photo by Lukas Marek on Unsplash

2.4.1 Pumped Hydro Storage System

PHS is a form of mechanical and gravitational ESS that uses water and an elevation difference to store and release energy. During off-peak periods or when surplus power generation from RE sources or base load generation, electric pumps transfer water from a lower reservoir to an upper reservoir, converting electrical energy into gravitational potential energy. During periods of high demand, water is released through turbine-generators, reconverting stored potential energy into electrical energy. The system establishes itself as the most mature bulk energy storage technology globally.

PHS is widely recognised as a key enabler of high RE energy penetration, including in small or autonomous power systems. Hybrid wind-integrated or solar-integrated PHS plants can provide scalable solutions when appropriately sized. PHS remains the most commercially mature large-scale energy storage technology and is primarily deployed for peak load management and system balancing. However, its low energy density requires either large reservoir volumes or significant elevation differences. The schematic diagram of a typical PHS plant is presented in Figure 59[112].

Figure 59 Schematic diagram of a typical PHS plant



Source: P Nikolaidis et al.; 2017

PHS facilities require suitable geographical conditions, typically involving two natural or artificial reservoirs located at different elevations. Due to the utilisation of water and gravitational force, PHS is characterised by very large storage capacities in terms of both power and energy, and long discharge durations extending over many hours, making it suitable for grid scale load levelling. The round trip efficiency of modern PHS plants typically ranges from 70 percent to 80 percent[113].

112 P. Nikolaidis, and A. Poullikkas. "A comparative review of electrical energy storage systems for better sustainability." Journal of power technologies 97.3 (2017): 220-245.

113 G. A. M. Castorino et al., 'Optimization of sizing and operation of pumped hydro storage plants under current and future economic scenarios', J. Energy Storage, vol. 119, p. 116130, May 2025.

☀ KEY INSIGHT

Pumped hydro remains the world's dominant bulk storage technology, providing nearly 95% of global storage capacity through long-duration energy shifting, system balancing, and grid stability support.

Although energy losses occur due to hydraulic friction, turbulence, and reservoir evaporation, economic value can be realised by shifting low cost off peak energy to high value peak demand periods. Environmental considerations for PHS encompass both aquatic and terrestrial resources. Aquatic impacts include effects on surface water quality and quantity, groundwater interactions, and aquatic ecosystems. Terrestrial considerations involve geology, soils, land use, ecological systems, recreation, visual impacts, and cultural resources. PHS is widely regarded as a mature and reliable technology, with plant lifetimes often exceeding 50 years and offering the largest volumetric storage capacity among energy storage technologies. It is currently deployed for load balancing, peak supply, and grid stability services.

2.4.1.1 Historical Development and Global Status

The development of PHS dates to the late nineteenth and early twentieth centuries. Early installations were commissioned in Switzerland and Italy during the 1890s and early 1900s to support hydropower balancing. The technology expanded significantly in the mid-twentieth century as interconnected electricity grids developed and nuclear and thermal baseload generation increased the need for off-peak energy storage. Between the 1960s and 1980s, many countries deployed PHS facilities to shift surplus night-time generation to periods of peak daytime demand. By the end of the twentieth century, PSH had become the dominant large-scale energy storage technology globally.

The earliest PHS installation is commonly attributed to the Engeweiher facility near Schaffhausen, Switzerland, which commenced hydraulic pumping operations in 1890[114]. Subsequent developments included larger projects such as the 30 MW Lugano plant in Switzerland during the 1930s, while in the United States early facilities such as the 30 MW Rocky River plant began operation in 1929. During the 1970s and 1980s, several large-capacity plants exceeding 1,000 MW were commissioned, including the Bath County facility in the United States[115], commissioned in 1985 with a capacity of 3000 MW and 24 GWh, which remains one of the largest pumped storage installations globally. By 1990, numerous large PHS facilities were operational worldwide. Since the 1990s, technological advancements have included the adoption of variable-speed units to enhance operational flexibility and grid support capability, with the first commercial installation commissioned in Japan at the Okawachi Pumped Storage Power Station[116]. As of the mid-2020s, PHS remains the principal bulk energy storage technology, although new projects face constraints related to extended project duration, capital intensity, and site-specific feasibility.

PHS today is by far the largest-capacity energy storage technology, accounting for about 95 percent of all grid storage globally. As of March 2026, the global PSH capacity stood at 196.17 GW, demonstrating a continuous growth in its installed capacity. This scale overwhelmingly surpasses all other ESS, including BESS, which, despite rapid growth in recent years, still represent only a small fraction of this capacity. Countries leading in PHS deployment in terms of installed capacity and

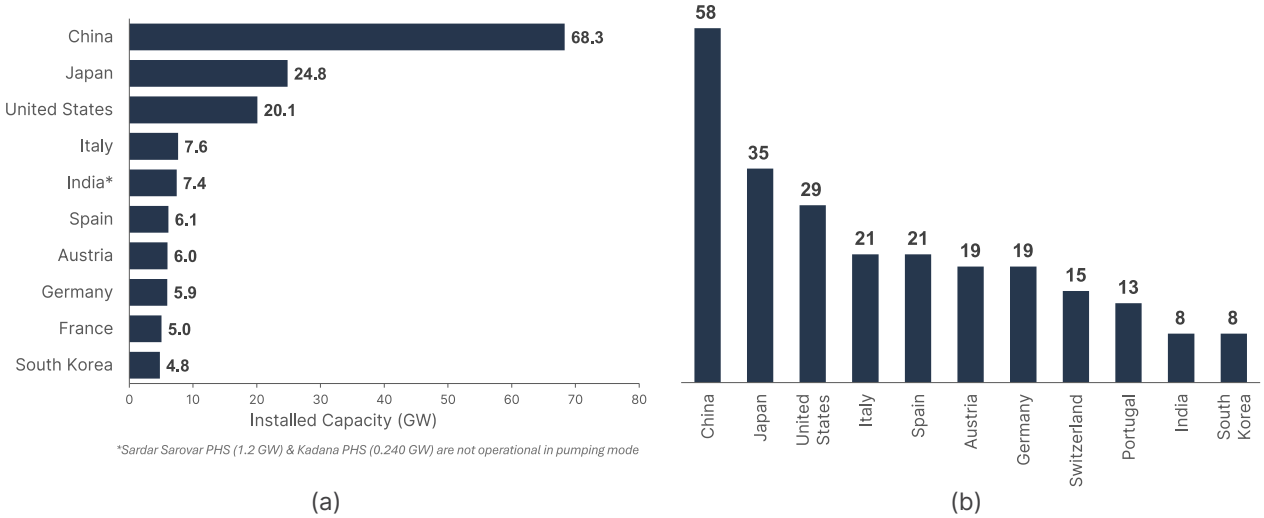
114 Drax Group, Pumping Power: Pumped Storage Stations Around the World

115 Dominion Energy, Bath County Pumped Storage Station.

116 IEA Hydropower TCP, Hydropower Case Histories – Volume 2, IEA Hydropower Technology Collaboration Programme, 2000.

number of PHS include China, Japan, the United States, and European nations as shown in Figure 60(a) and Figure 60(b)[117]. China has accelerated the deployment of PHS to balance its growing wind and solar capacity, currently leading at 68.3 GW, followed by Japan with 24.8 GW, and United States with 20.1 GW of installed capacity of PHS as of March 2026.

Figure 60 Global PHS scenario: (a) Installed capacity (b) Number of installations



(a) (b)

Data as of March 2026 *Data Source: Global Energy Monitor*

2.4.1.2 Working Principle

In a PHS facility, two reservoirs at different elevations are connected through penstocks to a powerhouse housing reversible pump-turbine unit. During charging, grid electricity drives a motor that operates the pump, transferring water from the lower to the upper reservoir and increasing gravitational potential energy. During discharge, water flows downward through the penstock, driving turbines typically of the Francis type coupled to generators, thereby converting stored potential energy into electrical energy. Modern installations predominantly employ reversible pump-turbines, in which the same hydraulic machine operates alternately as pump and turbine by reversing rotation and flow. Mode transition is achieved through control of rotational speed and guide vanes. Advanced PSH units may incorporate variable-speed drives to optimise efficiency and enable grid regulation in pumping mode.

- Fundamental energy storage relationship is: $E = mgh$
- Electrical power output is expressed as: $P = \eta \rho g H Q$

Here, ρ denotes water density, H represents effective head, Q is volumetric flow rate, and η is overall efficiency, typically in the range 0.7 to 0.85. Output can be rapidly adjusted by controlling wicket gates or guide vanes, enabling units to ramp from zero to full load within tens of seconds. Some plants operate in spinning mode to provide immediate response and frequency regulation in both generating and pumping modes.

In conventional PSH configurations, the hydraulic machine operates alternately as pump and turbine, and the synchronous machine functions as both motor and generator. Transition between modes requires reversal of shaft rotation and is typically operator-initiated, taking several minutes. Consequently, steady-state studies generally model pumping and generating modes separately. For high-head sites or where enhanced flexibility is required, ternary PHS units provide an advanced

117 Global Energy Monitor, “Global Hydropower Tracker,” Global Energy Monitor

configuration. A ternary system consists of a separate turbine and a separate pump mechanically coupled to a common motor-generator shaft. All components rotate in same direction in both modes, eliminating rotational reversal and enabling faster transitions. A defining feature is hydraulic short-circuit operation, in which pump and turbine operate simultaneously. The net electrical exchange with the grid equals the difference between turbine output and pump consumption, permitting continuous regulation of consumed or injected power without interrupting pumping.

Ternary units may be configured with vertical or horizontal shafts, with clutches to disengage the pump during pure generation and auxiliary systems to facilitate controlled start-up. Guide vane control enables precise regulation, particularly during short-circuit operation. Compared with conventional reversible units, ternary PSH offers faster mode transition, full regulation capability in both modes, and enhanced operational flexibility, making it well suited to power systems with high RE penetration.

2.4.1.3 Components and Design

A typical PHS plant comprises the following principal components:

- **Upper and lower reservoirs:** Two water bodies at different elevations provide the storage medium and may be natural or artificial impoundments. The upper reservoir stores water at elevated potential energy, while the lower reservoir collects discharged water. Energy capacity is determined by reservoir volume and hydraulic head. Reservoirs are engineered using natural geological formations or lining systems to ensure containment. Systems may operate in open-loop mode when natural inflow feeds the upper reservoir, or in closed-loop mode when fully isolated. The elevation difference between reservoirs is a critical design parameter.
- **Water conveyance system:** Large-diameter penstocks or tunnels connect the reservoirs to the powerhouse and are designed to withstand high hydraulic pressures. Surge tanks or chambers mitigate pressure transients caused by rapid valve operations. Intake structures equipped with gates and screens regulate flow and protect hydraulic equipment.
- **Powerhouse:** The powerhouse contains pump-turbine units and motor-generators, often located underground near the lower reservoir to optimise hydraulic performance. It includes auxiliary systems, transformers, and switchgear for interconnection to the high-voltage grid.
- **Pump turbine and motor generator:** Most PHS facilities employ reversible Francis pump-turbines operating across medium to high head ranges of approximately 100 to 700 m. In generation mode, water drives the turbine to produce electrical power. In pumping mode, the machine operates as a motor to elevate water. Reversible configurations use a single rotating unit for both modes, simplifying plant layout but requiring performance compromise between pumping and generating conditions. Ternary configurations utilise separate pump and turbine units coupled to a common shaft with a clutch, enabling independent optimisation and faster transitions. Some modern plants incorporate variable-speed motor-generators, such as doubly fed induction machines or converter-fed synchronous machines, to enhance efficiency and controllability.
- **Power electronics and control systems:** Conventional synchronous units are directly grid-connected with standard excitation and governor systems. Variable-speed units require power electronic converters. Integrated control systems manage start-up, shutdown, guide vane positioning, and grid synchronisation, while circuit breakers enable operational mode transitions.

- **Ancillary Systems:** Supporting systems include intake and isolation gates, main inlet valves, cooling and lubrication systems, hydraulic governors, oil pressure systems, and protection equipment to ensure safe and reliable operation.

During the design phase, a PHS plant must be engineered to withstand hydraulic pressures proportional to the available head. For example, a head of 700 m can impose pressures on the order of 7 MPa within the penstock system[118]. Accordingly, the structural design of tunnels, surge tanks for transient mitigation, and underground caverns is critical. Hydraulic machines are designed for reliable operation in both pumping and generating modes, with particular attention to cavitation avoidance in pump mode under reduced inlet pressure and to mechanical integrity during rotational reversal. The motor-generator assembly is typically configured as a vertical-axis machine that is mounted directly above turbine. Large thrust bearings support the rotating mass and, together with guide bearings, are designed for bidirectional operation.

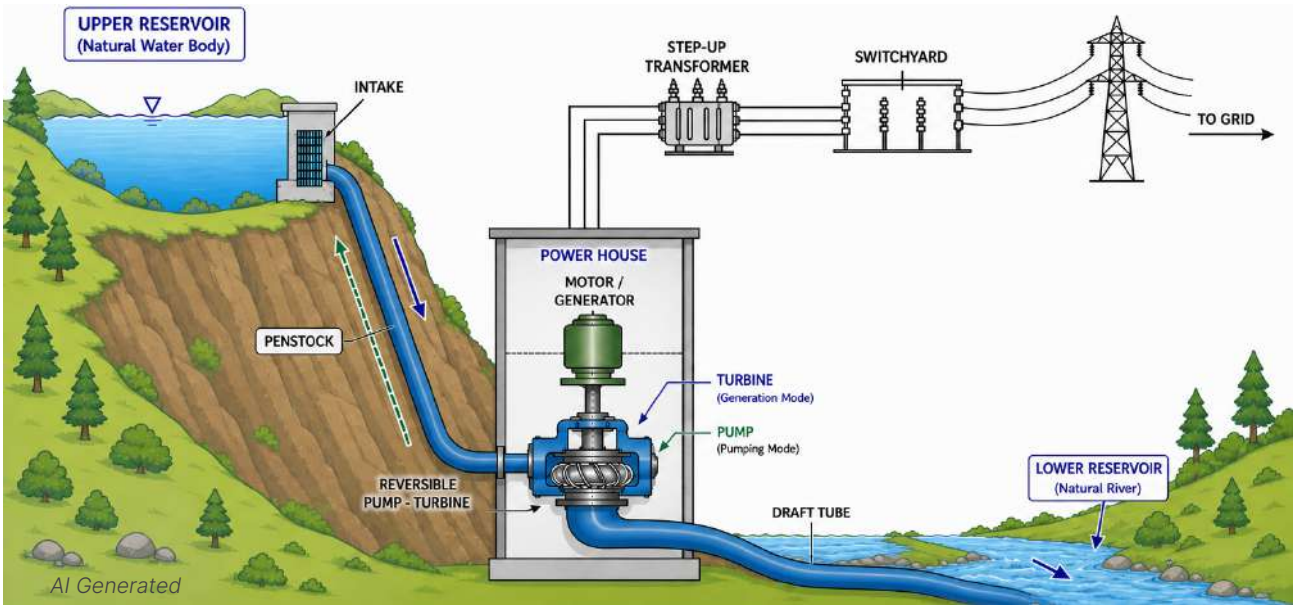
2.4.1.4 Types of PHS

Pumped hydro storage can be classified according to several technical and operational criteria as described below:

Open-loop and closed-loop PHS:

PHS systems may operate in open-loop mode as shown in Figure 61. Open-loop PHS maintains a hydraulic connection with a natural water body, such as a river or lake, and may receive natural inflows. In such configurations, the plant can partially operate as a conventional hydroelectric facility[119].

Figure 61 Schematic of open loop pumped hydro storage plants

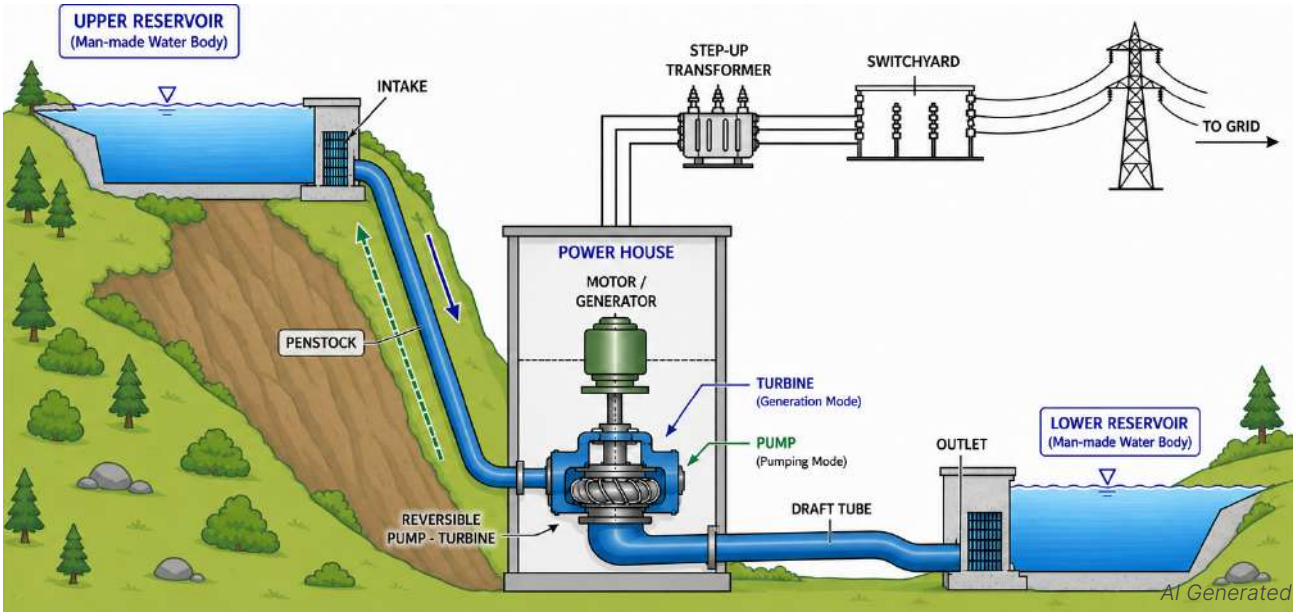


The closed-loop PHS mode is shown in Figure 62. It consists of two isolated reservoirs dedicated exclusively to storage, with water cycling between them and only minor losses due to evaporation. Closed-loop systems are generally preferred for new developments to reduce ecological impacts on natural waterways[119].

118 S. Rehman, L. M. Al-Hadhrami, and Md. M. Alam, 'Pumped hydro energy storage system: A technological review', Renew. Sustain. Energy Rev., vol. 44, pp. 586–598, Apr. 2015

119 Bo Saulsbury, "A comparison of the environmental effects of Open-Loop and Closed-Loop pumped storage hydropower," HydroWires, U.S. Department of Energy, Apr. 2020.

Figure 62 Schematic of closed loop pumped hydro storage plants



Fixed-Speed and variable speed PHS:

Conventional PHS units operate at synchronous speed in both pumping and generating modes. Variable-speed systems implemented using doubly fed induction machines or full-converter-based drives, enable adjustable rotational speed and pump power consumption. This enhances efficiency across varying hydraulic heads and improves capability for frequency regulation and grid support. Such PHS configurations are further explained in detail in Chapter 3.

Advanced concepts in PHS:

Innovative approaches include undersea PHS and integration of PSH with co-located wind or solar generation to enhance RE buffering. Concepts such as pumped heat storage are distinct from hydro-based PHS and rely on thermodynamic cycles rather than hydraulic storage. These alternatives remain supplementary to conventional hydro-based configurations.



Sirbatch at English Wikipedia, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

2.4.1.5 Performance Parameters

The performance parameters of PHS are compiled in Table 22[120]:

Table 22 Performance parameters of pumped hydro storage plants

Parameter	Range
Energy Density (Wh/kg)	0.2 - 2
C Rate	0.05 - 0.2
Life Span (years)	50 - 80
Round Trip Efficiency (%)	70 - 85
Discharge time (hours)	4 - 16
Depth of Discharge (%)	90 - 100
Response time (mins)	1 - 5
Storage Duration	Hours to Months

2.4.1.6 Application of PHS

PHS provides a broad range of large-scale power system applications as described below:

- **Peak shaving and load balancing:** PHS stores surplus generation during low-demand periods and releases energy during peak demand, flattening the load curve and enabling efficient operation of base load generation such as coal and nuclear plants. This reduces reliance on peaking units and supports economic optimisation through energy price arbitrage.
- **Frequency regulation and grid stability:** Owing to rapid response capability, PHS units adjust active power output to counter frequency deviations. Variable-speed units can also modulate power consumption in pumping mode. The substantial rotating mass of large PHS generators contributes inertia and short-circuit strength, enhancing frequency and voltage stability. PHS plants regularly participate in ancillary service markets for frequency control, spinning reserve, and voltage support.
- **Reserve and black start capability:** PHS serves as fast spinning reserve, with some units maintained at speed-no-load condition to enable rapid ramping. Many installations provide black start capability, allowing self-starting and energisation of grid sections following system outages.
- **RE integration:** PHS supports variable RE generation by consuming excess wind or solar energy and releasing it during deficit periods. It enables multi-hour smoothing, reduces curtailment, and provides stability support in systems with high RE penetration. The inherent inertia of synchronous machines compensates for reduced system inertia associated with converter-based resources.
- **Deferral of network reinforcement:** By shifting energy temporally and modifying power flows, PHS can alleviate transmission congestion and defer investment in transmission and distribution infrastructure.

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- **Energy market participation:** PHS operators exploit price differentials by purchasing electricity during low-price periods and generating during high-price intervals. Increasing RE penetration, often associated with midday or night time price depressions, enhances arbitrage opportunities.
- **Voltage regulation and reactive support:** When operated in synchronous condenser mode, PHS motor-generators can supply or consume reactive power, contributing to voltage control, particularly near major load centres.
- **Fast ramping and load following:** PHS units respond rapidly to steep net-load ramps, such as those associated with declining solar output, complementing slower thermal generation and improving overall system flexibility.
- **Other applications:** In specific configurations, PHS can support water management objectives or serve remote and isolated systems through small-scale or subsurface concepts, although such applications remain limited in commercial deployment.

Overall, PHS functions as a multi-service infrastructure asset, providing energy shifting, capacity support, and system stability. Historically deployed to optimise base load generation and meet peak demand, it is increasingly integral to maintaining reliability in RE-dominant power systems.

2.4.1.7 Economics of PHS

PHS is characterised by high capital expenditure, low operating costs, and long asset life, resulting in economic characteristics distinct from batteries and gas turbines.

- **Capital cost:** Development requires extensive civil works and heavy electromechanical equipment. Typical capital costs range from 2.2 to 4.5 million USD per MW[121], depending on site conditions. On an energy basis, costs may range from 2 to 50 USD per kWh, making PHS one of the lowest-cost options for large-scale, long-duration storage despite high upfront investment[122].
- **Long life and operating cost:** PHS plants commonly operate for at least 50 years or more, enabling capital recovery over extended periods and reducing annualised cost. Performance degradation is minimal compared with BESS. Operating expenses are relatively low i.e. around 1 to 4 percent of investment cost[123], with variable costs primarily associated with pumping losses of approximately 20 percent per cycle[124]. Economic performance depends on energy price differentials and ancillary service revenues.
- **Economies of scale and revenue streams:** Larger installations benefit from improved efficiency and lower unit costs due to favourable scaling of civil infrastructure. Revenue is derived from energy arbitrage, capacity remuneration mechanisms, ancillary services, and black start capability. In vertically integrated systems, PHS can provide system-wide cost savings by deferring new generation and network investments[125].

121 National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory, Office of Energy Efficiency and Renewable Energy, and Office of Fossil Energy and Carbon Management, 'Electricity Annual Technology Baseline (ATB) Data (2024)'. 2024.

122 J. D. Hunt et al., "Compressed air seesaw energy storage: A solution for long-term electricity storage," J. Energy Storage, vol. 60, no. 106638, p. 106638, 2023.

123 International Renewable Energy Agency, Renewable Power Generation Costs in 2020, IRENA, Abu Dhabi, United Arab Emirates, Jun. 2021.

124 A. Blakers, M. Stocks, B. Lu, and C. Cheng, "A review of pumped hydro energy storage," Prog. Energy, vol. 3, no. 2, p. 022003, 2021.

125 Scottish Renewables, The Economic Impact of Pumped Storage Hydro, Scottish Renewables, Edinburgh, U.K.

- **Environmental and social considerations:** Permitting complexity, land use constraints, and environmental mitigation requirements contribute to development risk and affect overall project economics[124].

Although PHS is capital-intensive, it offers durable, large-scale storage with competitive Levelised Cost of Storage (LCOS). Its economic attractiveness is strongest where suitable sites and stable market frameworks exist.

2.4.1.8 Environmental Impacts and Social Considerations

Although PHS relies on water and gravity rather than chemical processes, it can involve significant environmental and social impacts due to land and water use. Several major challenges associated with PHS are mentioned below[126, 127]

- **Land use and habitat alteration:** Construction of reservoirs, particularly artificial upper reservoirs, can inundate forests, agricultural land, and wildlife habitats. Large installations may require extensive land areas in mountainous or elevated terrain, potentially affecting terrestrial ecosystems and local communities. Visual impacts from reservoirs, dams, and associated transmission infrastructure are also relevant, especially in environmentally sensitive or scenic regions.
- **Hydrological and water quality impacts:** Open-loop PHS systems connected to natural water bodies can alter flow regimes, affecting downstream ecology through changes in timing, magnitude, and water-level fluctuations. Closed-loop systems have limited interaction with natural hydrology aside from initial filling and minor seepage. Water quality considerations include thermal stratification, sediment disturbance, dissolved oxygen variation, and entrainment of aquatic organisms at intake structures. Mitigation measures such as fish screens, controlled flow management, and intake design optimisation are commonly implemented.
- **Wildlife and ecosystem effects:** Reservoir development may require vegetation clearing and can fragment habitats. Construction activities introduce temporary disturbances, including noise, dust, and increased human presence. Fluctuating reservoir levels may limit stable shoreline habitats, affecting amphibians and aquatic plant communities.
- **Greenhouse gas considerations:** PHS does not produce direct operational emissions. However, reservoir inundation of biomass can generate methane and carbon dioxide through decomposition. On a life-cycle basis, PHS exhibits a low carbon footprint per MWh relative to fossil-fuel-based peaking plants and contributes indirectly to emission reduction by enabling RE integration.


Pexels


Pexels


U.S. Army Corps of Engineers Norfolk District from United States, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons

126 S. Karambelkar, A. Cantor, T.-K. Bui, B. Turley, M. Fischer, and S. Ames, "Pumped storage hydropower in the United States: Emerging importance, environmental and social impacts, and critical considerations," WIREs Water, vol. 12, no. 2, 2025.

127 B. M. Pracheil, K. P. Duffy, J. Zeng, and J. W. Saulsbury, Environmental Impacts of Closed-Loop Pumped Storage Hydropower, Pacific Northwest National Laboratory, Richland, WA, USA, Tech. Rep. PNNL-36322, Jun. 2024.

- **Social and cultural impacts:** Land acquisition and potential displacement of communities can present social challenges. Projects may face public opposition related to safety concerns, landscape alteration, and perceived environmental risks. Cultural and archaeological sites may require protection through careful site assessment and design adaptation. Transparent stakeholder engagement and equitable compensation mechanisms are essential for social acceptance.
- **Environmental mitigation and management:** Contemporary projects undergo comprehensive environmental impact assessments. Mitigation measures may include ecological compensation, managed downstream flow releases, habitat restoration, and recreational development. Site selection on previously disturbed land, such as abandoned quarries or depleted industrial areas, can significantly reduce environmental footprint.
- **Safety considerations:** Dams, high-pressure conveyance systems, and underground caverns require rigorous structural design and dam safety programs. Although typically smaller than large conventional hydro dams, PHS facilities must adhere to strict engineering standards to mitigate flood risk and ensure operational safety.

Overall, the environmental profile of PHS is broadly comparable to that of medium-scale hydro power, often with smaller reservoir footprints. Impacts can be substantially reduced through appropriate siting, engineering controls, mitigation strategies, and ongoing environmental monitoring. When integrated into decarbonisation strategies, PHS provides a net environmental benefit by supporting higher RE penetration and reducing dependence on fossil generation.

2.4.1.9 Global Deployments

PHS are widely deployed globally due to their high energy storage capacity and long discharge durations. Few of the globally deployed PHS plants are listed in Table 23[128].

Table 23 Global deployment of pumped hydro storage plants

PHS Plant	Location	Size	Commissioning year
United States			
Bath County PHS	Bath County, Virginia	24 GWh / 3 GW	1985
Ludington PHS	Ludington, Michigan	18.3 GWh / 2.29 GW	1973
Raccoon Mountain PHS	Marion County, Tennessee	36.3 GWh / 1.65 GW	1978
Castaic PHS	California	15.6 GWh / 1.5 GW	1973
Helms PHS	California	9.7 GWh / 1.12 GW	1984
China			
Fengning PHS	Hebei Province	40 GWh / 3.6 GW	2024
Meizhou PHS	Guangdong	16 GWh / 2.4 GW	2025
Changlongshan PHS	Zhejiang	12.5 GWh / 2.1 GW	2022
Huizhou PHS Station	Huizhou, Guangdong	14.7 GWh / 2.45 GW	2011

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PHS Plant	Location	Size	Commissioning year
Jixi PHS Station	Jixi County	10.8 GWh /1.8 GW	2021
Yangjiang PHS	Guangdong	20 GWh / 1.2 GWh	2022
Qingyuan PHS	Qingxin District	11.6 GWh / 1.28 GW	2016
	Japan		
Kannagawa PHS	Nagano	18.8 Gwh / 2.82 GW	2005
Okutataragi PHS	Asago	10.5 GWh / 1.9 GW	1974
Okukiyotsu PHS Station (No.1 & No.2)	Yuzawa	7.5 GWh / 1.6 GW	1978
Okuyoshino PHS Station	Totsukawa	14.7 GWh / 1.2 GW	1980
	India		
TEHRI	Uttarakhand	1 GW	2025
Greenko AP01 IREP Private Limited	Andhra Pradesh	1.68 GW	2025
Bhira PHS	Pune	0.150 GW	1949
Srisailam LBPH	Telangana	0.9 GW	1985
N J Sagar	Telangana	0.7056 GW	1985
	Africa		
Ingula PHS Scheme	KwaZulu-Natal	21 GWh / 1.32 GW	2017
Drakensberg PHS	Northern Drakensberg	27.6 GWh / 1 GW	1981
Palmiet PHS Scheme	Western Cape	0.4 GW	1988
Afourer PHS Station	Azilal Province (Afourer)	3 GWh / 0.465 GW	1979
	Australia		
Tumut 3 PHS	New South Wales	1.8 GW	1973
Wivenhoe PHS	Queensland	5.7 GWh / 0.570 GW	1984
Kidston PHS	Queensland	2 GWh / 0.250 GW	2025
	European Union		
Grand'Maison Dam	Vaujany, Isère, France	14 GWh / 1.8 GW	1987
Cortes La Muela II PHS	Valencia, Valencian Community, Spain	15 GWh / 1.76 GW	2013
Vianden PHS	Vianden, Luxembourg	5 GWh / 1.29 GW	2015
Tâmega PHS	Vila Real, Portugal	40 GWh / 1.15 GW	2024
Entracque PHS	Piedmont, Italy	10 GWh / 1.06 GW	1982

PHS Plant	Location	Size	Commissioning year
Edolo PHS	Lombardy, Italy	6 GWh / 1 GW	1983
Goldisthal PHS	Goldisthal, Thuringia, Germany	8.5 GWh / 1.06 GW	2003

2.4.2 Compressed Air Energy Storage Systems

CAES operates by compressing air using electrical energy and storing it at high pressure for subsequent power generation. Although investigated for several decades as a grid-scale storage solution, CAES has experienced limited large-scale deployment, with only two major commercial facilities commissioned in 1978 and 1991 in Germany and USA respectively[129]. CAES is a mechanical energy storage technology in which electrical energy drives motor-operated compressors to convert electrical input into the pressure potential energy of compressed air. The compressed air is stored in engineered reservoirs, such as underground caverns or high-pressure vessels, as illustrated in Figure 63. During discharge, the stored air is expanded through turbines to generate electricity. Surplus electrical energy is thus used to increase air pressure during charging, and the stored pressure energy is later reconverted into electrical output during expansion.

Figure 63 Compress air storage mechanism: (a) salt caverns (b) pressurised tanks



Source: Pexels

(a)



Source: Pexels

(b)

CAES is a large-scale mechanical energy storage technology in which surplus electrical energy is used to compress air to high pressure, typically 50 to 100 bar, and store it in underground caverns or engineered vessels. During discharge, the compressed air expands through a turbine to generate electricity. In conventional diabatic CAES, the heat generated during compression is rejected, and fuel which is usually natural gas, is added during expansion to reheat the air, resulting in a hybrid configuration combining storage and gas turbine operation. Advanced adiabatic or near-isothermal concepts aim to capture and reuse the heat of compression, thereby eliminating or minimising fossil fuel input and improving overall efficiency as described in later sections. CAES can provide multi-hour, hundred-MW-scale output comparable to PHS. However, deployment is constrained by the availability of suitable geological storage formations and effective integration of thermal management systems.

129 X. Zhang et al., "Advanced compressed air energy storage systems: Fundamentals and applications," Engineering (Beijing), vol. 34, pp. 246–269, 2024.

2.4.2.1 Historical Development and Global Status

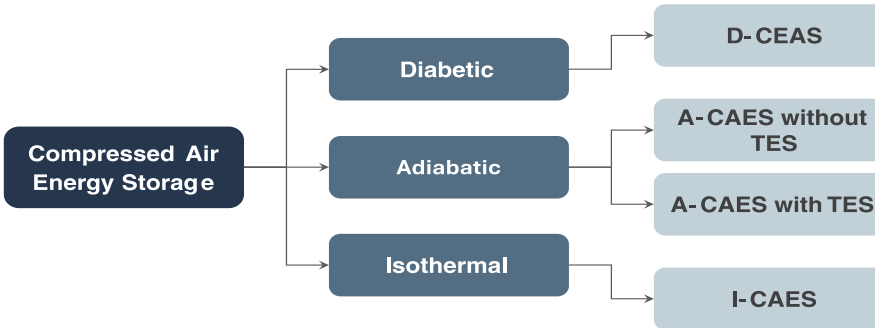
The origins of CAES can be traced to nineteenth-century compressed air distribution systems, such as those in Paris, which pioneered large-scale air compression and energy transport. Modern CAES for electricity storage emerged in the mid-twentieth century alongside gas turbine development. The first utility-scale plant, Huntorf in Germany, was commissioned in 1978 with a capacity of 290 MW and approximately 580 MWh of storage using salt caverns in a diabatic configuration. It operates at roughly 42 percent RTE, excluding the chemical energy contribution of fuel input. The McIntosh plant in the United States, commissioned in 1991, provides 110 MW with approximately 2860 MWh of storage and incorporates heat recuperation to improve efficiency to about 54 percent while reducing gas consumption. For several decades, these two facilities represented the only large-scale CAES plants, demonstrating technical viability and operational reliability[129].

Since the 2000s, interest in CAES has revived due to the need for long-duration storage for RE integration. Advanced adiabatic and near-isothermal designs reduce fossil fuel use by storing compression heat, with projected efficiencies near or above 70%. China's 600 MW/2.4 GWh Jiangsu CAES project and other 60–100 MW installations indicate strong policy support[130]. Other developments include hard-rock cavern concepts and liquid air energy storage as related approaches. Nevertheless, global deployment remains limited due to geological constraints, capital intensity, and lower effective efficiency relative to competing technologies. CAES viability is highly site-specific, requiring suitable underground formations such as salt caverns or engineered rock caverns. While regions such as the United States and parts of Europe possess favourable geology, countries with limited cavern resources face constraints on large-scale adoption[129].

2.4.2.2 Working Principle for CAES Systems

A range of CAES concepts has been developed, differing in thermodynamic design, technological maturity, and application focus. As illustrated in Figure 64, CAES systems are generally classified into Diabatic CAES (D-CEAS), Adiabatic CAES (A-CEAS), and Isothermal CAES (I-CAES) based on treatment of heat generated during compression and its management prior to expansion. In D-CAES, compression heat is rejected to the ambient, and external fuel is required during discharge to reheat the air and prevent excessive cooling, condensation, or icing in the turbine. A-CAES captures and stores compression heat in dedicated thermal energy storage units for reuse during expansion, eliminating the need for auxiliary heat input. I-CAES seeks to maintain near-constant temperature during compression and expansion, thereby reducing thermal losses and distinguishing it from both diabatic and adiabatic configurations[129]. These concepts differ in performance metrics such as RTE, energy density, and response characteristics, as well as in qualitative dimensions including technological maturity, system complexity, and suitability for specific grid applications.

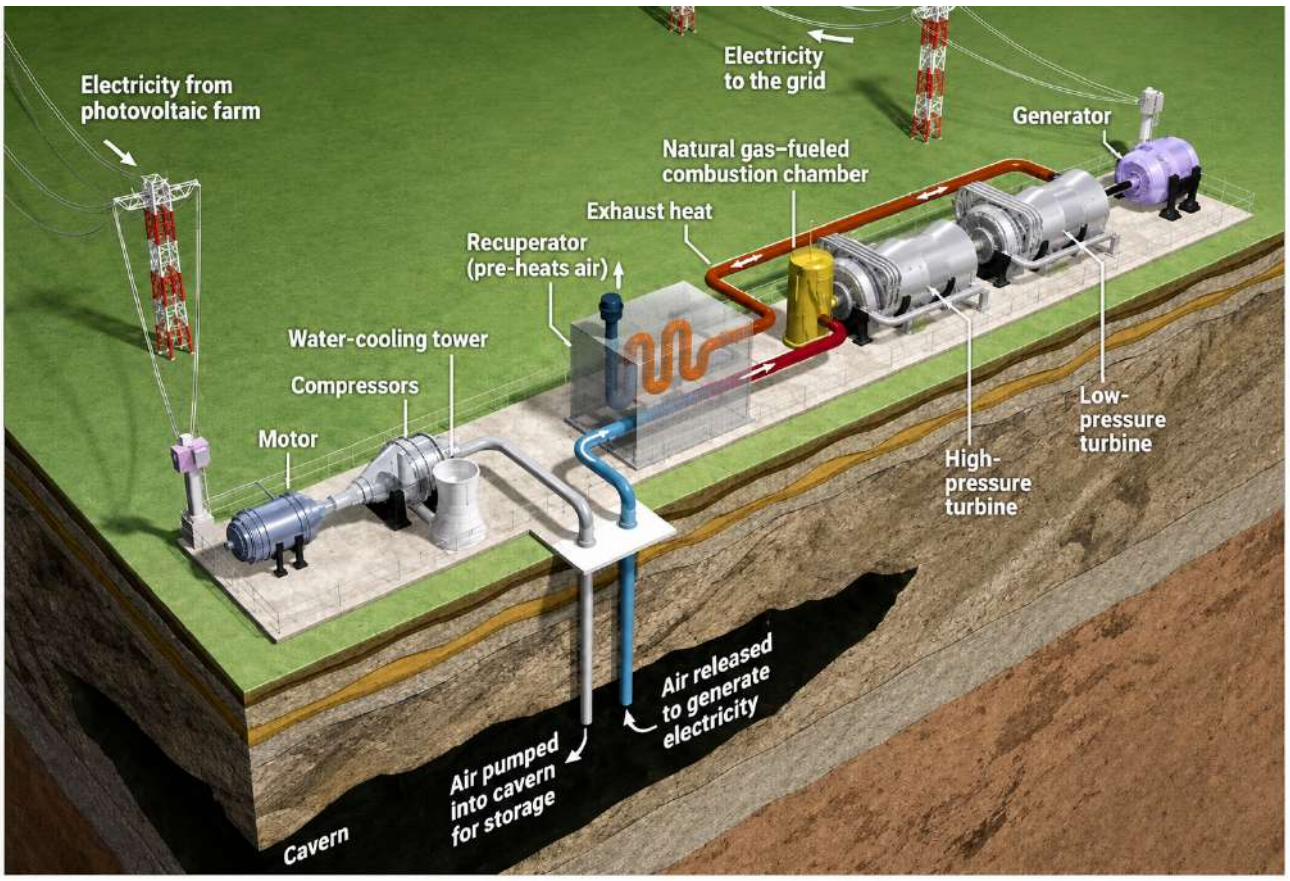
Figure 64 CAES concepts classified by their idealised change of state



130 "China commissions world's largest CAES station of 600 MW/2,400 MWh," Renewables Now, Mar. 2026

The operating principle of CAES comprises three sequential stages: compression during charging, high pressure air storage, and expansion during discharge, with integrated thermal management across all stages. A schematic representation of CAES operation is presented in Figure 65[131].

Figure 65 Schematic layout of a CAES System



Source: United Nations CTCN

Compression (Charging): Compression during charging is achieved using a compressor train, typically comprising multiple stages with inter cooling to reduce specific compression work. Ambient air is drawn in and compressed sequentially through low-pressure and high-pressure stages. As pressure increases, temperature rises, and inter coolers remove heat between stages to lower air temperature prior to further compression, thereby reducing energy consumption in accordance with thermodynamic principles. An after cooler may further reduce air temperature before storage to protect the reservoir and maximise storage density. The compressed air is then directed into the storage reservoir, where pressure typically varies within a defined operating range, for example 45 to 70 bar. In large underground caverns, pressure variation is gradual over charge and discharge cycles, particularly when water-compensation schemes are employed to stabilise pressure. Compression continues until the target pressure is reached or surplus electricity is exhausted. In A-CAES, the heat generated during compression is captured in a dedicated thermal energy storage system rather than rejected. The stored thermal energy is subsequently reintroduced during expansion, enabling high-temperature discharge without auxiliary fuel input. This configuration requires efficient high-temperature storage media and integrated heat exchangers, with some designs targeting storage temperatures approaching 600°C. I-CAES seeks to maintain near-constant temperature during compression through slow compression rates or enhanced heat-exchange mechanisms,

131 "Compressed Air Energy Storage (CAES)," UN Climate Technology Centre and Network.

such as liquid sprays. This approach reduces thermal losses and improves theoretical efficiency but presents significant practical challenges at large scale[132].

Storage: The geological formations beneath the Earth's surface have long been utilised for natural gas storage and are increasingly adapted for large-scale CAES due to their ability to accommodate high-pressure gas volumes. Storage technologies can be categorised according to the type of storage medium, as outlined below:

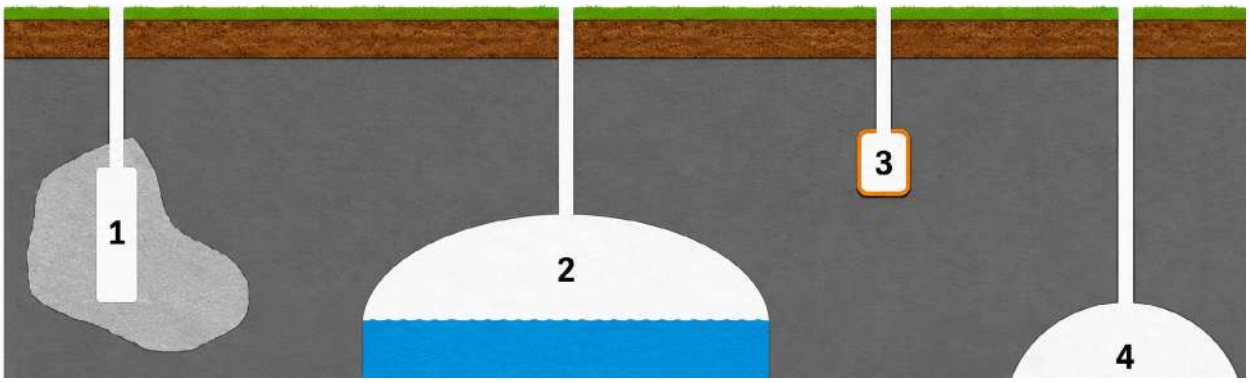
- **Salt caverns:** Solution-mined salt caverns represent the most mature and widely deployed storage option for commercial CAES. Rock salt is highly impermeable and exhibits visco-elastic self-sealing behaviour, supporting long-term structural integrity. Caverns are typically constructed at depths of 500 to 1500 m and can operate at pressures exceeding 100 bar. Their mechanical uniformity, high cycling capability, and relatively low base gas requirement enable frequent charge-discharge operation and high injection and withdrawal rates required for grid-scale applications. Development risk is often reduced where prior geological characterisation exists, although solution mining requires substantial water use.
- **Porous aquifers and depleted hydrocarbon reservoirs:** In these formations, compressed air occupies pore space within permeable rock, displacing water or residual hydrocarbons. While offering large theoretical storage capacities, practical implementation is constrained by challenges related to air containment, leakage control, geochemical interactions, and operational complexity.
- **Hard-rock caverns and abandoned mines:** Engineered rock caverns or repurposed mine voids can serve as storage volumes when equipped with appropriate lining systems to withstand high internal pressure. Although technically feasible, such configurations generally involve higher capital expenditure and increased construction risk compared with salt caverns.
- **Surface pressure vessels:** Above-ground storage in large steel vessels or pipe arrays is technically viable but becomes economically and spatially prohibitive at utility scale. These systems are more suited to small-scale or modular applications rather than bulk grid storage.
- **Underwater or constant-pressure concepts:** Underwater compressed air storage relies on hydrostatic head to maintain near-constant pressure conditions. Although several pilot demonstrations have been undertaken, this approach has not yet reached commercial maturity.

During storage, compressed air typically cools toward ambient temperature in the absence of dedicated thermal management, leading to pressure variation between charged and discharged states. For example, the Huntorf facility operates within a defined pressure range, requiring turbine control strategies such as throttling or multi-stage expansion to manage variable inlet conditions. The principal underground storage configurations are illustrated in Figure 66[133].

132 A. M. Hamiche, A. B. Stambouli, S. Flazi, and H. Koinuma, "Compressed air storage: Opportunities and sustainability issues," Energy Storage, 2023.

133 M. King, A. Jain, R. Bhakar, J. Mathur, and J. Wang, "Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK," Renewable and Sustainable Energy Reviews, vol. 139, p. 110705, Apr. 2021

Figure 66 Types of underground energy storage chambers. 1 - Salt cavern, 2 - Aquifer storage, 3 - Lined rock cavern, 4 - Depleted gas reservoir



Source: M. King et al.; 2021

Expansion (Discharging): Expansion during discharge begins with withdrawal of compressed air from the storage reservoir. In D-CAES, the air is reheated prior to expansion, typically by combustion of a limited quantity of fuel such as natural gas. Because the air is already pressurised, the fuel requirement is lower than in a conventional gas turbine, where fuel must support both compression and heating. The heated high-pressure air expands through one or more turbine stages, driving a generator and producing electrical power. Exhaust heat may be partially recovered through a recuperator to improve overall efficiency[129].

In A-CAES, reheating is achieved using previously stored compression heat from a thermal energy storage system rather than auxiliary fuel. The air passes through heat exchangers before entering the turbine, enabling expansion at elevated temperature and improving round-trip efficiency, with design targets approaching 70 percent under projected conditions. In this configuration, electrical output is derived from the initially stored electrical and thermal energy. I-CAES seeks to maintain near-constant temperature during expansion through enhanced heat exchange or controlled thermal input[129]. This approach reduces thermal losses but remains technically challenging at large scale.

2.4.2.3 Performance Parameters

The performance parameters of CAES are compiled in Table 24[134].

Table 24 Performance parameters of Compressed Air Energy Storage

Parameter	Range
Energy Density (Wh/kg)	30 - 60
C Rate	0.05 - 0.25
Cycle Life	>15000
Round Trip Efficiency (%)	40-70
Discharge time (hours)	24+ hours
Depth of Discharge (%)	40 – 50
Response time (mins)	Few minutes
Storage Duration	Hours to Months

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2.4.2.4 Key Components

A CAES plant comprises multiple integrated subsystems combining large-scale air compression, high-pressure storage, thermal management, and turbine expansion[135].

- **Compressors and motor-generator:** CAES facilities employ multi-stage axial or centrifugal compressors driven by large electric motors, often sharing a common shaft with a synchronous motor-generator through mechanical clutches. During charging, the machine operates in motoring mode to drive the compressor train, which incorporates inter cooling to reduce compression work and improve efficiency. Increasing the number of compression stages with effective inter cooling enhances performance and approaches near-isothermal behaviour.
- **Storage reservoir:** Underground salt caverns are the most mature and widely used storage medium due to their low permeability, self-sealing characteristics, and suitability for high-pressure cycling. Cavern energy capacity depends on volume and operating pressure range. Alternative options such as aquifers, depleted reservoirs, or lined hard-rock caverns are technically feasible but involve greater sealing complexity and higher cost.
- **Thermal management systems:** In conventional D-CAES, compression heat is rejected, and reheating during discharge requires fuel combustion. Advanced adiabatic configurations incorporate thermal energy storage systems to capture and reuse compression heat, improving round-trip efficiency and enabling fuel-free operation. Recuperators may recover exhaust heat to enhance performance.
- **Turbines and expansion system:** Expansion is typically performed using modified gas turbine expanders arranged in high-pressure and low-pressure stages. In fuel-based systems, combustion occurs prior to expansion, whereas adiabatic systems rely on stored thermal energy. Turbines must accommodate variable inlet pressure as cavern pressure changes, often requiring throttling or staged expansion strategies.
- **Balance of plant and safety systems:** Airflow control is achieved through high-pressure valves, isolation systems, and non-return devices. Auxiliary systems include lubrication, cooling circuits, plant automation, and, where applicable, fuel handling infrastructure. Environmental considerations primarily relate to cooling water requirements and brine management from solution-mined caverns. Safety systems incorporate pressure relief devices, well integrity monitoring, and combustion safety protocols in fuel-based designs.
- **Design challenges:** Key technical challenges include maintaining long-term storage integrity, preventing leakage in porous formations, managing efficiency variation due to changing cavern pressure, avoiding compressor oil contamination, and ensuring thermal energy storage materials withstand repeated thermal cycling.

In summary, a CAES plant integrates industrial gas compression equipment, underground storage infrastructure, and turbine generation technology. Although most components are commercially established, overall performance depends on effective integration of storage and thermal management subsystems.

135 A. G. Olabi, T. Wilberforce, M. Ramadan, M. A. Abdelkareem, and A. H. Alami, “Compressed air energy storage systems: Components and operating parameters – A review,” J. Energy Storage, vol. 34, no. 102000, p. 102000, 2021.

2.4.2.5 Applications

CAES provides applications broadly similar to PHS in bulk energy management, while offering additional flexibility through integration with gas turbine technology and siting in suitable geological formations[129,132].

- **Peak load shifting and energy arbitrage:** The primary application of CAES is to store low-cost electricity and deliver power during peak demand periods. Early CAES installations were designed for peak shaving and to enable steady operation of baseload generation. In modern systems, CAES can store surplus RE generation, such as midday solar or off-peak wind, and discharge during evening peaks, thereby mitigating net-load ramps.
- **Grid stability and ancillary services:** CAES units can provide spinning reserve, frequency regulation, and voltage support while generating. When operating at partial load, they can ramp output within minutes to support system balancing. The rotating mass of turbo machinery contributes inertia to the grid. In compression mode, particularly in variable-speed configurations, CAES can function as a controllable load to absorb surplus power. CAES plants may also support black start strategies through controlled start-up and synchronisation procedures.
- **RE integration and capacity firming:** CAES can smooth variable RE output by compressing air during periods of high generation and releasing it during deficits, thereby reducing curtailment and enhancing utilisation. By coupling CAES with wind or solar facilities, it can provide firm capacity in capacity markets and improve reliability in high-RE-penetration systems.
- **Grid deferral and regional applications:** Where suitable geology exists near load centres, CAES can shift energy temporally and alleviate transmission congestion, potentially deferring network reinforcement. In isolated or islanded systems, CAES may reduce reliance on imported fuels, although deployment at small scale remains limited by economic constraints.
- **Industrial and sector coupling applications:** CAES concepts have been explored for industrial energy management and behind-the-meter arbitrage, though commercial deployment remains limited. Advanced configurations integrate thermal recovery for combined heat and power applications. Alternative working-fluid concepts, including closed-loop systems using carbon dioxide, have been demonstrated at pilot scale, indicating potential improvements in thermal efficiency and compactness.
- **Large-scale RE time shifting and site repurposing:** CAES offers potential for multi-GWh storage in regions with suitable underground formations, serving as an alternative to large battery installations for long-duration applications. Repurposing abandoned mines or salt caverns can provide storage capacity and support regional economic transition.

2.4.2.6 Challenges and Limitations in Large-Scale Adoption

Despite technical feasibility and suitability for long-duration storage, CAES faces structural, economic, and technological barriers that have constrained widespread deployment. The key limitations are summarised below[130,136]:

- **Geological dependency:** CAES deployment is highly site-specific and dependent on suitable underground formations such as salt caverns. Many regions lack appropriate geology, limiting

136 E. Bazdar, M. Sameti, F. Nasiri, and F. Haghighat, "Compressed air energy storage in integrated energy systems: A review," Renew. Sustain. Energy Rev., vol. 167, no. 112701, p. 112701, 2022.

siting options. Alternatives such as aquifers or lined rock caverns introduce greater technical complexity, higher leakage risk, and increased capital cost.

- **Capital risk and financing:** The limited number of operational plants has contributed to perceived investment risk. Large project scale, extended development timelines, and uncertain revenue streams discourage private financing. Several projects evaluated under unfavourable market conditions have been cancelled after substantial preliminary expenditure.
- **Market structure:** In deregulated markets, reliance solely on energy arbitrage may be insufficient due to volatile or narrowing price spreads. Stable revenue mechanisms such as capacity payments or long-term contracts are often required to ensure financial viability.
- **Technical risk:** Advanced adiabatic CAES remains unproven at full commercial scale. Performance uncertainties related to thermal energy storage durability, heat exchanger reliability, and system integration present barriers to first-of-a-kind projects.
- **Fuel reliance in diabatic systems:** Conventional diabatic CAES depends on fossil fuel combustion during discharge, reducing its alignment with decarbonisation pathways and potentially exposing projects to carbon pricing. Although co-firing with low-carbon fuels is technically feasible, adiabatic configurations are more consistent with long-term climate objectives.
- **Competition from alternative technologies:** Fast-response services are increasingly dominated by batteries and flywheels, limiting CAES participation in high-value short-duration markets. CAES is therefore more competitive in multi-hour energy shifting and firm capacity applications.
- **Environmental and siting constraints:** Cavern development requires deep drilling and may raise concerns regarding brine disposal, groundwater interaction, and induced seismicity. Regulatory permitting and environmental compliance increase development complexity and modular battery systems.

Hence, CAES offers potential for large-scale, long-duration storage with competitive levelised cost under favourable conditions. However, widespread adoption depends on successful commercial demonstration of advanced designs and the availability of supportive regulatory and market frameworks.

2.4.2.7 Global Deployments

There is limited deployment of CAES due to their several challenges as mentioned in above sections. Few of the global CAES deployment is compiled in Table 25[137].

Table 25 Global deployment of compressed air energy storage

Country	Plant Name	Region	Capacity
Germany	Huntorf power station	Lower Saxony	321 MW
United States	McIntosh Power Plant	Alabama	110 MW
Canada	Goderich Energy Storage Centre (A-CAES)	Ontario	7 MWh / [1.75 MW (discharge), 2.2 MW (charge)]

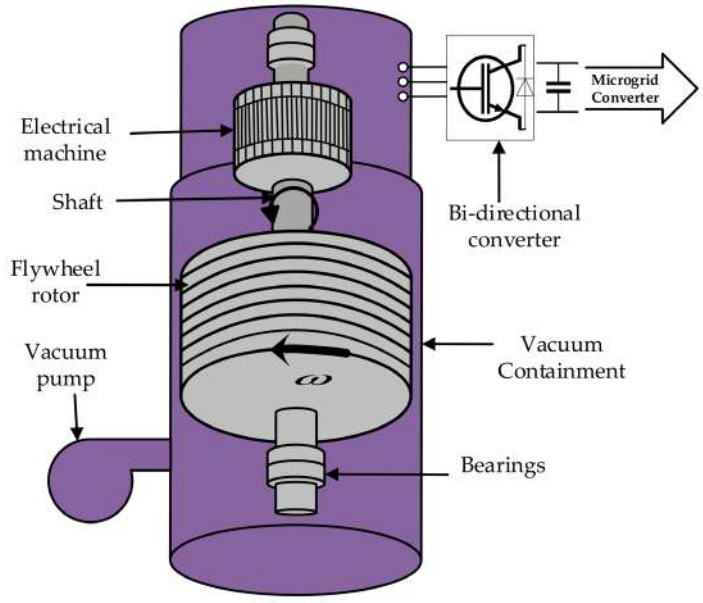
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Country	Plant Name	Region	Capacity
China	Jiangsu Jintan Salt Cavern CAES Project	Jiangsu	300 MWh / 60 MW
	Zhangjiakou Advanced CAES Demonstration Project	Hebei	400 MWh / 100 MW
	Feicheng Advanced CAES National Demonstration Power Station	Shandong	1,800 MWh / 300 MW
	Yingcheng Salt-Cavern CAES Power Station	Hubei	1,500 MWh / 300 MW
	Guoxin Suyan Huai'an Salt Cavern CAES Demonstration Project	Jiangsu	2,400 MWh / 600 MW

2.4.3 Flywheel Energy Storage System

Flywheel Energy Storage System (FESS) is a mechanical energy storage technology that stores energy as rotational kinetic energy by accelerating a rotor to high angular speed as shown in Figure 67[138]. During charging, electrical energy drives the rotor, converting electrical input into stored rotational energy. During discharge, the same electromechanical assembly operates as a generator, converting the stored kinetic energy back into electrical output as the rotor decelerates. Energy capacity depends on the rotor's moment of inertia and rotational speed, enabling design optimisation through increased speed or greater rotor mass. Modern FESS employ high-strength composite rotors, magnetic bearings to minimise frictional losses, and vacuum enclosures to reduce aerodynamic drag. These design features enable very high rotational speeds, rapid charge and discharge capability, and high cycling endurance. Owing to high power density, fast dynamic response, and long service life, FESS are particularly suited to applications requiring frequent cycling and short-duration energy buffering.

Figure 67 Schematic representation of FESS



Source: A. Soomro et al.; 2021

138 A. Soomro, K. R. Pullen, and M. E. Amiryar, "Hybrid PV System with High Speed Flywheel Energy Storage for Remote Residential Loads," Clean Technologies, vol. 3, no. 2, pp. 351–376, Apr. 2021.

There are two broad categories of FESS:

- **Low-speed, high-mass flywheels:** These conventional systems operate at rotational speeds typically in the range of 3,000 to 10,000 RPM and employ heavy steel rotors. Energy storage is achieved primarily through rotor mass, resulting in larger size and lower energy density for a given capacity. They are generally suitable where cost sensitivity is high and space constraints are limited.
- **High-speed, lightweight flywheels:** Modern advanced systems operate at rotational speeds typically in the range of 20,000 to 100,000 RPM and utilise composite rotors. They are more compact but involve higher cost due to precision bearings, magnetic suspension systems, and vacuum enclosures. These designs achieve significantly higher energy-to-weight ratios and improved specific energy performance.

2.4.3.1 Historical Development

FESS has a long historical lineage, originating from early mechanical applications used for rotational smoothing in industrial machinery and steam engines during the nineteenth and early twentieth centuries. Although these systems were not intended for deliberate electrical energy storage, they established the mechanical foundation for later developments. In the mid-twentieth century, particularly during the 1950s, experimental transportation applications demonstrated the feasibility of flywheel propulsion concepts. Subsequently, in the 1960s and 1970s, aerospace research programs investigated high-speed flywheel systems for space missions, focusing on vacuum enclosures, magnetic bearings, and advanced rotor dynamics. These efforts provided the technical basis for modern electrically integrated flywheel storage technologies.

A major technological transition occurred during the 1980s and 1990s with the introduction of high-strength composite materials, improved magnetic bearing systems, and solid-state power electronic converters, enabling higher rotational speeds and efficient grid interfacing. By the early 2000s, commercial-scale flywheel plants were deployed for grid frequency regulation and fast-response ancillary services, demonstrating rapid ramp rates and high cycle durability. Although broader market penetration has been limited by economic and competitive factors, operational projects since the 2010s have validated flywheels as a technically robust solution for short-duration, high-power applications in contemporary power systems[139].

2.4.3.2 Working Principle

The working principle of a flywheel energy storage system can be described in terms of charging and discharging operation[140]:

Charging operation - acceleration

During charging, surplus electrical energy is supplied to the motor-generator, which operates in motoring mode and applies electromagnetic torque to accelerate the rotor. As rotational speed increases, electrical energy is converted into kinetic energy stored in the rotating mass. The stored energy depends on rotor inertia and the square of angular speed, indicating that higher rotational speed significantly increases energy capacity.

Power electronic converters regulate current, torque, and speed to ensure controlled acceleration and grid compatibility. The rotor typically operates within a vacuum enclosure to minimise

139 K. R. Pullen, “The Status and Future of Flywheel Energy Storage,” Joule, vol. 3, no. 6, pp. 1394–1399, June 2019.

140 X. Li and A. Palazzolo, “A review of flywheel energy storage systems: state of the art and opportunities,” Journal of Energy Storage, vol. 46, p. 103576, Feb. 2022.

aerodynamic drag and is supported by magnetic bearings to reduce mechanical friction. Losses during charging primarily arise from electrical resistive losses in the motor and converter, together with minor bearing and windage losses. Charging duration depends on motor rating and rotor inertia and typically ranges from seconds to a few minutes.

Discharging operation - deceleration

During discharge, the motor-generator operates in generating mode. The power converter applies controlled electromagnetic torque opposite to the direction of rotation, extracting kinetic energy from the rotor and converting it into electrical energy. As energy is delivered to the grid or load, rotor speed decreases.

Because rotor speed varies during discharge, bidirectional converters maintain constant output voltage and frequency for grid integration. Output power is limited by the rating of the motor-generator and converter, while response time is extremely fast, typically in the millisecond range. Round-trip efficiency is high due to minimal mechanical losses and commonly approaches 85 to 95 percent in advanced systems.

2.4.3.3 Performance Parameters

The performance parameters of FESS are compiled in Table 26[141].

Table 26 Performance parameters of FESS

Parameter	Range
Energy Density (Wh/kg)	50 - 300
C Rate	100 C+
Cycle Life	1,00,000 +
Round Trip Efficiency (%)	80 - 85
Discharge time (hours)	Seconds - minutes
Depth of Discharge (%)	80 - 100
Response time (mins)	Milliseconds
Storage Duration	15 mins - 1 hour

2.4.3.4 Key Components

A typical FESS consists of several integrated components as shown in Figure 104, each designed to optimise performance and address technical challenges[142]:

- **Rotor:** The rotor is the primary energy storage element and is designed to maximise moment of inertia while safely operating at high rotational speeds. Modern systems often use rim-type geometries to concentrate mass at larger radius. Materials range from steel in low-speed systems to high-strength carbon-fibre composites in high-speed designs, enabling higher energy density and improved safety margins. Precise balancing and stress management are essential for reliable operation.

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142 S. Choudhury, "Flywheel energy storage systems: A critical review on technologies, applications, and future prospects," Int. Trans. Electr. Energy Syst., vol. 31, no. 9, 2021.

- **Motor-generator:** The motor-generator converts electrical energy to rotational energy during charging and vice versa during discharge. Permanent magnet synchronous machines are commonly used due to high efficiency and wide speed capability. The machine is directly coupled to the rotor and operates over a broad speed range.
- **Power electronic converter:** A bidirectional converter interfaces the motor-generator with the grid or DC bus. It regulates torque, speed, and power flow to ensure controlled charging and discharging. The converter also enables independent control of active and reactive power for grid support applications.
- **Bearings:** Magnetic bearings are typically used to support the rotor without mechanical contact, minimising friction and enabling high-speed operation. Active control systems maintain rotor stability. Mechanical touchdown bearings are incorporated as backup during startup, shutdown, or fault conditions.
- **Vacuum enclosure:** The rotor and motor assembly are housed within a vacuum-tight enclosure to reduce aerodynamic drag and standby losses. The enclosure also provides mechanical containment in the event of rotor failure.
- **Cooling and auxiliary systems:** Cooling systems remove heat from the motor and power electronics. Monitoring systems track vibration, rotor speed, and vacuum pressure. Protective mechanisms, such as dynamic braking and controlled shutdown, ensure safe operation under abnormal conditions.
- **System integration:** FESS are typically modular and can be operated in parallel to achieve higher power or energy capacity. Designs range from high-speed composite systems for grid applications to lower-speed steel systems for cost-sensitive applications such as uninterruptible power supply.

2.4.3.5 Applications

FESS is primarily deployed in applications that require high power, rapid response, and very high cycle capability rather than long-duration energy storage[139, 143].

- **Grid ancillary services:** Flywheels are widely used for primary frequency control and fast regulation services. Their ability to transition between charge and discharge within milliseconds makes them effective for correcting short-term power imbalances and stabilising grid frequency. Because regulation signals are typically zero-mean over short intervals, the limited energy capacity of flywheels is sufficient. They also provide fast ramping support, spinning reserve, and synthetic inertia in converter-dominated grids.
- **Uninterruptible power supply and ride-through:** In critical facilities such as data centres, hospitals, and semiconductor plants, flywheels provide short-duration backup power during grid disturbances. They supply immediate power for seconds to minutes until diesel generators or alternate sources start. Compared with battery-based UPS systems, flywheels offer lower maintenance, high power density, and long operational life under frequent cycling.
- **Power quality and voltage support:** Flywheels are used to mitigate voltage sags, flicker, and rapid load variations in industrial and utility networks. By injecting or consuming active power rapidly, they stabilise voltage at the point of common coupling and improve overall power quality.

143 A. A. K. Arani, H. Karami, G. B. Gharehpetian, and M. S. A. Hejazi, “Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids,” Renewable and Sustainable Energy Reviews, vol. 69, pp. 9–18, Mar. 2017.

- **RE smoothing and microgrids:** In systems with high penetration of wind or solar generation, flywheels smooth short-term fluctuations caused by cloud transients or wind turbulence. They manage second-to-minute variations, supporting frequency and voltage stability in weak grids and microgrids. Flywheels are often deployed in hybrid configurations with batteries, where they address rapid fluctuations while batteries provide longer-duration energy balancing.
- **High-power pulse applications in grid-connected facilities:** Flywheels are suitable for research facilities or industrial processes requiring short bursts of high power. They charge gradually from the grid and discharge rapidly to supply transient loads, reducing stress on the upstream network.

2.4.3.6 Challenges and Limitations in Large-Scale Adoption

Several challenges associated with FESS are highlighted below[142,144] :

- **High self-discharge and system losses:** FESS exhibit relatively high self-discharge due to electrical losses in windings and magnetic components, mechanical losses in bearings, residual aerodynamic drag, and converter-related losses. Although vacuum enclosures and magnetic bearings significantly reduce friction, standby losses remain higher than in electrochemical storage, limiting long-duration energy retention. Reducing parasitic losses through improved sealing, low-loss bearings, and optimised electromagnetic design remains an important development focus.
- **Low energy density and short duration:** FESS generally provide short discharge durations, typically minutes rather than hours, because of lower energy density compared with batteries. While suitable for high-power services such as frequency regulation and ride-through support, they are not economically attractive for bulk energy shifting. Extended-duration designs have been proposed but are not widely deployed.
- **Rotor mechanical constraints:** Stored energy increases with rotational speed, but higher speeds impose significant centrifugal stresses on the rotor. Advanced composite materials improve strength-to-weight ratio and specific energy yet increase manufacturing complexity and cost. Structural integrity and burst containment remain critical design considerations.
- **Bearing system limitations:** Bearing technology significantly influences efficiency, speed capability, and reliability. Mechanical bearings introduce friction and wear, whereas magnetic bearings enable high-speed, low-loss operation but require complex sensing and control systems. Hybrid configurations incorporating backup touchdown bearings are common, although cost and technical complexity remain challenges.
- **Economic competitiveness:** FESS compete primarily with batteries and supercapacitors. They are less suitable for low-cycle, energy-oriented applications but become attractive where extremely high cycle life, minimal degradation, and rapid response are required. Their economic value is therefore strongest in ancillary service markets.
- **Need for hybridisation:** Due to limited energy capacity, flywheels are often integrated with batteries or other storage technologies. In hybrid systems, flywheels manage fast, high-power transients, while complementary storage technologies address longer-duration energy requirements.

144 C. Matos, E. Rosales-Asensio, J. A. Carta, and P. Cabrera, “Flywheels in renewable energy Systems: An analysis of their role in managing intermittency,” J. Energy Storage, vol. 122, no. 116674, p. 116674, 2025.

2.4.3.7 Global Deployments

FESS have progressed from laboratory-scale demonstrators to commercial grid-support assets, particularly in applications requiring fast response, high cycling capability, and precise frequency regulation. Few of the global FESS deployments are compiled in Table 27[145]

Table 27 Global deployment of FESS

Country	Plant Name	Region	Capacity
Germany	Max Planck Institute FESS	Bavaria	387 MW
	Piller flywheel technology	Dresden	5 MW
United States	Beacon Power Corporation	Massachusetts	0.1 MWh /20 MW
	PG&E – Amber Kinetics	California	80 MWh / 20 MW
	Beacon Power	Pennsylvania	20 MW
Canada	Temporal Power Flywheel Facility	Ontario	4 MW
China	Dinglun FESS	Shanxi Province	30 MW
	CHN Energy Pengla	Shandong	3 MWh / 12 MW
	China CRRC Ruicheng	Shanxi Province	0.41 MWh / 50 MW
	Wenshui Flywheel Hybrid Storage Demonstration Station	Shanxi Province	2 MW
Japan	New Energy Development Organization	Kawasaki City	10 MWh
	Railway Technical Research Institute	Kokubunji	0.1 MWh / 0.3 MW
	ROTES flywheel system	Okinawa	26.5 MW
Portugal	ABB PowerStore FESS	La Graciosa Island	0.5 MW
Kenya	OXTO Energy	Kenyan tea factory	0.8 MW
Philippines	De La Salle University (DLSU) Flywheel Innovation Hub	Laguna	4 MWh / 1 MW

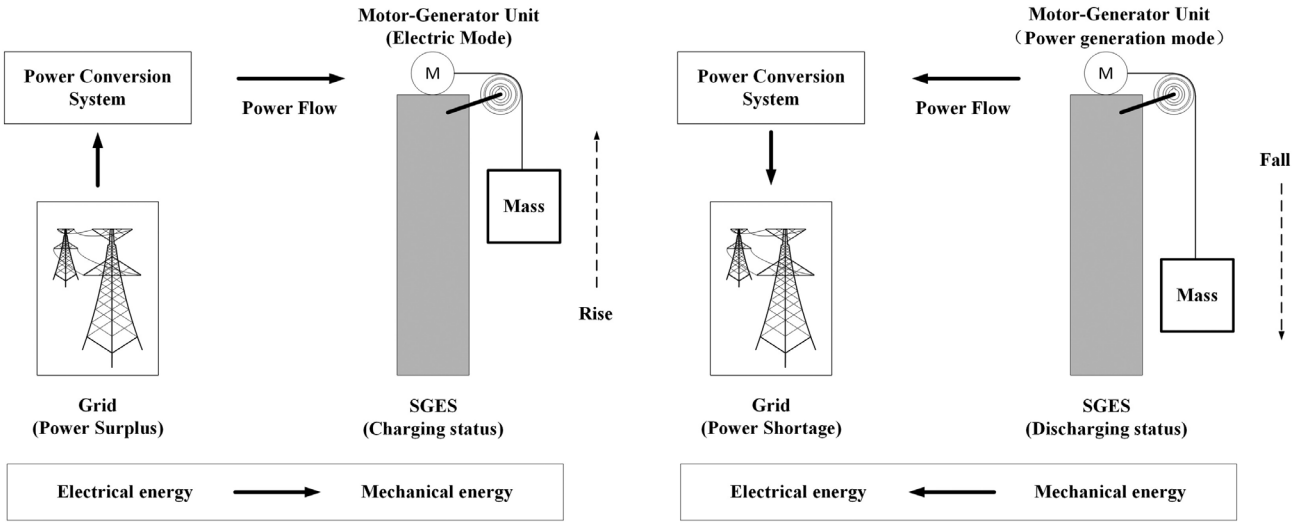
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2.4.4 Gravitational Energy Storage Systems

Gravitational Energy Storage Systems (GESS) are mechanical storage technologies that store energy by lifting a mass to a higher elevation using surplus electrical power and releasing that energy by lowering the mass to drive a generator as shown in Figure 68[146]. The stored energy depends on the mass of the object and the vertical height difference achieved. By employing heavy masses or significant elevation differences, substantial amounts of energy can be stored. During periods of excess generation, electromechanical systems raise the mass. During power deficits, controlled descent of the mass converts the stored gravitational potential energy back into electrical energy for grid support.

Figure 68 Operating principle of gravitational energy storage



Source: W. Tong et al.; 2022

The most established form of GESS is PHS, in which water is lifted to an elevated reservoir. Emerging concepts instead raise solid masses such as concrete blocks, rock, or other heavy materials within towers, shafts, or vertical structures. Gravitational storage is attractive due to long operational lifetime, minimal self-discharge, and reliance on abundant, non-electrochemical materials. Power capability depends on the speed and mass of the moving system, while total energy capacity is determined by the overall mass and elevation difference, enabling flexible scaling. Conceptually similar to weight-driven mechanical clocks but implemented at grid scale, these systems can achieve relatively high round-trip efficiencies, with losses primarily arising from mechanical friction and aerodynamic drag. However, achieving competitive energy density and cost-effectiveness requires large structures or substantial masses to match the storage capacity of alternative technologies[44].

2.4.4.1 Historical Development and Global Status

The use of gravity for energy storage dates to the early twentieth century with the development of pumped hydroelectric storage, first implemented in Switzerland in the early 1900s. Over the twentieth century, pumped hydro became the dominant form of large-scale energy storage worldwide, demonstrating high reliability, long operational life, and the ability to store large amounts of energy. However, deployment has been limited to suitable geographic locations with adequate elevation and water availability. Beyond water-based systems, concepts involving solid masses

146 W. Tong et al., “Solid gravity energy storage: A review,” J. Energy Storage, vol. 53, no. 105226, p. 105226, 2022.

have appeared intermittently, including experimental weighted hoists and rail-based systems that moved heavy loads uphill using surplus electricity and recovered energy during descent.

Renewed interest in non-hydroelectric gravitational storage emerged in the 2010s, driven by the need for long-duration and location-flexible storage. Several industries started developing systems that lift and lower heavy blocks, rail-mounted masses, or weights suspended in mine shafts. Demonstration projects since 2017 have validated technical feasibility and rapid response capability, often leveraging existing infrastructure such as disused mines. While PHS remains the most mature and widely deployed gravitational technology, modern solid-mass concepts aim to extend gravity-based storage to regions without traditional hydro resources[147].

2.4.4.2 Working Principle

All GESS operate on the same principle: electrical energy is converted into gravitational potential energy by lifting a mass and recovered by lowering the mass to drive a generator. Core components include the mass (solid or fluid), a lifting mechanism such as a motor–generator, pump, or winch, and elevated and lower storage positions[144].

- **Charging:** Surplus electricity powers a motor or pump to raise the mass against gravity. The work done in lifting is stored as potential energy at the higher elevation.
- **Storage:** Once elevated, the mass can remain in position with minimal losses, since gravitational potential does not degrade over time. Losses are limited to minor mechanical friction or standby system consumption, resulting in very low self-discharge compared to electrochemical systems.
- **Discharging:** When energy is required, the mass descends in a controlled manner, driving the motor in generator mode or flowing through a turbine in hydro-based systems. Output power is regulated by controlling the descent rate: faster motion yields higher power for shorter duration, while slower descent extends discharge time.

2.4.4.3 Key Components

Several configurations are being developed to implement gravitational energy storage, each applying the same lifting-lowering principle to different site conditions and infrastructure contexts.

- **Elevated mass tower systems:** These systems use purpose-built vertical structures in which heavy blocks, typically concrete or composite materials, are lifted and stacked during charging and lowered during discharge. Early prototypes employed crane-based designs, while newer enclosed structures resemble automated storage systems with motorised winches. Energy capacity scales with the number of blocks, and power capacity depends on lifting speed and parallel operation. These systems require substantial civil works but can be deployed on flat terrain using established lifting and automation technologies[144].
- **Underground mine-shaft systems:** These designs repurpose deep, disused mine shafts to raise and lower suspended masses. Energy is stored by hoisting weights to the top of the shaft and recovered through controlled descent driving generators. The underground configuration minimises surface footprint and leverages existing infrastructure, although feasibility depends on suitable shaft depth and structural integrity. Multiple weights can be sequenced to extend discharge duration[148].

147 B. L. Taylor, Can Gravity Batteries Solve Our Energy Storage Problems? BBC Future, May 11, 2022.

148 Interreg Danbe Region and European Union, “Gravity Energy Storage: Harnessing the Power of Nature for a Sustainable Future,” StoreMore.

- **Rail-based and inclined systems:** Rail-based concepts move heavy rail cars along inclined tracks during charging and recover energy during descent through regenerative braking. Capacity can be increased by extending track length or adding vehicles. These systems use established rail technology but require significant land area and appropriate gradients[149].
- **Hybrid and piston-based systems:** Some emerging concepts combine solid masses with hydraulic or fluid systems, such as large pistons operating in deep shafts where water is pumped beneath the mass during charging and released through turbines during discharge. These designs aim to increase effective head and compactness while retaining gravitational storage principles[150].

Across all configurations, precise control and safety systems are required to manage large moving masses, prevent oscillations, and ensure fail-safe operation. The optimal configuration depends on site conditions, available infrastructure, land constraints, and economic considerations, reflecting efforts to extend gravity-based storage beyond traditional pumped hydro locations.

2.4.4.4 Performance Parameters

The performance parameters of GESS are compiled in Table 28[151].

Table 28 Performance parameter of GESS

Parameter	Range
Energy Density (Wh/kg)	0.5 - 5
C Rate	0.1 – 0.5 C
Cycle Life	1,00,000 +
Round Trip Efficiency (%)	80 – 90
Discharge time (hours)	4 - 50
Depth of Discharge (%)	100
Response time (mins)	Seconds

2.4.4.5 Applications

GESS can support multiple roles within modern power systems, particularly where long asset life, large capacity, and mechanical robustness are valued[144].

- **Grid energy shifting and peaking:** GESS can charge during periods of excess RE generation and discharge during peak demand, providing multi-hour firm capacity. Similar to PHS, they can reduce reliance on peaking plants and support round-the-clock RE supply.
- **Ancillary services and frequency support:** With fast ramping capability, GESS can provide frequency regulation, spinning reserve, and bidirectional grid support. By adjusting lifting or lowering speed, systems can rapidly absorb or inject power, contributing to stability in RE-dominant grids.

149 H. Ma, X. Hou, Y. Sun, Z. Wei, and M. Su, “Rail gravity energy storage: Distributed-driven configuration, efficiency analysis and multi-objective evaluation,” J. Energy Storage, vol. 153, no. 120829, p. 120829, 2026.

150 D. He, Y. Shen, and N. Luo, “Performance analysis and optimization of a 20 MWh piston hydraulic gravity energy storage (PHGES) system,” Energy (Oxf.), vol. 323, no. 135768, p. 135768, 2025.

151 GIL Research

- **RE integration:** GESS can be co-located with solar or wind plants to smooth output and reduce curtailment. They convert variable RE into dispatchable supply, particularly in regions with suitable land, shafts, or terrain.
- **LDES applications:** Although most current projects target hourly storage, sufficiently large systems can support extended-duration balancing. Deep shafts or large-scale installations offer potential for multi-day storage in high-RE scenarios, subject to economic constraints.
- **BTM and industrial use:** In select cases, gravity systems integrated into buildings or industrial facilities may reduce peak demand charges by storing energy during low-tariff periods and releasing it during peak pricing windows. Such applications remain niche and site dependent.
- **Resilience and remote applications:** Due to long service life and minimal degradation, GESS may suit remote or infrastructure-limited regions, supporting RE-powered microgrids and improving energy resilience.

Hence, GESS is positioned as a durable, multi-hour mechanical alternative to ECES, particularly where site conditions and infrastructure enable practical deployment.

2.4.4.6 Challenges and Limitations in Large-Scale Adoption

Challenges associated with large scale deployment of GESS are mentioned below[144,152]

- **Energy density and footprint:** GESS exhibits low energy density, requiring either very heavy masses or large elevation differences to store significant energy. This results in substantial civil structures, such as tall towers or deep shafts, leading to increased land use, visual impact, and longer construction timelines compared with modular battery systems.
- **High upfront capital cost:** Projects are capital-intensive and typically require large-scale construction from the outset, limiting incremental deployment. Securing financing can be challenging without established revenue streams, particularly for emerging designs competing with mature battery technologies.
- **Site and infrastructure constraints:** Although not dependent on water resources like pumped hydro, gravity systems still require suitable infrastructure, such as deep mine shafts, available land for tower structures, or inclined terrain for rail-based systems. Site availability, permitting, and zoning considerations may restrict deployment in certain regions.
- **Mechanical wear and maintenance:** Unlike static storage technologies, gravity systems involve continuous movement of heavy components, leading to mechanical wear in cables, winches, bearings, and braking systems. Long-term reliability depends on robust structural design, redundancy, and planned maintenance strategies.
- **Efficiency and control complexity:** Achieving high RTE requires minimising friction, aerodynamic drag, and mechanical losses. Multi-mass or crane-based systems demand advanced control and safety mechanisms to prevent oscillations and operational faults, increasing mechanical and automation engineering complexity.
- **Market and policy fit:** GESS have to compete directly with BESS in many markets. Its advantages, including long operational life and mechanical durability, are most relevant for multi-hour or long-duration applications. However, existing market structures may not fully recognize lifecycle benefits, potentially requiring supportive regulatory frameworks.

152 K. Cai, Y. Han, R. Xia, J. Wu, J. Wang, and P. D. Lund, “Gravity energy storage: A review on system types, techno-economic assessment and integration with renewable energy,” Wiley Interdiscip. Rev. Energy Environ., vol. 13, no. 6, 2024.

- **Public perception and technology maturity:** As a relatively new category beyond PHS, GESS must demonstrate reliability, safety, and economic viability at scale. Early commercial deployments are important to build confidence among investors, regulators, and the public.

While challenges remain, most are engineering and financial rather than fundamental physical limitations. Continued technological refinement and market adaptation could improve competitiveness in long-duration storage applications.

2.4.4.7 Global Deployments

Globally, there are a limited deployments or pilots of GESS compiled in Table 29[153]:

Table 29 Global deployment of GESS

Country	Plant Name	Region	Capacity
United States	ARES Nevada Gravity Line demonstration site	Nevada	100 MWh / 25 MW
China	Energy Vault EVx GESS	Gansu Province	68 MWh / 17 MW
	Energy Vault EVx GESS	Jiangsu Province	3 MWh / 12 MW
United Kingdom	Gravitricity demonstrator	Scotland	250 kW
Switzerland	Energy Vault EV1 Tower	Ticino	5 MW

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Pexels

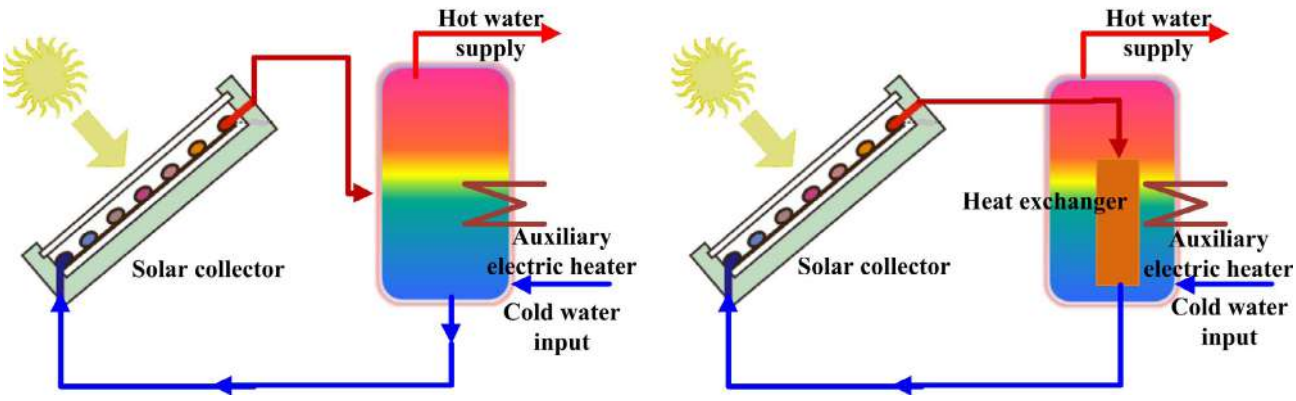
2.5 Thermal Energy Storage Systems

Thermal Energy Storage Systems (TESS) are an important class of ESS technologies that store energy in the form of heat or cold for later use. They contribute to improved energy efficiency, integration of RE sources, and support for decarbonisation strategies. By storing surplus thermal energy and releasing it when required, TESS enables load shifting and improved utilisation of generation and conversion assets. These systems are generally classified into Sensible Heat Storage, Latent Heat Storage using phase-change materials, and Thermochemical Storage approaches.

2.5.1 Sensible Heat Energy Storage System

Sensible Heat Energy Storage Systems(SHESS) is the most mature and widely deployed form of TESS. It stores energy by increasing or decreasing the temperature of a material without phase change. The stored energy is proportional to the mass, specific heat capacity, and temperature difference of the storage medium, resulting in a nearly linear enthalpy-temperature relationship, as illustrated in Figure 69[154]. During charging, heat from a working fluid raises the temperature of the storage material. During discharging, the material releases heat as its temperature decreases.

Figure 69 Schematic of domestic hot water system with electrical heater (a) direct mode (b) indirect mode



Source: Gang Li; 2016

Common SHESS materials include liquids such as water, thermal oils, and molten salts within single-phase operating ranges, as well as solids such as rocks, concrete, sand, and natural stones including basalt and granite. A typical system consists of a storage tank or packed-bed structure and a heat transfer fluid circuit that facilitates heat exchange during charging and discharging. SHESS systems are valued for simplicity, low cost, high cycle life, and technological maturity.

However, SHESS has relatively low energy density, requiring large volumes to achieve substantial storage capacity. Thermal losses over time and slower heat transfer in solid media can further limit performance. Despite these constraints, SHESS remains widely used in building heating and cooling, solar thermal systems, industrial process heat applications, and cold-chain systems. Ongoing research focuses on enhancing heat transfer rates and improving system compactness.

154 G. Li, "Sensible heat thermal storage energy and exergy performance evaluations," Renew. Sustain. Energy Rev., vol. 53, pp. 897–923, 2016.

2.5.1.1 Historical Development and Global Status

Sensible heat storage is among the oldest and most established TESS approaches, with early forms seen in masonry heaters and domestic hot water tanks. Its modern development accelerated in the 20th century alongside solar thermal research, with early large-scale water tank systems used for space heating. By the 1980s, SHESS gained utility-scale relevance through steam accumulators and the expansion of solar thermal power plants[155].

Beyond power generation, SHESS is widely used in district heating. Denmark's Vojens pit thermal storage facility integrates a large water basin with a solar collector field to supply a substantial share of annual heating demand, while Canada's Drake Landing Solar Community demonstrated near-complete solar heating by storing summer heat in underground boreholes for winter use. These deployments highlight the technical maturity and scalability of SHESS across residential, district, and grid-scale applications[156].

2.5.1.2 Working Principle

In a sensible heat storage system, thermal energy is stored by increasing the temperature of a material and recovered by decreasing it. The governing relation is:

$$Q = mc_p\Delta T$$

Where Q is the stored energy, m is the storage mass, c_p is the specific heat capacity, and ΔT is the operating temperature range. Storage capacity therefore depends on material mass, heat capacity, density, and allowable temperature swing[157].

Material selection is essential aspect for SHESS design. Suitable media should provide high specific heat capacity, thermal and chemical stability, non-toxicity, and low cost. Water is widely used for low- to medium-temperature systems due to favourable thermal properties, while solids such as concrete, rock, and ceramics are preferred in high-temperature applications because they tolerate wider temperature ranges. Unlike latent heat storage, SHESS exhibits continuous temperature variation during charge and discharge, which can lead to declining outlet temperature unless stratification or multi-tank configurations are implemented.

Common configurations include stratified liquid tanks, two-tank molten salt systems, and thermocline packed-bed systems. Stratification preserves thermal layering and improves outlet temperature stability, while two-tank systems enable near-constant outlet temperature over most of the discharge cycle. Thermocline systems reduce capital cost by combining fluid and filler material within a single tank. Overall performance is governed by heat transfer rates, heat exchanger design, internal thermal resistance, and thermal losses, which together determine charge and discharge power capability and system efficiency.

2.5.1.3 Key Components

An SHESS system generally includes a storage medium contained within a tank or reservoir, a heat transfer mechanism to add or extract heat, and thermal insulation to minimise losses. System design varies according to temperature level, storage duration, and application scale[44].

155 "Solar One | Science | Research Starters | EBSCO Research," EBSCO.

156 Y. Xiang, Z. Xie, S. Furbo, D. Wang, M. Gao, and J. Fan, "A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications," J. Energy Storage, vol. 55, no. 105716, p. 105716, 2022.

157 P. Sharma, B. Debnath, A. K. Shukla, J. Pawar, and G. Singh, "A comprehensive review of sensible heat thermal energy storage for high temperature applications," Energy Storage, vol. 7, no. 5, 2025.

- **Hot water tanks:** Widely used in buildings and district heating networks, these systems store thermal energy in insulated water tanks. Stratification is maintained using diffusers or flow management devices to preserve temperature layering. Storage volumes range from small domestic tanks to large underground district heating reservoirs. With proper insulation and design, heat losses can be limited to a few degrees Celsius per month, depending on tank size and ambient conditions.
- **Molten salt systems:** Common in concentrated solar power plants, these systems use high-temperature nitrate salt mixtures in two-tank configurations, separating hot and cold reservoirs. Pumps circulate molten salt through solar receivers or heat exchangers during charging and discharging. Large allowable temperature differences improve energy density. Alternative designs include thermocline systems and solid-particle media for higher-temperature applications.
- **Solid medium storage:** These systems include packed-bed rock storage, concrete modules, and ceramic or metal blocks. In packed-bed systems, hot fluid flows through solid media to store heat, and the flow direction is reversed during discharge. Concrete storage modules with embedded heat exchanger pipes are used in industrial applications due to low cost and modularity. Such systems are suitable for medium- to high-temperature industrial waste heat recovery.
- **Low-temperature storage:** Chilled water tanks and building thermal mass are used for cooling load shifting. Water is cooled during off-peak hours and used during peak demand, reducing electricity costs and grid stress. Across all SHESS systems, effective insulation using materials such as mineral wool or polyurethane is essential to limit thermal losses and maintain system efficiency.



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P. Metha et al., Nature

2.5.1.4 Performance Parameters

The performance parameters of SHESS are compiled in Table 30[158]:

Table 30 Performance parameter of SHESS

Parameter	Range
Energy Density (Wh/kg)	40–110 Wh/kg
C rate	0.01–1 C
Cycles	>10,000
Round trip efficiency (%)	50–90%
Discharge time (hours)	1–24 h
Depth of Discharge (%)	70–100
Response time (mins)	0.1–10+ min

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2.5.1.5 Applications

SHESS is applied across multiple sectors where thermal energy supply and demand are temporally mismatched[44,150]:

- **Building heating and hot water:** Hot water tanks are widely used in residential and commercial buildings to store heat from solar collectors, boilers, or off-peak electricity. The stored heat is subsequently used for space heating or domestic hot water. In passive solar buildings, structural materials such as concrete and brick provide thermal mass to moderate daily temperature fluctuations.
- **District heating and seasonal storage:** Large-scale SHESS systems support district heating networks by storing surplus heat from solar collectors or CHP plants for later use. Seasonal storage concepts, including pit thermal energy storage and borehole systems, enable summer heat to be utilised in winter, reducing fossil fuel consumption.
- **Concentrated solar power:** High-temperature SHESS, typically using molten salt, enables dispatchable solar electricity in CSP plants. By storing thermal energy during sunny periods and releasing it after sunset, these systems increase plant capacity factor and enhance grid stability.
- **Industrial process heat:** Industries use SHESS to capture and reuse waste heat or to shift electrical heating loads to off-peak hours. Packed-bed regenerators, ceramic media, and concrete storage modules are common in medium- to high-temperature applications.
- **Cooling and load shifting:** Chilled water storage is widely adopted in large buildings to shift air-conditioning loads from peak to off-peak hours. By producing cooling at night and storing it for daytime use, facilities reduce electricity costs and grid stress.
- **Power-to-heat-to-power systems:** Emerging Carnot battery concepts use SHSS to store surplus electricity as heat and later reconvert it to electricity through heat engines. Although still under development, such systems may expand SHESS applications into grid-scale ESS.

SHESS remains a versatile and mature solution for storing thermal energy across buildings, industry, and power systems.

2.5.1.6 Challenges and Limitations in Large-Scale Adoption

Despite its technological maturity, sensible heat storage exhibits several inherent limitations[44,150].

- **Low energy density and space requirement:** SHESS requires large volumes to store significant amounts of energy, making it less suitable for space-constrained or mobile applications. Structural requirements and land availability can become limiting factors, particularly in urban environments.
- **Heat losses and temperature degradation:** Thermal losses are unavoidable, especially for long-duration storage, leading to gradual cooling over time. During discharge, the outlet temperature typically declines, reducing the thermal quality of delivered heat and limiting efficiency in power-generation applications.
- **Material and operational constraints:** High-temperature systems face challenges such as corrosion, thermal stress, and material degradation. Molten salt systems require freeze protection and careful thermal management, increasing system complexity and operational requirements.

- **Limited suitability for multi-day power storage:** While effective for daily or seasonal heat shifting, SHESS becomes less practical for extended multi-day electricity storage without very large installations and efficient heat-to-power conversion systems.
- **Integration and market barriers:** Advanced applications such as power-to-heat-to-power systems require complex integration and may face limited policy recognition or market mechanisms compared with electrical storage technologies.

2.5.1.7 Global Deployments

The global deployments or pilots of SHESS are compiled in Table 31[159].

Table 31 Global deployment of SHESS

Region	Storage Plant	Capacity
United States		
Arizona	Solana Generating Station	250 MW / 1500 MWh
Nevada	Crescent Dunes Solar Energy Project	110 MW / 1100 MWh
Spain		
Andalusia	Gemasolar Thermosolar Plant	19.9 MW / 299 MWh
Extremadura	Extresol 1	50 MW / 375 MWh
Castilla–La Mancha	Manchasol 1	50 MW / 375 MWh
Andalusia	Andasol 1	50 MW / 375 MWh
Morocco		
Drâa-Tafilalet	Noor I	160 MW / 480 MWh
	Noor II	200 MW / 1400 MWh
	Noor III	150 MW / 1050 MWh
United Arab Emirates		
Dubai	Noor Energy 1 (3×200 MW Trough)	600 MW / 6600 MWh
Dubai	Noor Energy 1 (100 MW Tower)	100 MW / 1500 MWh
Chile		
Antofagasta	Cerro Dominador	110 MW / 1925 MWh
South Africa		
Northern Cape	KaXu Solar One	100 MW / 250 MWh
	Bokpoort	50 MW / 465 MWh
	Xina Solar One	100 MW / 550 MWh
	Kathu Solar Park	100 MW / 500 MWh
	Ilanga I	100 MW / 450 MWh
	Khi Solar One	50 MW / 100 MWh
	Redstone	100 MW / 1200 MWh

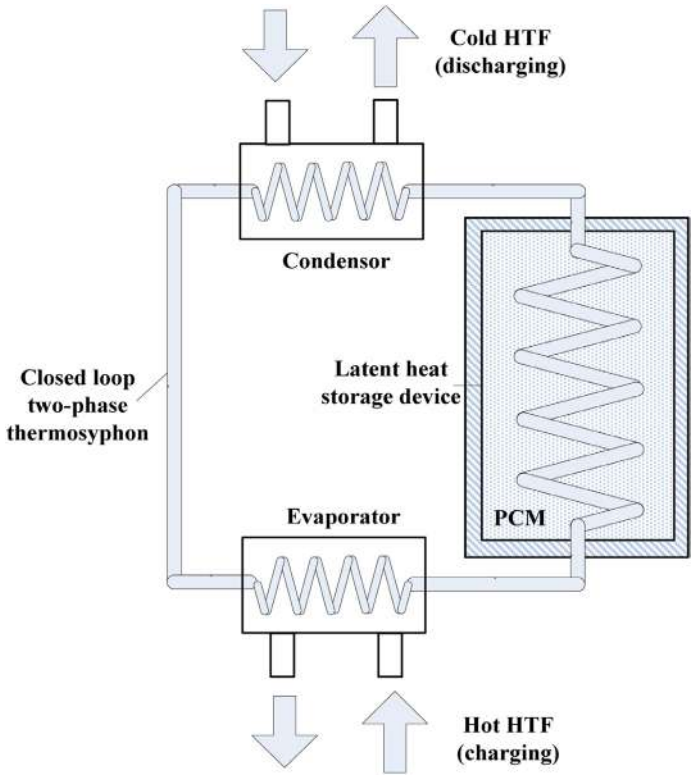
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Region	Storage Plant	Capacity
	China	
Gansu	Shouhang Dunhuang Phase II	100 MW / 1100 MWh
Qinghai	SUPCON Delingha	50 MW / 350 MWh
Xinjiang	CEEC Hami	50 MW / 650 MWh
Gansu	Yumen Xinneng	50 MW / 450 MWh
Qinghai	CGN Delingha	50 MW / 450 MWh
	Italy	
Sicily	Archimede	5 MW / 40 MWh
	Spain	
Murcia	Puerto Errado 2	30 MW / 15 MWh

2.5.2 Latent Heat Energy Storage System

Latent Heat Energy Storage (LHESS) stores thermal energy through the phase change of a material, most commonly from solid to liquid and back as shown in Figure 70[160] . During melting, a phase change material absorbs a large amount of heat at nearly constant temperature, and during solidification it releases that heat. This near-isothermal behaviour enables LHESS to deliver stable thermal output while achieving higher energy density than SHESS.

Figure 70 Schematic of LHES



Source: S. Zhang et al.; 2020

160 S. Zhang, L. Wang, Y. Bai, X. Lin, L. Peng, and H. Chen, "Experimental and theoretical analysis of a closed loop two-phase thermosiphon under various states for latent heat storage," Energy Rep., vol. 6, pp. 1–7, 2020.

A wide range of phase change materials is available, covering temperatures from sub-zero levels for cooling applications to several hundred degrees Celsius for industrial heat. Common examples include water and ice, paraffin waxes, salt hydrates, fatty acids, and high-temperature salts or metal alloys. The phase-change temperature is selected according to the intended application, enabling effective thermal management in buildings, solar energy systems, and industrial process heat[161].

Although the concept has been studied for decades, including early solar house experiments in the mid-twentieth century, recent research has focused on improving material stability, enhancing thermal conductivity, and developing reliable encapsulation techniques. LHES offers compact storage and stable temperature control, making it suitable for applications where space constraints or strict thermal regulation are critical.

2.5.2.1 Historical Development

The development of LHESS parallels early solar energy research. A significant milestone was the Dover Sun House in 1948, where Glauber's salt was employed as a phase change material for residential heating. Although the system encountered material stability issues, it demonstrated the high storage potential of PCMs. Renewed interest during the 1970s energy crisis led to systematic documentation of PCMs for solar heating[162], followed by extensive material research in the 1980s and 1990s. One of the earliest commercial successes was ice thermal storage for air-conditioning, which was widely adopted in large buildings to shift cooling loads from peak to off-peak hours[163]. Applications subsequently expanded to building materials, electronics cooling, textiles, and transportation refrigeration.

Since the 2000s, research has focused on improving thermal conductivity, long-term stability, and encapsulation methods, including the development of composite and nano-enhanced PCMs. While molten salt sensible storage remains dominant in concentrated solar power plants, pilot projects have explored high-temperature PCMs for solar and industrial heat applications. Globally, the most widespread latent storage application remains ice storage in HVAC systems, with additional deployment in passive buildings and cold-chain logistics[161]. Overall, LHESS is recognised for high energy density and temperature stability. However, large-scale integration into mainstream energy systems remains limited due to cost, long-term material reliability, and system-level integration complexity[164].

161 A. de Gracia and L. F. Cabeza, "Phase change materials and thermal energy storage for buildings," Energy and Buildings, vol. 103, pp. 414–419, Sept. 2015, doi: 10.1016/j.enbuild.2015.06.007.

162 M. Telkes, "Thermal energy storage in salt hydrates," Solar Energy Materials, vol. 2, no. 4, pp. 381–393, July 1980

163 S. K. S. Boetcher, "Cool Thermal Energy Storage," in Solid–Liquid Thermal Energy Storage, Boca Raton: CRC Press,pp. 243–256, 2022

164 M. Opolot, C. Zhao, M. Liu, S. Mancin, F. Bruno, and K. Hooman, "A review of high temperature (≥ 500 °C) latent heat thermal energy storage," Renew. Sustain. Energy Rev., vol. 160, no. 112293, p. 112293, 2022.

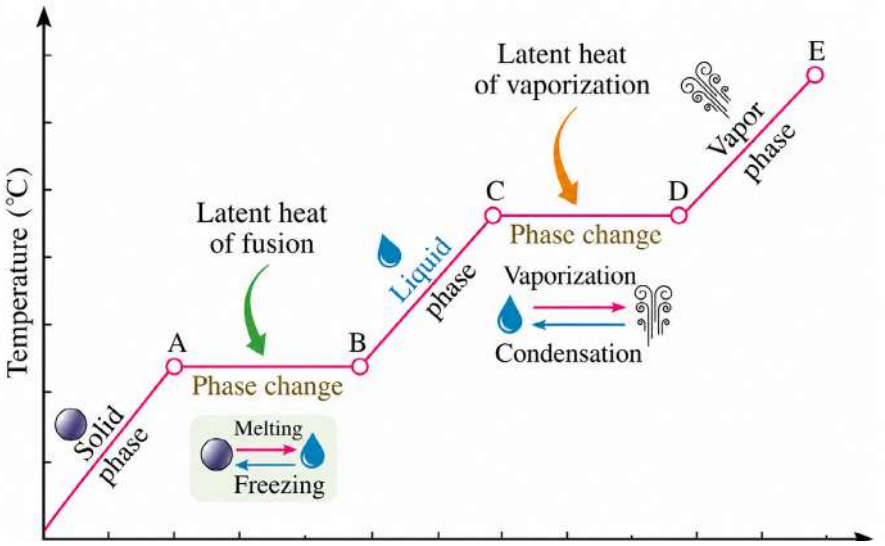


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2.5.2.2 Working Principle

The working principle of LHESS can be described by distinguishing the charging and discharging processes, as illustrated in through the enthalpy-temperature curve in Figure 71[44].

Figure 71 Temperature-Energy diagram for heating and cooling of a substance



Source: J. Mitali et al.; 2017

Charging process - melting phase: During charging, heat is supplied to the PCM through a heat transfer fluid or an embedded heat exchanger. As shown in Figure 71, the temperature of the solid PCM initially increases `within the sensible heating region of the solid phase. Once the melting temperature is reached, the curve enters a plateau region. In this interval, additional heat input does not significantly increase temperature but is absorbed as latent heat while the PCM transitions from solid to liquid. This near-constant temperature region is the defining characteristic of latent heat storage. A substantial amount of energy is stored with minimal temperature variation, enabling high energy density and stable thermal output. After complete melting, further heat input increases the temperature of the liquid phase sensibly, moving the curve upward beyond the phase-change region.

Discharging process - solidification phase: During discharging, heat is extracted from the PCM. The liquid PCM first cools sensibly until it reaches the phase-change temperature. Solidification then begins, and latent heat is released while the temperature remains nearly constant, corresponding to the plateau region in Figure 71. This constant-temperature heat release is advantageous for applications requiring stable thermal output, such as space conditioning or industrial process heat. After complete solidification, further cooling releases only sensible heat, and the temperature decreases accordingly.

In practical systems, phase change typically occurs over a finite temperature range rather than at a perfectly sharp transition, resulting in a slightly inclined plateau. Heat transfer limitations can also slow melting and solidification, as many PCMs exhibit relatively low thermal conductivity. Consequently, system designs often incorporate fins, encapsulation techniques, or conductive additives to enhance heat transfer performance. Hence, LHESS enables compact and temperature-stable energy storage by utilising the high enthalpy associated with phase transitions.

2.5.2.3 Key Components

LHESS systems incorporate specialised components in addition to standard thermal storage elements such as containment and insulation. The key components involved in LHESS are mentioned below[165]:

- **Phase change material:** The PCM is the core component and is selected based on melting temperature, latent heat capacity, cycling stability, material compatibility, and cost. PCMs are broadly classified as organic, inorganic, or eutectic mixtures. Organic PCMs such as paraffins and fatty acids are chemically stable and exhibit minimal supercooling but generally have low thermal conductivity and may present flammability concerns. Inorganic PCMs such as salt hydrates and low-melting metals typically provide higher latent heat and improved thermal conductivity but may experience supercooling, phase segregation, or corrosion. Eutectic mixtures enable tuning of melting temperature and can enhance volumetric storage density[166].
- **Encapsulation and containment:** Unlike SHESS, PCMs commonly require modular encapsulation to manage phase change behaviour and associated volume variation. Typical configurations include spherical capsules, flat panels, shell-and-tube heat exchangers, and plate-based modules. Encapsulation materials must be chemically compatible with the PCM and withstand the operating temperature range. In cold storage applications, PCM modules are often integrated with refrigeration systems, whereas high-temperature systems may employ metallic containers and structured heat exchanger assemblies.
- **Heat transfer enhancement:** Efficient heat exchange is essential because many PCMs exhibit low thermal conductivity. System designs frequently incorporate fins, metal matrices, or enhanced encapsulation geometries to improve heat transfer rates. In larger installations, dedicated heat exchangers circulate a working fluid to facilitate melting and solidification. Cascaded configurations using multiple PCMs with different melting temperatures are sometimes applied to better match thermal profiles in industrial or solar thermal systems.

At the system level, modelling of LHESS commonly applies enthalpy-based methods that incorporate latent heat effects within transient heat transfer equations. Overall performance depends on PCM selection, thermal conductivity enhancement strategies, encapsulation design, and integration with the heat transfer loop.

2.5.2.4 Performance Metrics

The performance parameters of LHESS are compiled in Table 32[167]:

Table 32 Performance parameters of LHESS

Parameter	Range
Energy Density (Wh/kg)	Up to 500
Cycles	1,000+

165 H. Jouhara, A. Żabnieńska-Góra, N. Khordehgah, D. Ahmad, and T. Lipinski, "Latent thermal energy storage technologies and applications: A review," International Journal of Thermofluids, vol. 5–6, no. 100039, p. 100039, 2020.

166 R. Mabrouk, H. Naji, A. C. Benim, and H. Dhahri, "A State of the Art Review on Sensible and Latent Heat Thermal Energy Storage Processes in Porous Media: Mesoscopic Simulation," Applied Sciences, vol. 12, no. 14, p. 6995, July 2022.

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Parameter	Range
Round trip efficiency (%)	60–80%
Discharge time (hours)	Minutes to Few hours
Depth of Discharge (%)	100
Response time (mins)	15 - 100

2.5.2.5 Applications

Latent heat storage is applied across several domains, with particular relevance to power systems in load shifting, RE integration, and thermal buffering[168,158].

- **Active cooling and grid load shifting:** The most established application is ice-based or PCM-based thermal storage in large HVAC systems. In commercial buildings and district cooling networks, chillers operate during off-peak hours to freeze water or solidify a PCM, and the stored cooling capacity is used during peak demand periods. This shifts electrical load away from peak hours, reduces grid congestion, and lowers demand charges. Compared with conventional ice storage, higher-temperature PCMs can improve chiller efficiency by enabling operation at higher evaporator temperatures.
- **Solar thermal and dispatchable heat-to-power systems:** PCMs are investigated in solar thermal systems to stabilise outlet temperature and enhance dispatchability. By storing heat at nearly constant temperature, latent storage can improve turbine inlet temperature stability in concentrated solar power or hybrid heat-to-power systems. Although sensible molten salt storage remains commercially dominant, high-temperature PCMs and cascaded latent configurations are under research to reduce storage volume and maintain thermal quality.
- **Power-to-heat-to-power systems:** In emerging thermal battery concepts, surplus electricity is converted to heat and stored in thermal media. PCMs may be incorporated to maintain a stable temperature reservoir, improving cycle efficiency and thermal management. Their near-isothermal behaviour supports controlled charging and discharging in integrated thermal-electrical conversion systems.
- **Cold chain and backup cooling with grid impact:** PCM-based refrigeration and cold storage systems reduce dependence on continuous electrical supply by providing passive cooling during outages or peak periods. At scale, these systems contribute indirectly to grid stability by smoothing demand and reducing peak compressor loading.

LHESS supports demand-side flexibility, enhances RE integration, and contributes to thermal-based electricity storage concepts, particularly where stable temperature delivery and compact storage are required.

2.5.2.6 Advantages

LHESS is applied in several domains, but its relevance to power systems lies primarily in load shifting, RE integration, and thermal buffering[44,159].

- **Active Cooling and Grid Load Shifting:** The most established application is ice-based or PCM-based thermal storage in large HVAC systems. In commercial buildings and district

168 A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," Renewable and Sustainable Energy Reviews, vol. 13, no. 2, pp. 318–345, Feb. 2009.

cooling networks, chillers operate during off-peak hours to freeze water or solidify a PCM, and the stored cooling is used during peak demand periods. This shifts electrical load away from peak hours, reduces grid congestion, and lowers demand charges. Compared to conventional ice storage, higher-temperature PCMs can improve chiller efficiency by allowing operation at higher evaporator temperatures.

- **Solar Thermal and Dispatchable Heat-to-Power Systems:** PCMs are explored in solar thermal systems to stabilise outlet temperature and enhance dispatchability. By storing heat at nearly constant temperature, latent storage can improve turbine inlet stability in concentrated solar power or hybrid heat-to-power systems. Although sensible molten salt remains dominant commercially, high-temperature PCMs and cascaded latent systems are under research to reduce storage volume and maintain thermal quality.
- **Power-to-Heat-to-Power:** In emerging thermal battery concepts, surplus electricity is converted to heat and stored in thermal media. PCMs may be used to maintain a stable temperature reservoir within these systems, improving cycle efficiency and thermal management. Their near-isothermal behaviour can support controlled charging and discharging in integrated thermal–electrical conversion plants.
- **Cold Chain and Backup Cooling with Grid Impact:** PCM-based refrigeration and cold storage systems reduce reliance on continuous electrical supply, providing passive cooling during outages or peak periods. At scale, such systems contribute indirectly to grid stability by smoothing demand and reducing peak compressor loads.

Hence, LHESS plays a strategic role in power systems by enabling demand-side flexibility, enhancing RE integration, and supporting thermal-based electricity storage concepts, particularly where stable temperature delivery and compact storage are required.

2.5.2.7 Challenges and Limitations in Large-Scale Adoption

Despite their advantages, LHESS present several practical limitations[158,159,161].

- **Thermal and material constraints:** Many PCMs exhibit low thermal conductivity, which limits charging and discharging rates unless enhanced through fins, conductive additives, or advanced encapsulation techniques. Certain materials, particularly salt hydrates, may experience supercooling, phase segregation, or long-term degradation. These phenomena reduce reliability and decrease effective storage capacity over repeated cycles.
- **Encapsulation and stability issues:** PCMs require controlled containment to accommodate volume changes during phase transitions and prevent leakage. At high temperatures, corrosion and material compatibility become critical design considerations. Ensuring long-term durability of encapsulation under cyclic operation is a significant engineering challenge.
- **Cost and system complexity:** PCMs are generally more expensive than other storage media, and system integration often requires specialised heat exchangers and control systems. Monitoring SoC and maintaining predictable phase transitions increases operational complexity, which limits large-scale deployment.
- **Application-specific limitations:** Each PCM operates within relatively narrow temperature range, reducing operational flexibility compared with sensible storage. Scaling systems to industrial capacity introduces additional heat transfer and mechanical challenges. Safety considerations like flammability or toxicity for certain materials, further constrain design options. Overall, while LHESS offers high energy density and stable temperature output, cost, long-term reliability, and engineering complexity continue to limit widespread adoption.

2.5.2.8 Global Deployments

Globally, there are a limited deployments or pilots of LHESS compiled in Table 33[169].

Table 33 Global deployment of LHESS

Country	Region	Storage plant	Capacity
Austria	Vienna (Alsergrund)	MedUni Campus Mariannengasse District Cooling Centre (Wien Energie)	17.7 MW / 6 MWh
China	Xinjiang	High-temperature cPCM TES demonstration plant (district heating / wind curtailment mitigation)	6 MW / 36 MWh
France	Paris	City of Paris district cooling (Climespace / Fraîcheur de Paris)	280 MWh
	Paris	La Défense district cooling ice storage (Enertherm / Idex La Défense)	122 MW / 240 MWh
Malaysia	Sarawak	University of Malaysia, Sarawak (UNIMAS) district cooling – ice TES	24.6 MWh
Sweden	Sundsvall	Sundsvall Regional Hospital snow cooling plant – seasonal snow	1.5 MW / 1000 MWh
Australia	South Australia	Pernod Ricard Winemakers – “Fridge 9” PCM TES (water/ice PCM)	2.6 MWh
	Queensland (Townsville)	Reef HQ – PCM TES (water/ice PCM)	1.2 MWh
	WF Montague	WF Montague – PCM TES	0.4 MW / 4.0 MWh

2.5.3 Thermochemical Storage Systems

Thermochemical Energy Storage (TCESS) stores heat in the form of chemical potential through reversible reactions. During charging, heat drives an endothermic reaction that converts reactants into higher-energy products. When heat is required, the reverse exothermic reaction recombines the products, releasing the stored energy. Because energy is stored in chemical bonds rather than as sensible temperature rise, thermochemical systems can achieve higher energy density and enable long-term storage with minimal standby losses, provided the reactants remain physically separated.

Typical examples include hydration and dehydration reactions of metal oxides, salt hydrates, and carbonate systems. Although the concept has been investigated for several decades, practical deployment remains limited. Interest has increased due to the requirement for long-duration and seasonal storage to support RE integration. At present, thermochemical storage is largely at pilot and research stages, with ongoing efforts focused on material stability, reactor engineering, and system scalability[170].

169 GIL Research"Figure 1 Global CO2 emissions, (a) Share of emissions from different energy sectors, (b) Global share of emissions in 2025" on page 3

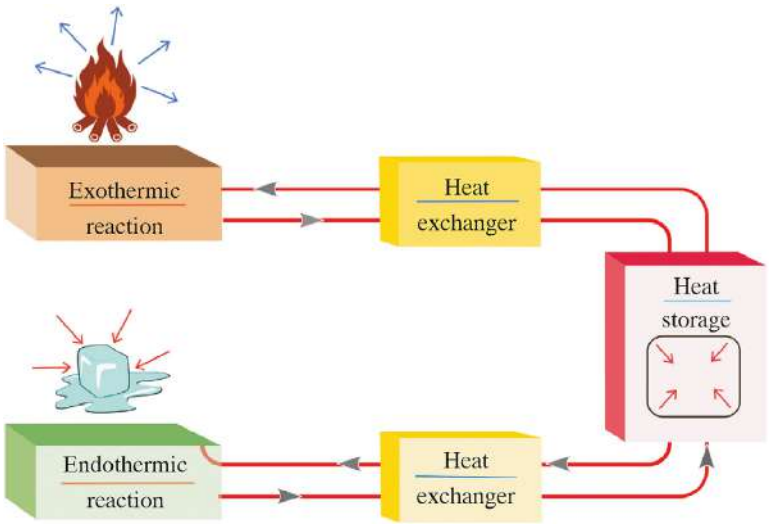
170 C. K. Ho and A. Ambrosini, “THERMAL ENERGY STORAGE TECHNOLOGIES ,” Sandia National Laboratories, Albuquerque, New Mexico, 2021.

2.5.3.1 Working Principle

TCESS operates by cycling a reversible chemical reaction within a reactor, as illustrated in Figure 72[44]. During charging, external heat drives an endothermic reaction that converts a low-energy reactant into higher-energy products. For example, in dehydration-based systems, heat removes water vapour from a hydrated salt or hydroxide, producing a dehydrated solid and separated vapour. These products constitute the charged state, with energy stored in chemical bonds rather than as elevated temperature. When the reactants are stored separately, standby heat losses are minimal.

During discharging, the separated reactants are recombined, initiating the reverse exothermic reaction and releasing the stored reaction enthalpy as useful heat through a heat exchanger. TCESS systems may employ integrated reactors, where solid material remains within a single vessel and gas is introduced or removed during cycling, or separated configurations, where charged and discharged materials are stored in different tanks to enable more continuous operation. In both configurations, stored energy scales with the mass of reactive material, making TCESS suitable for long-duration and seasonal heat storage applications.

Figure 72 Reversible chemical reaction based thermochemical energy storage system



Source: J. Mitali et al.; 2017

2.5.3.2 Key Components, Design, and Configuration

TCESS comprises a reactor in which reversible endothermic and exothermic reactions occur, storage vessels for charged and discharged materials in either integrated or separate configurations, heat exchangers for thermal input and output, and gas-handling components such as pumps or condensers in solid-gas systems. Reactor design is critical, as it must ensure effective heat and mass transfer within reactive solids while controlling gas flow and pressure. Packed-bed reactors with internal heat exchanger tubes are commonly employed and are often supported by condensers or evaporators to manage vapour during charging and discharging[171].

Systems are typically configured as closed-loop arrangements, where reactants circulate under sealed conditions for controlled operation, or as open systems that interact with ambient air. Material selection strongly influences performance, with common candidates including salt hydrates, metal oxides, and adsorption materials. Key design challenges relate to heat and mass transfer limitations and long-term material stability under repeated cycling[172].

171 S. Kiyabu, A. Shkatulov, A. Ahmed, S. M. Greene, H. P. Huinink, and D. J. Siegel, "Materials for thermochemical energy storage and conversion: attributes for low-temperature applications," Mater. Horiz., 2025.

☀ KEY INSIGHT

TCESS can support power systems by storing surplus RE or thermal energy for long-duration and seasonal use, but its current grid role remains limited due to low deployment maturity and slow response compared with BESS.

2.5.3.3 Performance Metrics

The performance parameters of TCESS are compiled in Table 34[172].

Table 34 Performance parameters of TCESS

Parameter	Range
Energy Density (Wh/kg)	100 - 250
Cycles	1,000+
Round trip efficiency (%)	60–80%
Discharge time (hours)	Hours to Months
Depth of Discharge (%)	100
Response time (mins)	Seconds to Minutes

2.5.3.4 Applications

The applications of TCESS are mentioned below[170,173] :

- **Concentrated Solar Power integration:** TCESS can enhance CSP plants by storing high-temperature solar heat through reversible chemical reactions, enabling extended electricity generation after sunset. Compared with molten salt systems, TCESS offers higher energy density and the potential for elevated operating temperatures, which can improve turbine efficiency and dispatch flexibility in RE-dominated grids.
- **LDES:** By coupling thermochemical reactors with heat engines, surplus RE electricity can be converted into stored chemical potential and later reconverted into electrical power. This approach enables multi-hour to multi-day storage, supporting grid stability, RE firming, and system adequacy during prolonged low-generation periods.
- **Industrial waste heat recovery for grid decarbonisation:** TCESS can capture high-temperature industrial waste heat and store it for subsequent use in power generation or process heating. This reduces fossil fuel consumption, improves overall energy efficiency, and indirectly supports grid decarbonisation by lowering industrial electricity demand during peak periods.
- **Seasonal and district ESS:** TCESS systems can store surplus heat, such as from solar

172 GIL Research

173 A. Padamurthy, P. K. Gandla, A. Sheelwant, H. Vemanaboina, P. Paramasivam, and A. G. Ayanie, "Emerging trends and future prospects of thermochemical energy storage systems for building space and water heating applications," Int. J. Energy Res., vol. 2025, no. 1, 2025.

thermal systems or power-to-heat conversion, for seasonal use in district heating networks. Their minimal standby losses make them suitable for long-term storage, enabling higher RE penetration and improved sector coupling between electricity and heat systems.

2.5.3.5 Advantages

Thermochemical energy storage offers several compelling advantages[173]:

- **Very high energy density:** TCESS stores substantially more energy per unit mass or volume than sensible or latent systems, enabling compact configurations suitable for long-duration applications.
- **Long duration with minimal losses:** Energy is stored in chemical form, enabling storage over extended periods with negligible self-discharge, which is advantageous for seasonal RE balancing.
- **Wide operating temperature range:** TCESS can operate from low building temperature levels to above 800 °C for industrial applications, supporting diverse thermal and power uses.
- **No standing thermal losses:** Charged materials can remain near ambient conditions without continuous heating, reducing auxiliary losses and improving operational safety.
- **Low-cost and abundant materials:** Many TCESS materials, such as salts and metal oxides, are relatively inexpensive, widely available, and environmentally benign.
- **Flexible integration:** TCESS can be charged using heat or electricity and can deliver heat, power, or cooling, enhancing system-level flexibility.
- **Long cycle life potential:** Reversible reactions can enable high cycle durability with limited degradation, depending on material stability and reactor design.
- **Modular and scalable design:** Systems can be implemented in modular reactor units and scaled from building-level installations to grid-scale capacities.

2.5.3.6 Global Deployments

Globally, there are a limited deployments or pilots of CHESS compiled in Table 34[174]:

Table 35 Global deployment of CHES

Country	Region	Storage plant	Capacity
Germany	Bavaria	ZAE Bayern zeolite 13X storage system	1.3–1.4 MWh
	North Rhine-Westphalia	DLR $CaO/Ca(OH)_2$ pilot reactor	0.010 MW / 0.100 MWh
Netherlands	North Brabant	Eindhoven Univ. of Technology segmented zeolite 13X pilot	0.0036 MW / 0.012 MWh

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2.5.4 Pumped Thermal Energy Storage Systems

Pumped Thermal Energy Storage System (PTESS), also referred to as Pumped Heat Energy Storage or a Carnot battery, is a long-duration energy storage technology that converts electrical energy into thermal energy and subsequently reconverts it into electricity. During charging, surplus electrical power drives a heat pump that transfers heat from a cold reservoir to a hot reservoir, establishing a temperature difference. During discharge, the stored thermal gradient is utilised within a heat engine to generate electricity. The system operates on fundamental thermodynamic principles, with practical performance bounded by Carnot efficiency.

Unlike pumped hydro, PTESS does not depend on specific geographical features and can utilise relatively low-cost storage media such as rocks, molten salts, thermal oils, or concrete. By employing established power engineering components, including compressors, turbines, and heat exchangers, PTESS offers a scalable and location-independent approach to grid-scale long-duration energy storage, particularly in systems with high RE penetration.

2.5.4.1 Historical Development

The concept of PTESS can be traced to the early twentieth century, when patents proposed storing electricity using reversible heat pump and heat engine cycles. Although technically feasible, these concepts were not realised at the time due to economic and technological limitations. Interest resurfaced in the 1970s in connection with large power plants, but practical development accelerated only in the 2010s with the rapid expansion of wind and solar generation, which increased demand for long-duration storage.

In 2015, a notable modern milestone was developed by Isentropic Ltd. in the United Kingdom, which employed a closed-loop Brayton cycle with gravel-filled packed beds serving as hot and cold reservoirs, demonstrating reversible large temperature operation[175]. Since then, PTESS development has diversified into multiple configurations, including rock-based systems coupled with steam turbines, molten salt Rankine cycle concepts, and supercritical CO_2 cycles targeting higher efficiency. By the mid-2020s, PTESS has progressed from laboratory research to pilot and demonstration projects, positioning it as a promising option for 8-24 hour and longer grid-scale energy storage, although full commercial maturity has not yet been achieved.

2.5.4.2 Working Principle

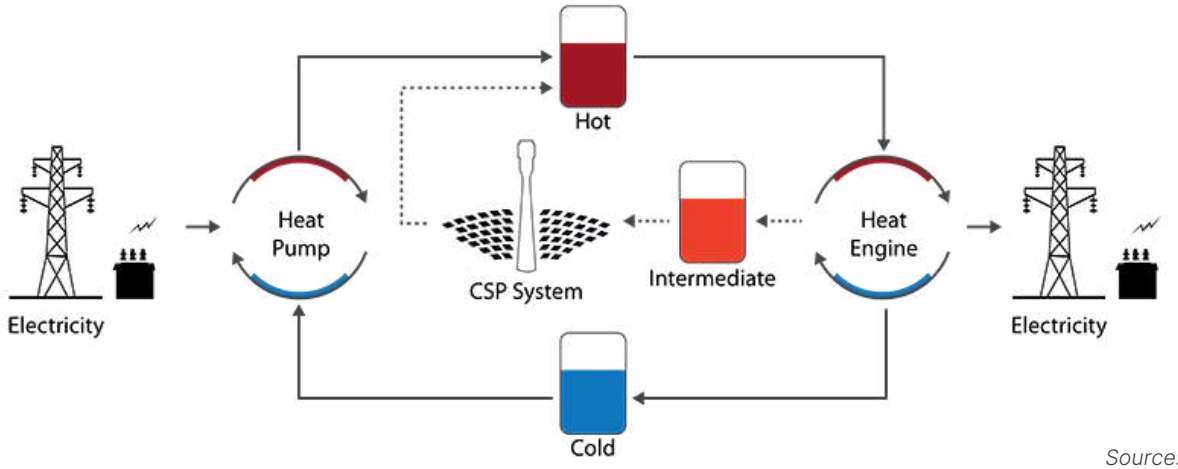
The operation of a PTESS system, illustrated in Figure 73[176], consists of two principal phases: charging, in which electricity is converted to heat, and discharging, in which stored heat is reconverted to electricity.

Charging phase - electrothermal charging: During charging, electricity drives a heat pump cycle, typically based on a Brayton or Rankine configuration. In a Brayton-based system, a motor-driven compressor increases the pressure and temperature of a working gas, which transfers heat to the hot thermal store. The gas is subsequently expanded to reduce its temperature and absorbs heat from the cold store, thereby lowering the cold reservoir temperature. This process transfers heat from the cold reservoir to the hot reservoir, establishing a temperature difference that represents stored energy. Rankine-based systems follow the same thermodynamic principle but involve phase-change processes during compression and expansion.

175 J. Howes, “Concept and development of a pumped heat electricity storage device,” Proc. IEEE Inst. Electr. Electron. Eng., vol. 100, no. 2, pp. 493–503, 2012.

176 National Laboratories for Rockies, "Pumped Thermal Electricity Storage".

Figure 73 Simplified PTESS process diagram



Source: NLR

Thermal storage and discharging phase: Once charged, energy is retained in insulated hot and cold reservoirs, typically using media such as rocks, molten salts, concrete, or chilled fluids. During discharge, the system operates as a heat engine. Heat from the hot store drives a turbine or expander connected to a generator, while rejected heat is transferred to the cold store. In principle, charging and discharging are thermodynamic reversals. In practice, losses arise from turbomachinery inefficiencies and heat exchanger irreversibility. Advanced designs report round-trip efficiencies in the range of 50-65%, depending on operating temperature levels and system optimisation.

2.5.4.3 Key Components

A PTESS system consists of several major subsystems[177]:

- **Heat pump and compressor system:** Consumes electricity during charging to raise the temperature and pressure of the working fluid. Multi-stage compression with intercooling is commonly applied to improve efficiency and manage thermal limits.
- **Heat engine and turbine system:** Operates during discharge to convert stored thermal energy back into electricity. This may employ a Brayton-cycle gas turbine or a Rankine-cycle steam or organic turbine, depending on temperature levels and design objectives.
- **Hot thermal store:** Stores high-temperature energy using media such as molten salts, rocks, concrete, ceramics, or thermal oils. The storage system must be well insulated and designed to accommodate thermal expansion and repeated thermal cycling.
- **Cold thermal store:** Maintains low-temperature energy, typically using chilled liquids, cooled solids, or phase-change media to stabilise the cold-side temperature.
- **Heat exchangers and recuperators:** Facilitate efficient heat transfer between the working fluid and storage media. Internal recuperation enhances cycle efficiency by recovering and reusing residual heat within the thermodynamic loop.
- **Power electronics and control systems:** Manage transitions between charging and discharging, regulate turbomachinery operation, and ensure stable grid integration.

177 L. Chai and S. A. Tassou, "A technology review of pumped thermal energy storage based on CO2 cycles," Appl. Therm. Eng., vol. 281, no. 128586, p. 128586, 2025.

PTESS systems are generally configured as closed-loop cycles, with the working fluid circulating internally. Advanced configurations may incorporate multiple temperature levels or cascaded reservoirs to reduce thermodynamic irreversibility and improve overall system performance.

2.5.4.4 Performance Metrics

Key performance metrics for PTESS are compiled in Table 36[178]:

Table 36 Performance parameter of PTESS

Parameter	Range
Energy Density (Wh/kg)	50 - 100
Cycles	10,000 – 30,000+
Round trip efficiency (%)	50 - 70
Discharge time (hours)	2 – 10
Depth of Discharge (%)	100
Response time (mins)	Seconds to Minutes

2.5.4.5 Applications

PTESS is a versatile storage approach that can serve a variety of applications[176,179]:

- **Grid energy storage for RE integration:** PTESS stores surplus wind and solar generation and releases it during peak demand, enabling large-scale time shifting and reducing RE curtailment. Its relative location independence makes it suitable in regions where pumped hydro is not feasible.
- **Peaking and firm capacity replacement:** PTESS can operate as a multi-hour peaking resource, charging during low-price periods and discharging during peak demand. It can reduce dependency on gas peaker plants and contribute firm capacity in high-RE grids.
- **Energy arbitrage and ancillary services:** PTESS can perform energy arbitrage and provide grid services such as spinning reserve, load-following, and frequency support. Turbine-based configurations can contribute rotational inertia and ramping capability.
- **Integration with CSP and thermal plants:** PTESS can enhance CSP dispatchability or support repurposing of retired thermal power plants by utilising existing turbines and infrastructure, thereby facilitating decarbonisation while retaining grid assets.
- **Industrial and cogeneration applications:** PTESS can supply both electricity and high-temperature process heat, enabling sector coupling and improving overall energy efficiency in industrial facilities.
- **Strategic and long-duration reserve:** With multi-hour to multi-day storage capability, PTESS can support energy security and system resilience during prolonged RE shortfalls or extreme grid events.

178 GIL Research

179 T. R. Davenne and B. M. Peters, “An analysis of pumped thermal energy storage with DE-coupled thermal stores,” Front. Energy Res., vol. 8, 2020.

2.5.4.6 Advantages

PTESS offers a number of distinct advantages as an energy storage solution[176,178]:

- **Large-scale, long-duration capability:** PTESS supports multi-hour to multi-day storage using relatively low-cost thermal media, making it suitable for deep RE integration without sharply increasing cost at longer durations.
- **Geographic flexibility:** Unlike pumped hydro or CAES, PTESS does not require specific topography or geological formations and can be deployed near load centres, RE generation sites, or existing grid infrastructure.
- **Use of abundant materials:** Storage media such as rocks, sand, molten salts, and water are widely available and relatively inexpensive, reducing dependence on critical minerals and facilitating large-scale deployment.
- **Long lifespan and stable cycling:** Thermal storage media generally exhibit limited degradation with cycling, and overall plant lifetimes can exceed 30 years, contributing to reduced lifecycle costs compared with electrochemical storage technologies.
- **Competitive round-trip efficiency:** Advanced PTESS designs report round-trip efficiencies of approximately 60% or higher, positioning it among the more efficient long-duration storage technologies outside pumped hydro.
- **Operational and sector coupling flexibility:** PTESS can deliver electricity, heat, and potentially cooling, enabling multi-service operation, cogeneration, and integration with existing thermal power infrastructure.

2.5.4.7 Challenges and Limitations in Large-Scale Adoption

While PTESS has many appealing features, several challenges and limitations could impede its widespread adoption[175]:

- **Moderate round-trip efficiency:** With round-trip efficiency typically around 60%, PTESS is less efficient than lithium-ion batteries or pumped hydro, which can affect economic performance in markets where efficiency strongly influences revenue.
- **Early-stage deployment risk:** Utility-scale PTESS lacks extensive long-term operational experience, and scaling from pilot projects to large commercial plants introduces technical and financial uncertainty.
- **High upfront capital cost:** Large PTESS facilities require substantial initial investment, which may discourage private developers in the absence of policy support or long-term revenue certainty.
- **System integration complexity:** PTESS integrates turbomachinery, thermal storage systems, and advanced control architectures, increasing engineering complexity and operational requirements.
- **Thermal losses and material stress:** Extended storage durations require high-performance insulation, and repeated thermal cycling can introduce mechanical and material stresses that must be managed through design and maintenance.
- **Regulatory and market barriers:** Storage classification frameworks, grid interconnection requirements, and competition from declining battery costs may constrain adoption unless PTESS demonstrates clear advantages in long-duration or multi-service applications.

2.5.4.8 Global Deployments

Globally, there are a limited deployments or pilots of PTESS compiled in Table 37[180]:

Table 37 Global deployment of PTESS

Country	Region	PTESS plant	Capacity
Germany	Altenwerder	ETES Demonstration Plant	1.4 MW / 130 MWh
	Bergedorf	ETES Pilot Plant	0.7 MW / 5 MWh
United Kingdom	Newcastle	Pumped-Heat Demonstrator	0.15 MW / 0.6 MWh
Spain	Puertollano	Project Humidity (Store2Grid / Store2REpower)	10 MW (charging) / 4 MW (discharging) / 14 MWh
USA	Healy, Alaska (Railbelt)	POLAR PTESS	50 MW / 1,200 MWh (24 hr)

2.6 Chemical Energy Storage Systems

2.6.1 Hydrogen Energy Storage Systems

Hydrogen storage is a crucial component of the hydrogen value chain,that enables the use of hydrogen when and where it is required. Although hydrogen contains a very high amount of energy per unit mass, it is extremely light and occupies a large volume under normal conditions[181]. So, hydrogen cannot be used effectively without converting it into a form that is easier to store, transport, and handle. The term “hydrogen storage” consists of a wide range of technologies from compressed and liquid storage to solid materials and large underground formations, each designed to address the challenges created by hydrogen’s unique properties[182].

The significance of hydrogen storage extends far beyond the technologies themselves. How hydrogen is stored influences the feasibility of fuel-cell vehicles, the practicality of RE hydrogen production, and the role hydrogen can play in long-duration energy storage and industrial decarbonisation. Different storage methods offer different advantages: compressed tanks provide fast refuelling, cryogenic liquids offer higher density, solid-state systems promise safer and more compact storage, and geological formations enable storage at very large scales[183,184]. Yet each approach also has trade-offs in terms of weight, volume, efficiency, cost, and safety, which is why no single technology currently meets the full set of performance targets needed across mobility, grid, and industrial applications.

180 GIL Research

181 E. Rivard, M. Trudeau, and K. Zaghib, “Hydrogen Storage for mobility: a review,” Materials, vol. 12, no. 12, p. 1973, Jun. 2019

182 M. Ni, “An overview of hydrogen storage technologies,” Energy Exploration & Exploitation, vol. 24, no. 3, pp. 197-209, 2006

183 P. K. Panigrahi, B. Chandu, M. R. Motapothula, and N. Puvvada, “Potential benefits, challenges and perspectives of various methods and materials used for hydrogen storage,” Energy & Fuels, vol. 38, pp. 2630-2653, 2024.

184 International Energy Agency, “Global hydrogen review 2024,” 2024. IEA Annual Report on Hydrogen Market and Policy.

2.6.1.1 Historical Development, Storage Pathways and Global Status

Hydrogen storage technology represents a critical enabler for the transition to sustainable energy systems. As a fuel with high gravimetric energy density with no direct CO_2 emissions during combustion, hydrogen must be effectively stored and transported to fulfil its role in decarbonising hard-to-abate sectors. This section examines the historical evolution of hydrogen storage technologies, from early laboratory discoveries to modern commercial deployment, and assesses the current global status of hydrogen storage infrastructure and production capacity. The analysis reveals significant implementation gaps between announced projects and realised capacity, highlighting both technological maturity in certain storage domains and persistent economic and policy challenges. Hydrogen storage research can be traced back to the discovery of hydrogen as an element in the late 17th century. The scientific understanding of hydrogen as a distinct substance and its properties formed the foundation for later storage methodologies. The recognition of hydrogen's potential as an energy carrier emerged gradually through the 20th century, driven by advances in thermodynamic understanding and materials science[185].

The first commercial implementation of gas mixture storage with high content of hydrogen began in 1971 at salt caverns in Cologne, Germany. At this site, industrial gas containing approximately 62% hydrogen was stored at pressures between 8 and 10 MPa. This pioneering project demonstrated the technical feasibility of large-scale hydrogen storage in geological formations. In 1972, a significant advancement occurred when pure hydrogen storage commenced at the same location, establishing salt caverns as a reliable medium for long-term hydrogen retention. The transition from mixed industrial gases to pure hydrogen storage was driven by improving the understanding of salt cavern properties. Salt formations at depths of 500 to 1500 meters proved ideal due to their low porosity, low permeability, high density, and self-healing characteristics. These properties minimize hydrogen leakage and enable caverns to maintain structural integrity over decades. Salt caverns at Cologne and subsequent sites demonstrated that storage lifetimes of 20-40 years were achievable[184].

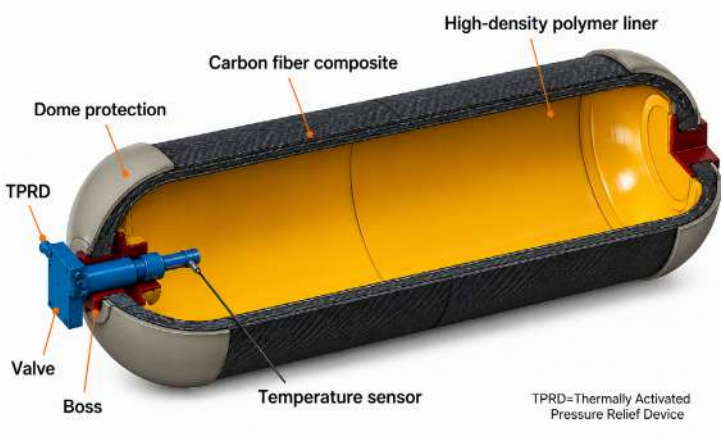
Compressed hydrogen storage evolved from high-pressure steel cylinders operating at 200 bar to increasingly sophisticated composite vessel designs. Traditional Type I vessels are constructed entirely from metal, whereas Type II vessels use a metallic liner reinforced with composite material around cylindrical section. The development of Type III composite vessels, consisting of a metallic liner fully wrapped with fibre-reinforced composite, enabled substantial weight reduction and operating pressures of up to 700 bar, depending on the vessel design and application[184]. Type IV composite vessels as shown in Figure 74 employ non-load-bearing polymer liners fully wrapped with carbon-fibre-reinforced composite, providing significant weight reduction and nominal working pressures of up to 700 bar.

185 W. F. Ekpotu, J. Akintola, M. C. Obialor, and U. Philemon, "Historical review of hydrogen energy storage technology," World Journal of Engineering and Technology, vol. 11, pp. 454-475, 2023.



Photo by Patrick Federi on Unsplash

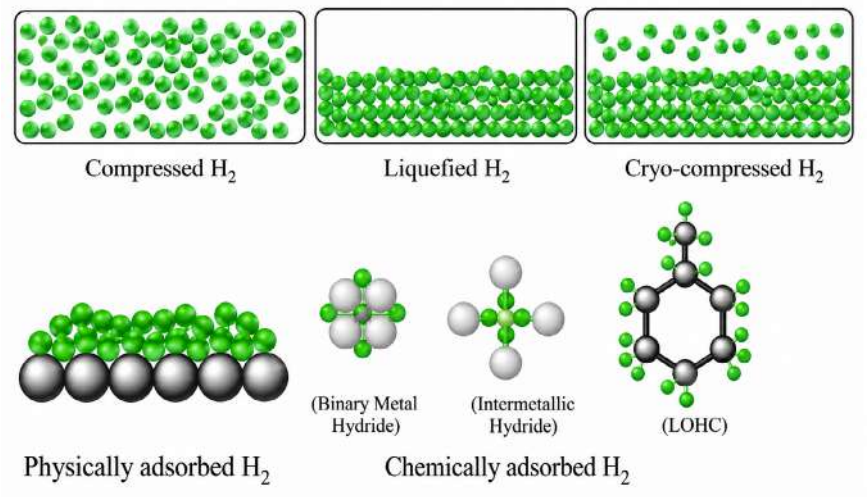
Figure 74 Schematic representation of Type IV composite compressed hydrogen storage tank



Source: E. Rivard et al.; 2019

Cryogenic hydrogen liquefaction as seen from Figure 75[183], was first demonstrated by James Dewar in the late 19th century using vacuum flask technology. Practical liquefaction processes, including the Linde cycle and Joule-Thomson expansion cycle, enable hydrogen storage at atmospheric pressure with densities of approximately 70 kg/m3 at -252.87∘C. Liquid hydrogen storage achieves volumetric densities over 800 times greater than gaseous hydrogen at standard conditions[185].

Figure 75 Schematic illustration of physical and chemical hydrogen storage mechanisms



Source: P. K. Panigrahi et al.; 2024

However, liquid hydrogen storage faces significant technical challenges. Heat transfer from the environment causes hydrogen boil-off at rates of 0.2-0.3% per day during storage and transportation. Energy losses during the liquefaction process consume approximately one-third of the produced hydrogen's energy value. Specialized refrigeration and advanced insulation technologies are essential to minimize energy losses. Despite these limitations, liquid hydrogen storage remains valuable for long-distance transportation and applications requiring rapid energy availability[185].

2.6.1.2 Comparative Analysis of Hydrogen Storage

A quantitative assessment of major hydrogen storage methods reveals distinct advantages and limitations for different applications. Table 38 summarizes key performance metrics for the primary hydrogen storage technologies currently deployed or under development.

Table 38 Comparative analysis of hydrogen storage models

Method	Efficiency (%)	Energy density (kWh/ m²)	Life	Cost (USD/kg)
Metal Hydride	69	244	< 2000 h	9.01 - 19.67
Liquid Hydrogen	40 - 50	2359	300 - 500 days	3.66
Compressed Gas (Type IV)	85	3.3 - 1320	> 20 years	> 466
Salt Cavern Storage	> 60	300	20 - 40 years	1.61

Underground salt cavern storage emerges as the most economically attractive option for large-scale, long-duration applications, with the lowest per-kilogram cost and competitive energy efficiency. Compressed Type IV vessels offer the highest efficiency among aboveground methods but at substantially elevated capital costs. Liquid hydrogen provides the highest volumetric energy density but experiences energy losses and limited storage duration. Material-based systems, while promising, remain economically and technically limited for widespread deployment[185].

2.6.1.3 Applications

Hydrogen storage technologies are being deployed across multiple sectors, each with distinct performance requirements, economic drivers, and integration challenges. The versatility of hydrogen as an energy carrier enables its use in transportation, grid-scale energy storage, RE energy buffering, and industrial processes.

- **Transport:** Compressed hydrogen at high pressure is the dominant onboard storage solution for fuel cell vehicles, offering fast refuelling and high specific energy. While liquid and cryo-compressed options provide higher volumetric density, they introduce additional complexity and energy penalties associated with liquefaction and thermal management. Hydrogen is particularly suited to heavy duty and fleet applications where range requirements and utilisation intensity exceed practical battery capability[181].
- **Grid scale LDES:** Large projects, including salt cavern based systems, integrate electrolysis with underground hydrogen storage to provide multi day to seasonal balancing. Although round trip efficiency is lower than that of batteries, hydrogen enables very high energy capacities and supports firm capacity and adequacy in RE intensive grids[186].
- **RE buffering:** Hydrogen consumes surplus wind and solar generation during low demand periods and reconverts it to electricity during supply deficits. Its scalability makes it suitable for multi day and seasonal storage beyond the economic duration limits of lithium ion systems[183].
- **Industrial and microgrid integration:** On site electrolysis combined with hydrogen storage supports industrial processes, reduces grid dependency, and enables participation in demand response programmes. For applications requiring storage durations exceeding 24 hours, hydrogen can offer cost advantages at scale despite lower round trip efficiency[183].

186 "Advanced Clean Energy Storage Project-Mitsubishi Power Americas, Inc.," Mitsubishi Power Americas, Inc., Jun. 23, 2025.

2.7 Electrical Energy Storage Systems

Electrical energy storage encompasses technologies that store energy directly in electric fields or magnetic field, enabling sub-second power injection and absorption with very high cycling capability. Compared with electrochemical and mechanical options, electrical storage offers exceptional power density and response speed but much lower energy density. As a result, it is particularly suited to power-quality applications, transient stability support, fast frequency response, and ride-through services in grids with high shares of converter-interfaced RE and sensitive industrial loads[44].

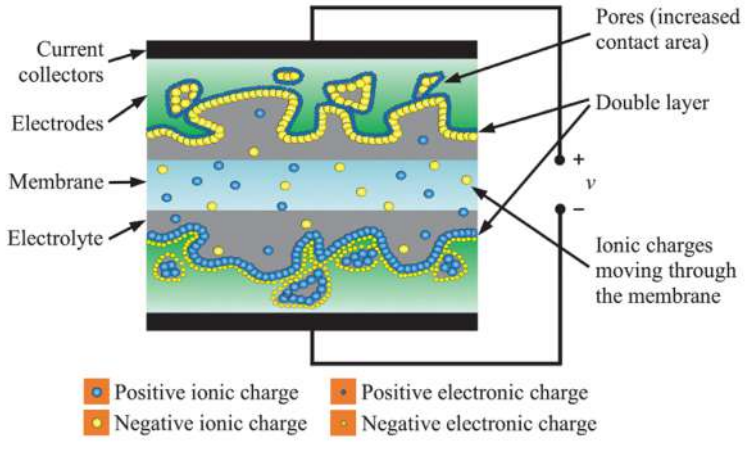
2.7.1 Supercapacitor Energy Storage Systems

Supercapacitor Energy Storage System (SESS) evolved from conventional capacitors into high-capacitance devices by exploiting electrode-electrolyte interfacial effects. Key milestones in the literature include the development of the Electric Double-Layer Capacitor (EDLC) concept in the 1950s, followed by patent activity in 1968, early production in 1979, and commercial availability in the 1980s. Subsequent research and development focused on hybrid supercapacitors and advanced electrode materials, including hybrid concepts in the early 2000s and the development of nanocomposites, micro-supercapacitors, and flexible solid-state architectures during the 2000s and 2010s[187].

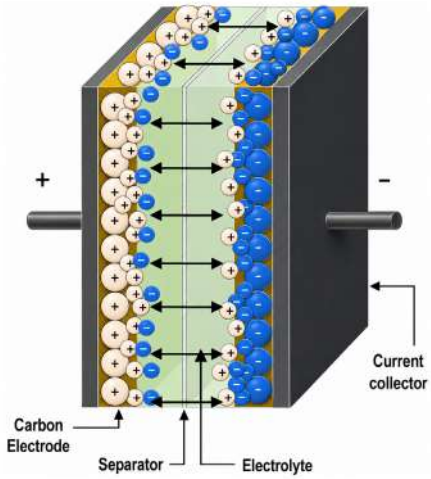
2.7.1.1 Working Principle

SESS, stores energy through electrostatic charge separation at the electrode-electrolyte interface rather than through chemical reactions. As shown in Figure 76, it comprises two porous electrodes, an electrolyte, and an ion-permeable separator. When a voltage is applied, electrons accumulate on the electrodes while ions in the electrolyte form electric double layers near the electrode surfaces, storing energy in the resulting electric field. High capacitance arises from the large surface area of porous carbon electrodes and nanometre-scale charge separation. Because charge storage is non-Faradaic, electrode materials undergo minimal chemical change, enabling fast charge-discharge operation and very high cycle life.

Figure 76 Operation of supercapacitor energy storage systems



Source: A Berrueta et al.; 2019



Source: K Dissanayaka et al.; 2024

187 A. Berrueta, A. Ursúa, I. S. Martín, A. Eftekhari and P. Sanchis, "Supercapacitors: Electrical Characteristics, Modeling, Applications, and Future Trends," in IEEE Access, vol. 7, pp. 50869-50896, 2019.

In addition to EDLC, some supercapacitors exhibit pseudo capacitance, where charge is stored through fast, reversible Faradaic reactions at the electrode surface. Devices combining EDLC and pseudocapacitive behaviour are termed hybrid supercapacitors and offer higher energy density at the cost of increased material ageing[188]. From a circuit perspective, a supercapacitor is typically modelled as a capacitance in series with an Equivalent Series Resistance (ESR). The stored energy in the capacitor is expressed as:

$$E = \frac{1}{2} \times CV^2$$

Here, E is energy stored in capacitor in Joule, C is the capacitance, and V is the terminal voltage. The deliverable power and thermal behaviour are strongly governed by ESR and the allowable voltage range. Low ESR enables high power injection and consumption, whereas excessive voltage or current can lead to overheating or failure. Accordingly, supercapacitors are operated within strict electrical and thermal limits enforced by control and power electronic interfaces.

In practical grid connected applications, supercapacitor cells are connected in series and parallel to meet voltage and energy requirements, with parallel connections increasing capacitance and series connections increasing voltage. Variations among cells can cause voltage imbalance in series strings, making passive or active balancing necessary for safe and reliable operation. Overall, supercapacitors combine interfacial electrostatics and fast ion dynamics to deliver very high power density and cycle life, but with lower energy density than electrochemical storage technologies.

2.7.1.2 Performance Metrics

Key technical performance metrics include specific energy, specific power, efficiency, response/ charge time, lifetime (cycle and calendar), operating voltage window, ESR, and temperature limits. The range of the performance metrics are given in Table 39[189].

Table 39 Performance metrics of SESS

Parameter	Range
Cell voltage (V)	2.3 - 2.75
Charge time/ response	Milliseconds to seconds
Energy density (Wh/kg)	1 - 10
Operating cycles	> 10^5 cycles
Round trip efficiency (%)	93
Operating temperature (°C)	-40 to 85

In addition, commercial examples of SESS show that design choices (electrode, packaging, ESR) shift the energy/power trade-off; reported module-level examples include energy density and power density combinations suitable for high-power, short-duration services.

188 K. Dissanayake and D. Kularatna-Abeywardana, "A review of supercapacitors: Materials, technology, challenges, and renewable energy applications," J. Energy Storage, vol. 96, no. 112563, p. 112563, 2024.

189 GIL Research

2.7.1.3 Applications in Power Systems

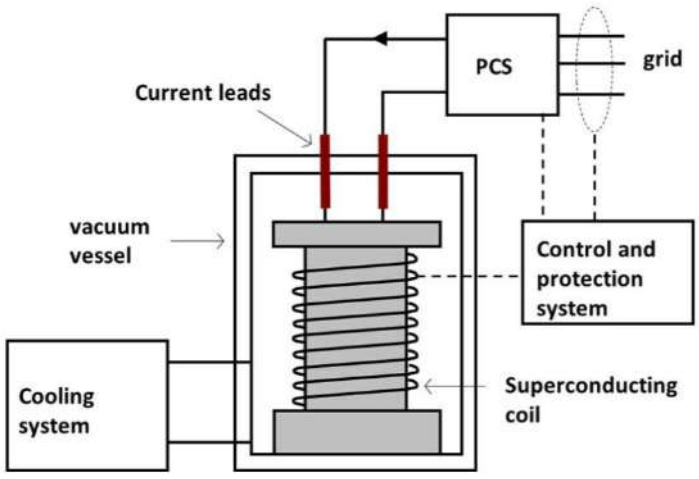
The applications of SESS in power systems are mentioned below[190]:

- **Power quality and voltage support:** SESS can mitigate short duration disturbances such as voltage sags, swells, flicker, and transients by rapidly injecting or absorbing high power. When interfaced through bidirectional converters, they support voltage regulation and improve ride through for sensitive loads.
- **RE integration:** In WTG and solar PV systems, SESS smooth power output, manage transient energy, reduce ramp rate stress on converters, and support DC bus stability during rapid resource changes.
- **Microgrids and converter-dominated systems:** SESS banks provide fast inertia like response, improving stability and power balance under rapid load or generation variations where rotating inertia is limited.
- **Fast frequency response / synthetic inertia:** Despite limited energy capacity, SESS deliver rapid frequency support and are often paired with BESS, with SESS handling fast dynamics and BESS providing longer duration energy.

2.7.2 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) stores electrical energy in the form of magnetic energy in a superconducting coil. The negligible electrical resistance enables millisecond-scale response and high power output with high efficiency, making SMES suitable for short-duration services such as power quality support and dynamic stability control. However, the required cryogenic system introduces significant cost and system complexity. A schematic diagram of SMES is shown in Figure 77[191].

Figure 77 Schematic representation of superconducting magnetic energy storage



Source: EERA; 2019

190 L. Zhang, X. Hu, Z. Wang, F. Sun, and D. G. Dorrell, "A review of supercapacitor modeling, estimation, and applications: A control/management perspective," Renew. Sustain. Energy Rev., vol. 81, pp. 1868–1878, 2018.

191 European Energy Research Alliance, "EERA Joint Program SP5 – Superconducting Magnetic Energy Storage Fact Sheet 01", March 2019.

2.7.2.1 Working Principle

A SMES operates electrically as a large inductor whose winding is made of superconducting material. Electrical energy is stored directly in the magnetic field generated by a DC current circulating in the superconducting coil. The stored energy is given by:

$$E = \frac{1}{2} \times LI^2$$

Here, E is the energy stored in inductor in Joules, L is the coil inductance and I is the coil current. Because the coil operates in the superconducting state, DC resistive losses are negligible, allowing energy to be stored as persistent current with very high efficiency[192]. In practical implementations, an SMES system consists of three tightly coupled elements namely a superconducting coil, a cryogenic system to maintain superconductivity, and a Power Conversion System (PCS) that interfaces the DC coil with the AC grid. During charging, the PCS converts AC power from the grid into DC and applies a controlled voltage across the coil terminals.

Once the desired current level is reached, an SMES retains energy by maintaining the coil current approximately constant. In the superconducting state, circulating current is sustained with negligible dissipation, and the magnetic field acts as an energy reservoir until discharge is commanded. Energy retention losses are therefore dominated by cryogenic refrigeration power and auxiliary systems rather than electrical losses in the coil. During discharge, the PCS reverses power flow by applying an appropriate voltage polarity across the coil, causing the current to ramp down.

The decreasing magnetic field induces electrical power that is converted by the PCS and delivered to the AC system. The PCS regulates active and reactive power to meet application requirements such as voltage sag compensation, oscillation damping, and rapid load balancing. Maintaining superconductivity requires cryogenic operation of the coil. Conventional low-temperature superconductors operate near liquid helium temperatures, while high-temperature superconductors enable operation at higher temperatures, reducing refrigeration burden. The cryogenic system, together with control and protection functions, is integral to safe and stable SMES operation, providing fault protection, controlled current ramping, and secure grid interfacing[192].

So, the working principle of SMES directly links magnetic energy storage in a lossless superconducting inductor with fast, bidirectional power electronic control. This enables millisecond-scale response, very high power capability, and high cycle efficiency, while limiting practical application to short-duration services due to cryogenic cost and system complexity.

192 B. B. Adetokun, O. Oghorada, and S. J. Abubakar, “Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications,” J. Energy Storage, vol. 55, no. 105663, p. 105663, 2022.



2.7.2.2 Performance Metrics

SMES is a high-power, short-duration storage option with very fast response. Table 40 summarises key technical performance metrics of SMES[193].

Table 40 Performance matrices of SMES

Parameter	Range
Energy density (Wh/kg)	0.5 - 10
Operating cycles	> 10^5 cycles
Round trip efficiency (%)	90-95
Operating temperature (°C)	-269 to -196
Response time	Milliseconds to seconds

2.7.2.3 Applications in Power Systems

The applications of super capacitor in power systems are mentioned below[191,192].

- **Power quality for industrial loads:** SMES can inject power almost instantaneously, making it effective for short events like voltage dips, flicker mitigation, rapid stabilization that disrupt sensitive industrial processes. This includes mitigation of voltage dips and fast active-power support for power-quality continuity.
- **Grid stability support:** SMES can modulate real power rapidly via its PCS, so it is suitable for damping electromechanical oscillations and supporting system frequency control over very short horizons; in practice it complements slower energy storage by addressing the fast component of disturbances.
- **Dynamic voltage and reactive support via converter integration:** SMES can be integrated with converter-based compensation devices like FACTS-like control structures to coordinate real/reactive power injection, improving transient voltage stability and stabilizing weak grids.

193 GIL Research



Pexel

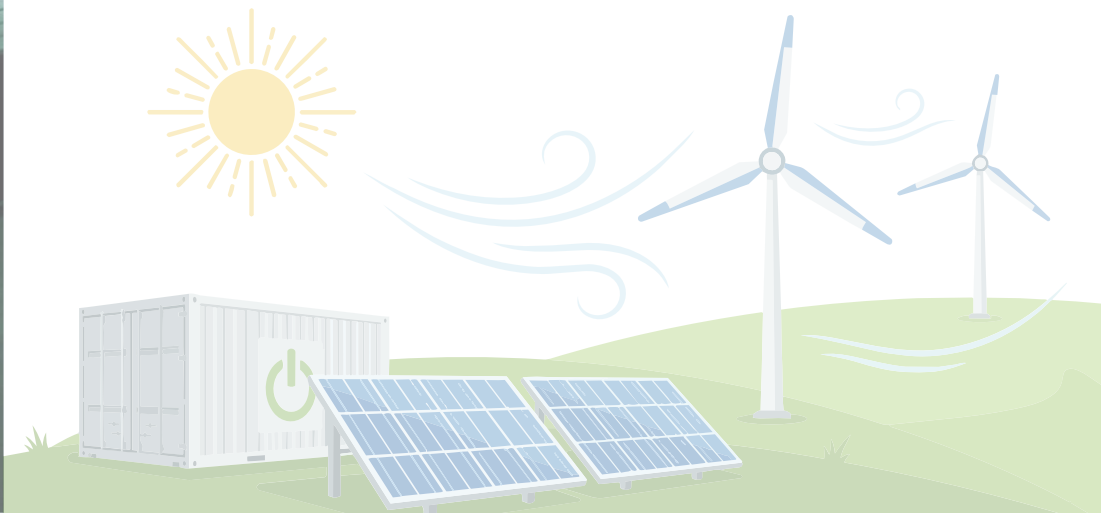
CHAPTER 3

03 POWER CONVERSION AND CONTROL OF ENERGY STORAGE SYSTEMS



Summary

- Explains the role of PCS as the electrical interface enabling controlled bidirectional active and reactive power exchange between ESS and the grid.
- Classifies ESS interfaces into converter based, machine based, and hybrid electromechanical systems, highlighting differences in controllability, inertia contribution, fault current behaviour, and grid code compliance.
- Reviews key PCS architectures, including single stage, two stage, multilevel, cascaded H bridge, modular multilevel, fixed speed, and variable speed machine based configurations.
- Compares grid following and grid forming ESS control, with emphasis on weak grid operation, black start, virtual inertia, islanding capability, and stability support in low inertia power systems.





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3.1 Introduction to Power Conversion in ESS

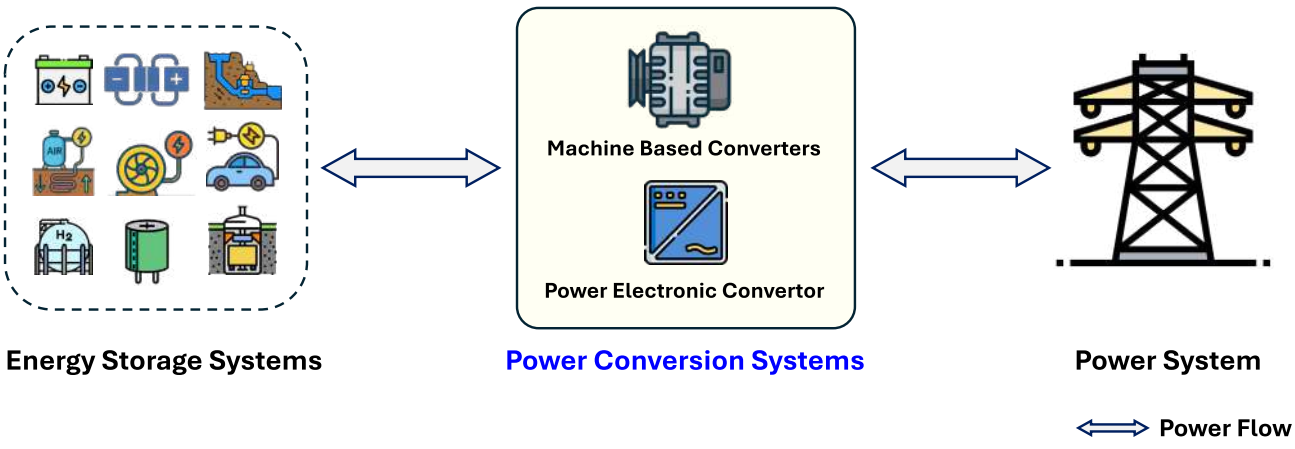
ESS interface with power systems through an electrical interface that enables controlled, bidirectional exchange of active and reactive power. Irrespective of the underlying storage medium, stored energy must ultimately be converted into electrical form for grid injection and reconverted during charging. This function is performed by the PCS, which regulates voltage, current, frequency, and power flow at the Point of Interconnection (POI).

In converter-based ESS, the PCS typically comprises power electronic converters that synthesise AC waveforms from DC sources and regulate current within prescribed limits in accordance with interconnection standards. In machine-based ESS, such as turbine-generator configurations, the electrical interface is realised through synchronous or induction machines equipped with excitation and governor control systems that regulate voltage and frequency response. The design and performance of the PCS directly influence dynamic response capability, short-circuit behaviour, harmonic emissions, and compliance with grid codes, particularly in systems with high penetration of converter-based resources. Accordingly, power conversion constitutes not merely an energy transfer function but a primary determinant of ESS controllability, stability contribution, and operational reliability in modern power systems.

3.1.1 Role of Power Conversion Systems

PCS constitute the controllable electrical interface through which ESS exchange power with the grid. As shown in Figure 78, PCS ensure that energy stored in electrochemical, mechanical, thermal, or chemical form is converted into grid-compatible electrical power within defined operational limits[194].

Figure 78 Interconnection of ESS with power system



- **Electrical interface between storage medium and grid:** The PCS establishes the physical and control boundary between the storage unit and the point of common coupling. It regulates voltage, frequency, and current to ensure compliance with interconnection requirements and maintains injected or absorbed power within prescribed limits.
- **Bidirectional power conversion:** The PCS enables controlled charging and discharging by converting electrical energy into stored form and reconverting it for grid injection. This bidirectional functionality includes active and reactive power control and must satisfy specified ramp-rate and current constraints.

194 A. B. Ahmad et al., "Renewable integration and energy storage management and conversion in grid systems: A comprehensive review," Energy Rep., vol. 13, pp. 2583–2602, 2025.



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Rsparks3, CC0, via Wikimedia Commons

- **Decoupling of storage dynamics from grid dynamics:** Internal storage processes, such as electrochemical reactions or turbine mechanical inertia, operate on time scales that differ from grid disturbances. The PCS implements fast control loops and current regulation to decouple storage medium constraints from short-term grid transients.
- **Provision of controllability and dispatch capability:** The PCS translates supervisory control commands into real-time electrical outputs, enabling participation in energy scheduling, frequency regulation, and voltage support services. Its control architecture determines response speed, stability contribution, and compliance with operational codes.

3.1.2 Classification of ESS by PCS Type

ESS can be systematically classified according to the nature of their electrical interface with the grid. This classification is essential because interface technology determines controllability, fault behaviour, dynamic response capability, and compliance characteristics under interconnection standards.

- **Converter-based systems:** In converter-based ESS, the storage medium is connected to the grid through a power electronic converter that synthesises AC voltage or injects controlled current. Representative technologies include ECES, flywheels with full converters, electrical ESS, electrolyser and fuel cell systems. Fault current contribution is typically limited by semiconductor current ratings, and dynamic response is governed primarily by control algorithms rather than inherent electromechanical inertia[195].
- **Machine-based systems:** Machine-based ESS interface with the grid through synchronous or induction machines driven by turbines or other mechanical prime movers. PHS and conventional CAES are representative examples. These systems inherently contribute short-circuit current and rotational inertia, and their dynamic behaviour is shaped by governor and excitation control systems consistent with generator standards[196].
- **Hybrid electromechanical converter systems:** Hybrid systems combine rotating electrical machines with partial or full power electronic conversion stages. Examples include variable-speed PHS with full converter interfaces and doubly fed machine configurations. These architectures provide enhanced controllability and variable-speed operation while retaining selected electromechanical characteristics such as inertia contribution[197].

195 M. G. Molina, "Energy Storage and Power Electronics Technologies: A Strong Combination to Empower the Transformation to the Smart Grid," in Proceedings of the IEEE, vol. 105, no. 11, pp. 2191-2219, Nov. 2017.

196 Q. Fu, C. Dai, S. Bu, and C. Y. Chung, "Integrating power electronics-based energy storages to power systems: A review on dynamic modelling, analysis, and future challenges," Renew. Sustain. Energy Rev., vol. 213, no. 115460, p. 115460, 2025.

197 K. R. Vasudevan, V. K. Ramachandaramurthy, G. Venugopal, J. B. Ekanayake, and S. K. Tiong, "Variable speed pumped hydro storage: A review of converters, controls and energy management strategies," Renew. Sustain. Energy Rev., vol. 135, no. 110156, p. 110156, 2021.

3.1.3 Functional Requirements of PCS

PCS must satisfy defined functional requirements as shown in Figure 79 to ensure safe, reliable, and compliant operation of ESS within interconnected power systems. These requirements are established by interconnection standards, operational codes, and system stability criteria.

Figure 79 Requirements from power conversion systems



- **Active power regulation:** The PCS shall regulate active power injection or consumption within rated limits and in accordance with dispatch commands or local control objectives. This includes implementation of ramp-rate limits, droop characteristics, and power set point tracking to support frequency regulation and scheduled energy delivery[197]. Accurate active power control is essential to maintain system balance and prevent frequency deviations.
- **Reactive power capability:** The PCS shall provide reactive power support within specified capability curves at the point of interconnection. Interconnection standards typically require operation over defined power factor ranges and the capability to inject or absorb reactive current during voltage disturbances. Reactive power regulation supports voltage stability, reduces network losses, and enhances system strength under weak grid conditions[198].
- **Fast dynamic response:** The PCS shall demonstrate rapid response to changes in frequency, voltage, or dispatch signals, with response times ranging from milliseconds for converter-based systems to seconds for machine-based systems. Fast active power response is particularly critical in low-inertia systems where frequency nadir and RoCoF constraints are significant. Control bandwidth and current limiting mechanisms determine achievable dynamic performance[198].
- **Fault ride through:** The PCS shall remain connected and operate in accordance with fault ride-through requirements during defined voltage disturbances. This includes controlled

198 M. S. Rafaq, B. A. Basit, S. A. Q. Mohammed, and J.-W. Jung, "A comprehensive state-of-the-art review of power conditioning systems for energy storage systems: Topology and control applications in power systems," IET Renew. Power Gener., vol. 16, no. 10, pp. 1971–1991, 2022.

current injection, reactive current prioritisation where mandated, and stable post-fault recovery. Converter-based systems typically limit fault current to protect semiconductor devices, whereas machine-based systems may contribute higher short-circuit currents governed by their reactance characteristics[199].

- **Grid code compliance:** The PCS shall comply with applicable interconnection and operational standards covering voltage limits, frequency ranges, harmonic emissions, protection coordination, and communication requirements. Compliance ensures interoperability, safe integration, and predictable system behaviour under normal and abnormal operating conditions. Certification and testing procedures verify adherence to these requirements prior to commercial operation[199].

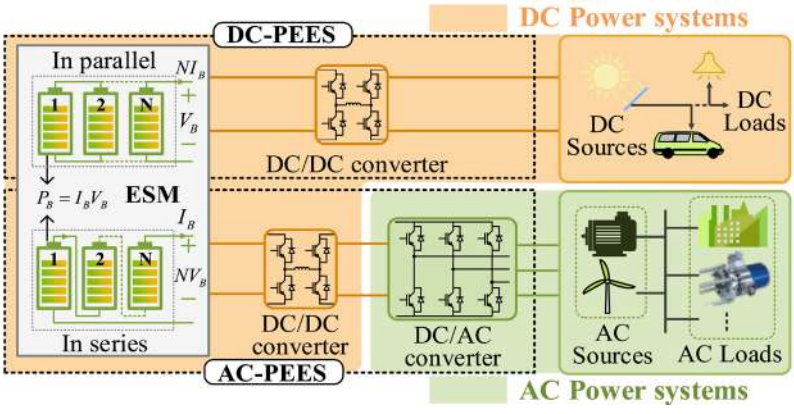
3.2 Power Conversion System Architecture

PCS architectures define the structural configuration through which ESS interface electrically with the grid. These architectures can be broadly categorized into converter based conversion systems, machine based conversion systems, and variable speed or hybrid electromechanical converter systems. Each configuration differs in its method of AC power synthesis, dynamic response characteristics, fault current contribution, and controllability under grid disturbances. The selection of architecture directly influences harmonic performance, inertia contribution, protection behaviour, and compliance with interconnection requirements. A systematic understanding of these architectures is therefore essential for evaluating technical suitability across diverse storage technologies and grid operating conditions.

3.2.1 Converter-Based Conversion Systems

Converter-based conversion systems interface an energy storage device to an AC network using power electronic stages that regulate charging and discharging while satisfying AC-side requirements. The typical architecture of integrating ESS with DC and AC power systems is shown in Figure 80[196]. A primary structural distinction is between single-stage interfaces, in which a single bidirectional AC-DC converter directly exchanges energy with the grid, and two-stage interfaces, in which a dedicated DC-DC stage regulates the storage side while a DC-AC stage performs grid-side conversion. The selection of topology is driven by storage voltage range, required DC-link voltage, isolation requirements, efficiency targets, and fault containment considerations.

Figure 80 PCS for energy storage system integration with grid



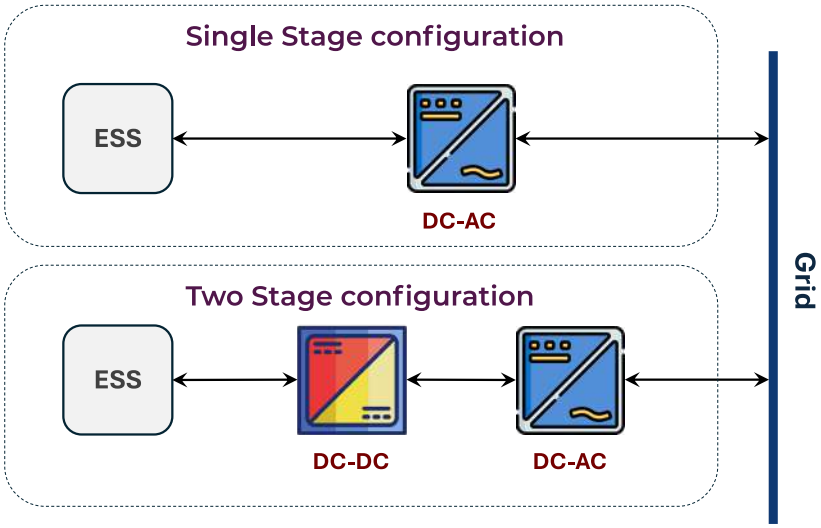
Source: Q. Fu et al.; 2025

199 "IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," in IEEE Std 2800-2022.

3.2.1.1 Converter topology families and architectural placement

Standard two-port converter structures are implemented as either single-stage or two-stage interfaces as shown in Figure 81. In single-stage configurations, a bidirectional AC-DC converter performs both grid interfacing and storage charge control. This reduces component count and associated losses but constrains AC voltage synthesis relative to the DC-link voltage and imposes tighter constraints on storage voltage selection[198].

Figure 81 PCS topologies for ESS integration with grid



In two-stage configurations, a DC-DC stage regulates storage-side voltage and current, while a DC-AC converter stage interfaces with the grid. This arrangement improves flexibility for low-voltage storage devices and enables modular parallel connection of multiple storage modules to a common DC bus when appropriately controlled.

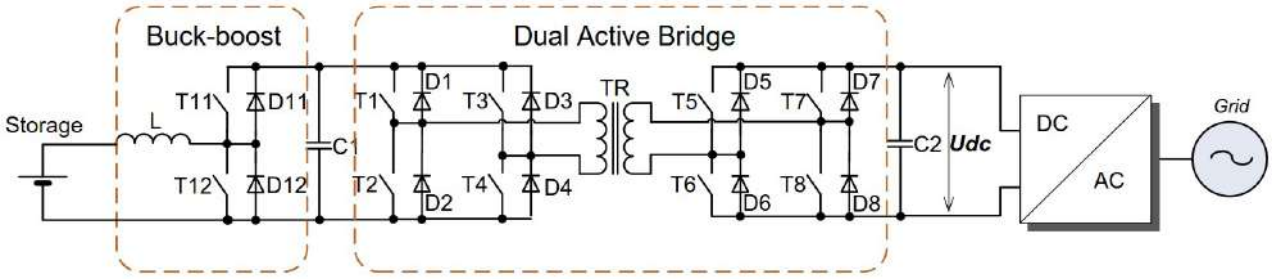
3.2.1.2 Bidirectional DC-DC conversion

In two-stage architectures, a widely adopted DC-DC approach is the bidirectional buck-boost family, supporting both step-down and step-up operation depending on charging or discharging mode. The bidirectional half-bridge with an inductor is commonly used due to simplicity and high efficiency. However, limitations include restricted boost ratio, controllability constraints associated with diode conduction paths, and vulnerability to DC-link short circuits unless additional fault isolation measures are implemented. Variants such as cascaded buck-boost arrangements extend operating range and avoid output polarity reversal in cascaded forms, at the expense of increased component count and control complexity.

Where galvanic isolation or higher conversion ratio is required, isolated DC-DC stages employ transformer-coupled structures. Configurations include dual active bridge and dual half-bridge topologies, with the dual active bridge widely adopted as an isolated solution as shown in Figure 82[200]. In some cases, a preceding buck-boost stage regulates the dual active bridge input to maintain high efficiency near a defined operating point. The transformer provides electrical isolation and additional voltage conversion capability, with the principal trade-off being increased component count, losses, and cost.

200 V. Fernão Pires, E. Romero-Cadaval, D. Vinnikov, I. Roasto, and J. F. Martins, “Power converter interfaces for electrochemical energy storage systems – A review,” Energy Convers. Manag., vol. 86, pp. 453–475, 2014.

Figure 82 Bidirectional DC-DC converter with dual active bridge



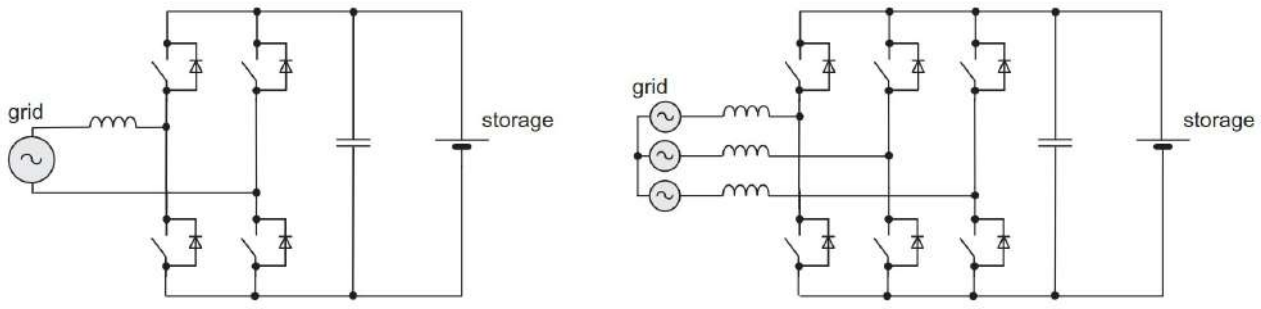
Source: V. F. Pires et al.; 2014

3.2.1.3 Single Stage DC-AC conversion

Single-stage converter-based conversion architectures employ a bidirectional AC-DC Voltage Source Converter (VSC) as the sole grid interface, directly coupling the AC system to the storage side through a controlled DC link. Such non-isolated single-stage topologies are widely recognised as among the simplest and most efficient approaches for interfacing energy storage with AC networks. Full-bridge structures are commonly used for single-phase systems, while three-phase bidirectional converters are applied for three-phase interconnection as shown in Figure 83[200]. The converter regulates power exchange through modulation and closed-loop control of AC currents while maintaining the DC-link voltage within defined operating limits.

The principal advantages of the single-stage approach are reduced component count and a direct energy path, typically resulting in lower conversion losses and reduced cost compared to multi-stage solutions. However, conventional VSC operation is generally limited to buck behaviour, such that the achievable AC voltage magnitude is constrained by the DC-link voltage. Consequently, low-voltage storage systems may require extensive series connection to satisfy DC-link requirements, increasing sensitivity to module-level failures unless bypass provisions are incorporated. Converter reliability is also influenced by shoot-through risk associated with gating errors, necessitating dead-time insertion, which can increase waveform distortion. In neutral-connected implementations using split DC-link capacitors, capacitor stress may increase under highly unbalanced conditions. Single-stage architectures are therefore most suitable where storage voltage can be appropriately matched to the required DC-link level and where system design accommodates these constraints. Variants such as impedance-source, dual-buck, and matrix converter structures have been developed to address specific limitations, including boost capability and shoot-through mitigation[200].

Figure 83 (a) Single phase and (b) three phase DC-AC VSC



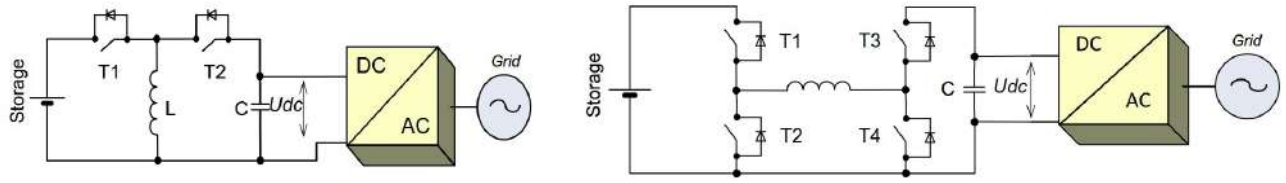
(a) (b)

Source: V. F. Pires et al.; 2014

3.2.1.4 Double Stage DC-AC Conversion

A double-stage interface converter comprises a DC-DC conversion stage followed by a DC-AC converter stage, as illustrated by the two-stage structure in Figure 84[200]. The functional role of the DC-DC stage is to boost or regulate the storage-side DC voltage to a level suitable for the converter stage, enabling direct interfacing to a low-voltage AC grid even when the storage voltage is comparatively low or varies over a wide operating range. Within non-isolated DC-DC options, multi-year research experience indicates that the conventional bidirectional buck-boost topology is a practical choice for the DC-DC stage. The bidirectional buck-boost converter is derived from the classical buck-boost structure by incorporating a dual switch–diode arrangement, enabling step-down and step-up operation in both charging and discharging directions. This bidirectional capability makes it suitable for applications where storage voltage varies significantly, while the converter stage performs DC-AC conversion under closed-loop control to exchange power with the grid at the required voltage and frequency.

Figure 84 DC/DC converters for ESS: (a) bidirectional buck-boost converter (a), bidirectional buck-boost cascade converter



Source: V. F. Pires et al.; 2014

The main advantages of the bidirectional buck-boost DC-DC stage are low component count and structural simplicity, which support cost-effective implementation of the two-stage architecture. A limitation is similar to the classical buck-boost converter, the bidirectional buck-boost topology produces a reversed output voltage, which can restrict its implementation depending on grounding and polarity requirements at the DC link. For applications requiring step-up and step-down operation without output voltage reversal, a buck-boost cascade topology may be employed, formed by cascading a buck converter with a boost converter. This arrangement increases component count but reduces electrical and thermal stress and provides a non-reversed output voltage[201].

At the architectural level, the two-stage approach can avoid series connection of storage elements by using multiple DC-DC modules connected in parallel to a common DC bus. This enables independent control of each storage element and supports a DC distribution configuration, provided that the control system prevents circulating currents arising from unequal DC-DC output voltages. In practice, this architecture is applied where wide storage voltage variation must be accommodated, where modular scaling is required, or where isolation or higher boost ratios are needed through extensions such as combining a buck-boost stage with an isolated converter. These enhancements improve flexibility but increase component count and conversion losses[201].

3.2.1.5 Two-level and three-level VSCs

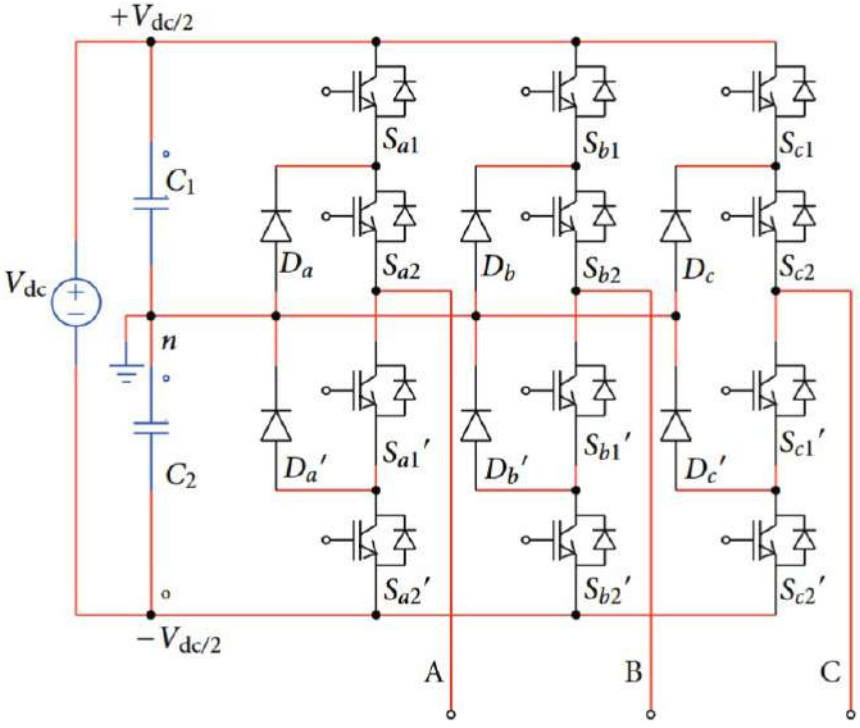
Two-level VSC as shown in Figure 83 (a), are widely used as the baseline DC-AC interface in converter-based conversion systems due to their low device count and straightforward modulation and control implementation. In energy transfer from storage to the AC grid, the converter typically performs a buck function, meaning the AC output voltage cannot exceed the DC-link voltage.

201 M. Liu et al., “A Review of Power Conversion Systems and Design Schemes of High-Capacity Battery Energy Storage Systems,” in IEEE Access, vol. 10, pp. 52030-52042, 2022.

Consequently, the DC link must be designed at a higher voltage than the required AC output. This constraint can necessitate series connection of storage modules when storage voltage is low, introducing reliability concerns because failure of a single module may require replacement or external bypass. The two-level structure is also exposed to shoot-through risk arising from cross-conduction, which necessitates dead-time insertion and can contribute to waveform distortion[202]. These characteristics make the two-level converter most suitable for low- to medium-voltage applications where DC-link voltage is sufficient and where simplicity, cost, and efficiency are prioritised over reduced device voltage stress and enhanced waveform quality.

Three-level VSC are adopted when higher-voltage operation or improved waveform quality is required, since multilevel topologies synthesise the desired AC voltage from multiple DC voltage levels and reduce the voltage blocking requirement of each power switch. A common three-level implementation is the neutral-point-clamped converter as shown in Figure 85[203], which divides the DC-side voltage using a series string of capacitors to generate multiple voltage levels. This approach can provide high efficiency and cost-effective operation, but it requires capacitor voltage balancing control. The neutral-point-clamped structure may exhibit unequal loss distribution among devices and is generally not extended to a high number of levels beyond three without additional complexity. Active neutral-point-clamped variants increase the number of switching states available for the zero output level, enabling improved loss distribution and higher switch utilisation at the expense of increased component count[202].

Figure 85 Three level VSC with neutral point clamped



Source: P. Chaturvedi et al.; 2014

Three-level converters are therefore applied where reduced device voltage stress, improved output waveform quality, and medium-voltage interfacing requirements justify multilevel synthesis, while accepting additional control and hardware complexity relative to two-level conversion.

202 L. S. Xavier, C. V. De Sousa, H. A. Pereira, and V. F. Mendes, "Design and performance comparisons of power converters for battery energy storage systems," Int. J. Circuit Theory Appl., vol. 51, no. 7, pp. 3146–3166, 2023.

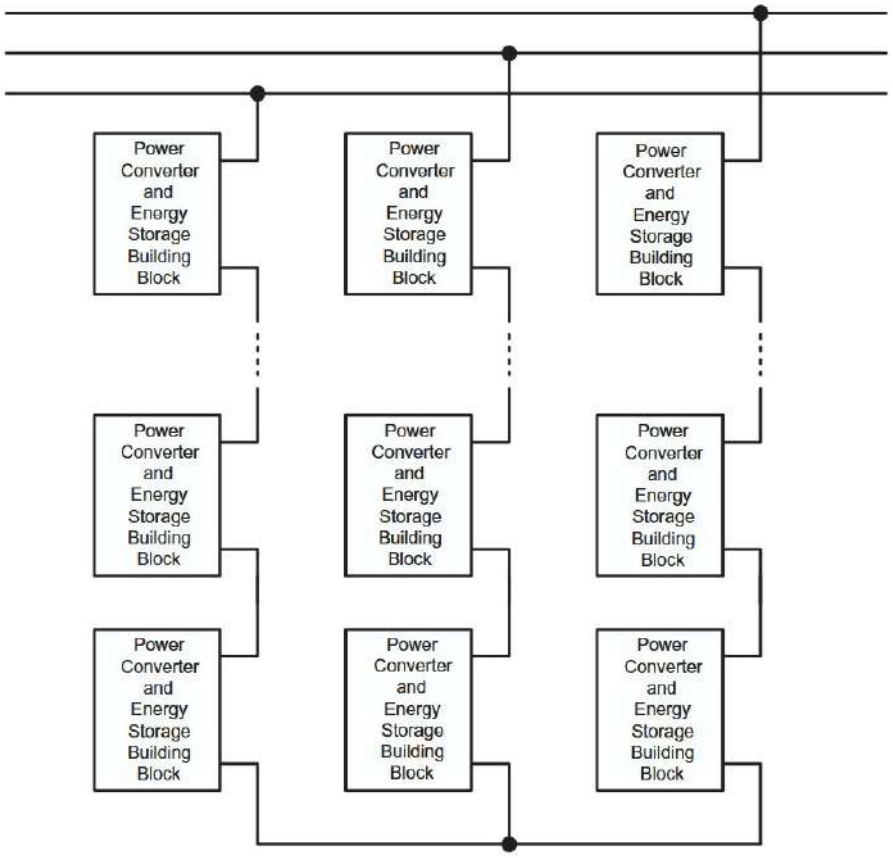
203 P. Chaturvedi, S. Jain, and P. Agarwal, "Carrier-Based common mode voltage control techniques in Three-Level Diode-Clamped inverter," Advances in Power Electronics, vol. 2012, pp. 1–12, Sep. 2012.

3.2.1.6 Cascaded H-bridge multilevel converters

Cascaded H-bridge converters connect multiple H-bridge cells in series, with each cell supplied by an independent DC source as shown in Figure 86. This structure enables modular scaling of AC voltage while distributing device voltage stress across individual cells. The modular arrangement supports high-quality voltage synthesis with lower harmonic distortion than two-level conversion at comparable switching frequency, thereby reducing filtering requirements.

A key advantage for storage applications is module-level fault management. A failed cell can be bypassed or isolated, allowing the overall converter to continue operating in a derated mode rather than requiring complete shutdown, subject to the adopted fault-tolerant design. The same modularity enables architectures in which local DC-DC stages decouple storage-unit voltage from the converter cell DC link[200]. This widens the effective operating range on the AC side while maintaining cell-level control flexibility.

Figure 86 Energy storage system based on the cascade H-bridge multilevel converter



Source: V. F. Pires et al.; 2014

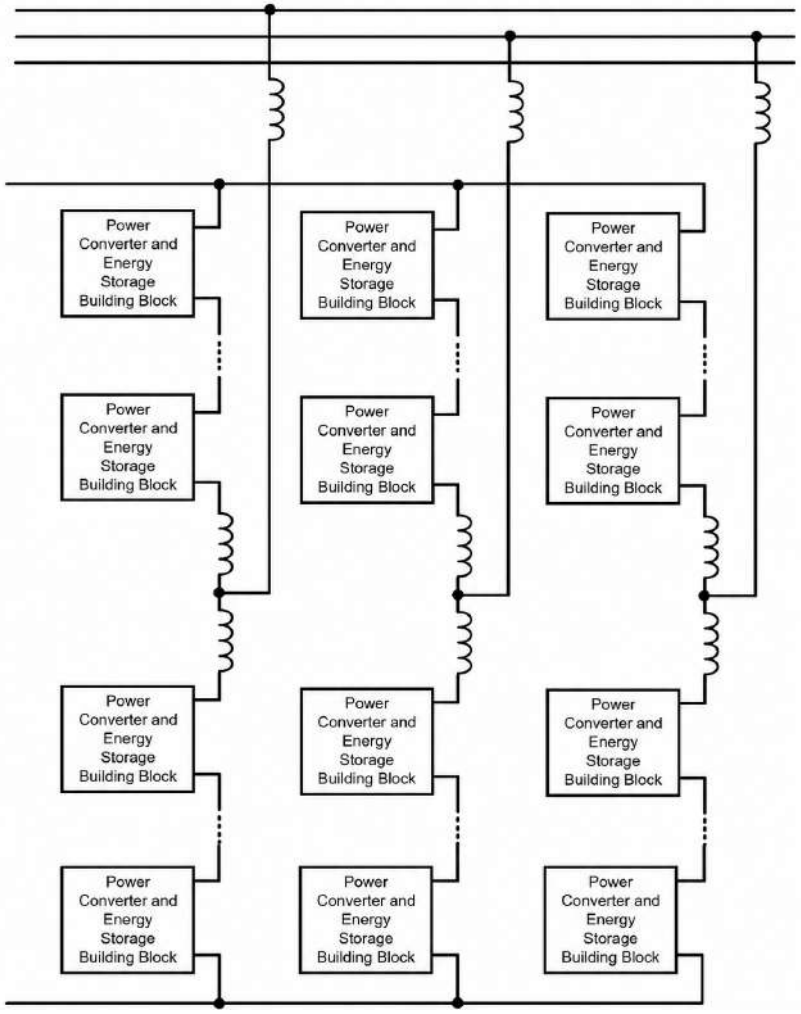
The principal disadvantages arise from the requirement for multiple isolated or independently managed DC sources, together with increased component count and more complex control, including cell-level voltage regulation and power sharing among modules. Implementation complexity increases further when bypass capability, redundancy, and coordinated protection schemes are incorporated to meet availability requirements. The large number of semiconductor devices can also increase footprint, and maintenance demands relative to simpler converter structures. Cascaded H-bridge converters are therefore most suitable for applications that benefit from modular medium-voltage synthesis and distributed DC sources, such as medium-voltage drives, static reactive power compensation systems, and grid-connected interfaces where DC sources are inherently

segmented into modules, including modular storage strings and hybrid RE–storage plants designed around distributed DC links[204].

3.2.1.7 Modular multilevel converters

Modular multilevel converters are a class of multilevel VSC developed by combining principles from cascaded H-bridge and flying capacitor topologies as shown in Figure 87[200]. The structure consists of a series connection of identical submodules, commonly half-bridge cells, together with arm inductors. This arrangement enables scalable voltage synthesis and makes the topology well suited for medium and high voltage conversion applications. Owing to this modularity, the topology has been examined for medium-voltage storage interfaces. Alternative submodule-level implementations include reduced-component cells, cells incorporating an interleaved boost stage to reduce inductor current ripple, and cells based on a dual active bridge structure to achieve high efficiency and high boost ratios. These variations aim to improve performance and extend voltage conversion capability at the submodule level.

Figure 87 Modular multilevel VSC



Source: V. F. Pires et al.; 2014

The key advantages of the modular multilevel approach arise from its modular construction and multilevel waveform synthesis capability. Multilevel converters inherently reduce harmonic distortion

204 K. T. Maheswari, R. Bharanikumar, V. Arjun, R. Amrish, and M. Bhuvanesh, "A comprehensive review on cascaded H-bridge multilevel inverter for medium voltage high power applications," Mater. Today, vol. 45, pp. 2666–2670, 2021.

and electromagnetic interference, while modular structures can lower manufacturing complexity through repetitive cell design. The presence of redundant submodules can enhance reliability and support SoC balancing across distributed storage elements. For modular multilevel topologies, the modular structure also reduces output filter requirements due to improved waveform quality. When a large number of submodules is employed, cell-level bypass capability enables continued operation under certain fault conditions, improving availability. The principal disadvantages include increased cost resulting from the large number of semiconductor devices and associated control hardware. Second-harmonic current ripple can appear in storage cells, particularly under unbalanced or low-frequency operating conditions. In modular multilevel converters specifically, circulating currents within each phase arm require dedicated control strategies and additional inductance, increasing system complexity. Consistent with these characteristics, modular multilevel converters are applied where medium- and high-voltage interfacing, modular scalability, and high-quality AC waveform synthesis are prioritised, including medium-voltage storage interfaces and other high-power grid-connected conversion applications[205].

Across converter based conversion systems for ESS, converter selection is primarily a trade-off among voltage scalability, efficiency, waveform quality, controllability, and fault containment. Single stage VSC interfaces offer structural simplicity and low losses, while double stage architectures add a bidirectional DC to DC stage, often buck boost based, to accommodate wide storage voltage variation and improve DC link regulation. Multilevel DC to AC options, including three level NPC variants, cascaded H bridge, and modular multilevel converters, are adopted to reduce device voltage stress and improve harmonic performance at higher voltages, with added component count and control complexity.

3.2.2 Machine-Based Conversion Systems

Machine-based conversion systems interface energy storage to the grid through rotating electrical machines coupled to a mechanical conversion train. This interface class is defined by electromechanical energy conversion, where power exchange is governed by turbine and machine dynamics and regulated through governor and excitation control rather than semiconductor current limits. In practical power system studies and interconnection assessments, these interfaces are characterised by their inertia contribution, their ability to supply short-circuit current, and their distinct transient and sub transient behaviour during disturbances.

3.2.2.1 Machine-based Conversion Systems in PHS

Machine-based conversion is characteristic of PHS as shown in Figure 88[206] and CAES as shown in Figure 65, where stored potential or compressed air energy is converted to mechanical shaft power and subsequently to electrical power via a generator. Such type of ESS is mainly classified in Fixed Speed and Variable Speed PHS. These plants typically employ synchronous machines, although induction machine variants may be used depending on plant configuration and operational objectives. Variable-speed PHS and certain adjustable-speed configurations remain fundamentally machine-based but may incorporate partial or full power electronic conversion for speed control. This modifies some interface attributes while preserving core rotating machine dynamics. The main components involved in both Fixed Speed and Variable Speed PHS are described below:

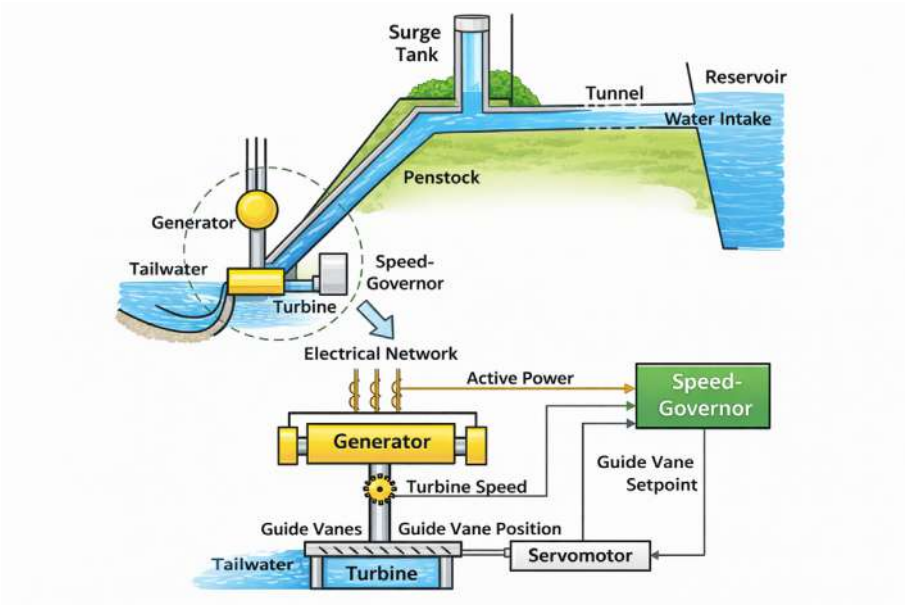
205 G. Li and J. Liang, “Modular Multilevel Converters: Recent Applications [History],” in IEEE Electrification Magazine, vol. 10, no. 3, pp. 85-92, Sept. 2022

206 D. Gezer, Y. Taşcıoğlu, and K. Çelebioğlu, “Frequency containment control of hydropower plants using different adaptive methods,” Energies, vol. 14, no. 8, p. 2082, 2021.

☀ KEY INSIGHT

Machine-based ESS such as PHS and CAES provide inherent inertia, fault-current contribution, and voltage support, making governor and excitation control critical for grid stability during disturbances.

Figure 88 Electrical Systems in PHS



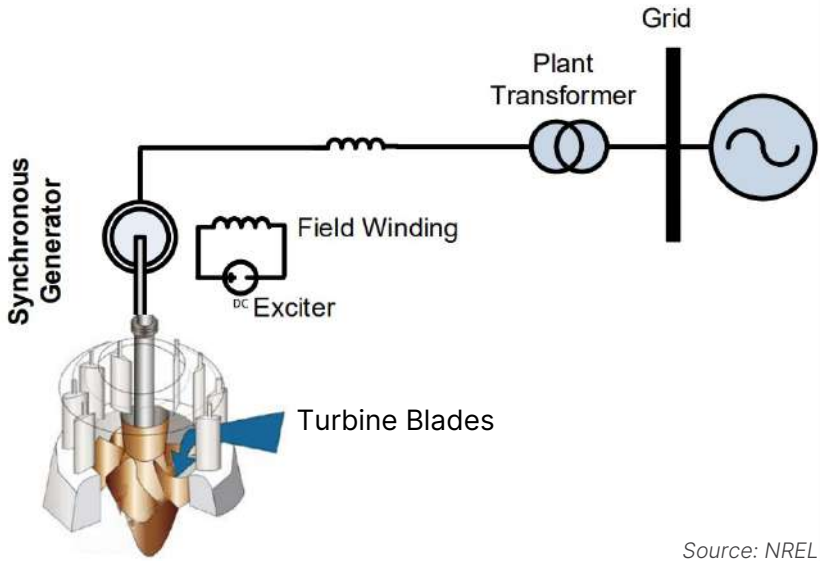
Referred from: D. Gezer et al.; 2021 and modified

- **Synchronous machine:** Synchronous machines are commonly used in machine-based storage plants. Their dynamic behaviour is represented using direct-axis and quadrature-axis equivalent circuits with transient and sub transient reactance and associated time constants. This modelling framework supports evaluation of electromechanical oscillations, voltage recovery, and transient stability following faults or large disturbances. Modelling guidance emphasises importance of pairing machine models with appropriate control systems to ensure stability-relevant representation across different time scales.
- **Governor systems:** Governor systems regulate mechanical input power by controlling turbine actuators such as wicket gates or valves in response to frequency deviations and dispatch setpoints. Application guidance for hydro turbine governing systems indicates that plant-specific and system-level features materially influence governing performance, and that effective governor design and tuning are critical for dynamic stability and frequency response. In machine-based storage, governor response provides primary frequency support consistent with rotating machine behaviour, with response speed and damping shaped by hydraulic or pneumatic dynamics and control parameterisation.
- **Excitation control:** Excitation systems regulate synchronous generator field voltage to control terminal voltage and reactive power exchange. Recommended excitation modelling practices provide mathematical representations of excitation systems and associated supplementary controls, including stabilising functions and limiters suitable for large-scale stability studies. In machine-based ESS, excitation control determines voltage regulation strength and influences fault recovery and oscillation damping through coordinated action with stabilising controls were implemented.

3.2.2.2 Fixed Speed PHS Configuration

In fixed-speed configurations, the generator is directly connected to the grid as shown in Figure 89[207], and rotational speed is largely locked to grid frequency, resulting in a narrow optimal speed range. As such systems are based on rotating machine interfaces directly coupled with the grid, it inherently provides kinetic inertia through the turbine generator mass, supporting grid stability by reducing the rate of change of frequency and moderating frequency nadir during disturbances. This inertial response is a natural physical characteristic, unlike synthetic inertia in converter based systems. In addition, such systems contribute substantial short circuit current, governed by machine reactance and transient characteristics, which is essential for reliable fault detection and protection coordination. These inherent features make fixed speed PHS particularly advantageous for maintaining system strength and stability in grids with declining synchronous generation.

Figure 89 Coupling between hydro turbine and synchronous generator



Source: NREL

3.2.2.3 Variable Speed Systems

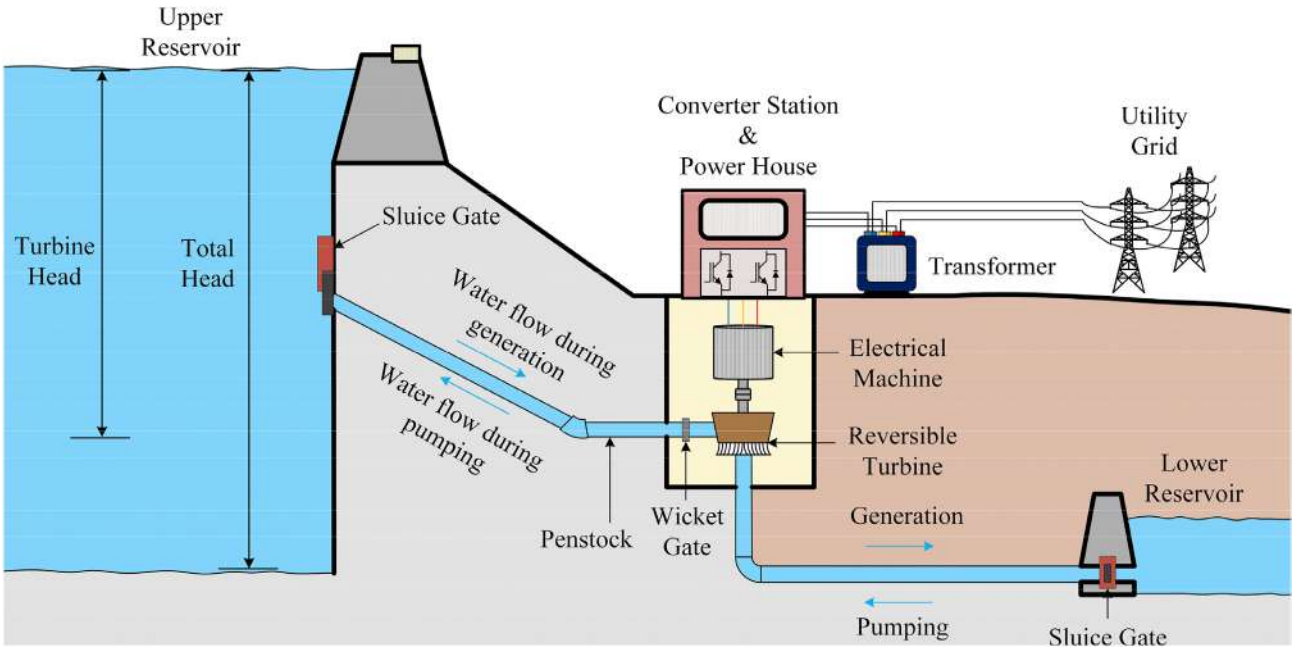
Variable-speed PHS is an example of variable speed ESS that has been developed to overcome the limited operating flexibility of conventional fixed-speed PHS. It is typically designed for maximum efficiency at rated hydraulic conditions and cannot operate effectively beyond defined hydraulic limits. Variable Speed PHS are further categorized into adjustable-speed PHS based on Doubly Fed Induction Generator (DFIG) and adjustable-speed PHS based on Full Conversion (FC) generator.

Adjustable-speed PHS based on DFIG

Adjustable speed PHS based on a DFIG as shown in Figure 90[197] enables variable speed operation by allowing power exchange through both stator and rotor circuits. Under normal operation, the stator delivers most of the generated power directly to the grid, while the rotor handles a smaller fraction depending on slip, enabling operation in both sub synchronous and super synchronous regions. This dual path power flow allows the turbine to operate over a wider speed range, improving energy capture and conversion efficiency. Since only a portion of total power flows through the converter, the required converter rating is typically around 30 percent of generator capacity, resulting in reduced cost and losses compared to full scale converter based systems.

207 E. Muljadi et al., "Electrical systems of pumped storage hydropower plants: electrical generation, machines, power electronics, and power systems," National Renewable Energy Laboratory, Technical Report NREL/TP-5000-74721, Jun. 2021.

Figure 90 Variable speed PHS based on DFIG



Source: K. Vasudevan et al.; 2021

The control implementation relies on coordinated operation of machine side and line side converters. As shown in Figure 91[207], the Machine Side Converter (MSC) regulates stator active and reactive power by controlling rotor currents using closed loop control. It tracks reference signals for active power and reactive power, ensuring optimal turbine operation and maintaining the desired output. The control structure typically uses decoupled current control loops with Proportional Integral (PI) regulators to independently manage active and reactive components, enabling precise control under varying operating conditions.

Figure 91 Operation of machine side converter

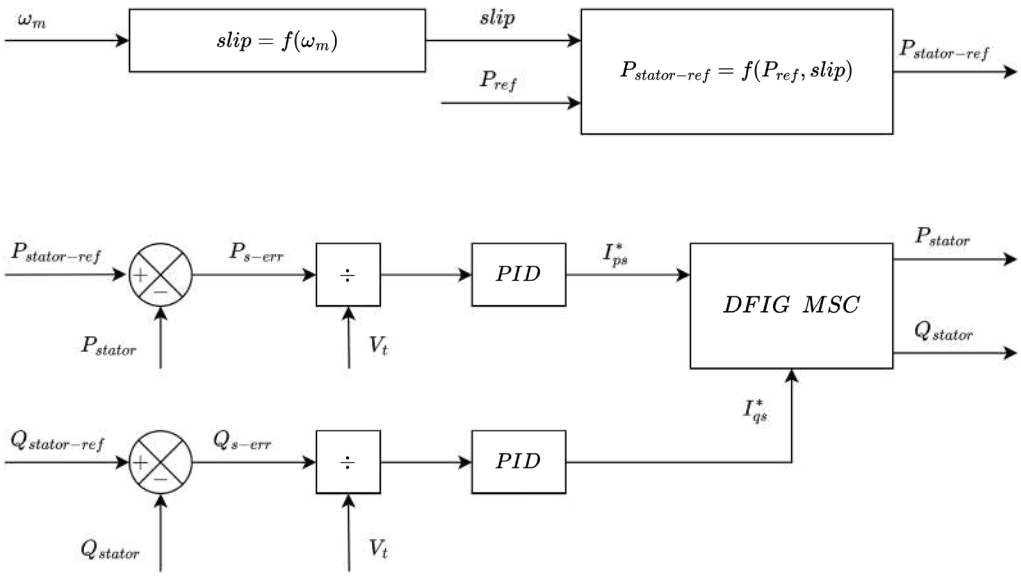
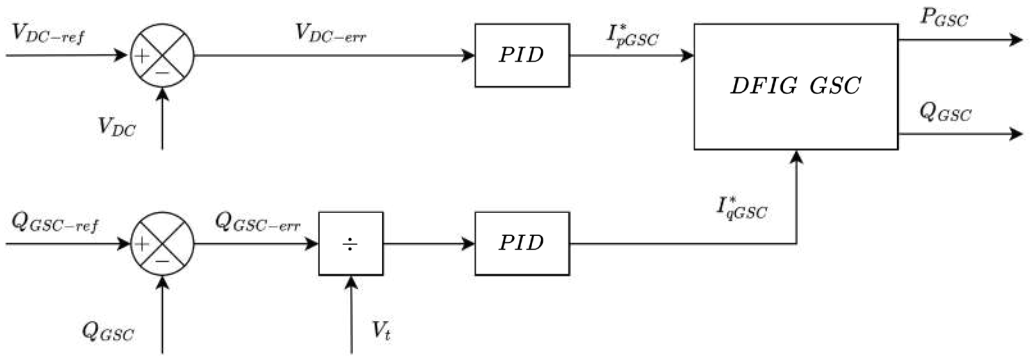


Figure 92[207] illustrates the Grid Side Converter (GSC), which maintains DC link voltage and manages reactive power exchange with the grid. By regulating the DC bus voltage, the GSC ensures stable transfer of rotor power between the converter and the grid, while also providing voltage support

through reactive power control. This dual converter architecture enables stable and flexible operation, improved efficiency through variable speed capability, and enhanced grid support functions such as voltage regulation and oscillation damping.

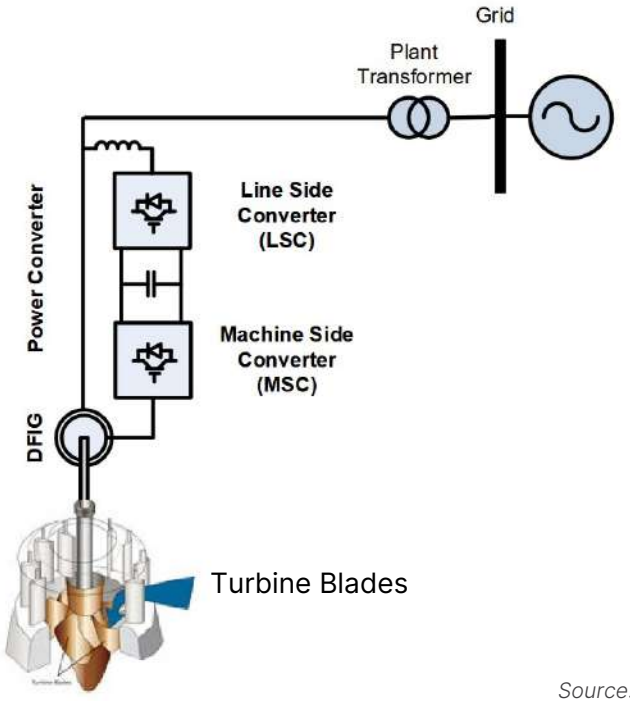
Figure 92 Operation of grid side converter



Adjustable-speed PHS based on Full Converter generator

Adjustable speed PHS based on a FC generator is shown in Figure 93[206]. Here, the generator is typically a Permanent Magnet Synchronous Generator (PMSG), which is fully decoupled from the grid through back to back power converters. This architecture enables complete control over generator operation, allowing variable speed functionality across a wide operating range. Unlike DFIG based systems, where only a fraction of power flows through the converter, the FC configuration routes the entire generated power through the machine side and line side converters before delivery to the grid. This provides greater flexibility in controlling active and reactive power, improving efficiency and dynamic performance under varying operating conditions.

Figure 93 Full conversion PHS with PMSG



Source: NREL

From a design and operational perspective, synchronous generators in FC systems can accommodate a higher number of poles without adversely affecting power factor, unlike induction based DFIG systems. However, this requires a full scale power converter, increasing system complexity and cost.

In contrast, DFIG based adjustable speed systems use partial rated converters but operate over a limited speed range. In addition, under sub synchronous operation, DFIG systems may experience power flow from the grid into the rotor, leading to circulating power and associated efficiency losses. FC based PMSG systems avoid these limitations, offering wider operational flexibility and more consistent performance across the full speed range.

3.3 Control Strategies for ESS

Control strategies for ESS determine the regulation of active and reactive power, the speed and nature of dynamic support, and the manner in which the storage unit responds to grid disturbances. In machine-based systems, turbine governor and excitation controls are mature, standardised, and supported by long-established modelling and operational practices. In contrast, converter-based systems rely entirely on power electronic control algorithms to define voltage synthesis, current regulation, frequency response characteristics, and fault behaviour. Their grid interaction is therefore dictated by control structure and its parameters rather than inherent electromechanical properties. Accordingly, this section concentrates on control architectures for power electronic-based ESS, where performance is fundamentally governed by converter topology, control loop design, bandwidth selection, and tuning methodology rather than intrinsic mechanical inertia or machine physics.

3.3.1 Need for Control in Converter Based ESS

Power electronic based energy storage systems are inherently control governed resources, meaning their interaction with the grid is determined by converter control algorithms rather than intrinsic electromechanical dynamics. Unlike rotating machines, converter based systems do not possess inherent inertia or natural fault current behaviour and therefore require explicitly designed control functions to shape power exchange, voltage response, and protection characteristics in accordance with interconnection requirements[208]. The importance of control mechanism is highlighted below:

- **Decoupling of storage dynamics from grid:** Converter control enables electrical decoupling between the internal storage medium and the grid by regulating DC link voltage and AC side currents independently. This allows the storage device to operate within its own voltage, current, and state of charge constraints while presenting a controlled and grid compliant interface at the point of interconnection. Such decoupling is essential for accommodating wide storage voltage variation without directly transferring these variations to the AC system[209].
- **Fast bidirectional power regulation:** Inverter based ESS can transition rapidly between charging and discharging modes through controlled current references, enabling fast active and reactive power regulation. Closed loop current control allows response on time scales significantly faster than mechanical systems, supporting frequency response, ramp rate control, and fast reserve provision as required by interconnection standards. The absence of mechanical inertia enables high bandwidth control but also necessitates careful tuning to avoid instability[210].

208 F. Blaabjerg, R. Teodorescu, M. Liserre and A. V. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," in IEEE Transactions on Industrial Electronics, vol. 53, no. 5, pp. 1398-1409, Oct. 2006.

209 A. Yazdani and R. Iravani, Voltage-sourced converters in power systems: Modeling, control, and applications. Hoboken, NJ: Wiley-Blackwell, 2010.

210 North American Electric Reliability Corporation, Inverter-Based Resource Performance Guideline, NERC, Atlanta, GA, USA, 2023.

- **Grid code compliance:** Interconnection standards require converter based resources to meet defined performance criteria for voltage regulation, frequency response, ride through capability, and reactive current injection during disturbances. Control systems must therefore implement functions such as power factor regulation, droop control, ramp rate limiting, and fault ride through logic to ensure compliance under both normal and abnormal grid conditions. These requirements are embedded within the control architecture rather than arising from physical machine characteristics[211]
- **Stability contribution in low inertia systems:** In low inertia power systems with high penetration of converter interfaced resources, control strategies must be designed to support frequency and voltage stability. This may include implementation of grid forming or grid following control structures, synthetic inertia functions, and damping controllers to emulate or supplement services traditionally provided by synchronous machines. The stability contribution of converter based ESS is therefore contingent on control design and parameterization[210].
- **Current limitation and protection coordination:** Unlike synchronous machines that can deliver high sub transient fault currents, converter based systems are typically current limited by semiconductor ratings and control constraints. Control algorithms must manage overcurrent events, implement fast current limiting, and coordinate with protection systems to ensure safe operation while maintaining required grid support functions. Protection coordination is therefore closely linked to converter control strategy, particularly during voltage depressions and fault recovery[209].

3.3.2 Control Layers of ESS

The hierarchical control architecture of an ESS organised into primary, secondary, and tertiary control layers based on response times and functional roles as depicted in Figure 94[212]. Primary control operates on millisecond to second time scales, directly managing the converter and enabling fast response to grid disturbances during charging and discharging. Secondary control operates over seconds to minutes, refining voltage and frequency regulation by correcting deviations from primary control and updating reference signals. Tertiary control operates over minutes to hours, determining charge discharge schedules based on economic objectives, system demand, and RE generation availability. This layered framework ensures coordinated operation, balancing fast dynamic response with system level efficiency and profitability.

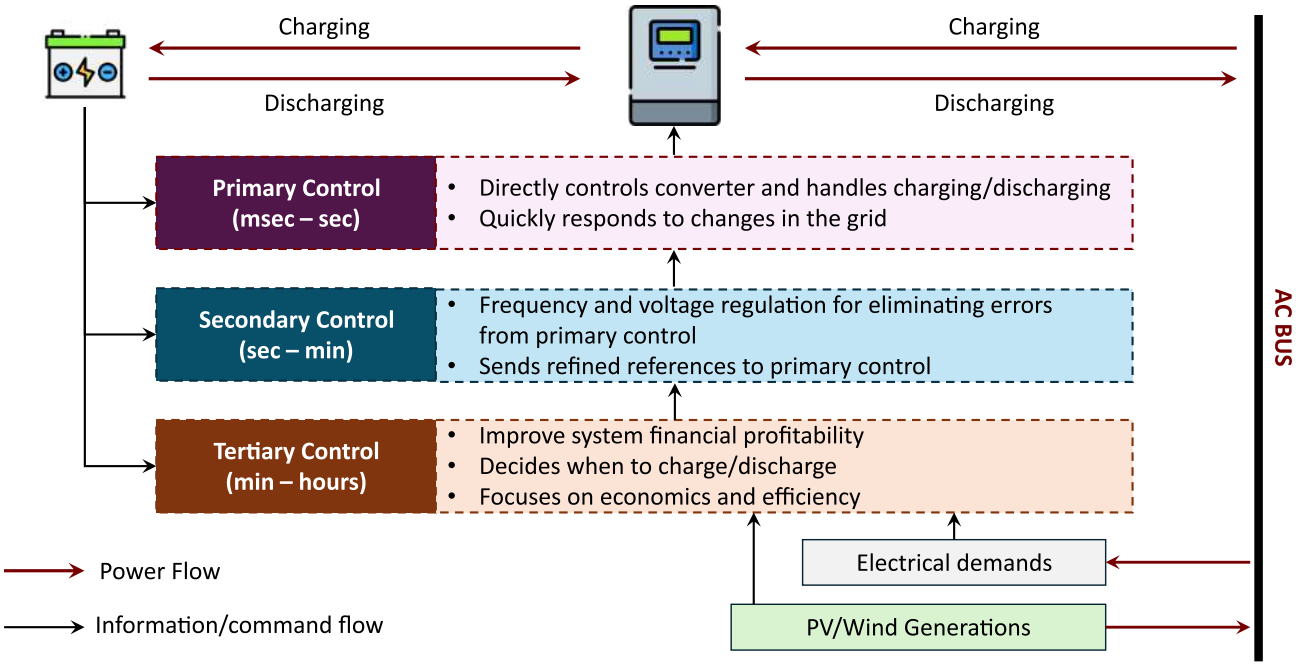
211 Midcontinent Independent System Operator, IBR Performance Requirements: IEEE 2800 (PAC-2024-2), MISO, Carmel, IN, USA, Mar. 12, 2024.

212 Y. Yang, S. Bremner, C. Menictas, and M. Kay, "Modelling and optimal energy management for battery energy storage systems in renewable energy systems: A review," Renew. Sustain. Energy Rev., vol. 167, no. 112671, p. 112671, 2022.



Qurren, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

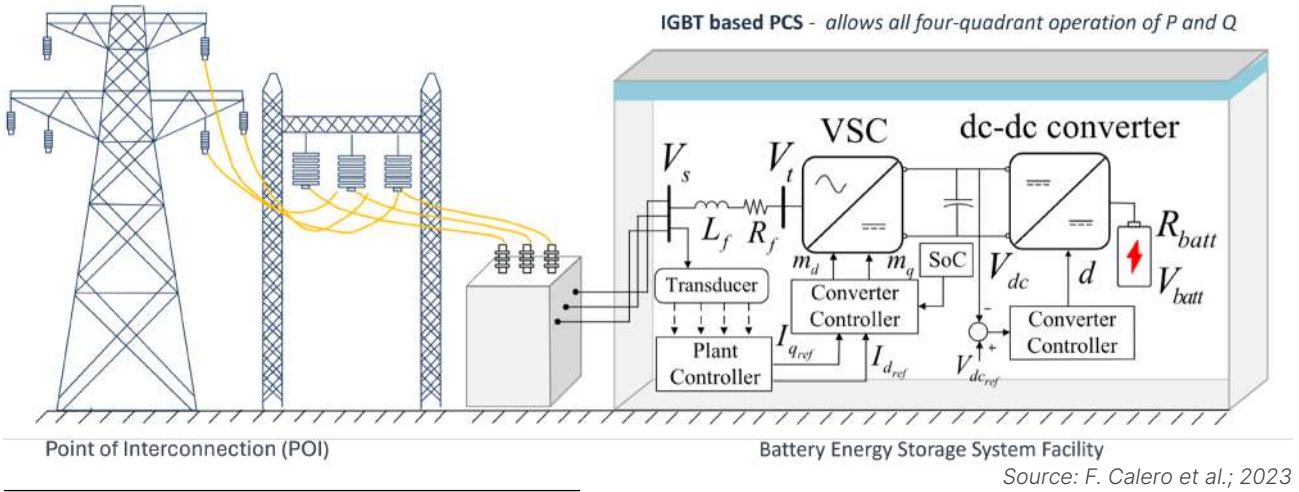
Figure 94 Generalised control layers



3.3.3 Generalised Control Architecture of Converter based ESS

A generalized control architecture for converter-based ESS is typically organised in hierarchical layers that coordinate storage-side regulation, converter-level current control, and plant-level supervisory functions. As shown in Figure 95[213], the PCS enables four-quadrant operation of active and reactive power through coordinated control of a VSC and, where implemented, a bidirectional DC-DC stage. Although supporting diagrams are often illustrated for BESS, the same architecture is applicable to a broad range of ESS interfaced through power electronic converters. The supervisory layer processes dispatch commands and measurements from the point of common coupling to generate appropriate reference signals for lower-level controllers.

Figure 95 Typical control blocks of ESS

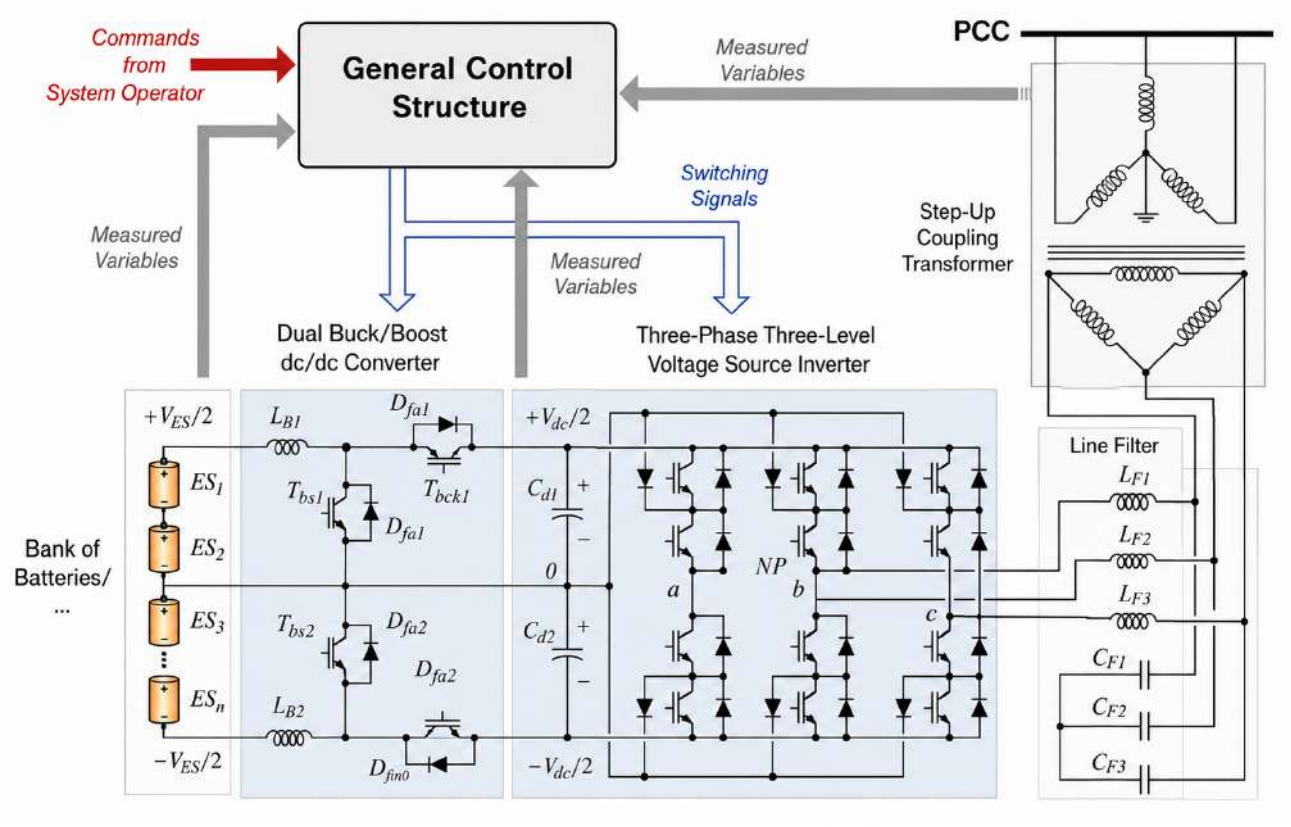


Source: F. Calero et al.; 2023

213 F. Calero et al., "A review of modeling and applications of energy storage systems in power grids," Proc. IEEE Inst. Electr. Electron. Eng., vol. 111, no. 7, pp. 806–831, 2023.

At the converter level, high-bandwidth inner current control loops regulate AC-side currents and stabilise the DC-link voltage. Here, the controller synchronises to grid voltage using a phase-locked mechanism and regulates active and reactive current components, while outer control loops manage DC-link voltage or active power references. Where a DC-DC stage is present, as illustrated in Figure 96[214], an additional control layer regulates storage-side current or voltage, thereby decoupling storage dynamics from the DC link and ensuring operation within SoC and current limits.

Figure 96 General control architecture of ESS



Source: M. G. Molina et al.; 2017

The supervisory layer enforces ramp-rate limits, SoC constraints, and fault ride-through logic, and coordinates protective actions such as current limitation during disturbances. This hierarchical separation between fast inner-loop control and slower energy management functions enables scalable implementation across diverse storage technologies while maintaining consistent grid-facing behaviour.

3.3.4 Control Strategies of ESS

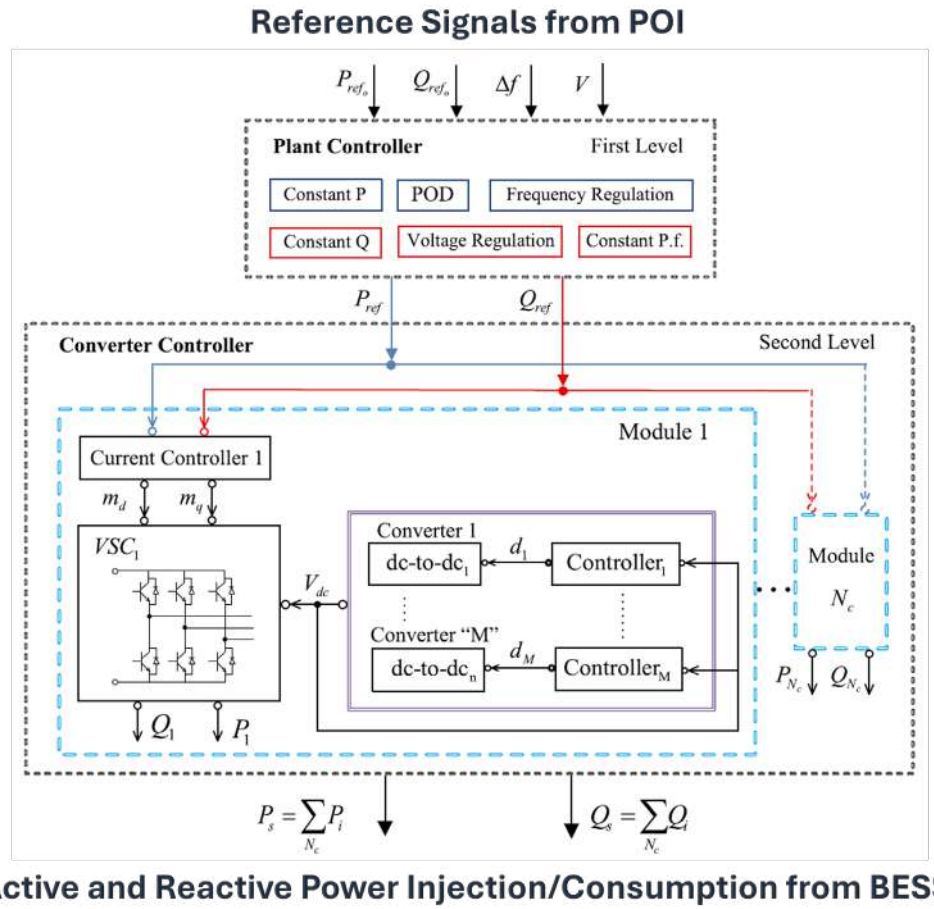
Control strategies for converter-based ESS are typically structured hierarchically to coordinate plant-level objectives with converter-level current regulation. As illustrated in Figure 97[213], a two-level control architecture is implemented, comprising a plant controller at the first level and converter or module controllers at the second level.

At the first level, the plant controller receives reference signals from the POI, including active power reference, reactive power reference, voltage reference, and frequency deviation. Based on the selected operating mode, the plant controller determines appropriate setpoints for constant

214 M. G. Molina, "Energy storage and power electronics technologies: A strong combination to empower the transformation to the smart grid," Proc. IEEE Inst. Electr. Electron. Eng., vol. 105, no. 11, pp. 2191–2219, 2017.

active power operation, power oscillation damping, frequency regulation, constant reactive power, constant power factor, or voltage regulation. These setpoints are distributed across multiple converter modules as shown in Figure 97, ensuring coordinated operation of parallel units. This supervisory layer performs energy management and grid support function selection while enforcing system constraints such as ramp-rate limits and state-of-charge boundaries.

Figure 97 Two-level hierarchical control of ESS



Source: F. Calero et al.; 2023

At the second level, the converter controller implements current regulation and switching control. Active and reactive power references are translated into current references that are tracked by high-bandwidth inner current control loops within each module. Where a DC-DC stage is present, it regulates storage-side current or voltage to maintain DC-link stability and enforce storage constraints. The three-phase voltage source converter synthesises the required AC voltages through pulse-width modulation to achieve the commanded power exchange. Aggregated module outputs produce the total active and reactive power injection or consumption at the grid interface.

Active power control enables provision of primary frequency response, secondary frequency regulation, and oscillation damping through modulation of real power injection in response to system frequency or supervisory commands. Reactive power control enables voltage regulation, constant power factor operation, or constant reactive power operation at the point of common coupling. The hierarchical structure separates slower supervisory functions from fast inner current control loops, ensuring both stable high-bandwidth dynamic response and coordinated plant-level behaviour. This layered approach is fundamental for reliable grid integration of converter-based ESS, particularly in networks with high penetration of converter-interfaced resources[213].

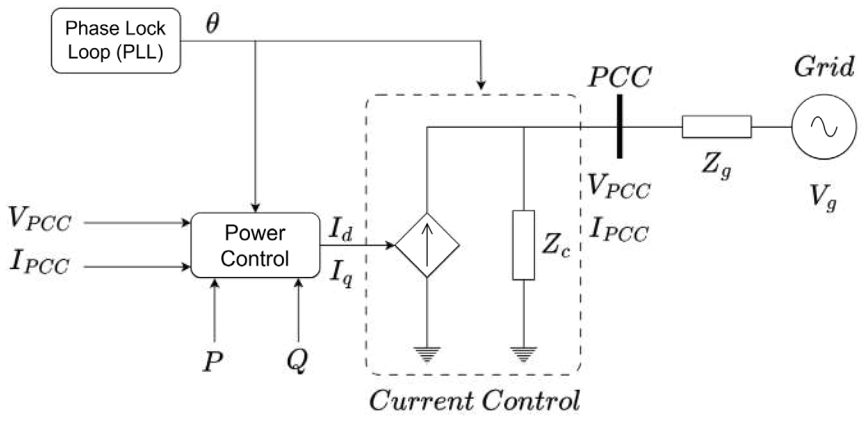
3.3.5 Grid Interaction Modes: Grid Following and Grid Forming Control

Grid interaction control modes define how converter-based ESS establish their electrical relationship with the power system and regulate voltage, frequency, and power exchange. These modes are broadly categorised as Grid-Following (GFL) mode and Grid-Forming (GFM) mode control, which differ fundamentally in their synchronisation philosophy and dynamic behaviour. In GFL, the converter synchronises to an existing grid voltage, typically using a phase-locked mechanism, and injects controlled current to regulate active and reactive power. The converter therefore behaves as a current-controlled source whose operation depends on the presence of a stable external voltage reference. In GFM, the converter actively establishes and regulates voltage magnitude and frequency at its terminals, behaving as a controlled voltage source. Power exchange with the grid is then determined by network impedance and control laws, rather than by explicit current injection commands alone[215]. The selection of control mode has significant implications for small-signal stability, fault response, system strength interaction, and operation under low-inertia or weak-grid conditions. Consequently, control mode choice is a critical design decision in modern power systems with high penetration of converter-interfaced resources.

3.3.5.1 Grid Following Mode of ESS PCS

GFL control is the predominant control philosophy used in present grid-connected ESS deployments, particularly in BESS and other converter-interfaced storage technologies. In this mode, the converter operates as a controlled current source that synchronises to the existing grid voltage using a phase-locked loop, thereby acting as a grid follower. As illustrated in Figure 98, the measured point-of-common-coupling voltage is processed by a phase-locked loop to obtain the synchronisation angle. This angle is used to transform measured currents into a rotating reference frame, enabling decoupled active and reactive current control. Active and reactive power references are converted into d-axis and q-axis current commands, which are tracked by high-bandwidth inner current controllers that generate the converter switching signals. The grid therefore establishes voltage magnitude and frequency, while the energy storage system injects or absorbs controlled current in accordance with reference setpoints[216].

Figure 98 Typical GFL control model

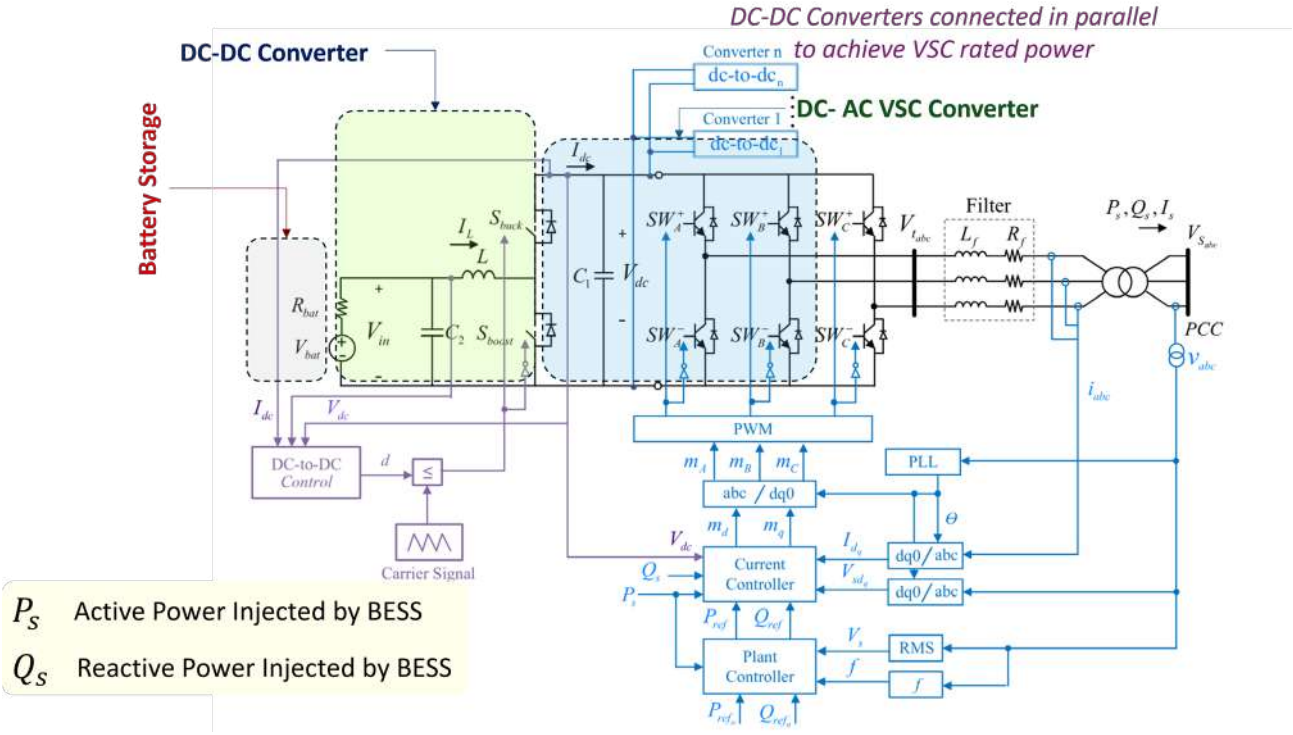


215 B. Xu, V. Paduani, H. Yu, D. Lubkeman and N. Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," 2022 IEEE Power & Energy Society General Meeting (PESGM), Denver, CO, USA, 2022.

216 M. Tozak, S. Taskin, I. Sengor, and B. P. Hayes, "Modeling and control of grid forming converters: A systematic review," IEEE Access, vol. 12, pp. 107818–107843, 2024.

In GFL mode, the ESS operates as a controlled current source that synchronises to the existing grid voltage at the point of common coupling using a phase-locked loop, as illustrated in Figure 99. The measured three-phase grid voltages at the POI are processed by the phase-locked loop to extract the phase angle θ, which is used for abc-dq0 and dq0-abc transformations[212].

Figure 99 Detailed GFL control architecture of ESS



Source: F. Calero et al.; 2023

The plant controller generates active and reactive power references P_{ref} and Q_{ref} based on supervisory commands and measured variables such as RMS voltage V_s and frequency f. These power references are converted into d-axis and q-axis current references within the current controller. The inner current control loops regulate the converter output currents I_d and I_q through pulse-width modulation signals m_A, m_B, and m_C applied to the DC-AC VSC. The DC-link voltage V_{DC} is maintained through coordination with the DC-DC control stage, which regulates the storage-side current I_{DC} and duty cycle d of the bidirectional buck-boost converter connected to the storage unit. This arrangement ensures controlled energy exchange between the storage element and the DC link while maintaining converter stability. The three-phase VSC, together with the line filter consisting of L_f and R_f and the step-up transformer, injects controlled active and reactive power P_S and Q_S respectively, into the grid, while the grid establishes voltage magnitude V_{abc} and frequency. The DC-DC converter decouples storage-side voltage V_{bat} and internal resistance R_{bat} from the DC-link capacitors C_1 and C_2, enabling stable operation across varying SoC conditions. In this configuration, GFL control provides precise active and reactive power regulation and fast bidirectional response, explaining its widespread deployment in grid-connected energy storage plants. However, stable operation depends on the presence of a sufficiently strong external grid for reliable phase-locked loop synchronisation. The converter is inherently current-limited and does not establish system voltage or frequency. These characteristics define GFL control as suitable primarily for strong-grid applications where accurate power injection and compliance with interconnection requirements are the principal objectives[213].

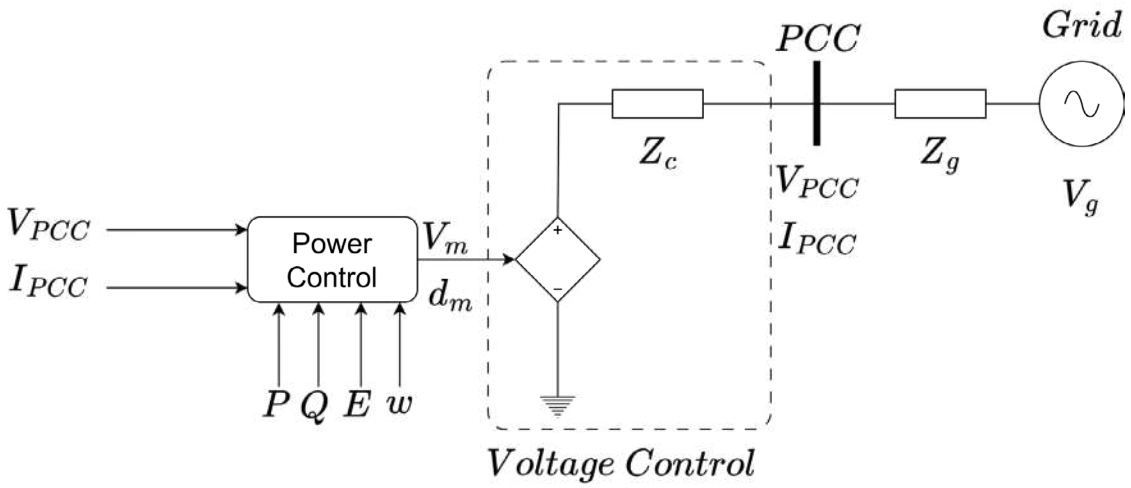
The principal advantages of GFL control include implementation maturity, fast current regulation, and straightforward integration into strong transmission or distribution networks where a stable

external voltage source is present. This architecture is widely deployed in commercial ESS because it supports precise active and reactive power control, rapid bidirectional power exchange, and compliance with interconnection requirements under normal operating conditions. However, GFL control inherently depends on the presence of a sufficiently strong grid for stable synchronisation. Its performance can degrade in weak-grid conditions, where voltage disturbances, low short-circuit ratio, or rapid phase-angle variations challenge phase-locked loop stability. Furthermore, because the converter behaves as a current-controlled source rather than a voltage-establishing source, it does not inherently provide physical inertia and contributes limited fault current compared to synchronous machines. These characteristics define both the suitability and limitations of GFL control in modern power systems with increasing penetration of converter-interfaced resources.

3.3.5.2 Grid Forming Mode of Control of ESS PCS

GFM control enables an converter-based ESS to operate as a controlled voltage source that independently establishes the local voltage magnitude and frequency at its terminals. As illustrated in Figure 100, the controller generates an internal voltage reference and regulates converter output through a voltage control loop, rather than synchronising to an externally imposed waveform as that of GFL control. In this configuration, the converter behaves as an active voltage source behind an internal impedance and interacts with the external network through the coupling impedance between the converter and the grid. Because the converter defines terminal voltage and frequency, it effectively establishes the electrical reference for other devices connected at the POI[217].

Figure 100 Typical GFM control model

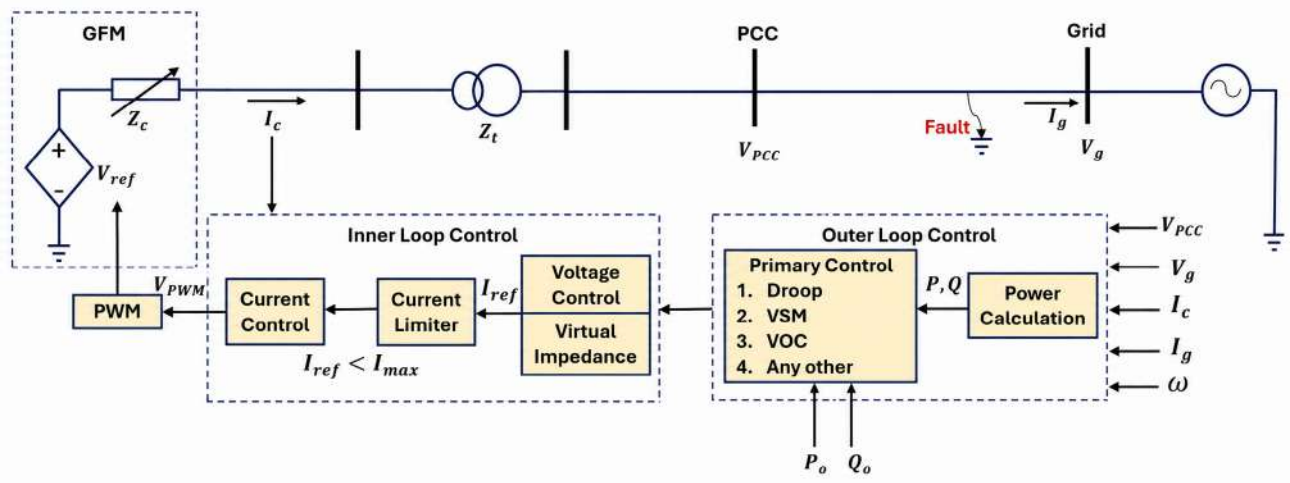


A simplified control architecture of a GFM converter, highlighting the interaction between outer and inner control loops is shown in Figure 101[218]. The outer loop implements primary control strategies such as droop control, virtual synchronous machine, or virtual oscillator control to generate voltage and frequency references based on power measurements. The inner loop provides fast dynamic response through voltage and current control, incorporating virtual impedance and current limiting to maintain stability and protect the system. Together, these coordinated control layers enable the converter to establish grid voltage and frequency, ensuring stable operation under weak grid and fault conditions.

217 H. H. Alhelou, N. Mohammed, and B. Bahrani, Grid-forming power inverters: Control and applications. Boca Raton: CRC Press, 2023.

218 Grid Controller of India Limited, Grid Forming Technology and Possible Applications in Indian Power System, Discussion Paper, Dec. 2025.

Figure 101 Simplified control architecture of GFM control for PCS



Source: Grid India

The detailed control architecture of GFM control of ESS is illustrated in Figure 102[219]. The storage unit feeds the DC link through appropriate DC-link filtering, and the converter synthesises a three-phase voltage that passes through AC filters and a coupling transformer before reaching the PCC. Unlike GFL control, synchronisation is not achieved by locking to an external waveform. Instead, the internal control structure directly defines the reference angle and voltage magnitude used by the pulse-width modulation and dq-abc modulation blocks. The measured PCC voltages and currents are transformed through abc-dq coordinates to enable coordinated regulation within the voltage, current, and power control loops. The converter interacts with the external network through the grid impedance and effectively behaves as a voltage-establishing source behind an internal or virtual impedance, thereby defining the local electrical reference rather than tracking it.

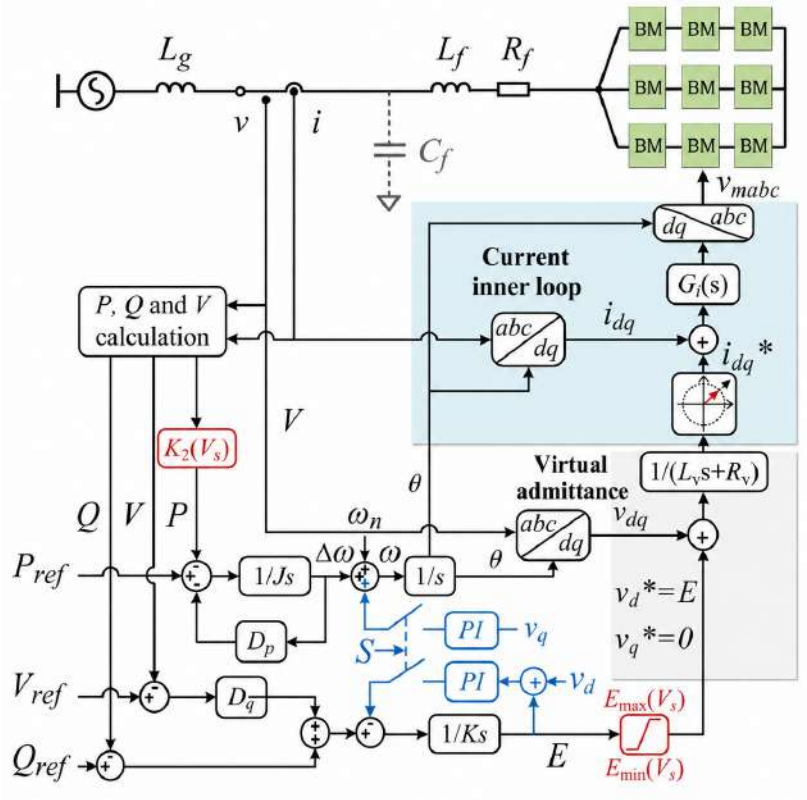
The operational need for GFM control arises in weak grids, islanded systems, and low-inertia networks where a strong external voltage reference may not be available. By actively regulating terminal voltage magnitude and frequency, the energy storage system establishes the local electrical reference and accommodates load variations while maintaining system stability. Coordinated outer voltage control loops and inner current control loops ensure that commanded active and reactive power exchange is achieved without compromising voltage regulation. The pulse-width modulation stage generates the switching signals required to synthesise the commanded AC waveform at the converter terminals.

Unlike GFL control schemes, GFM control does not depend on a phase-locked loop for synchronisation. This reduces reliance on external grid strength and enables stable operation during severe disturbances or temporary grid absence. To ensure robust performance, the control design must incorporate appropriate droop characteristics, virtual impedance implementation, and current-limiting mechanisms so that interaction with other converters and synchronous machines remains stable. Careful coordination between outer voltage regulation and inner current limitation is particularly critical during faults and large transients. Although implementation complexity is greater than in GFL approaches, GFM control provides enhanced system resilience, black-start capability, and improved dynamic stability in low-inertia, RE dominated power systems[220].

219 X. Wu et al., "Grid-forming control and experimental validation for high voltage transformerless battery energy storage system," IEEE Trans. Power Electron., vol. 40, no. 4, pp. 4889–4901, 2025.

220 D. Pattabiraman, R. H. Lasseter., and T. M. Jahns, "Comparison of grid following and grid forming control for a high inverter penetration power system," in 2018 IEEE Power & Energy Society General Meeting (PESGM), 2018, pp. 1–5.

Figure 102 Detailed GFM control architecture of ESS



Source: X. Wu et al.; 2025

3.3.5.3 GFM Control Modes

GFM control can be implemented using multiple control philosophies, each derived from a different theoretical interpretation of how a voltage source should emulate or reproduce synchronous machine behaviour. While all GFM strategies establish voltage and frequency at the converter terminals, they differ in dynamic order, inertia emulation mechanism, internal state variables, and sensitivity to measurement and grid conditions. Broadly, GFM controllers can be grouped into droop-based methods, machine emulation approaches, oscillator-based strategies, and matching-based techniques. These architectures vary in tunable parameters, transient performance, weak-grid robustness, and implementation complexity. The following consolidated Table 41 summarises the principal GFM control types and compares their governing principles, tunable parameters, dynamic characteristics, and grid support capabilities[221].

Table 41 Types of controllers for GFM based PCS

PCS controller	Principle	Key tunable parameters	Virtual inertia	Transient stability	Weak grid support	Key characteristics
Droop Control	Droop feedback	K_p, K_q(Droop coefficients)	No	Medium	Low	Simple design
Virtual Synchro-nous Generator	Swing equation	J - virtual inertia D - damping coefficient	Yes	Low	Medium	Inertia emulation

221 Y. Chen, H. Guo, C. Kang, and S. Onori, "Grid-forming battery storage: Enabling renewable-dominant power systems for a sustainable future," IEEE Energy Sustain. Mag., vol. 1, no. 2, pp. 17–31, 2025.

PCS controller	Principle	Key tunable parameters	Virtual inertia	Transient stability	Weak grid support	Key characteristics
Synchron-verter	Virtual excitation voltage	J, D	Yes	Low	Medium	Excitation characteristics emulation
Virtual Oscillator Control (VOC)	Nonlinear oscillator	g(v) - voltage dependence k_v - feedback coefficient	Yes	High	High	Resistive grid adaptability
Dispatch-able VOC	Oscillator + syn-chronizing feedback + magnitude control	η - synchronous gain α - magnitude control gain	Yes	High	High	Dispatchability
Matching Control	Dynamics similarity between DC-link voltage and frequency	n - matching ratio k_{dc} - compensator gain	Yes	High	High	Low measurement delay

3.3.5.4 Comparison between GFL and GFM Control Capabilities of ESS

The selection between GFL and GFM control has direct implications for the range and reliability of services that an energy storage system can provide. Although both approaches can support conventional market participation functions such as energy arbitrage and frequency regulation under normal operating conditions, their capabilities diverge significantly in weak-grid, low-inertia, and system restoration scenarios. GFL control is well suited to operation in strong grids where a stable external voltage reference exists, enabling precise active and reactive power injection. In contrast, GFM control extends functionality by establishing voltage and frequency references, supporting operation in islanded networks, low short-circuit ratio conditions, and black-start sequences. The following capability matrix as shown in Table 42 summarises the comparative functional attributes of GFL and GFM control modes across key system services, dynamic performance requirements, and operational scenarios, highlighting the expanded resilience and system-support functions enabled by GFM implementations[222].

222 R. Quint, A. Isaacs, L. Unruh, J. Matevosyan, and C. Baker, A Call to Action for a Stable Energy Transition: Grid-Forming Battery Energy Storage Systems, Brief for Decisionmakers, GridLab and Energy Systems Integration Group, Mar. 2025.

☀ KEY INSIGHT

GFM control enables converter-based ESS to set local voltage and frequency, making storage a stability-forming resource for weak grids, islanded operation, black start, and low-inertia renewable systems.

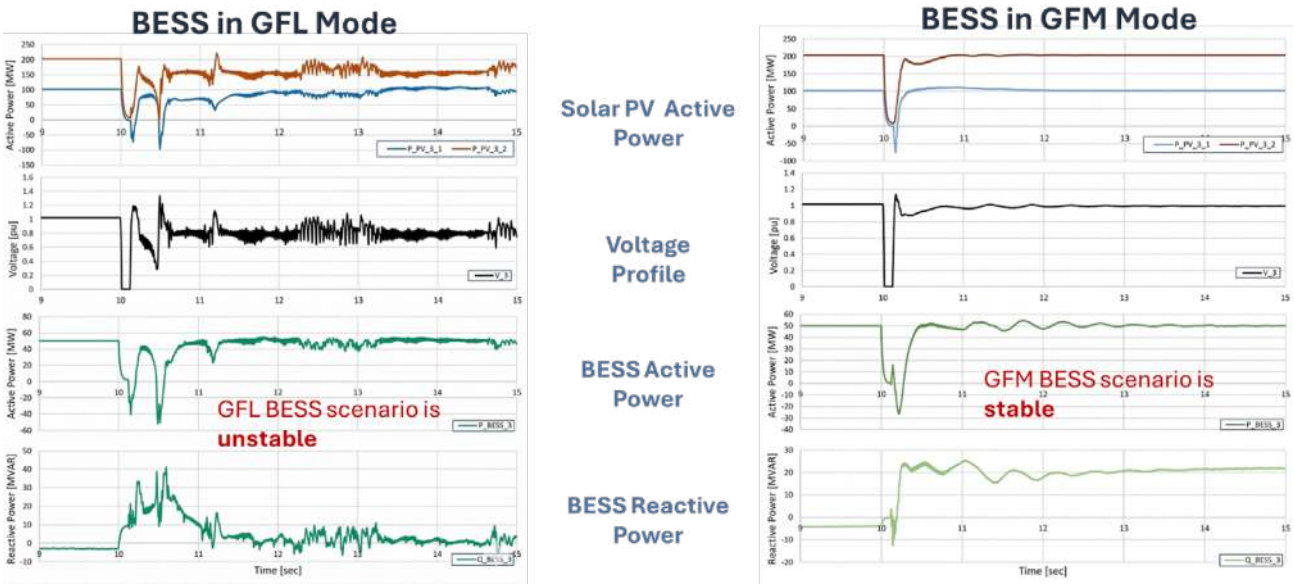
Table 42 Comparison between GFL and GFM mode of control

Service/ Product	Grid following ESS	Grid forming ESS
Energy Arbitrage	Proven, widely deployed	Same as GFL
Frequency Regulation	High Accuracy, very fast	High Accuracy, very fast + weak grid stability
Capacity Markets	Reliable participation	Reliable participation + resilience contribution
Black Start Services	Requires external voltage reference	Independent grid energization
Virtual Inertia	Limited capability	Synthetic inertia provision
Weak Grid Support	Performance degrades	Optimal for low Short Circuit Ratio (SCR) conditions
Islanding Capability	No	Seamless islanding and resynchronisation

3.3.5.5 Performance Comparison between GFL and GFM Control

The dynamic performance of BESS operating in GFL and GFM modes under a weak grid condition, characterised by a SCR i.e. SCR < 1.3 and the loss of a transmission circuit (N - 1 contingency) is shown in Figure 103[223]. In GFL mode, the system exhibits instability following the disturbance, with oscillations in solar PV active power, voltage profile, and BESS active and reactive power. The voltage shows sustained fluctuations and poor recovery, indicating limited capability of GFL control to stabilise the grid under low inertia conditions. The BESS response is also unstable, with large power swings and delayed damping.

Figure 103 Performance comparison of GFL vs. GFM control of BESS



Source: ESIG

223 R. Quint, A. Isaacs, L. Unruh, J. Matevosyan, and C. Baker, "A Call to Action for a Stable Energy Transition: Grid-Forming Battery Energy Storage Systems," GridLab and Energy Systems Integration Group, Mar. 2025.

In contrast, GFM mode demonstrates improved system stability and dynamic response. Following the same disturbance, the voltage profile recovers rapidly with minimal oscillations, and both solar PV output and BESS active power settle smoothly to steady state values. The BESS in GFM mode provides voltage and frequency support by establishing a reference waveform, enabling controlled reactive power injection and improved transient damping. This highlights the capability of GFM control to maintain stability in weak grids, supporting reliable integration of RE resources.



CHAPTER 4

04 APPLICATIONS & MODELLING OF ENERGY STORAGE SYSTEMS


AI Image

Summary

- Defines ESS as a multi service asset that supports transmission, distribution, and behind the meter applications through energy shifting, frequency response, voltage support, congestion relief, black start, resilience, and customer side optimisation.
- Distinguishes transmission level applications such as bulk energy shifting, inertial support, frequency regulation, voltage support, oscillation damping, congestion relief, long duration adequacy, and black start capability.
- Explains distribution level applications of ESS, including increased DER hosting, front of the meter and behind the meter storage, peak shaving, PV smoothing, voltage regulation, feeder congestion management, and aggregated flexibility services.
- Introduces ESS modelling requirements across component level, plant level, RMS, and EMT frameworks to support planning, stability assessment, protection coordination, and grid code compliance.





Achernar.sk, CC0, via Wikimedia Commons

ESS enables controlled temporal shifting of energy by charging at one time and discharging when required. This temporal decoupling allows ESS to deliver a range of grid support services, as illustrated in Figure 104 and Figure 105[198]. Service provision is governed by factors such as power rating, usable energy capacity, response time, and operational constraints, with multiple services often stacked on a single asset subject to SoC limitations and applicable market and grid code requirements. Some of major applications of ESS are described below:

Figure 104 Services provided by ESS

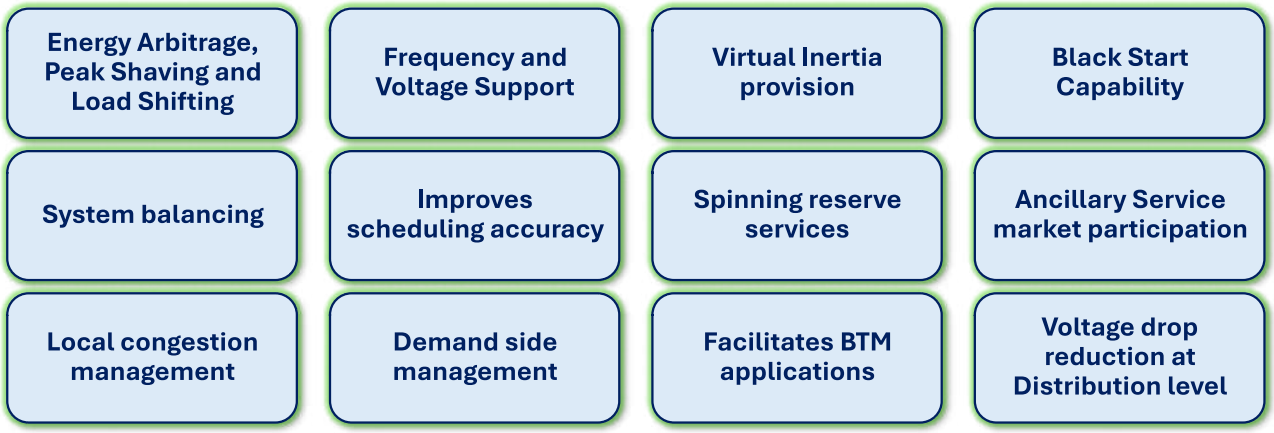
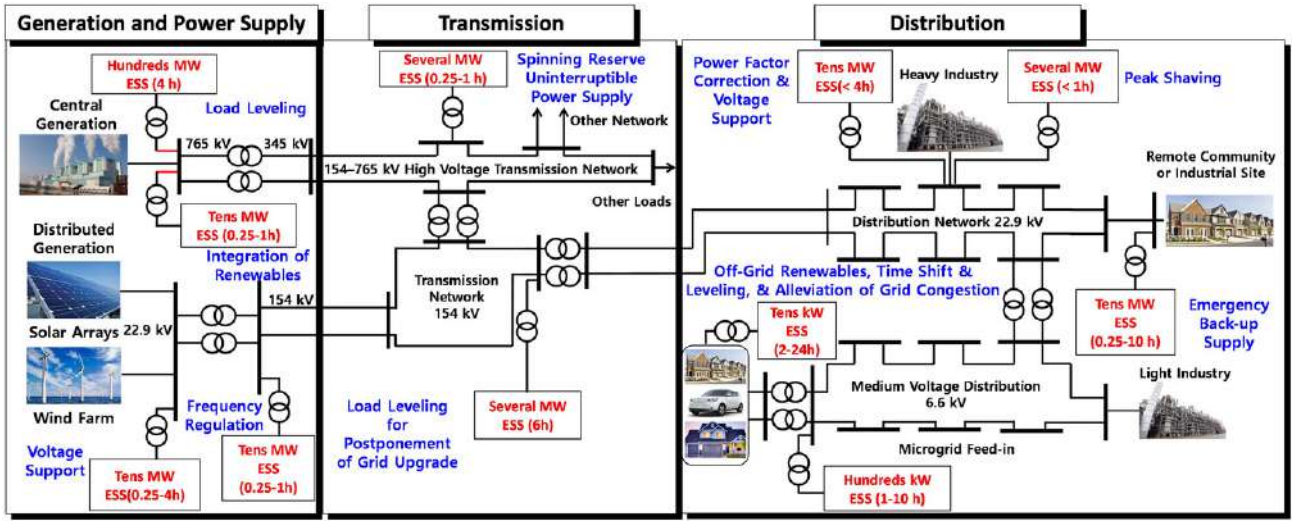


Figure 105 Application of ESS in power system



Source: M. S. Rafaq et al.; 2022

ESS provides multiple functions across the power system, with service requirements and technical expectations varying according to network hierarchy. While storage technologies are often discussed in context of energy shifting, their operational value increasingly derives from their ability to deliver fast dynamic services, stability enhancement, and infrastructure support under evolving grid conditions. The nature of these services depends on whether the storage unit is connected at the transmission network or within distribution networks closer to end users.

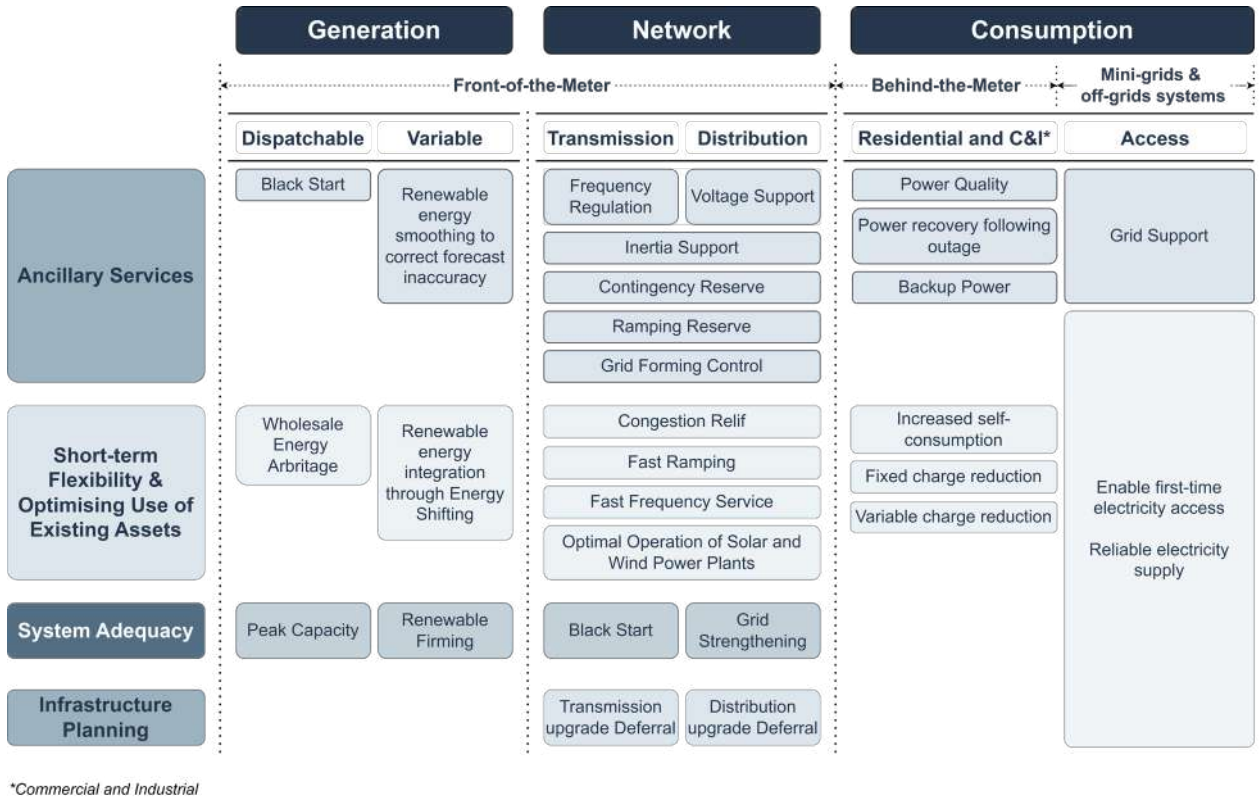
To provide a structured assessment, applications are categorized into transmission-level and distribution-level domains. Transmission-connected ESS is typically oriented toward bulk system reliability, stability reinforcement, congestion mitigation, and adequacy enhancement. In contrast, distribution-connected ESS emphasizes localized voltage regulation, RE hosting capacity, peak demand reduction, resilience, and customer-centric optimization. Although certain advanced

☀ KEY INSIGHT

ESS value depends strongly on grid location, with transmission storage supporting adequacy, stability, and congestion relief, while distribution and BTM storage improve voltage regulation, DER hosting, peak reduction, and customer backup supply.

services such as black start, GFM operation, and contingency support may be delivered at both levels. The functional mapping of ESS application across generation, network, and demand segments is illustrated in Figure 106[224].

Figure 106 ESS location in power system and representative applications



4.1 Transmission Level Applications

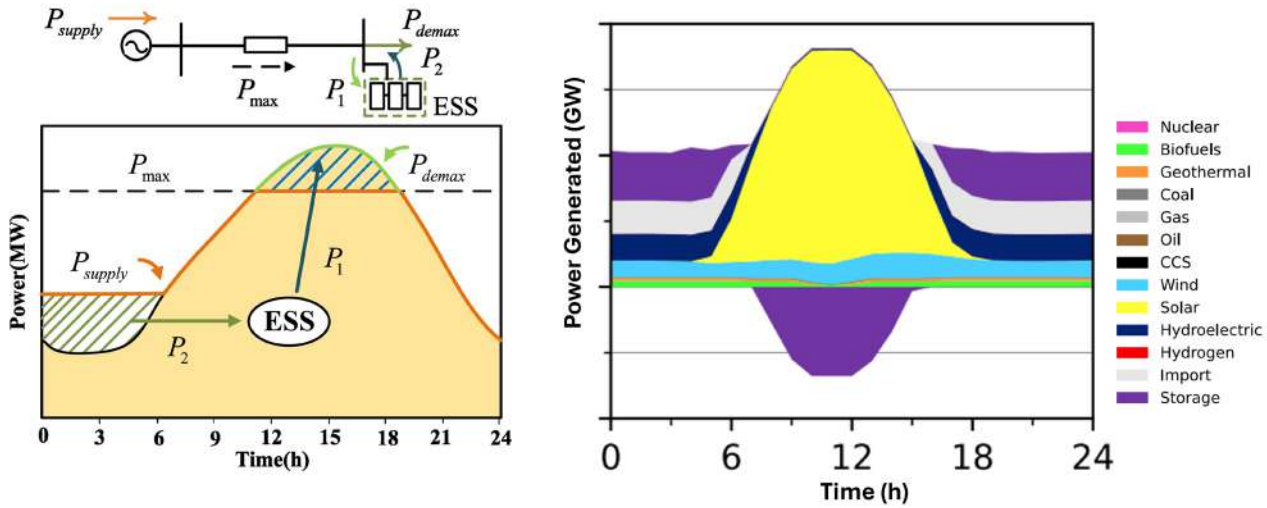
At the transmission level, utility scale ESS, typically deployed from several tens of megawatts to the gigawatt scale, operate as bulk system assets that enhance operational flexibility, stability margins, and resource adequacy. Interconnected at high voltage substations and major transmission nodes, they directly influence system frequency, voltage profiles, and large scale power flow dynamics. Their principal applications include energy time shifting, fast frequency response, primary and secondary frequency regulation, dynamic voltage support, synthetic inertia provision, and oscillation damping. In addition, transmission level ESS supports congestion management, deferral of network reinforcements, contingency reserves, ramping support during steep net load variations, long duration adequacy, and black start capability. These functions are particularly critical in RE dominant and low inertia systems, where fast and precise controllability aids secure and reliable grid operation.

224 GII Research

4.1.1 Bulk Energy Shifting or Energy Arbitrage

Bulk energy shifting, also referred to as energy arbitrage or load levelling, is a primary transmission level application of large scale ESS. In this application, energy is stored during periods of low demand or high RE generation and discharged during peak demand intervals to reduce system peak load and improve overall asset utilization. Technologies commonly deployed for bulk shifting include PHP, CAES, and increasingly large scale BESS with multi hour to long duration capability. At transmission nodes, such installations help mitigate price volatility, reduce reliance on peaking conventional generation, and enhance system adequacy by providing dispatchable capacity during critical demand periods. Figure 107[225,226] illustrates the application of ESS for providing energy arbitrage where ESS is discharged to fill the valley and charged during peak generation.

Figure 107 Energy arbitrage from ESS



Source: S. Huang et al.; 2025

Source: M. Nicoli et al.; 2024

4.1.2 Virtual Inertia Support

Inertial support at the transmission level has become increasingly important due to the reduction in synchronous generation and associated decline in natural rotational inertia. ESS can contribute to frequency stability by rapidly injecting or consuming active power in response to frequency deviations and RoCoF events. GFM based ESS operating in virtual synchronous generator mode can emulate inertial behaviour by implementing frequency dependent power control that mimics the swing equation of a synchronous machine. This enables a fast active power response proportional to frequency deviation, thereby limiting frequency nadir and improving system stability during faults. Such functionality is highly relevant in RE dominated grids with low system strength[227].

In addition to power electronic based solutions, PHS plants inherently provide physical inertia through their rotating turbine generator sets, contributing to electromechanical stability and short term frequency containment. Adjustable speed PHS units can further enhance dynamic response by rapidly modulating active power through converter interfaced rotor control. While other ESS

225 S. Huang et al., "Energy storage system and applications in power system frequency regulation," J. Energy Storage, vol. 131, no. 117506, p. 117506, 2025.

226 M. Nicoli, V. A. D. Faria, A. R. De Queiroz, and L. Savoldi, "Modeling energy storage in long-term capacity expansion energy planning: an analysis of the Italian system," Journal of Energy Storage, vol. 101, p. 113814, Sep. 2024.

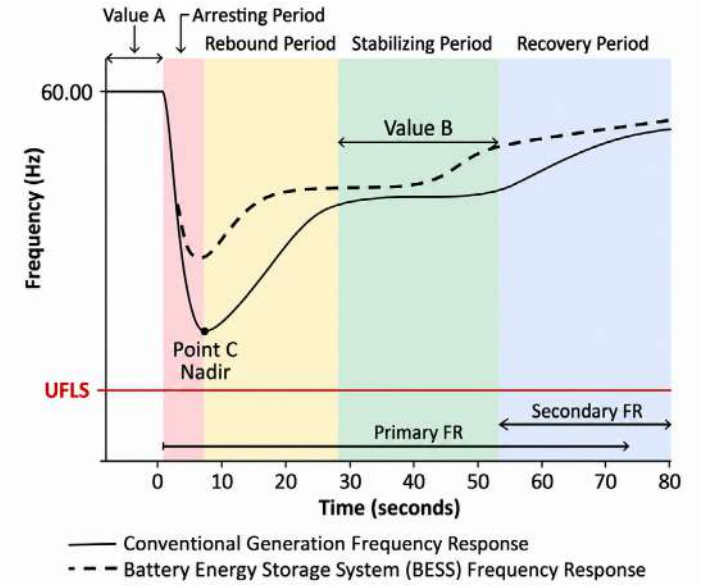
227 A. Bera, B. R. Chalamala, R. H. Byrne and J. Mitra, "Sizing of Energy Storage for Grid Inertial Support in Presence of Renewable Energy," in IEEE Transactions on Power Systems, vol. 37, no. 5, pp. 3769-3778, Sept. 2022

provide synthetic or virtual inertia through control algorithms, PHS offers natural inertia combined with high power capacity and sustained energy delivery. Together, these technologies enhance frequency resilience at the transmission level and reduce dependence on conventional thermal generation for inertial support[207].

4.1.3 Frequency Support Services

Frequency support service at the transmission level encompasses a hierarchy of response mechanisms designed to arrest frequency decline, and restore nominal frequency following a disturbance. As illustrated in Figure 108, a generation loss causes frequency to decline at a rate determined by system inertia, quantified as the RoCoF. The initial slope of the frequency trajectory reflects the RoCoF, which is inversely proportional to system inertia and directly related to the power imbalance. Fast frequency response is delivered within the first few hundred milliseconds to arrest the frequency drop before the nadir is reached. ESS operating in GFL or GFM mode with frequency dependent active power control are particularly suited for this service due to their sub second response capability. SESS and FESS can also provide ultra-fast active power injection during this arresting period, significantly reducing the frequency nadir compared to conventional generation, as illustrated shown in Figure 108[228].

Figure 108 Frequency regulation form ESS



Source: NERC

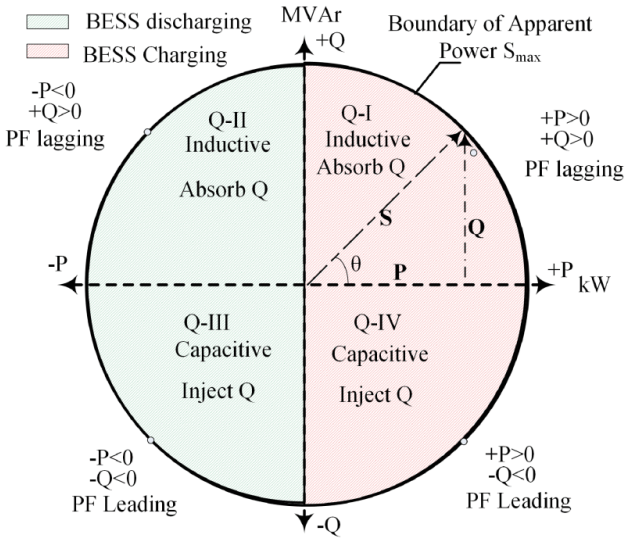
Primary frequency response follows the arresting phase and typically operates within a few seconds, stabilizing frequency through droop based active power control. Large scale BESS, PHS, and CAES plants can participate in primary response by modulating output proportionally to frequency deviation. Secondary frequency response, often referred to as automatic generation control support, restores frequency toward nominal over tens of seconds to minutes through redispatch of controllable resources. Multi hour BESS and PHS are commonly deployed for this specific purpose. Tertiary response, activated over longer time scales, involves manual or market based redispatch to fully restore system balance and replenish reserves. The rapid and precise controllability of power electronic based ESS enables improved RoCoF containment, a higher frequency nadir, and faster stabilization compared to conventional thermal generation alone, thereby enhancing transmission level frequency resilience.

228 North American Electric Reliability Corporation, State of Reliability 2025: Overview, NERC, Atlanta, GA, USA, 2025.

4.1.4 Voltage Support Services

Voltage support at the transmission level refers to the capability of ESS to regulate bus voltages through controlled reactive power injection and consumption, particularly under weak or disturbed grid conditions. As illustrated in Figure 109[229], converter based ESS operate in all four quadrants of the active reactive power plane, enabling independent regulation of active and reactive power within the converter apparent power limit. During undervoltage conditions, reactive power is injected to raise the voltage at the point of common coupling, whereas under overvoltage conditions reactive power is consumed to limit voltage rise. BESS with VSC is widely deployed for this function due to their fast dynamic response and accurate reactive current control. FESS and SESS with converter interfaces provide similar support, while PHS contributes through synchronous machine excitation control or automatic voltage regulators.

Figure 109 Capability curve of BESS



Source: T. H. M. Sumon Rashid et al.; 2022

4.1.5 Oscillation Damping

Oscillation damping at the transmission level addresses low frequency oscillations that arise due to disturbances such as generator outages, large load changes, line switching, or weak inter area tie lines. These oscillations, typically in the range of 0.1 - 2 Hz, occur when groups of synchronous machines swing against each other following a power imbalance. If insufficiently damped, such oscillations can persist, reduce power transfer capability, or in severe cases lead to loss of synchronism and system separation[230]. Traditionally, damping has been provided by power system stabilizers in synchronous generators and by flexible AC transmission devices. Most of the ESS offers a fast and controllable supplementary damping mechanism.

ESS interfaced through VSC can provide oscillation damping by modulating active power in response to measured frequency, power flow, or rotor angle deviations. Through appropriately

229 T. H. M. Sumon Rashid, M. Rabiul Islam and M. Muminur Rahman Sonic, "Strategic Integration of Battery Energy Storage Systems for Effective EV Charging Demand Management in Transactive Energy Markets," in IEEE Access, vol. 13, pp. 69307-69323, 2025.

230 Energy Systems Integration Group, Oscillations in Inverter-Based Resource-Dominated Power Systems: Technical Guide, ESIG, Reston, VA, USA, Aug. 2024.

designed control algorithms, the ESS injects power in phase opposition to oscillatory components, thereby dissipating oscillatory energy and improving damping ratios[231]. GFM BESS can further enhance damping by dynamically adjusting voltage phase and frequency references[217]. PHP plants also contribute to damping through governor and excitation control of synchronous machines, although their response speed is generally slower than power electronic based systems[207]. The high bandwidth controllability of converter based storage makes it particularly effective for inter area oscillation damping in RE rich transmission networks.

4.1.6 Transmission Network Congestion Mitigation

Congestion in transmission network occurs when power flows on one or more transmission corridors approach or exceed their thermal, stability, or voltage limits, preventing economically optimal dispatch of generation resources. Congestion is commonly driven by uneven geographic distribution of generation and load, high penetration of variable RE resources in remote areas, outage of critical transmission elements, or limited transfer capability across inter regional tie lines. Under such conditions, lower cost generation may be curtailed while higher cost local generation is dispatched, leading to increased system operating costs and reduced utilization of RE resources. Persistent congestion can accelerate the need for network reinforcement and limit overall system flexibility[232].

ESS deployed at strategic transmission nodes can reduce congestion by storing surplus power during periods of line loading and discharging when transfer capability is available. Large scale BESS are particularly suited for this application due to their rapid response, flexible siting, and ability to modulate both active and reactive power. PHS and CAES can also contribute where geographical and site constraints permit, particularly for multi hour congestion management. By shifting energy temporally and locally balancing power flows, ESS reduces loading on constrained corridors, improves utilization of transfer capability, and may defer costly transmission upgrades. In addition, coordinated reactive power support from converter based systems can improve voltage stability margins in congested areas, further supporting secure power transfer at the transmission level.

231 F. Arraño-Vargas, S. Jiang, B. Bennett, and G. Konstantinou, “Mitigation of power system oscillations in weak grids with battery energy storage systems: A real-world case study,” Energy (Oxf.), vol. 283, no. 128648, p. 128648, 2023.

232 N. Tarashandeh and A. Karimi, “Utilization of energy storage systems in congestion management of transmission networks with incentive-based approach for investors,” J. Energy Storage, vol. 33, no. 102034, p. 102034, 2021.



Pexels

4.1.7 Long-duration Storage for System Adequacy

LDES for adequacy at the transmission level ensures reliable supply during extended periods of low RE output, high demand, or system stress. With increasing RE penetration, multi hour to multi day supply deficits may arise that exceed the capability of short duration storage. Duration categories include medium duration systems around four hours, extended duration systems of 8-12 hours or more, multi day storage capable of sustained output over several days, and seasonal storage that shifts energy across months. These classifications are particularly relevant in systems with high shares of solar and wind generation, where prolonged low wind conditions or seasonal generation demand mismatches may occur. Technology suitability varies by duration range. Large scale BESS are widely deployed in the 2-4 hour range and are increasingly configured for 6-8 hours and beyond to support capacity markets and firm RE integration. PHS provides mature multi hour to multi day adequacy support due to its substantial energy reservoir and high power rating. CAES and advanced ECES such as FBESS are designed for discharge durations exceeding 8-12 hours. For seasonal shifting, hydrogen based storage and large scale TESS enable energy retention over weeks or months with subsequent reconversion to electricity. Through sustained discharge during prolonged supply shortfalls, long duration storage strengthens resource adequacy, reduces dependence on peaking fossil generation, and enhances transmission level reliability[233].

4.1.8 Black Start Services

Black start support at the transmission level refers to the capability of an ESS to energize a de energized grid segment and initiate system restoration without relying on an external voltage reference. Following a widespread outage, conventional restoration procedures typically depend on designated black start units, such as hydro or diesel generators, to establish an initial voltage and frequency reference. Converter based ESS operating in GFM mode can perform a similar function by independently establishing controlled voltage and frequency at the point of interconnection, thereby energizing transmission lines, transformers, and auxiliary loads. This capability is particularly valuable in systems with reduced availability of conventional black start generators[217].

BESS equipped with GFM control are increasingly deployed for black start applications due to their fast response, precise voltage regulation, and ability to transition between islanded and grid connected modes[234]. PHS plants also provide black start capability through their synchronous generator units, leveraging inherent inertia and established restoration procedures. During restoration, the ESS sequentially energizes network sections, supports transformer inrush currents, and stabilizes voltage and frequency as additional generation units are synchronized[235]. By reducing restoration time and enhancing operational flexibility, transmission connected ESS strengthen overall system resilience and recovery capability following major disturbances.

233 J. Twitchell, K. DeSomber, and D. Bhatnagar, "Defining long duration energy storage," J. Energy Storage, vol. 60, no. 105787, p. 105787, 2023

234 M. Beskar, Grid Forming Battery Energy Storage System for Black Start Studies, Oak Ridge National Laboratory, U.S. Department of Energy.

235 "Unlocking the value of Hydro Pumped Storage after the Iberian blackout," Hydropower.org.

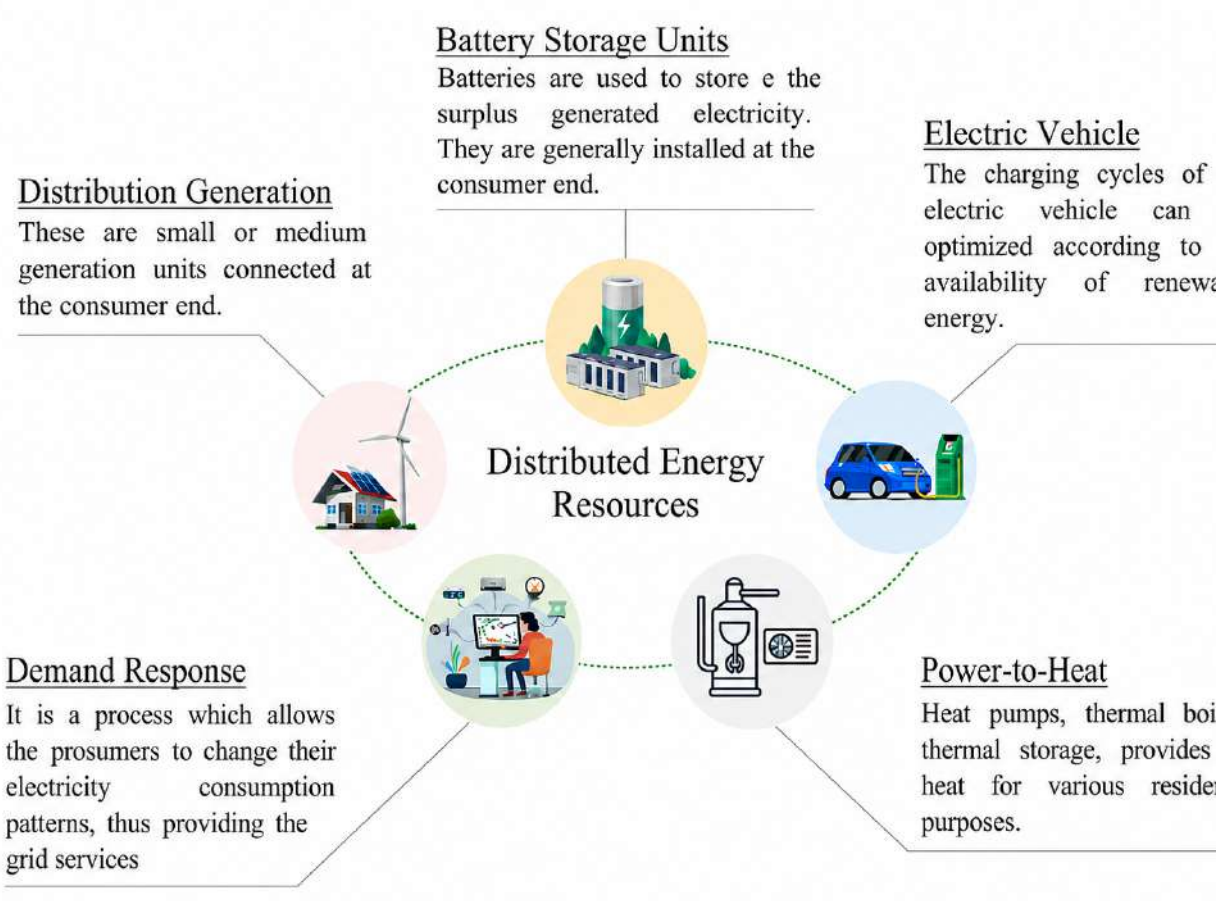


4.2 Distribution Level Applications

In distribution systems, Distributed Energy Resources (DERs) include small to medium assets that can inject, consume, or adjust power in response to system needs. BESS play a key role within DERs by enabling higher penetration of Distributed Generators (DG), particularly converter-based sources such as rooftop and community-scale solar PV. While DG provides clean and decentralised supply, large-scale adoption is constrained by variability, hosting capacity, and operational limitations at the distribution level. BESS address these challenges by providing operational flexibility, making them a critical enabler of sustained DG deployment.

Conceptually, DERs include DG, ESS, controllable demand, smart EV charging, and sector-coupling technologies. This classification is illustrated in Figure 110, which places BTM BESS alongside distributed generation as a core DER category. From a power system perspective, ESS is distinct because it operates bidirectionally and is not constrained by real-time primary energy availability. As a result, BESS enable time decoupling between generation and consumption, which is essential for increasing effective DER penetration on distribution feeders[236].

Figure 110 Classification of Distributed Energy Resources

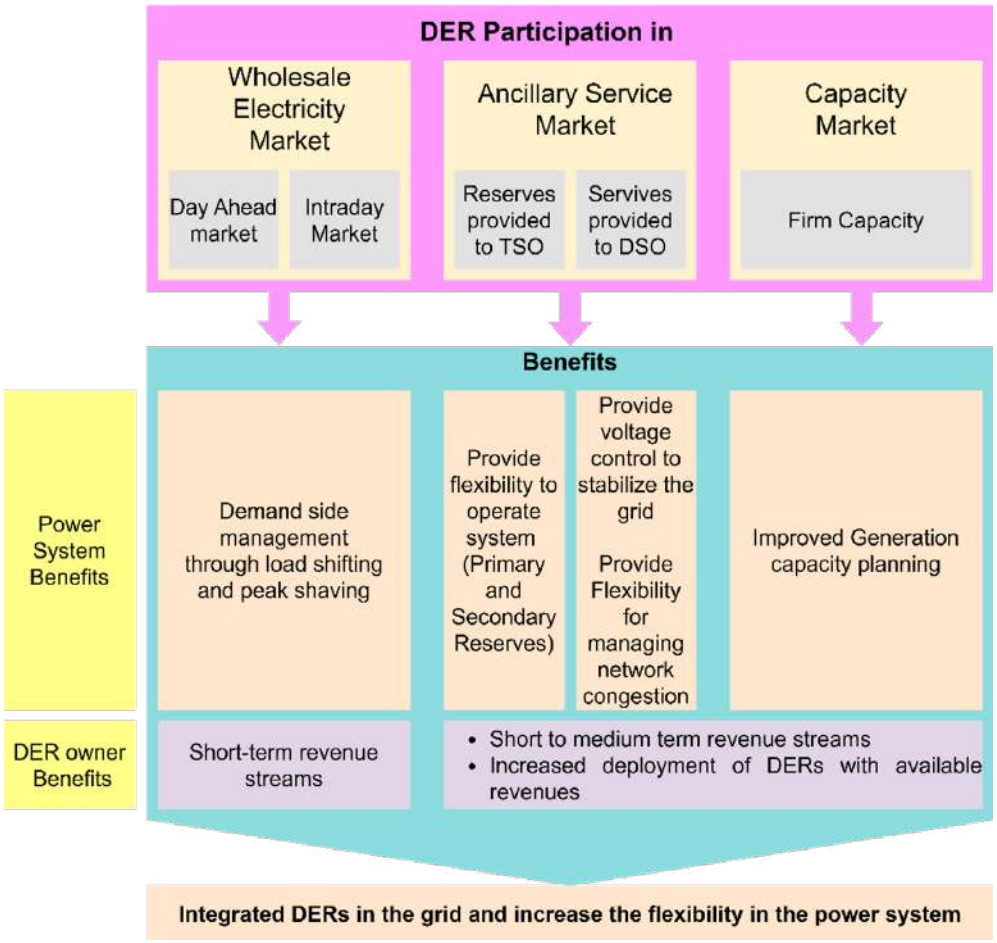


Beyond local network support, integrating BESS with DG enables participation across multiple electricity market layers, thereby improving DG project economics. The system and asset-level benefits of this participation are summarised in Figure 111 and include services such as load shifting, peak shaving, voltage support, congestion management, and improved capacity planning. In practice, many of these services rely primarily on storage-enabled flexibility rather than generation

236 International Renewable Energy Agency, Market Integration of Distributed Energy Resources: Innovation Landscape Brief, IRENA, Abu Dhabi, United Arab Emirates, 2019.

alone. For example, peak shaving and reserve provision require fast, dispatchable response, which is inherent to BESS but not to variable DG sources[236].

Figure 111 Market integration benefits of DERs



Regulatory frameworks that allow aggregated DER participation in wholesale and ancillary service markets further strengthen the role of BESS in DG expansion. When distributed ESS and ESS-coupled DG systems are permitted to aggregate and participate as market-facing resources, they can access additional revenue streams beyond self-consumption or energy export. This revenue stacking improves investment certainty and shortens payback periods, particularly in regions where the marginal value of DG declines as penetration increases. In this context, ESS acts as the primary interface through which DG can deliver firm capacity, reserves, and flexibility services at scale[237].

From a planning and operational perspective, higher DG penetration is closely linked with parallel deployment of BESS at both behind-the-meter and front-of-the-meter levels. Distribution systems with significant DG increasingly depend on ESS-enabled DER portfolios to maintain voltage within limits, manage congestion, and defer network upgrades. Therefore, BESS should be seen not as an add-on, but as a core infrastructure element that enables higher, more reliable, and more cost-effective integration of distributed generation in modern distribution networks[236,238].

237 Federal Energy Regulatory Commission, "Order No. 2222: Facilitating Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators," Washington, DC, USA, 2020.

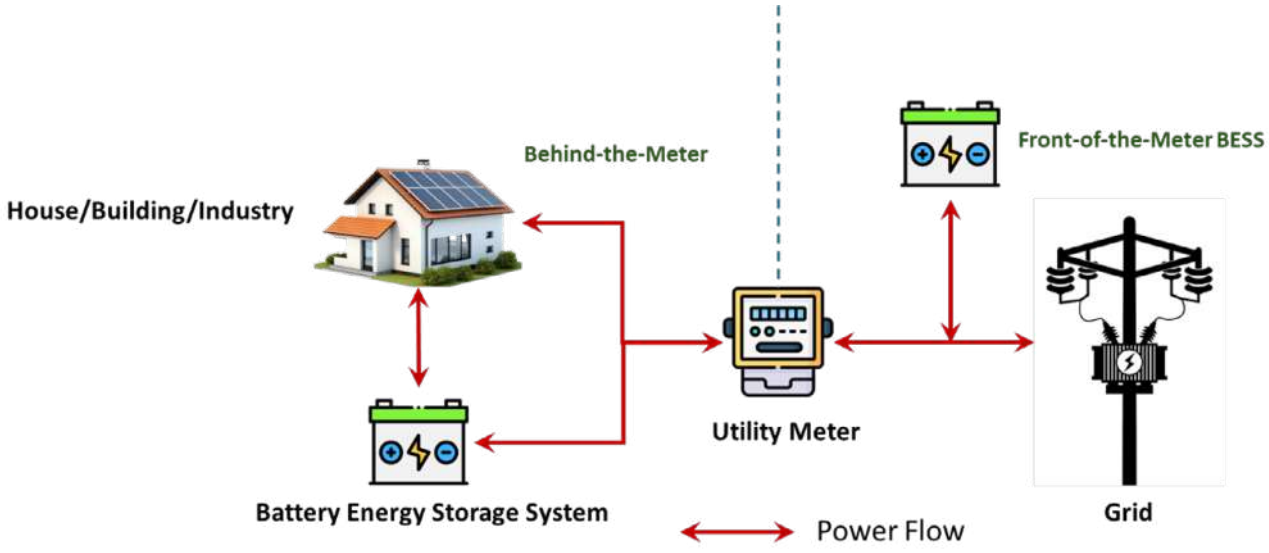
238 International Energy Agency, Unlocking the Potential of Distributed Energy Resources: Power System Opportunities and Best Practices, IEA, Paris, France, May 2022.

4.2.1 ESS Connection at Distribution Level

ESS connected at the distribution level are increasingly important for the reliable and efficient operation of networks with high penetration of converter-based resources. Distribution-connected ESS provide fast, controllable, bidirectional power support and can be deployed at network nodes or customer premises. They support voltage regulation, peak load management, congestion mitigation, and reliability enhancement, while enabling higher levels of distributed generation. Compared with conventional network reinforcement, ESS offer flexible and modular solutions that can adapt to evolving load profiles, electrification trends, and RE variability, making them a key source of local flexibility in actively managed distribution networks.

At the distribution level, ESS are commonly classified by point of coupling and ownership, as shown in Figure 112. Front-of-the-meter (FTM) storage is connected on the utility side and primarily supports network or market objectives, while BTM storage is installed on the customer side to serve load management, self-consumption, and resilience, with potential participation in aggregated grid services. This classification provides a basis for analysing the technical, operational, and regulatory roles of distribution level ESS[239].

Figure 112 Types of ESS connection in distribution network



4.2.1.1 Front-of-the-Meter Energy Storage Systems

FTM ESS are connected on the utility side of the customer meter and operate independently of end-user loads. They are typically owned or contracted by utilities, system operators, or third-party developers and are dispatched to meet network or market objectives. From an operational perspective, FTM storage is directly visible to the grid operator as a controllable resource capable of injecting or consuming active and reactive power, enabling use in distribution planning, real-time operation, and market participation under defined performance and availability requirements[240].

Large-scale ESS, primarily BESS, are increasingly deployed at the distribution level in response to

239 M. Adham, S. Keene, and R. B. Bass, "Distributed energy resources: A systematic literature review," Energy Rep., vol. 13, pp. 1980–1999, 2025.

240 J. Wüllner, N. Reiners, L. Millet, M. Salibi, F. Stortz, and M. Vetter, "Review of stationary energy storage systems applications, their placement, and techno-economic potential," Curr. Sustain./Renew. Energy Rep., vol. 8, no. 4, pp. 263–273, 2021.

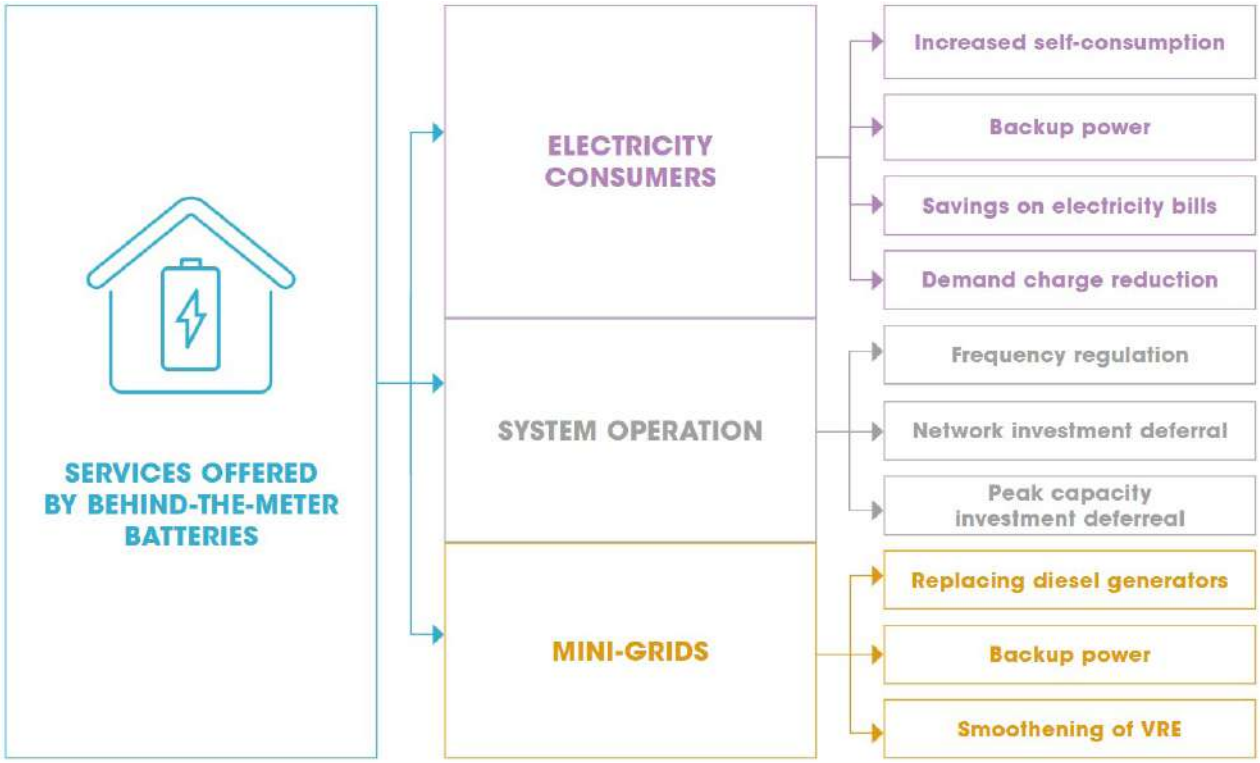
changing load and generation patterns. Growth in RTS PV, EV charging, and increased electrification has created local and time-varying stresses on feeders and substations that are not effectively addressed by bulk system resources. Distribution-connected BESS provide a fast and modular solution by reducing peak loading, managing voltage, consuming excess generation, and deferring network upgrades, with targeted placement near constrained locations proving more effective than centralised solutions239.

Beyond network support, FTM battery ESS can deliver multiple value streams by addressing distribution constraints and participating in energy, capacity, and ancillary service markets. Recent regulatory developments increasingly recognise this dual role, highlighting the contribution of distribution-connected ESS to RE integration, resilience, and active network operation. As a result, FTM BESS is emerging as a key distribution-level asset linking utility planning with market-based operation.

4.2.1.2 Behind-the-Meter Energy Storage Systems

BTM ESS are stationary storage systems connected on the customer side of the utility meter, where charging and discharging directly affect net electricity imports or exports. In this configuration, a BESS functions as a controllable load during charging and a controllable source during discharging, with the meter recording the net effect of on-site load, generation, and storage operation. Battery technologies dominate BTM applications due to their modularity, fast response, and compatibility with power electronics for precise power control[241]. The services provided by BTM BESS are shown in Figure 113[242].

Figure 113 Services offered by BTM BESS



Source: IRENA

241 M. Rezaeimozafar, R. F. D. Monaghan, E. Barrett, and M. Duffy, "A review of behind-the-meter energy storage systems in smart grids," Renew. Sustain. Energy Rev., vol. 164, no. 112573, p. 112573, 2022.

242 International Renewable Energy Agency (IRENA), Behind-the-Meter Batteries: Innovation Landscape Brief, Abu Dhabi, UAE, Sept. 2019.

BTM systems are owned and operated to meet customer objectives rather than network requirements, meaning utilities typically observe only the net load at the meter without direct visibility of BESS operation. This limited observability can lead to misalignment with network needs unless appropriate tariffs, incentives, or coordination mechanisms are implemented[243].

4.2.1.3 Drivers for Consumer Adoption of BTM ESS

Adoption of BTM ESS is primarily driven by customer level value streams. Customers act as the main investors and decision makers, with deployment motivated by benefits such as bill reduction, increased self-consumption, and backup power rather than distribution network objectives. Key drivers for consumer adoption of BTM ESS are outlined below:

- **Customer bill savings:** BTM ESS are primarily adopted to reduce electricity bills through peak shaving and energy time shifting under time-of-use or dynamic tariffs. Demand charge reduction is a key driver for commercial and industrial users, where demand charges constitute a significant share of total electricity costs.
- **Integration with RTS PV systems:** When paired with RTS PV, BTM ESS increase self-consumption by storing surplus generation, thereby reducing grid dependence and exposure to declining export compensation rates.
- **Reliable power supply and resilience:** BTM systems provide backup power during outages, improving supply reliability for users with high outage costs, such as critical infrastructure and industrial facilities.
- **Power quality improvement:** BESS using power electronic converters can mitigate power quality issues such as voltage sags, swells, and short-term frequency deviations. This capability is valuable for commercial and industrial customers that require stable voltage and frequency to protect sensitive equipment.
- **Energy arbitrage and energy time shift:** Under time-varying retail tariffs, BTM BESS allow customers to charge during low-price periods and discharge during high-price periods. However, arbitrage alone is often insufficient to justify investment due to BESS costs and efficiency losses, and it is typically combined with other services through value stacking.

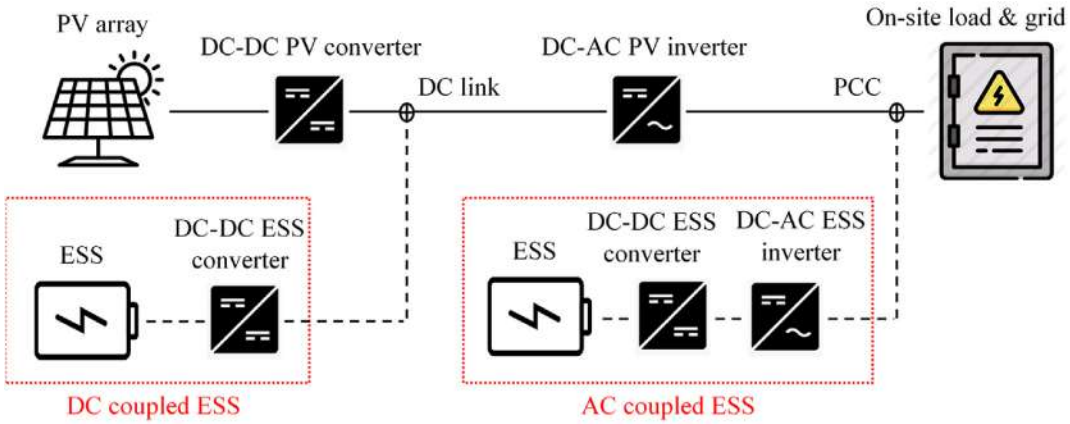
These drivers are collectively referred to as customer-facing services, as the primary benefits are realised directly by customers rather than by the distribution utility.

4.2.1.4 Technical Configuration and Control Implications

BTM BESS are commonly paired with on-site solar PV and managed by an EMS to optimise charging and discharging for bill reduction, resilience, and tariff compliance. As shown in Figure 114[241], two main architectures are used: AC-coupled systems, where the battery converter connects at the point of common coupling, and DC-coupled systems, where the battery connects on the PV DC side, with differences in efficiency, fault behaviour, and operational flexibility. Effective operation requires advanced metering, high-resolution measurement of imports and exports, and control algorithms that respond to tariffs, load forecasts, and PV variability. Advanced metering and automated control are therefore key enablers of BTM system value.

243 National Renewable Energy Laboratory, Behind the meter battery energy storage: frequently Asked Questions, NREL, Golden, CO, USA, 2021.

Figure 114 BTM BESS connection configuration



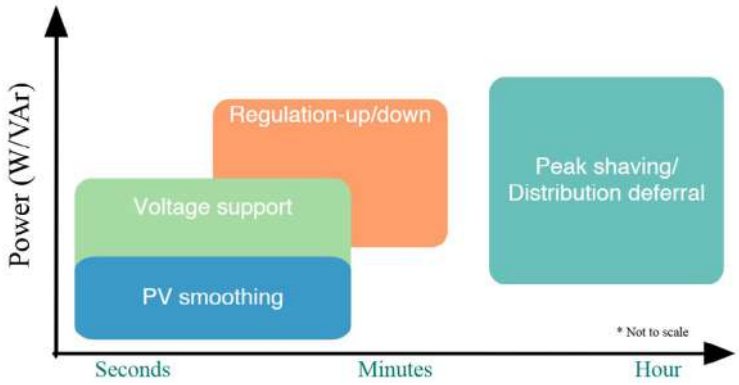
Source: M.Rezaeimozafar et al.; 2022

Although primarily driven by customer benefits, BTM BESS can also deliver distribution-level value when aggregated. Coordinated operation can reduce feeder and transformer loading and support local voltage management by reshaping net demand. However, these benefits depend on appropriate programme design, telemetry, and settlement mechanisms, as utilities typically lack direct control, making BTM storage an indirect resource that requires alignment between customer incentives and network needs.

4.2.2 Value Stacking Service Provision

Value stacking, also referred to as service or revenue stacking, describes the operation of a single ESS to deliver multiple value streams by sharing its limited power, energy, and converter capacity across services that occur at different times or are co-optimised under clear priority rules. As shown in Figure 115[244], fast power-oriented services such as solar PV generation smoothing, voltage support, and frequency regulation act over seconds to minutes, while energy-oriented services such as peak shaving and distribution deferral operate over minutes to hours . Combining services with different time characteristics improves project economics, particularly for distributed ESS where a single application may not justify investment. The feasibility of value stacking is strongly location and market-dependent and relies on regulatory frameworks, market access, and service eligibility[245].

Figure 115 Service categorization based on frequency of operation per day



Source: M. M. Baggu et al.; 2022

244 M. M. Baggu, A. Nagarajan, D. Cutler, D. Olis, T. O. Bialek and M. Symko-Davies, "Coordinated Optimization of Multiservice Dispatch for Energy Storage Systems With Degradation Model for Utility Applications," in IEEE Transactions on Sustainable Energy, vol. 10, no. 2, pp. 886-894, April 2019.

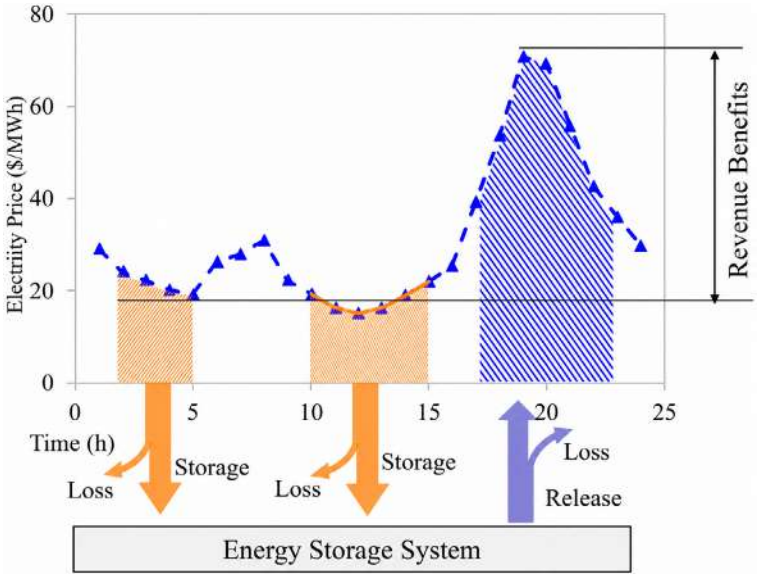
245 J. Hjalmarsson, K. Thomas, and C. Boström, "Service stacking using energy storage systems for grid applications – A review," J. Energy Storage, vol. 60, no. 106639, p. 106639, 2023.

At the distribution level, value stacking is constrained by converter apparent power limits, SoC bounds, cycling and degradation limits, metering definitions, and service compatibility rules that prevent double counting. In practice, services are combined through sequential stacking, capacity-differentiated stacking, or limited simultaneous stacking with defined priorities and verification.

4.2.2.1 Energy Arbitrage at Distribution Level

Energy arbitrage at distribution lebel refers to operating an ESS to charge during low-price periods and discharge during high-price periods to capture the price differential, subject to round-trip efficiency and cycling limits. As shown in Figure 116[246], an ESS charges when electricity prices are low and discharges when prices increase. In distribution-connected settings, arbitrage is often constrained by feeder limits, transformer loading, and local flexibility prices, which can render a purely wholesale price-based strategy suboptimal or infeasible.

Figure 116 Energy store and release operation w.r.t. electricity price



Source: Xinjing Zhang et al.; 2021

Energy arbitrage is primarily an active power scheduling problem over a defined horizon, typically day-ahead with intraday updates. Key constraints include SoC dynamics, charge and discharge power limits, converter rating, minimum and maximum SoC, and end-of-horizon SoC requirements to preserve future service capability. When arbitrage is stacked with local services, available converter capacity and energy headroom must be reduced to reserve capability for reliability-critical services.

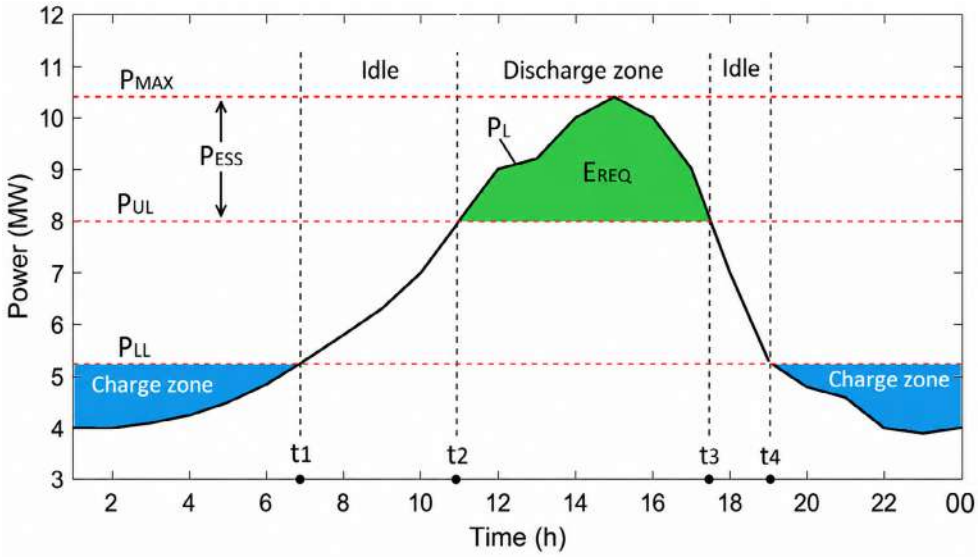
4.2.2.2 Peak Shaving at Distribution Level

Peak shaving at the distribution level refers to discharging ESS active power during defined peak periods to reduce the maximum demand seen by a constrained asset, such as a distribution transformer, feeder, or customer point of common coupling. As shown in Figure 117[247], the ESS discharges during peak demand and charges during low-demand periods. The primary operational benefit is reduced thermal stress and deferred network upgrades, while the economic benefit appears as lower demand charges in BTM cases or as compensated flexibility in FTM deployments.

246 X. Zhang, C. (chris) Qin, E. Loth, Y. Xu, X. Zhou, and H. Chen, “Arbitrage analysis for different energy storage technologies and strategies,” Energy Rep., vol. 7, pp. 8198–8206, 2021.

247 S. M. S. Danish, M. Ahmadi, M. S. S. Danish, P. Mandal, A. Yona, and T. Senjyu, “A coherent strategy for peak load shaving using energy storage systems,” J. Energy Storage, vol. 32, no. 101823, p. 101823, 2020.

Figure 117 Discharging of ESS during peak demand hours and charging during low demand



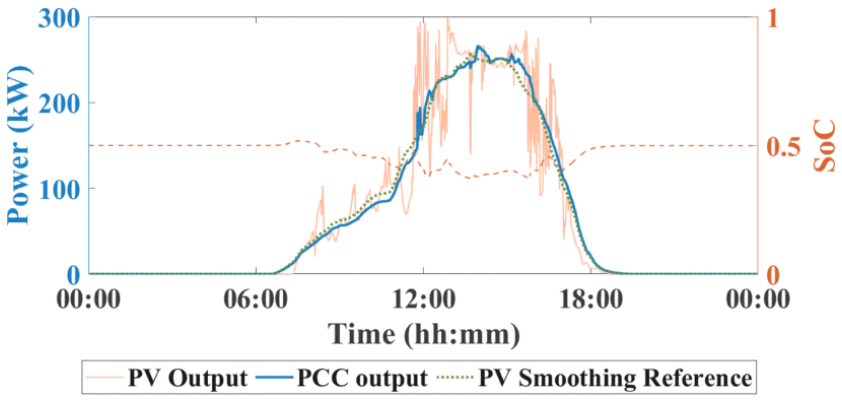
Source: S. M. S. Danish et al.; 2020

Peak shaving is an hours-scale service and is generally compatible with faster services such as PV smoothing and voltage support, provided SoC planning, converter headroom reservation, and service priority rules are clearly defined. In practical multi-service dispatch, peak shaving is often prioritised, with remaining power and energy capacity allocated to PV smoothing when service windows do not overlap, thereby avoiding simultaneous over-commitment of the ESS[247].

4.2.2.3 PV Smoothing at Distribution Level

PV smoothing refers to the use of an ESS to reduce short-term variability and ramping of solar PV output as observed at the local network or point of interconnection. This is achieved by charging during rapid increases in PV output and discharging during non solar hours, thereby shaping a smoother net power profile. The primary technical objective is to limit power ramps, reduce voltage fluctuations, and improve operational predictability at the feeder level, as shown in Figure 120. PV smoothing operates over seconds to minutes and therefore places high demands on power capability rather than energy capacity, making converter rating and ramp-rate constraints the key design considerations[248].

Figure 118 Point of interconnection solar PV generation profile after PV smoothing



Source: S. Patel et al.; 2020

248 S. Patel, M. Ahmed and S. Kamalasadan, "A Novel Energy Storage-Based Net-Load Smoothing and Shifting Architecture for High Amount of Photovoltaics Integrated Power Distribution System," in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 3090-3099, May-June 2020.



Herbie Pearthree, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons



AI Image

PV smoothing can increase cycling frequency if applied without forecasting or appropriate control logic. In value-stacking portfolios, it is therefore typically coordinated with short-term forecasts and SoC bounds to preserve energy for subsequent services. In service stacking, response-time suitability varies across ESS technologies and services, highlighting that electrical ESS with fast response characteristics is particularly well suited to short time-scale smoothing applications.

4.2.2.4 Frequency and Voltage Regulation

Frequency regulation is the rapid adjustment of ESS active power to correct power imbalances and maintain system frequency within allowable limits. Voltage regulation involves reactive power provision and, in some cases, active power adjustment to keep node voltages within statutory bounds. For distribution-connected ESS, voltage support is constrained by converter apparent power limits and local voltage sensitivity, making location-aware dispatch more effective than uniform droop settings.

Frequency regulation and voltage support are often high-value services, but they are coupled through the converter kVA limit. Delivering high active power for frequency response reduces the remaining reactive power capability available for voltage control. As a result, simultaneous stacking of these services requires explicit coupling of active and reactive power constraints. A flexibility market-oriented study demonstrates that distributed ESS can provide both upward and downward power flexibility alongside voltage support, with reactive capability directly dependent on the active power schedule and converter apparent power limits[249].

4.2.2.5 Distribution Feeder Congestion Management

Distribution congestion management uses ESS dispatch to relieve thermal or operational constraints in feeders, transformers, or other distribution assets. Performance is measured through reduced peak loading, shorter durations of constraint violations, or increased transfer headroom. While closely related to peak shaving, congestion management is driven by network constraints and system operator objectives rather than customer billing considerations. Distribution-level flexibility markets can reflect congestion and voltage value through locational prices for active and reactive flexibility. A bilevel market formulation shows that storage dispatch is guided by both energy prices and distribution flexibility price signals, effectively converting congestion relief into a revenue stream that can be stacked with wholesale and balancing services[241].

4.2.2.6 Black Start in Distribution Network

Black start capability is the ability of an ESS to support grid restoration after a major outage by supplying initial power, establishing reference voltage and frequency, and energising local loads in islanded operation. At the

249 R. Karandeh, M. Davoudi and V. Cecchi, “Distributed Control of Behind-the-Meter Energy Resources for Multiple Services,” in IEEE Transactions on Power Delivery, vol. 37, no. 3, pp. 2050-2059, June 2022.

distribution level, this function is most relevant for microgrid-enabled feeders or critical facilities, where converter-based ESS can operate in GFM and restore downstream loads prior to reconnection with the upstream network. From a value-stacking perspective, black start capability is maintained through minimum SoC requirements, reserved energy margins, and GFM converter capability. These requirements limit the flexibility available for arbitrage and other services. As a result, stacking black start services is most practical when the ESS is compensated for holding reserve energy or when restoration is limited to selected loads or partial feeder sections[241].

4.2.2.7 Practical Case Studies for BESS Providing Value Stacking Services

The below Table 43 summarises the global deployed BESS that are providing value stacking services[245,250].

Table 43 ESS providing value stacking services globally

Location	Storage technology	Rated capacity (MW/MWh)	Services (stacked)
Dinorwig, Wales	PHES	1728/9100	Energy time shift, Frequency regulation, Spinning reserve
Abingdon, England	FES	400/1.44	On site power supply, Frequency regulation
Huntorf, Germany	CAES	290/480	Minute reserve, Spinning reserve
Alabama, USA	CAES	110/2700	Energy time shift, Frequency regulation
Hornsdale, Australia	BESS	100/129	Spinning reserve, Energy arbitrage
Leighton Buzzard, England	BESS	6/10	Non spin reserve, Congestion relief
Uppsala, Sweden	BESS	5/20	Energy time shift, Frequency regulation
Vermont, USA	BESS	4/3.4	Non spin reserve, Congestion relief, Frequency regulation
Darlington, England	BESS	2.5/5	Backup power, Peak shaving, Congestion relief, Energy time shift, Voltage support
Victoria, Australia (Victorian Big Battery)	BESS	300/450	Energy arbitrage, FCAS markets, specialised grid services (frequency or voltage control)
California, USA (Moss Landing, Vistra)	BESS	750/3000	Resource adequacy capacity, Energy market participation, Ancillary services
South Australia, Australia (Horns dale Power Reserve)	BESS	100/129 (Phase 1)	Frequency control services, Grid stability services, Energy arbitrage

250 GIL Research

4.3 Modelling of Energy Storage Systems

The modelling of ESS is fundamental to their analysis, planning, and integration within modern power systems. Owing to the diversity of ESS technologies and control architectures, models must represent both internal storage dynamics and external grid interfacing behaviour[196]. Depending on the study objective, representations range from detailed component level formulations of electrochemical or mechanical processes to aggregated plant level models that incorporate converter control and supervisory functions. For simulation purposes, models are developed in both Root Mean Square (RMS) and Electromagnetic Transient (EMT) domains to address distinct time scale phenomena. RMS models support system level stability, frequency response, and adequacy studies, whereas EMT models capture fast switching behaviour, converter control interactions, and protection performance. A structured modelling framework is therefore required to ensure technically consistent and study specific representation of energy storage systems.

4.3.1 Importance for Accurate Modelling

Historically, ESS constituted a limited share of generation portfolios, with PHS often represented as a conventional generator or negative load. With the rapid deployment of grid scale ESS and hybrid plants, such simplified representations are no longer adequate. Accurate and validated modelling is essential to ensure reliable planning, secure operation, regulatory compliance, and protection coordination across diverse ESS technologies. Importance of accurate system modelling is summarised below[251]:

- **Reliability and stability assessment:** ESS contribute to frequency response, voltage control, and contingency support. Inadequate representation, such as neglecting converter limits or dynamic controls, can result in false estimation of stability margins, fault response, and interconnection impacts.
- **Control interaction and weak grid behaviour:** Converter interfaced ESS employ fast inner current loops and outer control layers that interact with system dynamics. Oversimplified models may fail to capture control induced oscillations, instability under low SCR conditions, or adverse interactions with other converter based resources.
- **Energy constraints and state tracking:** Unlike conventional generation, ESS output is constrained by stored energy. Accurate SoC tracking is required to represent sustained frequency events, extended dispatch cycles, and adequacy studies without overestimating available support.
- **Multi time scale consistency:** ESS influence both steady state scheduling and sub second transient dynamics. Consistent modelling across power flow, RMS, and EMT domains ensures coherent representation of dispatch behaviour, droop response, and fault performance.
- **Grid code compliance and protection design:** Demonstration of ride through capability, reactive current injection/consumption, and fault behaviour requires validated dynamic models. Detailed representations also support protection coordination and safe operation by capturing converter switching effects, overvoltage, and fault currents.

251 A. Thant, “Importance of IBR modeling and design evaluation,” North American Electric Reliability Corporation, 2024.

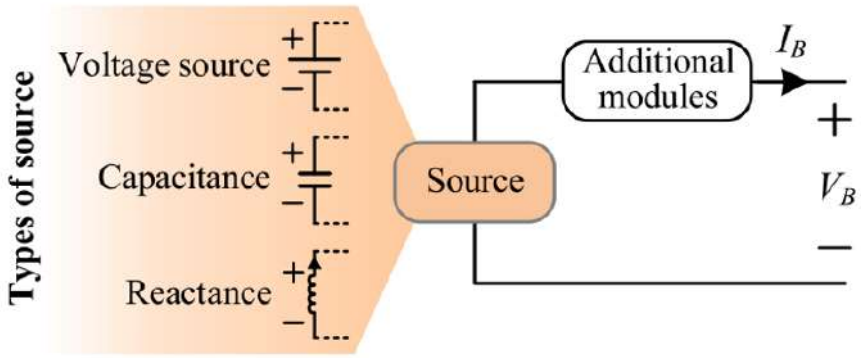
4.3.2 Modelling Approaches: Component Level and Plant Level

ESS can be represented using different modelling approaches depending on the intended application, required fidelity, and computational constraints of the study. Broadly, modelling strategies are categorized into component level modelling and plant level modelling, each serving distinct analytical purposes. Component level models aim to capture the intrinsic physical and control dynamics of individual subsystems, while plant level models provide an aggregated representation suitable for system wide simulations. The choice of approach depends on whether the objective is detailed device level analysis, control validation, or large scale grid integration study.

4.3.2.1 Component Level Modelling

Component level modelling represents the intrinsic electrical and dynamic behaviour of the storage medium prior to aggregation at the plant level. A generalised framework models the storage module as an equivalent electrical network comprising a controlled voltage source combined with resistive, inductive, and capacitive elements. As illustrated in Figure 119[196], ESS technologies can be abstracted using combinations of ideal voltage sources, capacitances, and reactance in accordance with their underlying physics. The internal voltage source represents the open circuit potential or electromotive force, while resistive elements capture ohmic and charge transfer losses. Inductive and capacitive branches represent transient dynamics, diffusion processes, and polarisation effects. Modular replication enables scalable representation of series and parallel cell or stack aggregation for battery packs, supercapacitor banks, and other modular storage arrays.

Figure 119 Generic modelling diagram of energy storage

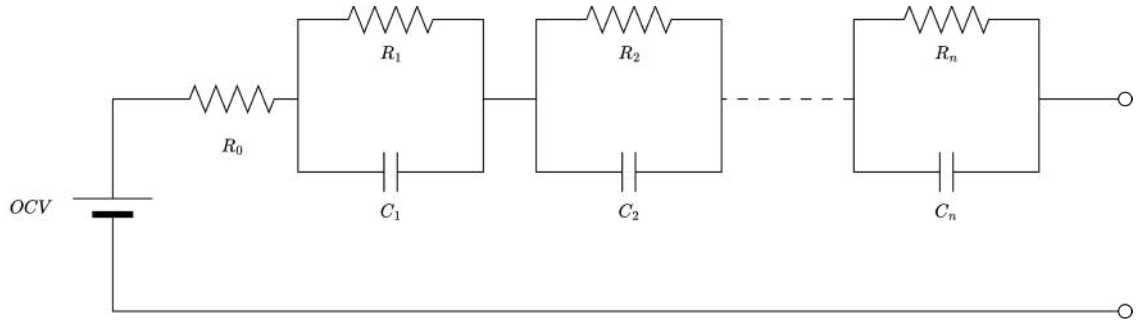


Source: Q. Fu et al.; 2025

For BESS, the equivalent circuit model typically includes an open circuit voltage source in series with internal resistance and one or more resistor capacitor branches, as shown in Figure 120[252]. The open circuit voltage is expressed as a function of state of charge to capture non-linear voltage variation with energy content. The series resistance represents instantaneous voltage drop due to conduction losses, while parallel RC branches model transient polarisation and diffusion dynamics during charge and discharge. Higher order models incorporate multiple RC branches to enhance dynamic fidelity. This representation enables accurate estimation of terminal voltage and transient response and supports state of charge and state of health algorithms.

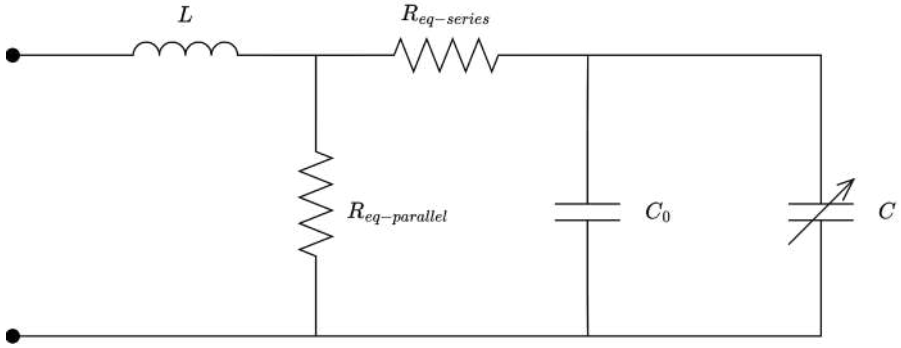
252 M. Ledro, J. M. Zepter, M. Paludan, and M. Marinelli, "Electrical modelling of a grid-connected battery energy storage system via EMS and BMS data," Measurement: Energy, vol. 6, no. 100048, p. 100048, 2025.

Figure 120 Equivalent modelling of battery cell



For supercapacitors, the equivalent model emphasises dominant capacitance with low internal resistance and comparatively minimal electrochemical time constants. As illustrated in Figure 121, storage behaviour is primarily governed by capacitance and an equivalent series resistance that defines power capability and internal losses. Additional RC branches may be included to represent leakage and distributed capacitance. Supercapacitor voltage varies approximately linearly with stored charge, and energy is proportional to the square of voltage. The RLC based modelling framework thus provides a unified and parameterizable approach for detailed time domain analysis of electrochemical and electrostatic storage technologies[253].

Figure 121 Equivalent modelling of supercapacitor



4.3.2.2 Plant Level Modelling

Plant level modelling represents the aggregated behaviour of an entire storage installation, integrating storage modules, power conversion systems, protection devices, auxiliary systems, and grid interfacing equipment into a unified framework. Unlike component level modelling, which focuses on cell or module dynamics, plant level models evaluate system level performance such as power dispatch capability, frequency response, voltage regulation, protection coordination, and interaction with the transmission or distribution network. The modelling abstraction typically includes an aggregated DC side representation, converter control blocks, transformer interface, and grid connection at the point of common coupling.

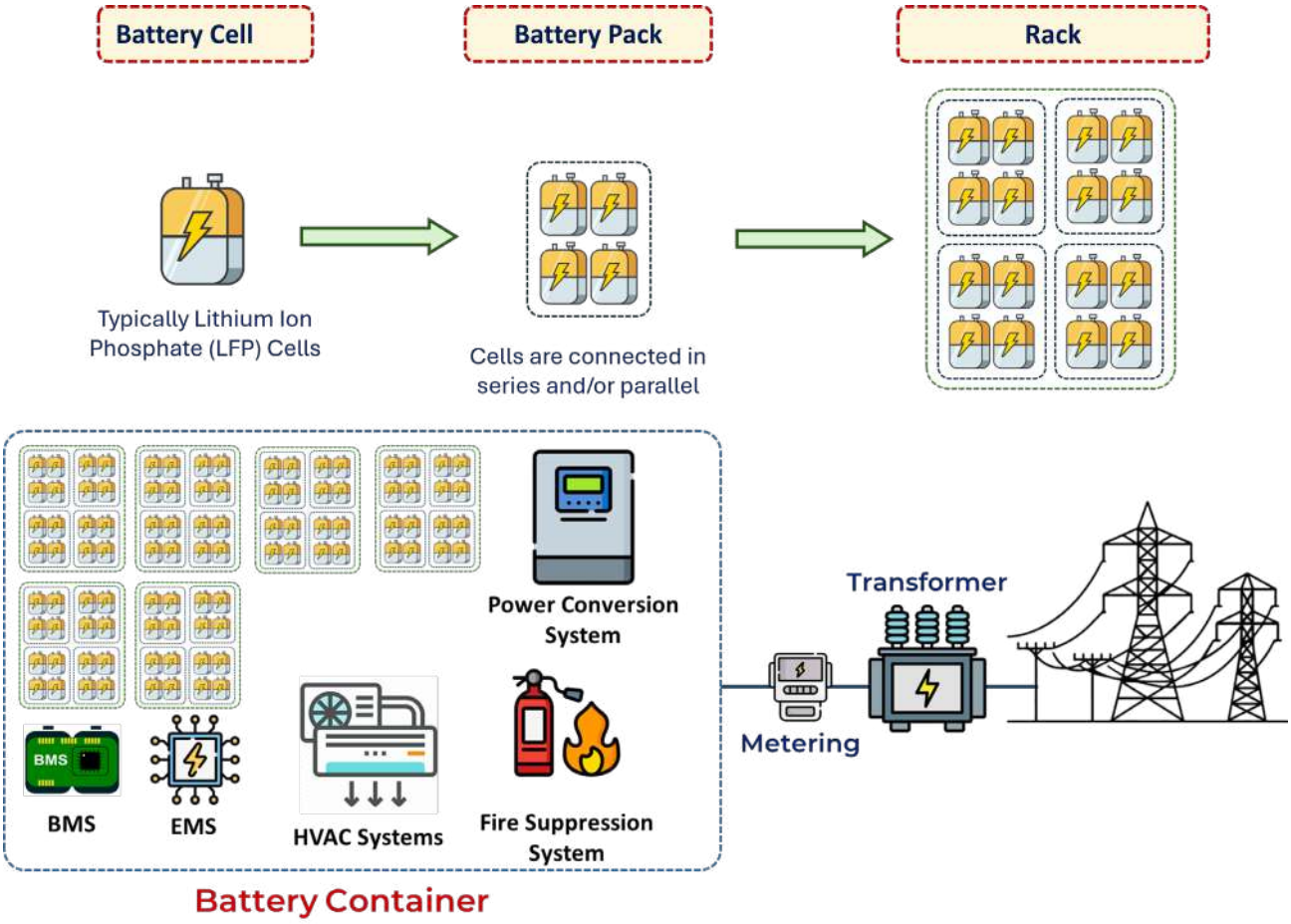
BESS modelling

The BESS architecture illustrated in Figure 122 shows hierarchical aggregation from cell to pack to rack within a containerised plant structure. At the plant level, individual cell dynamics are generally aggregated into an equivalent DC source model with defined voltage limits, state of charge dynamics, and power constraints. The BMS is represented through supervisory constraints such

253 M. Ates and A. Chebil, “Supercapacitor and battery performances of multi-component nanocomposites: Real circuit and equivalent circuit model analysis,” J. Energy Storage, vol. 53, no. 105093, p. 105093, 2022.

as maximum charge and discharge current, thermal limits, and SoC operating windows. The EMS is modelled as a higher level control block that dispatches active and reactive power setpoints to the PCS based on grid requirements or market signals.

Figure 122 Architecture of a grid connected BESS



The single line diagram of a BESS plant as seen from Figure 123, commonly used as the basis for RMS and EMT simulations. The DC side consists of battery racks connected through DC combiners to the PCS. The PCS, typically a bidirectional VSC, interfaces through an MV or LV transformer to the medium voltage bus and ultimately to the grid. In plant level modelling, the PCS is represented using averaged converter models for RMS studies or detailed switching models for EMT studies which will be explained in later sections. The transformer is modelled with leakage reactance and resistance. Protection devices such as breakers and relays are included depending on study scope. Auxiliary systems such as HVAC and fire suppression, although not electrically dominant, are represented as parasitic loads influencing plant availability and efficiency[254].

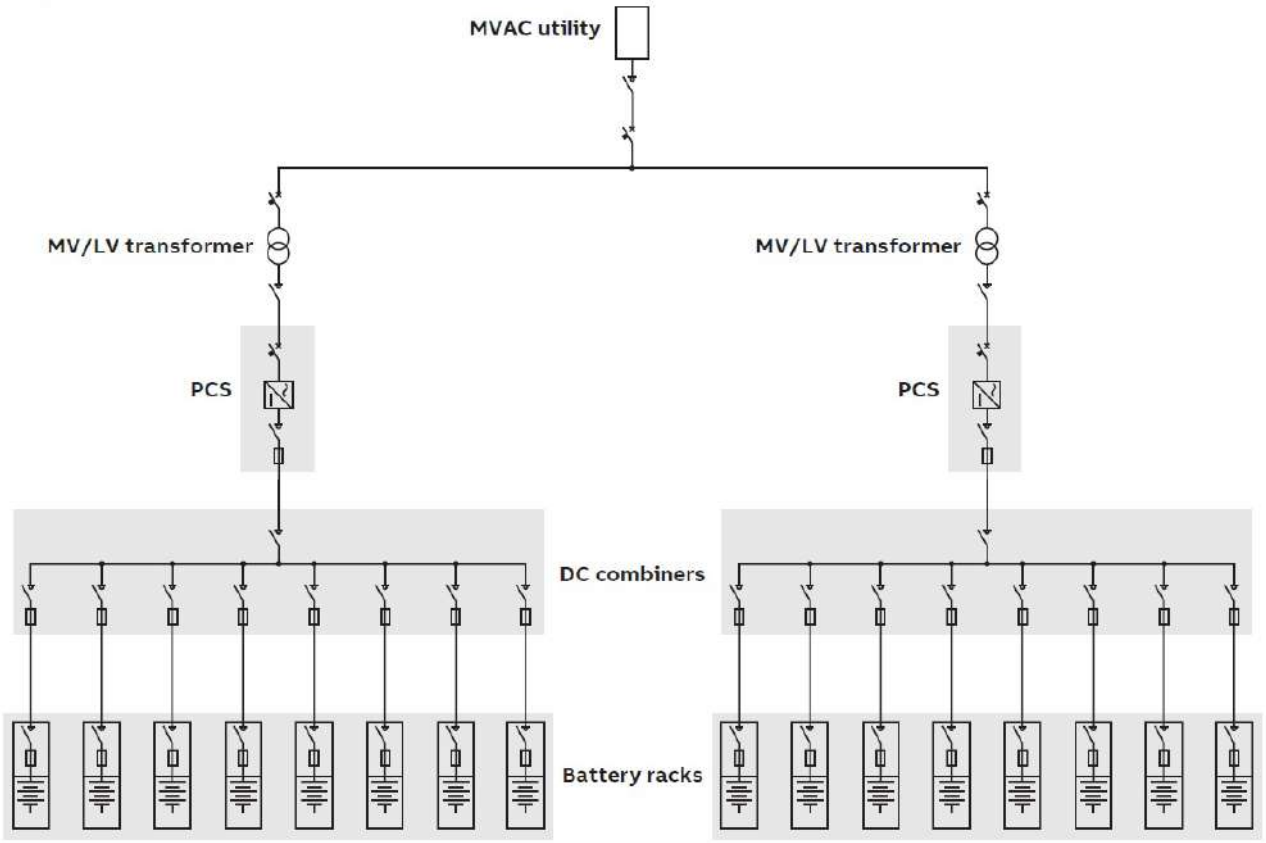
254 ABB, Utility-Scale Battery Energy Storage System (BESS): BESS Design IEC – 4.0 MWh System Design, White Paper.


AI Image

☀ KEY INSIGHT

ESS modelling must be selected by study objective: component-level models capture cell and device dynamics, while plant-level RMS and EMT models represent aggregated controls, PCS behaviour, protection, and grid interaction for system studies.

Figure 123 Single line diagram of grid connected BESS plant

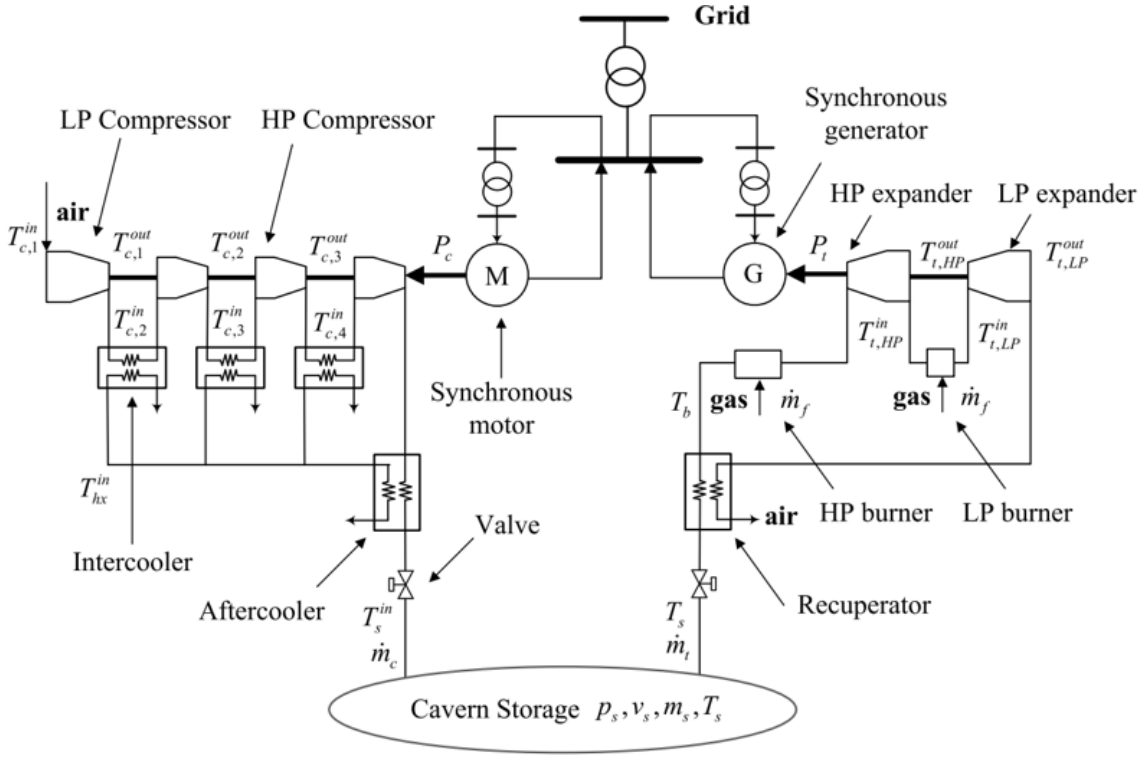


Source: ABB

CAES plant modelling

The modelling of CAES systems, as shown in Figure 124[213], requires representation of both electrical and thermodynamic subsystems. The plant consists of compressors, intercoolers, aftercoolers, cavern storage, expanders, recuperators, burners, and a synchronous motor generator set connected to the grid. During charging, the motor drives multistage compressors that store compressed air in an underground cavern. During discharge, stored air is reheated and expanded through turbines to drive a synchronous generator. Plant level modelling therefore includes dynamic representations of pressure, temperature, mass flow rate, and cavern thermodynamics, in addition to synchronous machine electrical models and excitation systems. In RMS studies, CAES plants are typically represented using synchronous generator models with turbine governor characteristics. Detailed EMT studies may include compressor and expander dynamics for transient performance evaluation.

Figure 124 CAES plant modelling

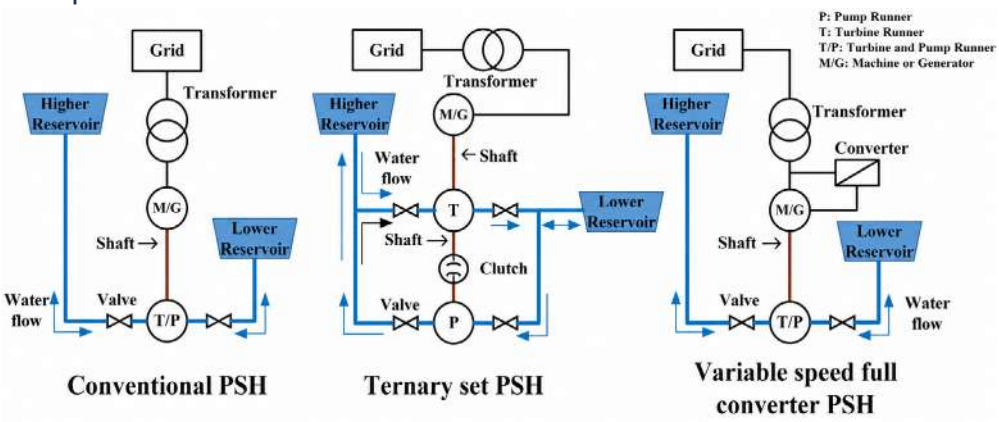


Source: F. Calero et al.; 2023

PHS plant modelling

Conventional, ternary set, and variable speed full converter PHS are illustrated in Figure 125[255]. In plant level modelling, the hydraulic subsystem includes upper and lower reservoirs, water column dynamics, penstock elasticity, turbine pump characteristics, and valve control. The electromechanical subsystem mainly includes the motor generator, excitation system, and governor. Conventional PHS is modelled using reversible pump turbine characteristics coupled to a synchronous machine. Ternary set configurations include separate pump and turbine runners with a clutch mechanism, requiring additional mechanical coupling models . Variable speed PHS incorporates power electronic converters between the machine and the grid, enabling speed control and enhanced frequency response. In such cases, both converter dynamics and machine dynamics are included in plant level representation.

Figure 125 PHS plant model



Source: Z. Dong et al.; 2023

255 Z. Dong et al., "Modelling and simulation of ternary pumped storage hydropower for power system studies," IET Gener. Transm. Distrib., vol. 13, no. 19, pp. 4382–4390, 2019.

Across all technologies, plant level modelling integrates storage medium dynamics, conversion equipment, supervisory control, and grid interface components into a coherent simulation framework. The objective is to capture realistic active and reactive power capability, dynamic response, fault behaviour, and control interactions at the point of common coupling. While component level details may be simplified through aggregation, plant level models must preserve essential constraints such as ramp rate limits, energy capacity limits, voltage support capability, and protection coordination to ensure accurate system level assessment.

4.3.3 Simulation Framework for ESS

The modelling of ESS for power system studies is broadly classified into steady state modelling and dynamic state modelling, depending on the time scale and phenomena of interest. Steady state models are primarily used for power flow, optimal power flow, and long term planning studies, where the objective is to determine operating points, voltage magnitudes, power dispatch levels, and network loading under quasi static conditions. In contrast, dynamic models evaluate time dependent behaviour following disturbances such as faults, generation outages, load changes, or frequency events. Dynamic modelling of ESS is further categorised into RMS domain models and EMT domain models, each suited to different temporal resolutions and analytical depth.

4.3.3.1 Steady State Modelling

In steady state analysis, an ESS is typically represented as a controllable active and reactive power source at the point of common coupling. The model includes constraints such as maximum charge and discharge power limits, converter apparent power limits, SoC dependent energy constraints, and reactive power capability curves. For transmission level studies, the ESS is commonly modelled as a PQ bus with specified real and reactive power injection, or as a PV bus when voltage regulation is enabled within reactive limits. The SoC may be treated as a slowly varying parameter updated between time steps in quasi static time series simulations.

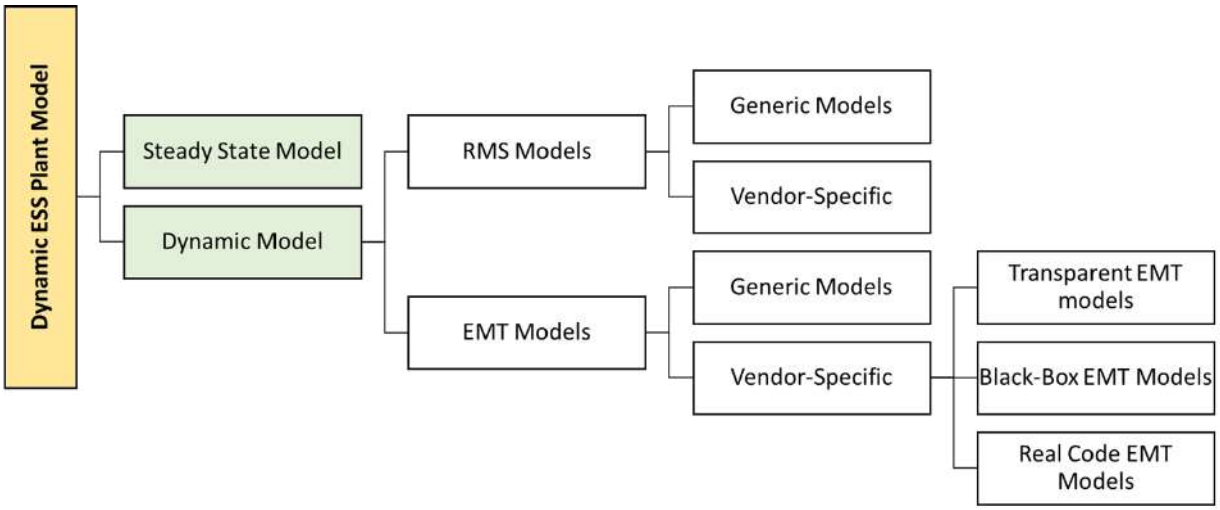
Steady state models are widely used for congestion management studies, energy arbitrage analysis, capacity adequacy evaluation, and network reinforcement planning. In such studies, internal converter switching dynamics and fast control loops are neglected, and only aggregated limits and dispatch logic are retained. While this abstraction reduces computational complexity, it does not capture transient stability, frequency dynamics, or protection behaviour. Therefore, steady state modelling is suitable for long horizon operational and economic assessments but insufficient for detailed stability analysis.

4.3.3.2 Dynamic State Modelling

Dynamic State Modelling is broadly categorised according to their intended use case and level of accessibility, as illustrated in Figure 126. At the steady state level, simplified representations are used for power flow and planning studies, whereas dynamic models are implemented in RMS or EMT domains depending on the required temporal resolution. The range of their applicability is summarised in Figure 127[256]. Within RMS modelling, widely adopted generic models are provided through frameworks such as WECC models, IEC standardised dynamic model structures, and CIGRE benchmark models, enabling consistent interconnection and stability studies across utilities. In contrast, vendor specific RMS models may include proprietary control logic while conforming to utility validation requirements.

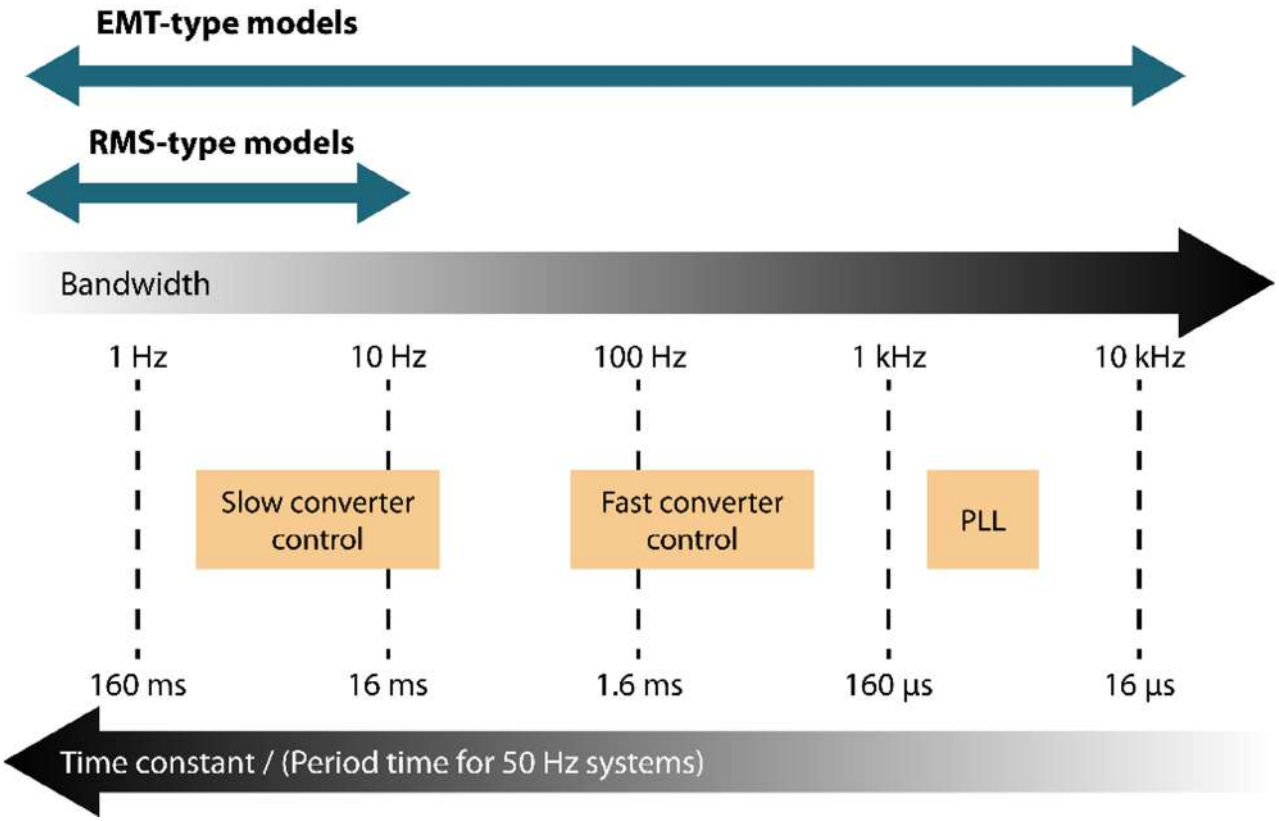
256 Energy Systems Integration Group, Introduction to EMT Simulations, ESIG, 2025.

Figure 126 Dynamic modelling classification



For EMT studies, generic models are commonly developed using standard VSC blocks with publicly documented control structures. Vendor specific EMT models may be delivered as transparent implementations, encrypted black box models, or real code models integrating compiled controller firmware. The availability of standardised generic models, such as WECC and IEC compliant structures, facilitates grid wide consistency and regulatory review, whereas vendor specific EMT models provide higher fidelity for detailed protection studies, weak grid assessment, and control interaction analysis.

Figure 127 Applicability range of RMS and EMT models



Source: ESIG

RMS modelling

RMS-domain modelling uses phasors to capture electromechanical dynamics over tens of milliseconds to seconds. ESS converters are represented by averaged models, replacing explicit switching with controlled voltage or current sources governed by differential equations. The dynamic model includes inner current control loops, outer active and reactive power control loops, DC link dynamics, SOC evolution, and plant level supervisory control. RMS models are widely used for transient stability studies, frequency response analysis, voltage recovery assessment, oscillation damping evaluation, etc. They allow representation of GFL and GFM control modes, droop characteristics, virtual inertia emulation, and current limitation behaviour during faults. Because switching harmonics are neglected, RMS models are computationally efficient and suitable for large scale network simulations. However, they cannot accurately capture fast electromagnetic transients, sub cycle phenomena, or detailed protection interactions.

EMT Modelling

EMT modelling represents instantaneous voltages and currents in the time domain, typically with time steps in the order of microseconds. In EMT simulations, the power electronic converter is modelled with explicit semiconductor switching devices, pulse width modulation strategies, DC link capacitance, and detailed control implementation. This enables accurate representation of switching harmonics, sub synchronous interactions, DC link oscillations, and protection device operation. EMT models are essential for evaluating converter control stability in weak grids, fault ride through performance, inrush current during transformer energisation, interaction between multiple converter based resources, and high frequency resonance phenomena. They are particularly relevant for GFM ESS, where voltage source behaviour and current limiting strategies during faults must be validated. While EMT modelling provides high fidelity, it is computationally intensive and typically limited to smaller network sections or detailed studies of specific substations.

Comparison between RMS and EMT modelling

Both RMS and EMT modelling have their own applications that depends on the type of analysis to be performed and parameters to be evaluated. The comparison between RMS modelling and EMT modelling is summarised in Table 44.

Table 44 Comparison between RMS and EMT odelling

Parameter	RMS modelling	EMT modelling
Time scale representation	Electromechanical time scale, typically milliseconds to seconds	Electromagnetic time scale, microseconds to milliseconds
Signal representation	Uses phasor quantities representing fundamental frequency components	Uses instantaneous time domain voltage and current waveforms
Converter representation	Averaged model without explicit semiconductor switching	Detailed switching model including IGBTs, diodes, PWM logic
Phenomena captured	Frequency response, voltage recovery, transient stability, oscillation damping	Switching harmonics, fault transients, protection coordination, resonance
Computational requirement	Lower computational burden, suitable for large network studies	High computational burden, typically limited to localized system sections

CHAPTER 5

05 ELECTRIC VEHICLES AS MOBILE ENERGY STORAGE SYSTEMS



Pexels



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Summary

- Presents electric vehicles as mobile energy storage systems by linking rapid global EV adoption with their growing role as distributed, controllable battery resources.
- Reviews global EV sales, market penetration, regional adoption, production concentration, and medium term projections, with emphasis on China, Europe, the United States, and emerging markets.
- Explains Li-ion battery requirements for EVs, including energy density, power capability, voltage stability, thermal management, cycle life, battery management, pack architecture, and charging behaviour.
- Discusses Vehicle-to-X applications, including V2G, V2H, V2B, V2L, and V2V, along with their grid support potential, battery health impacts, infrastructure needs, market barriers, and user related constraints.

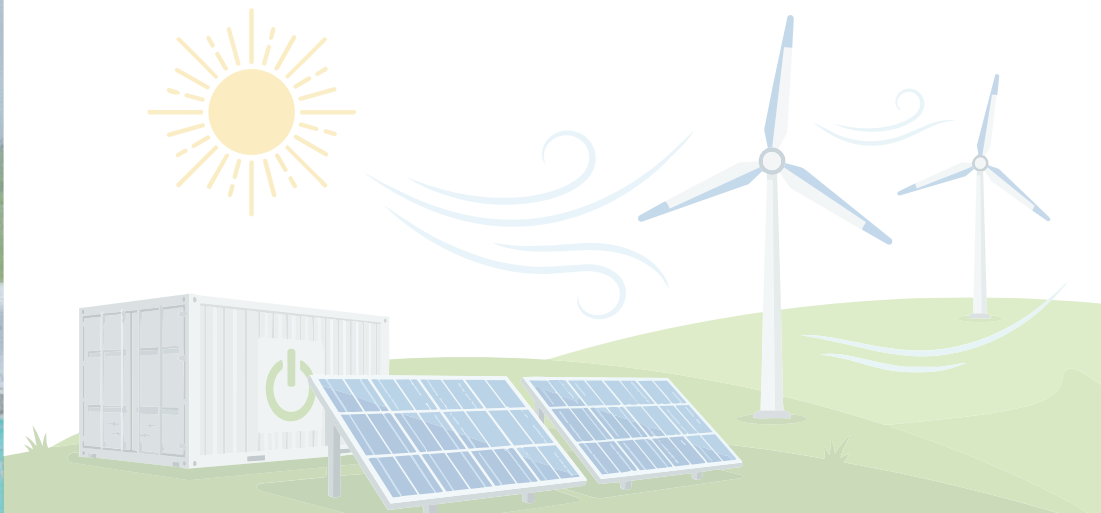
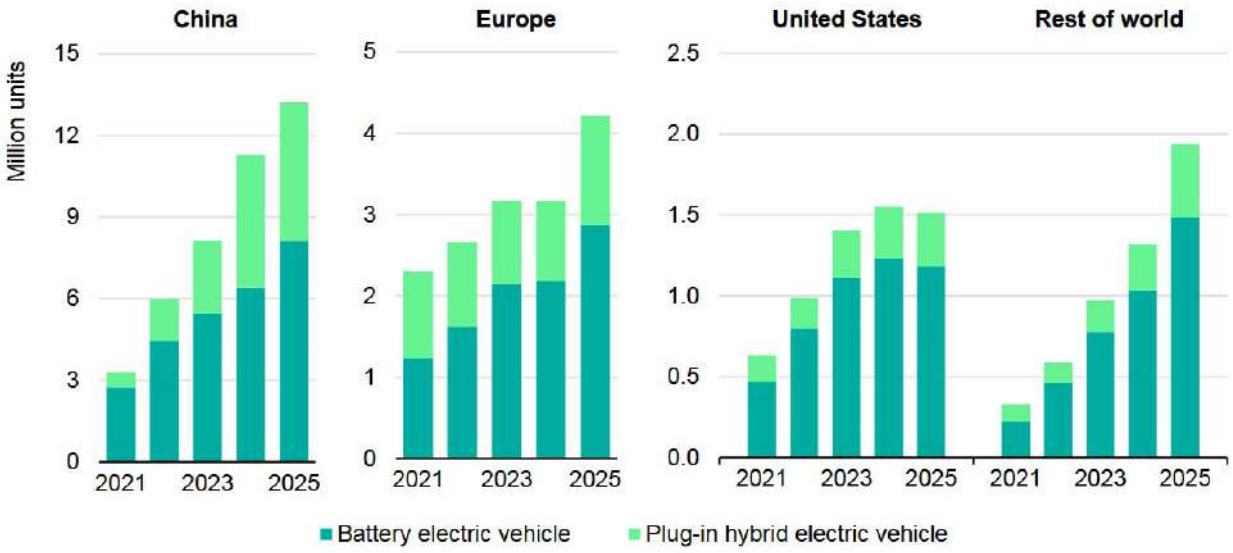




Photo by Precious Madubuike on Unsplash

EV market has undergone rapid expansion over the past decade[257,258,259]. Multiple studies have highlighted a steep acceleration in adoption driven by technology maturation, expanding model availability, declining costs, and strong policy support across major automotive markets. This has led to accelerated growth of EV sales across the globe as shown in Figure 128[4].

Figure 128 Global growth of electric car sales



Source: IEA

EV market achieved several significant milestones in recent years. Nearly 14 million electric cars were sold globally in 2023, representing an 18% share of all new car sales worldwide and marking a 35% year-on-year increase relative to 2022[258]. An additional step-change occurred in 2024, with sales exceeding 17 million and surpassing 20% of global new car sales, and EV sale increased by further 20% in 2025, rising car sale to 21 million units. EV stock has also expanded rapidly. At the end of 2023, the global electric car fleet reached approximately 40 million vehicles[258]. By the end of 2024, this stock had increased to nearly 58 million, more than tripling the total from 2021[259].

5.1 Model Availability, Consumer Preferences, and Pricing Trends

EV model portfolio has expanded significantly. More than 500 electric car models were available globally in 2022, with China accounting for nearly 300[257]. In increasing share of these models approximately 40% were Sport Utility Vehicles (SUVs), reflecting a shift in consumer preference toward larger vehicles. Similar trend was observed in the 2025, where Battery Electric Vehicles (BEV) represented roughly two-thirds of new EV models offered across major markets[259].

EV price difference across markets remains substantial. In 2022, the sales-weighted average price of a small BEV in China was below USD 10,000, while the equivalent prices in Europe and the United States exceeded USD 30,000[257]. An affordability advantage continues to underpin China's high adoption rates. EV price competition in China intensified further in 2023–2024, coinciding with a maturing market and consolidation among domestic manufacturers[258].

257 "Global EV outlook 2023: Catching up with climate ambitions," International Energy Agency, Paris, France, 2023.
258 "Global EV outlook 2024: Moving towards increased affordability," International Energy Agency, Paris, France, 2024.
259 "Global EV outlook 2025: Expanding sales in diverse markets," International Energy Agency, Paris, France, 2025.

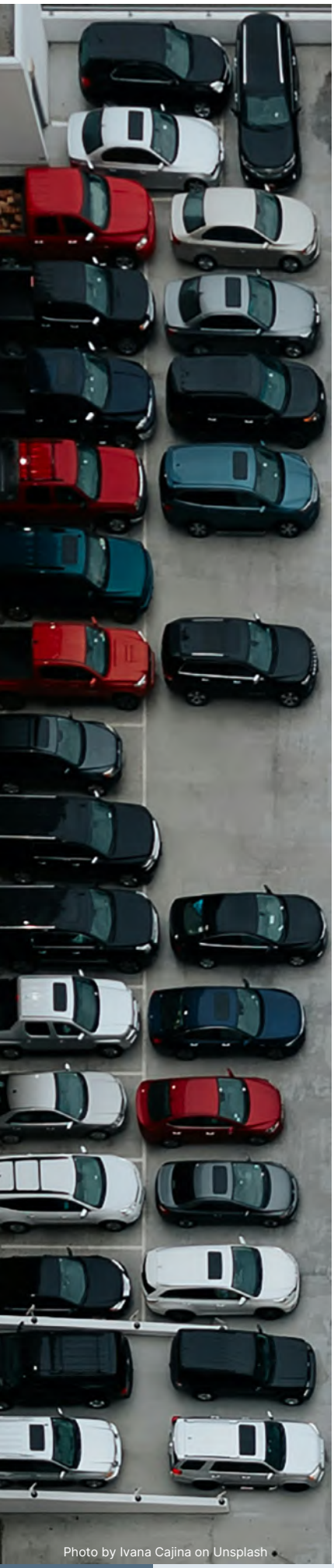


Photo by Ivana Cajina on Unsplash

EV deployment outlook provides a scenario-based assessment through 2030. Under the Stated Policies Scenario (STEPS), global EV stock across all modes except two/three-wheelers is projected to reach 250 million units by 2030, i.e. four times the 2024 level[259]. More than 90% of this stock is expected to be electric cars. EV sales share in Europe is projected to approach 60% by 2030, while the United States is expected to reach only around 20% under current policy directions. In Southeast Asia, strong policy support enables EV sales share of 25% by 2030, with electric two/three-wheelers reaching nearly one-third of total sales. A displacement of more than five million barrels of oil per day by EVs is forecast for 2030, with half of these savings occurring in China[259].

The market trends suggest that EV adoption is geographically concentrated but rapidly diversifying and strongly supported by evolving policy frameworks and rapidly improving cost competitiveness. EV market trajectory from 2022 to 2024 demonstrates a clear transition from early growth to market maturation, with China retaining global leadership, Europe advancing steadily, and the United States expanding under revised incentive structures. Emerging markets are beginning to contribute significantly, and medium-term projections indicate that EVs will continue to play a pivotal role in global transport decarbonisation through 2030.

5.2 Global EV Market

EV market has evolved into a complex, highly competitive global industry shaped by regional manufacturing strengths, trade flows, policy incentives, and consumer preferences.

5.2.1 Global Production and Supply Chain Landscape

EV production landscape remains geographically concentrated. As of 2025, China accounted for more than 70% of global electric car manufacturing in 2024[259]. EV production volume in China grew by 25% year-on-year, supported by strong domestic demand, economies of scale, and vertically integrated battery manufacturing. A domestic market share of Chinese OEMs exceeded 80% in 2024, reflecting strong internal competition and rapid innovation cycles.

EV manufacturing capacity in Europe remained stable at around 2.4 million units in 2024, as reported in the 2025, with production stagnating due to weakened consumer demand and reduced subsidies in several EU member states[259]. EV production in North America exhibited contrasting trends. The United States saw a decline in production, whereas Mexico's EV output doubled in 2024, accounting for a growing share of US based OEM manufacturing[259]. EV industry in Japan and Korea continued to grow moderately, contributing roughly 1 million electric cars in 2024.

5.3 Lithium ion Application in EVs

EVs rely on lithium ion batteries as their primary onboard energy storage devices. Lithium ion batteries are widely adopted in EV platforms because they offer high specific energy, favourable energy density, low self-discharge, and reliable cycling stability compared to legacy chemistries such as lead–acid, nickel–metal hydride, and silver–zinc batteries[260,261,262]. Their compact size and reduced mass support extended driving range and improved powertrain efficiency. Early demonstrations, showcased lithium ion batteries' suitability for traction applications, providing consistent performance, high coulombic efficiency, and dependable thermal behaviour under sustained operation[260].

5.3.1 Functional Characteristics and Operating Requirements

Lithium ion batteries deployed in EVs must meet demanding performance, durability, and safety requirements. EVs demand both high energy capability for long-range travel and high-power capability for acceleration. An lithium ion cell therefore needs to endure repeated high-rate charge–discharge cycles, deep DoD utilisation, and rapid charging without excessive degradation[263].

Modern EV platforms often adopt a modular battery design philosophy, where the same battery cells and modules are reused across multiple vehicle models, while the overall pack configuration is adapted to meet different performance and energy requirements. In a representative example, a standardized battery module is designed using identical pouch cells with fixed geometry and electrical characteristics. Each module contains a fixed number of series connected cells, ensuring a consistent module voltage across all applications as shown in Figure 129[264]. By keeping the module design unchanged, manufacturers can scale battery packs simply by varying the number of modules connected in series and parallel.

For a BEV requiring higher energy and power capability, multiple strings of these modules can be connected in parallel, while maintaining the same number of series modules to meet the target DC bus voltage. This results in higher total capacity and current handling capability. In contrast, a plug in hybrid or lower range vehicle can use a single series string of the same modules, reducing total cell count, weight, and cost, while still operating at the same system voltage. EVs also require an effective BMS to supervise voltage, temperature, and current; to estimate the SoC and SoH; and to perform functions such as protection, cell balancing, and data logging[265]. An effective BMS ensures safe operation, prevents electrical and thermal faults, and supports extended battery longevity[266].

260 B. Kennedy, D. Patterson, and S. Camilleri, "Use of lithium-ion batteries in electric vehicles," Journal of Power Sources, vol. 90, pp. 156–162, 2000,

261 Y. Miao, P. Hynan, A. von Jouanne, and A. Yokochi, "Current li-ion battery technologies in electric vehicles and opportunities for advancements," Energies, vol. 12, no. 6, p. 1074, 2019

262 M. A. Hannan, Md. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations," IEEE Access, vol. 6, pp. 19362–19378, 2018.

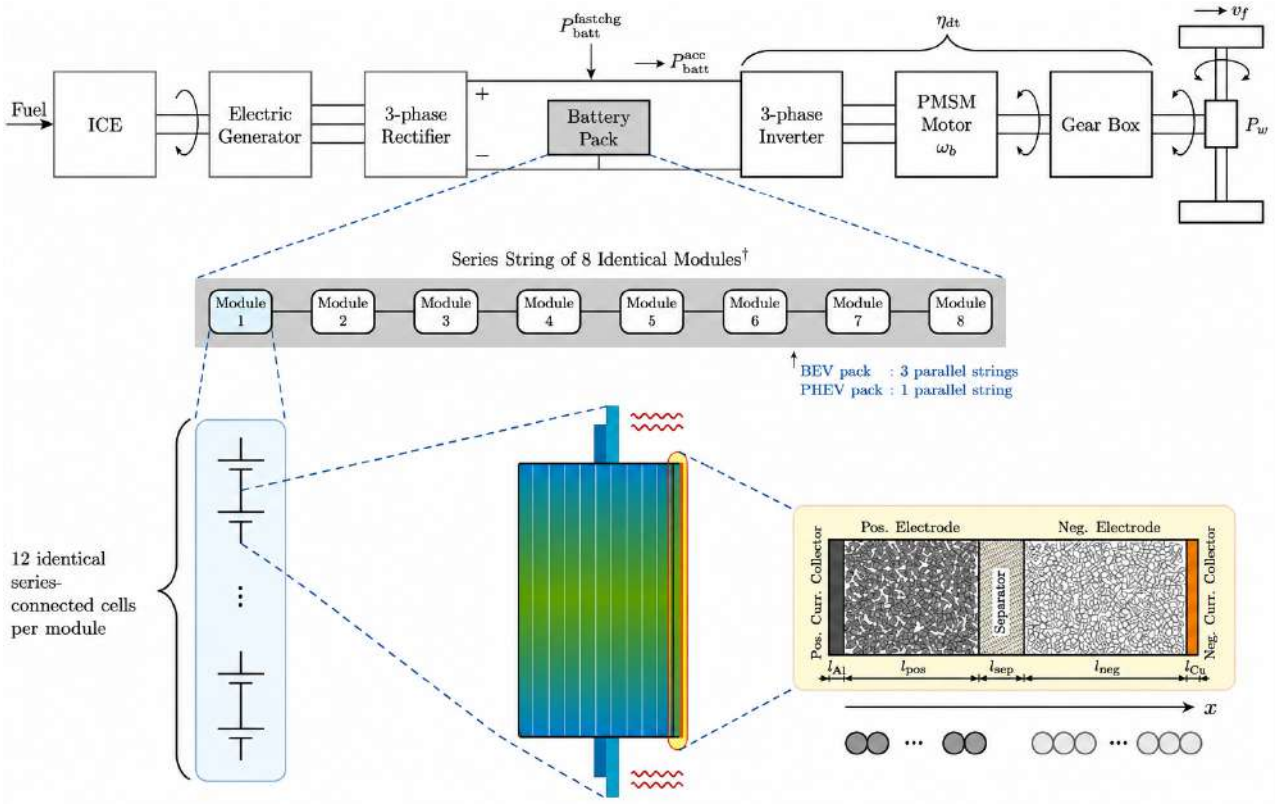
263 S. S. Rangarajan et al., "Lithium-ion batteries—the crux of electric vehicles with opportunities and challenges," Clean Technologies, vol. 4, no. 4, pp. 908–930, 2022.

264 I. D. Campbell, K. Gopalakrishnan, M. Marinescu, M. Torchio, G. J. Offer, and D. Raimondo, "Optimising lithium-ion cell design for plug-in hybrid and battery electric vehicles," Journal of Energy Storage, vol. 22, pp. 228–238, Feb. 2019,

265 Y. Miao, P. Hynan, A. von Jouanne, and A. Yokochi, "Current li-ion battery technologies in electric vehicles and opportunities for advancements," Energies, vol. 12, no. 6, p. 1074, 2019

266 M. A. Hannan, Md. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations," IEEE Access, vol. 6, pp. 19362–19378, 2018

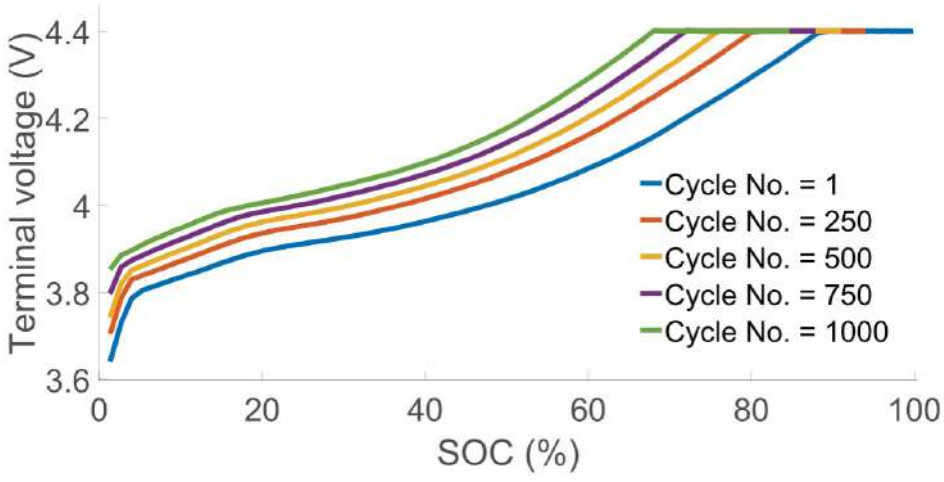
Figure 129 Schematic of a typical vehicle-to-cell hierarchical overview of an EV



Source: I. D. Campbell et al.; 2019

Beyond meeting energy and power requirements, the battery pack must also deliver a stable and predictable DC voltage to the vehicle power train under a wide range of operating conditions. The terminal voltage of a lithium ion cell is not constant and varies with state of charge, current, temperature, and cell chemistry. Typically, the cell voltage follows a non linear profile while being dependent on a range of factors including state of health, charging current etc. as shown in Figure 130[267]. When cells are connected in series, these voltage variations accumulate at the pack level, directly affecting the DC bus voltage supplied to the converter.

Figure 130 Relationship between terminal voltage of a typical lithium ion cell with SOC



Source: A. Neha et al.; 2020

267 A. Naha et al., "An incremental voltage difference based technique for online state of health estimation of li-ion batteries," Scientific Reports, vol. 10, no. 1, p. 9526, Jun. 2020

During load transitions such as rapid acceleration, regenerative braking, or sudden changes in auxiliary demand, the battery experiences transient current fluctuations. These transients can cause temporary voltage drops or rises due to internal resistance and electrochemical dynamics within the cells. Maintaining voltage stability during such events is critical, as it influences converter design margins, motor control performance, and protection settings. Excessive voltage sag can limit torque delivery, while overvoltage conditions during regenerative operation may constrain energy recovery.

5.4 Chemistry Options and Suitability for EV Deployment

EV manufacturers select suitable lithium ion chemistry based on targeted performance metrics such as energy density, thermal stability, cost, cycle life, safety constraints, and charging requirements. Few leading battery chemistries used in EVs are mentioned below[268]:

- **NCA:** EV using NCA chemistry benefits from high gravimetric energy density and good fast-charge capability, although careful thermal management is necessary.
- **NMC:** An NMC-based pack offers a balanced trade-off between safety, energy density, and life-cycle performance, and is widely used in mainstream passenger EVs.
- **LFP:** EV using LFP cells obtains excellent thermal stability, long cycle life, and improved safety characteristics at the expense of lower energy density.
- **LTO:** An LTO-based pack provides exceptional cycle life and rapid charge capability, although it exhibits reduced energy density.

An emerging chemistry based on niobium-doped materials offers improved conductivity and enhanced low-temperature behaviour, presenting an opportunity for improved EV battery packs in future vehicle generations.

5.5 Charging Infrastructure and Standards

Charging infrastructure forms a critical backbone of the EV ecosystem, enabling efficient energy delivery, ensuring interoperability, and supporting large-scale EV adoption. Modern charging systems integrate power-conversion hardware, communication interfaces, safety protections, and grid-interactive capabilities. Insights from national and international studies highlight the diverse technologies, standards, and regulatory structures that govern the deployment of EV charging infrastructure[269].

- **IEC 61851:** IEC 61851 defines the requirements for conductive AC and DC charging of electric vehicles, covering voltages up to 1000 V AC and 1500 V DC. The standard specifies mechanical, electrical, communication, and safety requirements for EV supply equipment, including operating modes, connection interfaces between the EV and Electric Vehicle Supply Equipment (EVSE), and protection mechanisms. IEC 61851 classifies EV charging into four modes based on the level of protection, controllability, and type of connection. Mode 1 involves direct connection to a standard outlet without additional protection or control. Mode

268 P. H. Camargos, P. H. J. D. Santos, I. R. D. Santos, G. S. Ribeiro, and R. E. Caetano, "Perspectives onLi-ionbattery categories for electric vehicle applications: A review of state of the art," International Journal of Energy Research, vol. 46, no. 13, pp. 19258–19268, Apr. 2022

269 Z. Rather, A. Nath, R. Banerjee, and C. Juta, "Report 2: International review on integration of electric vehicles charging infrastructure with distribution grid," tech. rep., NITI Aayog, 2022.

2 introduces limited control through an in-cable control box. Mode 3 uses a permanently connected EVSE with enhanced protection and control. Mode 4 refers to DC charging, where the EVSE converts AC grid power to DC before supplying the vehicle.

- **SAE J12:** SAE J1772 specifies AC and DC charging systems and is widely adopted in the United States and Japan. In contrast to IEC 61851, which is dominant in Europe, SAE J1772 provides detailed definitions of the control pilot signal used for communication between the EV and EVSE. The standard also categorizes charging into different levels based on voltage, current, and power ratings.
- **GB/T 20234:** The GB/T 20234 standard, issued by the Standardization Administration of China, defines plug, socket, and connector specifications for conductive EV charging. It is primarily followed in China and covers both AC and DC charging, including testing methods and electrical ratings. Several other standards related to EV charging address inductive charging, wireless power transfer, electrical safety, and grid interconnection requirements.

5.6 Charging Technologies and System Configurations

EV charging technologies fall into three broad categories:

- Conductive charging
- Wireless Power Transfer
- Battery swapping

Conductive charging for both AC and DC remains the primary method for EV charging worldwide, favoured for its proven reliability, standardized interfaces, and cost-effectiveness. According to IEC 61851 and SAE J1772 standards, AC charging uses the vehicle's on-board charger and typically delivers power levels between 2 kW and 22 kW, making it ideal for residential and workplace settings. In contrast, DC fast charging relies on off-board rectifiers and DC DC converters to provide higher power, ranging from 15 kW to several hundred kilowatts, depending on the connector type and cooling system design[270].

Modern fast-charging stations feature advanced power electronics, including active front-end rectifiers, galvanically isolated converters, and regulated DC output stages. These systems incorporate real-time SoC estimation and dynamic power allocation to maximize efficiency and safety. While wireless charging is less common, it employs inductive or capacitive power transfer technologies under ISO 19363 and SAE TIR J2954 standards. Battery swapping is increasingly adopted for two-wheelers, three-wheelers, and specific fleet operations, with standards covering battery traceability, mechanical alignment, and safety interlocks to ensure operational security and compatibility[270].

270 Z. H. Rather, R. Banerjee, A. Nath, P. Dahiwale, " Fundamentals of Electric Vehicle Charging Technology and its Grid Integration", NITI Aayog, 2021


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AI Image


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5.7 Impact of Charging on EV Battery Health

Battery life degradation occurs due to two primary mechanisms namely calendar ageing and cycle ageing. Calendar aging refers to the gradual loss of battery health over time even when the battery is not in use, while cycle aging results from repeated charging and discharging. The parameters that impact EV battery health are summarised below[270]:

- **Calendar aging:** Calendar aging is primarily influenced by battery temperature and SoC during storage. Batteries perform optimally near room temperature, and deviations from this range accelerate capacity loss. Higher storage temperatures lead to increased degradation even when the battery is not cycled. Similarly, storing batteries at high SoC results in greater calendar aging compared to lower SoC storage levels.
- **Cycle aging:** Cycle aging depends on the C rate, depth of discharge, number of cycles, and total energy throughput. Higher charging C rates reduce the cycle life of the battery, meaning fewer charge discharge cycles are possible before significant capacity loss occurs. Empirical studies show that capacity degradation remains relatively limited for C rates up to 1C, while higher C rates lead to faster degradation. Likewise, larger DoD per cycle reduces battery lifetime, as deeper charge discharge cycles accelerate wear.
- **Impact of charging:** Analysis of charging characteristics of popular EVs shows that AC charging typically operates well below 1C, and even DC fast charging at 50 kW generally remains close to 1C for most vehicles. As battery degradation remains limited below 1C charging, routine AC charging and moderate DC charging have minimal impact on battery health. Noticeable reductions in battery lifetime are observed primarily when charging exceeds 1C, such as during ultra-fast DC charging. Real world vehicle data further indicates that battery capacity degradation remains below 10 percent even after high mileage accumulation, demonstrating the robustness of modern EV batteries under typical charging practices.

The charging details of different few globally available EVs are mentioned in Table 45[270].

Table 45 Charging details of a few of the popular EVs

EV model	Battery capacity (kWh)	Charging power limit		C-rate in per hour by charger type			
		AC (kW)	DC (kW)	AC 7 kW	AC 22 kW	DC 50 kW	DC 150 kW
Tesla Model 3	55	11	170	0.13C	0.20C	0.91C	2.7C
Tesla Model S	100	16.5	250	0.07C	0.17C	0.5C	1.5C
BMW i3	42	11	49	0.17C	0.26C	1.17C	NA
Nissan Leaf	40 or 62	6.6	49	0.11C	0.11C	0.79C	NA
Renault ZOE	55	22	46	0.19C	0.40C	0.84C	NA
Hyundai IONIQ	40	7.2	44	0.18C	0.18C	1.10C	NA

5.8 Vehicle-to-Everything Applications

Vehicle-to-Everything (V2X) technologies transform EVs from passive electrical loads into active, controllable energy resources. V2X forms a foundation for next-generation smart infrastructures, enabling EVs to interact with grids, buildings, homes, loads, and other vehicles. V2X supports grid flexibility, enhances local resilience, enables energy cost reductions, and integrates EVs into broader energy-management and demand-response frameworks[271]. Recent reviews provide extensive evidence that V2X capabilities are becoming increasingly relevant as EV penetration grows and bidirectional-charging technologies mature[272, 273, 274, 275].

V2X operation relies on a bidirectional energy interface capable of both controlled charging and controlled discharging. V2X systems require the integration of multiple layers, including electrical power conversion, communication protocols, cybersecurity mechanisms, EMS algorithms, and coordination frameworks. At the core of the system is a bidirectional charger either on-board or off-board that manages active and reactive power flows and executes grid-following or grid-forming control modes depending on the operating context. The BMS ensures cell safety, enforces allowable DoD constraints, and monitors thermal and electrical limits. Above these components, an EMS interprets grid signals, tariff profiles, user mobility constraints, and contractual requirements to schedule EV participation in V2X services. Effective V2X operation therefore requires precise synchronisation between power electronics, communication layers, and higher-level optimisation functions, all while ensuring that user mobility requirements are never compromised.

5.8.1 Vehicle-to-Grid (V2G)

V2G is the most technically complex and widely studied V2X application. V2G enables controlled export of electrical energy from EV batteries to the electricity grid for the purpose of supporting grid stability, reliability, and economic optimisation. Figure 131[276] depicts V2G system architecture for resident, commercial, and public charging stations. V2G is a mechanism for delivering services such as frequency regulation, voltage support, congestion mitigation, peak-load reduction, and RE firming[271]. These services require rapid charger response and precise active–reactive power control, which in turn depend on stringent compliance with grid codes and interconnection standards. The large-scale V2G deployment typically relies on aggregators capable of coordinating thousands of EVs, thereby enabling participation in wholesale markets or ancillary service markets[274]. Aggregation, however, introduces uncertainties relating to vehicle availability, communication delays, spatial distribution of chargers, and heterogeneity in vehicle battery chemistries. A key concern associated with V2G adoption is battery degradation, but degradation impacts can be managed by optimising charge–discharge cycles, limiting discharge power, and prioritising services with low energy throughput but high remuneration, such as frequency response.

271 L. F. Mascioli et al., “Vehicle-to-grid and vehicle-to-building systems integrated in smart infrastructures: A comprehensive review of technologies, challenges and opportunities,” 2025 international conference on clean electrical power (ICCEP), 2025, pp. 631–645.

272 N. S. Pearre and H. Ribberink, “Review of research on V2X technologies, strategies, and operations,” Renewable and Sustainable Energy Reviews, vol. 105, pp. 61–70, 2019

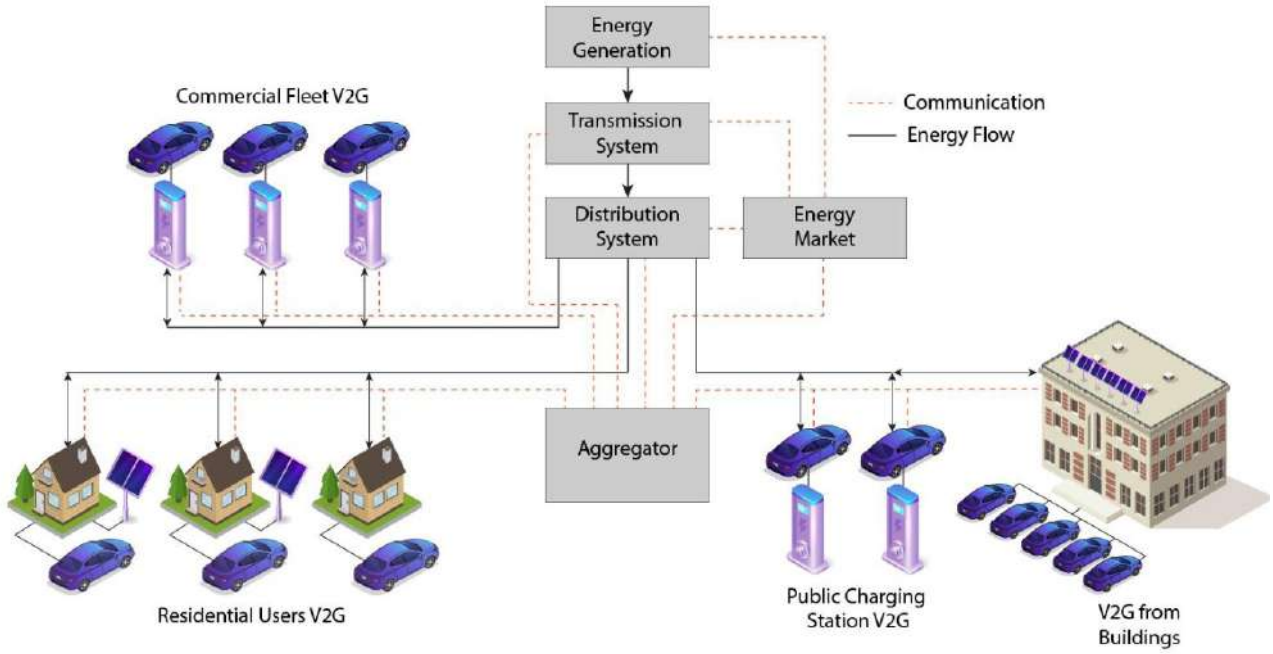
273 O. Oghorada, S. Zhao, Y. Zhang, and K. Li, “Benefits, barriers, and human factors of V2X implementation—a brief review,” in LSMS/ICSEE 2024, vol. 2218, in Communications in computer and information science, vol. 2218., Springer Nature Singapore, 2025, pp. 134–146.

274 R. Khezri, D. Steen, and A. T. Le, “A review on implementation of vehicle to everything (V2X): Benefits, barriers and measures,” in 2022 IEEE PES innovative smart grid technologies conference europe (ISGT-europe), IEEE, 2022, pp. 1–6.

275 A. Mohan and P. V. Manitha, “Hybrid electric vehicles with V2X topology and smart energy management: An overview of their potential and limitations,” in 2023 2nd international conference on futuristic technologies (INCOFT), IEEE, 2023.

276 IIT Bombay and CEA , “Executive Summary : Implementation of Vehicle-to-Everything (V2X) in India”, Dec. 2023.

Figure 131 V2G system architecture



5.8.2 Impact of V2G on Battery

A common concern regarding V2G operation is the impact of bidirectional charging currents on battery health. However, the current magnitudes involved in V2G are generally much lower than those experienced during normal vehicle operation, particularly during acceleration. During V2G operation, charging or discharging currents are typically limited by the charger rating and grid requirements. For most AC charging and moderate DC charging applications, the effective C rate remains below or around 1C. Even in bidirectional operation, V2G power levels are deliberately constrained to ensure thermal stability and grid compatibility, resulting in relatively smooth and controlled current profiles.

In contrast, during vehicle acceleration, batteries are subjected to significantly higher instantaneous discharge currents. Rapid acceleration, hill climbing, and high-speed driving can demand power levels corresponding to multiple C rates, often exceeding those seen in V2G applications. These high current pulses are short in duration but occur frequently during daily driving and are an inherent part of normal vehicle operation.

From a battery degradation perspective, short duration high current events during driving are already accounted for in battery design, thermal management, and warranty considerations. Compared to these events, V2G related charge and discharge currents are typically lower, longer in duration, and more controllable through energy management algorithms.

The impact of bidirectional charging on battery health depends strongly on the charging and discharging regime applied during V2G operation. Uncontrolled or profit maximizing V2G strategies can accelerate battery degradation, while optimized V2G control can mitigate or even improve battery health outcomes.

- **V2G with profit maximization strategy:** Studies show that V2G operation designed to maximize energy export and user revenue leads to increased battery degradation due to higher cycle count and larger depth of discharge per cycle. Experimental results indicate

that with two V2G cycles per day, battery capacity degradation can reach nearly 20 percent over five years, compared to around 10 percent without V2G. This increased degradation is primarily a consequence of aggressive battery utilization rather than V2G itself[277].

- **Optimized V2G for battery life extension:** Alternative V2G strategies have demonstrated that battery degradation can be reduced through intelligent control. By comparing degradation from battery storage at a given SoC with degradation from an additional charge discharge cycle, optimized algorithms allow discharging only when it is less harmful than storage. Such strategies have shown capacity fade reductions of up to 9.1 percent per year compared to EVs without V2G, indicating that controlled V2G operation can outperform conventional charging practices[278].
- **Role of SoC management in V2G:** Battery degradation is strongly influenced by operating SoC range. High degradation rates occur when batteries are charged or discharged near very high or very low SoC levels. Maintaining battery operation within a moderate SoC window, typically between 30 percent and 50 percent, significantly improves battery health. V2G control algorithms that regulate SoC within this optimal range have demonstrated measurable improvements in battery SoH over short operational periods[279].

5.8.3 Vehicle-to-Home (V2H)

Vehicle-to-Home (V2H) applications allow EV to power residential loads. V2H improves household resilience by supplying essential loads during outages, reducing energy bills during peak-tariff periods, and increasing the utilization of RTS PV generation[271]. V2H requires a coordination mechanism between the bidirectional charger, home EMS, and protection equipment to ensure compliance with anti-islanding requirements. The operational effectiveness of V2H largely depends on the relationship between the household's load profile, the availability and state-of-charge of the EV, and the local tariff structure. Users benefit most when V2H operation guarantees a minimum SoH reserve for mobility, provides clear charging schedules, and offers transparent economic benefits[272]. As V2H technologies mature, their integration with home microgrids, RTS PV systems, and stationary BESS is expected to increase.

5.8.4 Vehicle-to-Building (V2B)

Vehicle-to-Building (V2B) extends V2H concepts to larger commercial, industrial, and institutional facilities. These installations often have significant peak-demand charges, predictable occupancy patterns, and access to on-site RE resources. V2B can reduce building energy costs, support building microgrid stability, and facilitate participation in demand-response programmes[271]. For deploying V2B systems, it requires harmonisation between the building management system and the V2B controller to ensure optimal charging and discharging across multiple parked EVs. Due to the larger number of vehicles and the higher loads involved, V2B systems must also consider the loading limits of internal feeders, distribution transformers, and power-quality constraints. Coordination among multiple EVs introduces additional complexity, demanding the use of advanced optimisation algorithms capable of balancing building requirements, EV availability windows, and grid-support objectives.

277 M. Dubarry, G. Baure, and A. Devie, "Durability and Reliability of EV Batteries under Electric Utility Grid Operations: Path Dependence of Battery Degradation," Journal of the Electrochemical Society, vol. 165, no. 5, pp. A773–A783, Jan. 2018

278 K. Uddin, M. Dubarry, and M. B. Glick, "The viability of vehicle-to-grid operations from a battery technology and policy perspective," Energy Policy, vol. 113, pp. 342–347, Nov. 2017

279 A. Hoke, A. Brissette, D. Maksimović, D. Kelly, A. Pratt and D. Boundy, "Maximizing lithium ion vehicle battery life through optimized partial charging," 2013 IEEE PES Innovative Smart Grid Technologies Conference, Washington USA, 2013,.

☼ KEY INSIGHT

V2X can turn EVs into flexible energy resources, but large-scale adoption depends on bidirectional chargers, clear market incentives, user trust, battery-warranty clarity, and interoperable standards.

5.8.5 Vehicle-to-Load (V2L)

Vehicle-to-Load (V2L) enables EVs to function as portable power supplies for standalone loads. V2L does not require grid synchronisation and is therefore simpler from an interconnection standpoint[275]. V2L is widely used for off-grid operations, emergency response, outdoor activities, and applications requiring portable electricity. V2L output ratings typically range from a few kilowatts for AC outlets to higher capacities for DC discharge ports. The ease of operation and minimal infrastructure requirements make V2L an immediately deployable form of bidirectional capability, although it does not provide the broader system-level benefits associated with V2G, V2H, or V2B.

5.8.6 Vehicle-to-Vehicle (V2V)

Vehicle-to-Vehicle (V2V) energy transfer facilitates controlled charging of one EV using another. V2V can support emergency charging, fleet coordination, and roadside assistance[273]. Although still in early stages of development, V2V introduces opportunities for mobile energy-sharing networks, particularly in commercial fleet environments. Technical challenges arise from the need for standardised connectors, protective coordination, and authenticated communication between vehicles. Safe operation requires precise control of current flow, voltage matching, and compliance with battery protection algorithms implemented by both vehicles.

5.9 Barriers, Enablers, and Human-Factor Considerations

Despite technological advancements, V2X deployment faces several practical barriers. Several issues including limited availability of V2X-capable chargers, absence of harmonised standards, economic uncertainties, lack of clear market mechanisms for remuneration, and concerns regarding battery-warranty compatibility are identified in literature[273, 274, 275]. User-related factors also play an important role. User acceptance hinges on trust in system reliability, perceived complexity, privacy considerations, and assurance that mobility requirements will not be compromised. Effective V2X implementation therefore requires the development of transparent incentive structures, user-friendly interfaces, and clear communication of operational constraints.

V2X technologies provide substantial opportunities for integrating transportation and power systems, enabling EVs to support grid stability, reduce energy costs, increase resilience, and enhance RE utilisation. V2G, V2H, and V2B exhibit the greatest technical and economic potential due to their system-level benefits, while V2L and V2V fulfil specialised operational roles. Although progress in bidirectional charging, communication standards, and energy-management algorithms has accelerated V2X readiness, achieving widespread adoption will require advances in regulatory frameworks, market integration, user engagement, and technical interoperability. The collective evidence from current literature suggests that V2X is positioned to become a central component of future electrified energy ecosystems.

5.10 Technical, Economic, and Safety Barriers

Despite the advantages of extending battery life through repurposing, numerous barriers hinder widespread adoption. From a technical perspective, the heterogeneity in battery design, chemistry, cell format, and degradation history presents a significant challenge. Batteries reaching end-of-life differ widely in their state-of-health, internal resistance, remaining capacity, thermal behaviour, and degradation modes. The absence of standardised diagnostics makes it difficult to assess battery condition accurately and consistently across manufacturers and use cases. Comprehensive grading is essential, yet it can require time-consuming cycling tests, detailed cell characterisation, and complex modelling exercises.

Economic barriers associated with labour-intensive disassembly processes, logistic costs for battery collection and transport, and uncertainties in revenue generation from second-life deployments are identified[280]. Additionally, the falling price of new battery packs driven by manufacturing scale and technological advancements can undercut the economic attractiveness of second-life alternatives, especially when refurbishment costs are high. The techno-economic feasibility of Second-Life Batteries (SLB) depends heavily on local electricity markets, cost of labour, regulatory structures, and the value of grid-support services[281]. In some contexts, second-life batteries may offer favourable payback periods, while in others, new storage systems may be more competitive.

Safety remains a critical concern across all stages of second-life deployment. Aged batteries may exhibit elevated internal resistance, uneven cell degradation, gas formation, and weakened mechanical structures. Such conditions can increase the likelihood of thermal runaway, particularly under high loads or adverse thermal conditions. To mitigate these risks, second-life systems must incorporate advanced battery-management strategies, robust thermal management, and protective enclosures designed for stationary operation. In cases where degradation is too severe or heterogeneous, recycling becomes the safer and more practical option.

280 A. Kampker, H. H. Heimes, C. Offermanns, J. Vienenkötter, M. Frank, and D. Holz, "Identification of challenges for second-life battery systems—a literature review," World Electric Vehicle Journal, vol. 14, no. 4, p. 80, 2023

281 M. K. Al-Alawi, J. Cugley, and H. Hassanin, "Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review," Energy and Climate Change, vol. 3, p. 100086, 2022



Eshshiv, CC0, via Wikimedia Commons

06

CHAPTER 6

HYBRID & MULTI-USE ENERGY STORAGE SYSTEMS



Bureau of Land Management California, Public domain, via Wikimedia Commons

Summary

- Explains hybrid and multi use ESS as configurations that combine complementary storage technologies or service commitments to improve response speed, discharge duration, asset utilisation, and project economics.
- Distinguishes short duration technologies such as batteries, supercapacitors, flywheels, and SMES from long duration technologies such as pumped hydro, CAES, hydrogen, and thermal storage.
- Reviews major hybrid configurations, including battery hydrogen, battery flywheel, battery supercapacitor, and battery pumped hydro systems, with emphasis on time scale separation between fast power support and sustained energy delivery.
- Covers long duration storage, sector coupling, community storage, and global HESS projects that demonstrate value stacking across energy shifting, frequency regulation, power smoothing, voltage support, and black start.

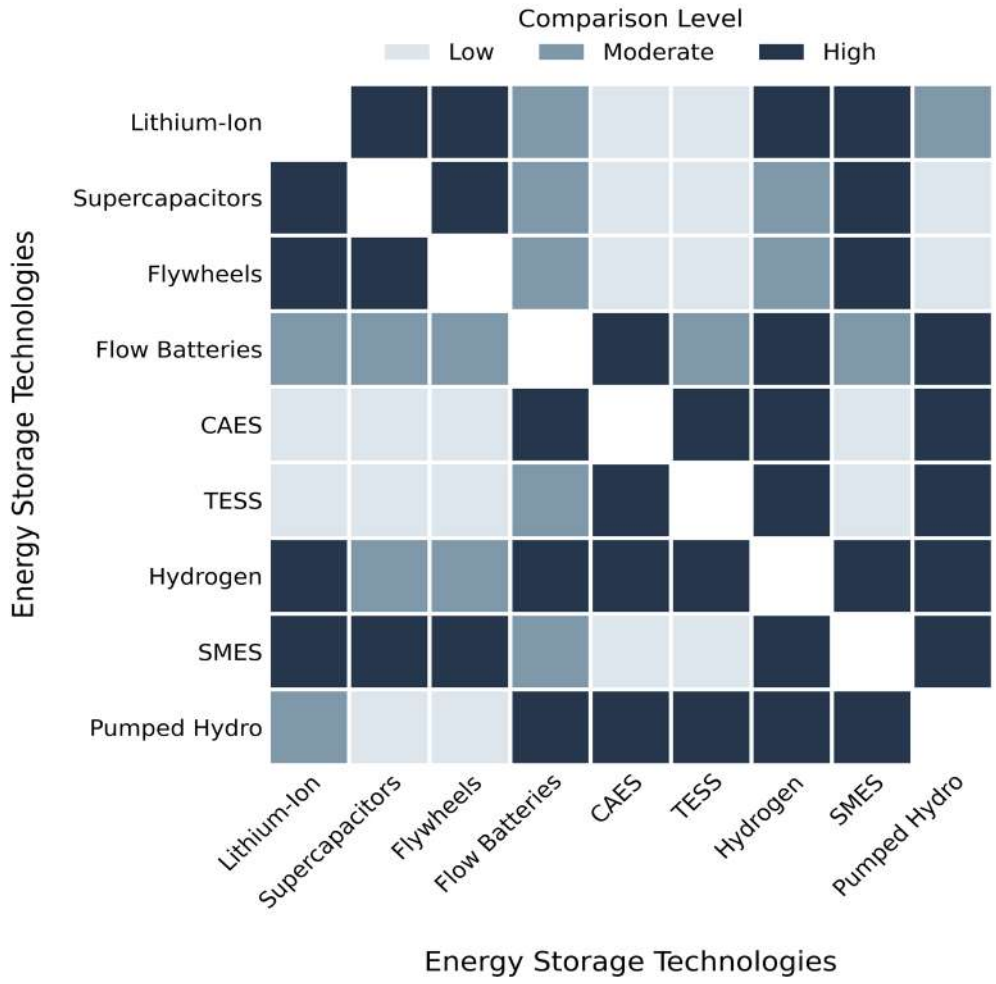




Ysc usc, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons

Hybrid and multi-use ESS coordinate multiple technologies or service commitments to extend response duration, improve usable power and energy capability, and enhance economics through value stacking. In power system terms, hybrid storage plants co-deploy complementary technologies behind a common interconnection, while multi-use plants operate a single asset across multiple services within converter, energy, and SoC limits. These configurations are increasingly important in power systems with high RE penetration that require both fast response and sustained energy shifting. Comparative assessments of storage technologies, including BESS, FESS, SESS, hydrogen storage, and PHS, provide a technical basis for hybridisation based on power and energy complementarity[58]. There is an increasing bifurcation between short-duration and long-duration system needs. BESS is well suited for intraday balancing and grid stability, while system studies indicate that multi-day and seasonal balancing require technologies such as PHS and hydrogen storage[40]. In this context, hybridisation functions as both a device and system-level strategy, with batteries managing fast variability and long-duration technologies supporting extended system adequacy. Policy frameworks increasingly recognise storage as an enabler of RE integration, ancillary services, and network deferral, strengthening the case for multi-use and hybrid storage portfolios. This differentiation is further illustrated in Figure 132[282], which presents a comparative capability matrix across major storage technologies and service attributes.

Figure 132 Comparative capability matrix of energy storage technologies across power system services and duration requirement



Data Source: A. M. Adeyinka et al.; 2025

282 A. M. Adeyinka, O. C. Esan, A. O. Ijaola, and P. K. Farayibi, "Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration," Sustainable Energy Research, vol. 11, no. 1, Jul. 2024, doi: 10.1186/s40807-024-00120-4.

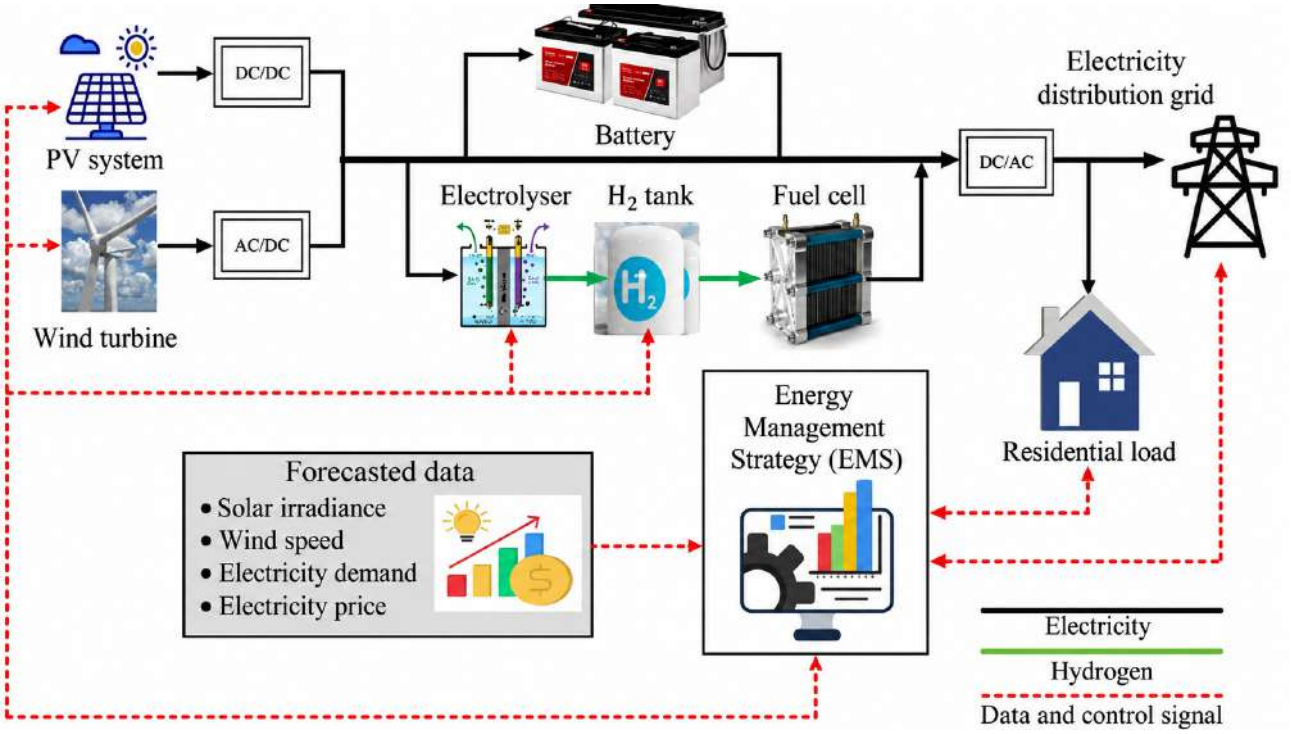
Technologies such as lithium ion BESS, SESS, FESS, and SMES exhibit strong performance in high power, fast response applications including frequency regulation, voltage support, and oscillation damping, but are comparatively limited for multi day or seasonal adequacy. In contrast, PHS, CAES, TESS, and hydrogen storage systems demonstrate high suitability for long duration energy shifting and adequacy support, albeit with lower responsiveness for sub second grid services. FBESS occupy an intermediate position, offering moderate to high capability across both power and duration dimensions. Therefore, the complementary nature of short duration and long duration energy storage technologies reinforces the rationale for hybrid ESS portfolios to address multi time scale system requirements.

6.1 Hybrid Storage Configurations

6.1.1 Hybrid Hydrogen and Battery Energy Storage Systems

A hydrogen-plus-battery hybrid combines a BESS with a power-to-hydrogen chain, including an electrolyser, hydrogen storage, and a reconversion unit such as a fuel cell or turbine, as shown in Figure 133[283]. In this configuration, BESS provide fast response and high efficiency for short-duration services, while hydrogen offers large energy capacity for long-duration and seasonal storage with lower efficiency and slower response. This complementarity addresses the limitations of BESS for multi-day balancing, positioning hydrogen as suitable for extended adequacy needs.

Figure 133 Schematic of hybrid hydrogen and BESS operation



Source: B. Modu et al.; 2025

Grid-connected operation typically employs a hierarchical EMS with time-scale separation. Hydrogen production and use are scheduled over day-ahead or intraday horizons based on RE surplus and

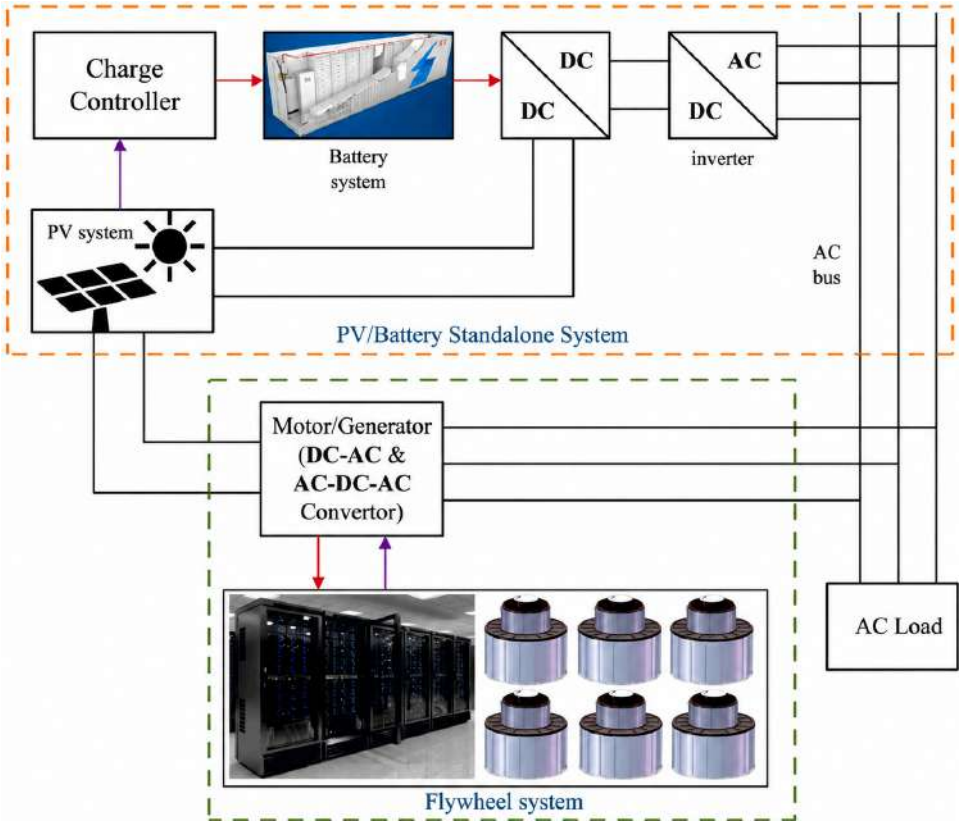
283 B. Modu, M. P. Abdullah, A. AlKassem, M. F. Hamza, and A. L. Bukar, "The role of hybrid hydrogen-battery storage in a grid-connected renewable energy microgrid considering time-of-use electricity tariffs," J. Energy Storage, vol. 105, no. 114729, p. 114729, 2025.

inventory targets, while batteries manage real-time power control, ramping, and fast frequency or voltage support. Key design variables include BESS power and energy ratings, electrolyser capacity, hydrogen storage size, and reconversion capacity. Due to conversion losses, hydrogen is reserved for long-duration requirements, while BESS deliver short-duration services, with additional coordination required when hydrogen also serves non-power-sector demands.

6.1.2 Hybrid Flywheel and Battery Energy Storage Systems

A battery-flywheel hybrid combines a BESS with a FESS, as shown in Figure 134[284]. FESS provide very fast response and high cycle capability for power smoothing, inertial response, and high-frequency regulation, while BESS supply higher energy for minute-to-hour scale services. Reviews highlight their use in RE smoothing and hybrid systems, noting reliability and failure mode considerations related to moving parts.

Figure 134 Schematic of hybrid BESS and FESS operation



Source: W. Ji et al.; 2024

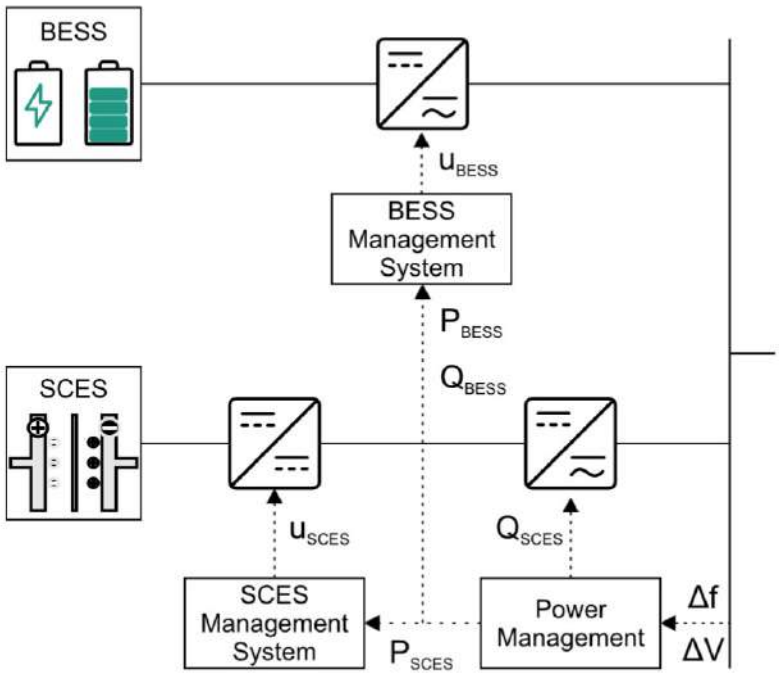
In typical control schemes, high-frequency power fluctuations are assigned to the FESS and lower-frequency energy balancing to the BESS using filtering or rule-based dispatch. This limits high-frequency battery cycling and extends battery life. Operation must respect shared constraints such as converter apparent power limits and POI thermal and protection limits. At the distribution level, the hybrid improves ramp-rate compliance and reduces voltage flicker by absorbing sub-second power variations.

284 W. Ji et al., "Applications of flywheel energy storage system on load frequency regulation combined with various power generations: A review," Renew. Energy, vol. 223, no. 119975, p. 119975, 2024.

6.1.3 Hybrid Super Capacitor and Battery Energy Storage Systems

A BESS - SESS hybrid system combines a high-energy BESS with a SESS that delivers very high power for short durations, as shown in Figure 135[58]. SESS provide ultra-fast power injection and absorption, reducing BESS stress during rapid load changes, converter transients, and short-duration grid disturbances. Their very high power density, low energy density, and high efficiency define a complementary service role.

Figure 135 Schematic of hybrid BESS and SESS



Source: G. De Carne et al.; 2024

In practice, the hybrid system is often implemented using a DC-link architecture, where the SESS is connected through a bidirectional DC-DC converter to stabilise DC-link voltage and supply fast transient current, while the BESS manages slower power and energy variations. Control focuses on DC-link stabilisation, current limiting, and coordinated SoC management to keep the SESS available for disturbances[58]. This hybrid is most effective for applications with frequent power transients, such as motor starting, microgrid islanding, fast frequency response, and voltage support, while also reducing high-frequency battery cycling and associated degradation.

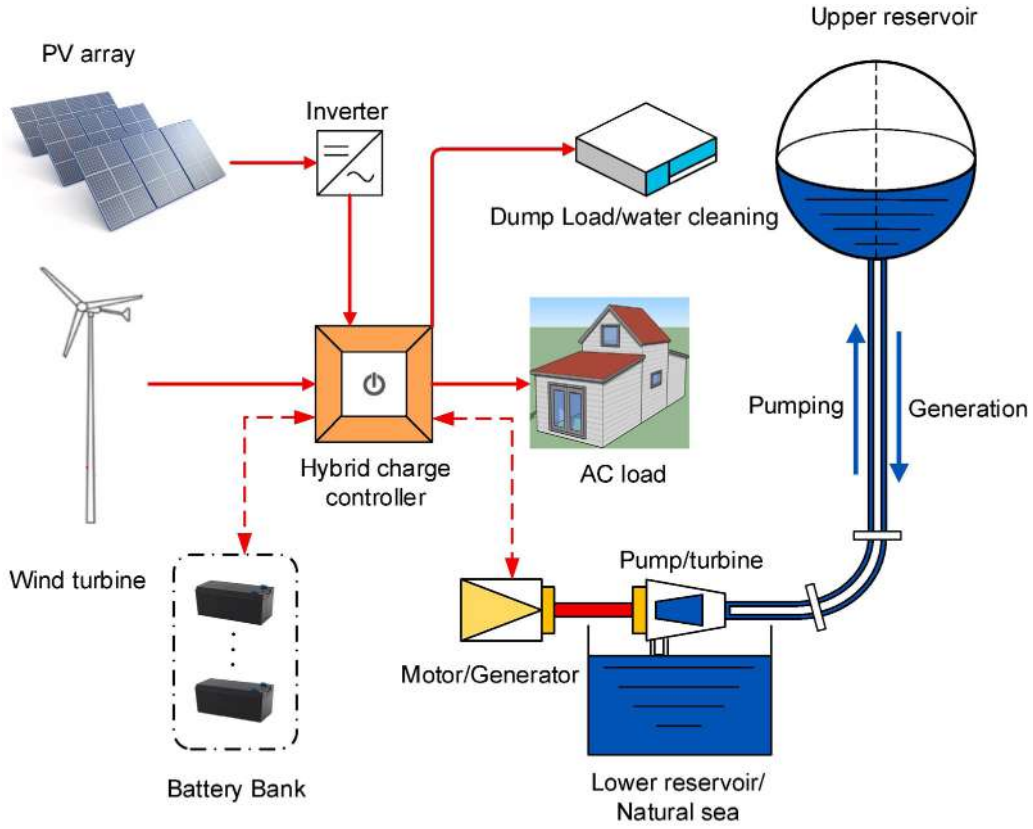
6.1.4 Hybrid Pumped Hydro Storage and Battery Energy Storage Systems

A BESS - PHS hybrid storage as shown in Figure 136[285] combines BESS for fast response and short-duration flexibility with PHS for large energy capacity and long-duration dispatch. System studies indicate that BESS are unsuitable for seasonal storage, while PHS multi-day to seasonal adequacy, making this a complementary planning approach.

285 M. S. Javed, D. Zhong, T. Ma, A. Song, and S. Ahmed, "Hybrid pumped hydro and battery storage for renewable energy based power supply system," Appl. Energy, vol. 257, no. 114026, p. 114026, 2020.

Operationally, PHS is reserved for long-discharge and adequacy needs, while batteries provide fast services such as frequency regulation, reserves, and congestion relief, coordinated through shared forecasting and scheduling. This hybrid is typically applied at the system planning level rather than co-located at distribution sites, clearly separating short-duration electrochemical storage from long-duration mechanical storage.

Figure 136 Schematic of hybrid BESS and PHS plant



Source: M. S. Javed et al.; 2020

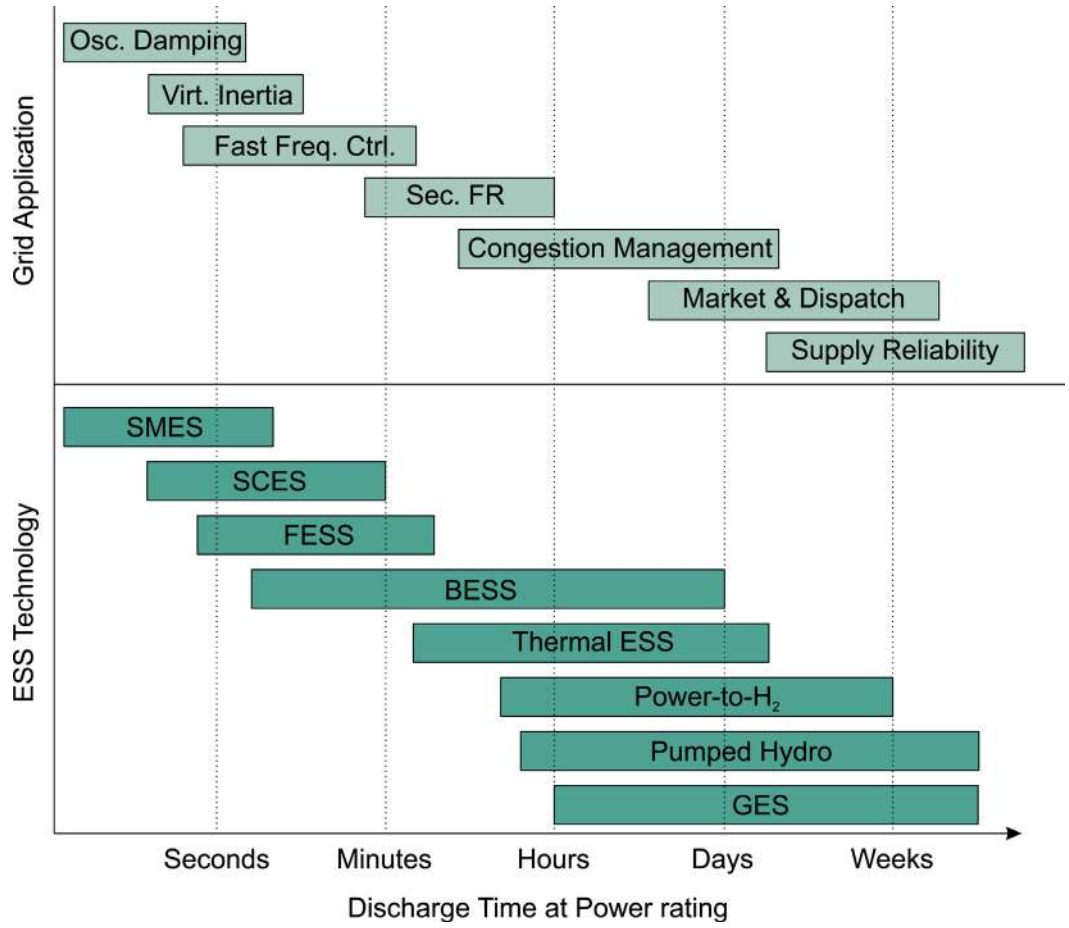
6.2 Seasonal and Long Duration Storage

Seasonal and LDES refer to shifting energy over multi-day to seasonal time scales to manage prolonged RE shortfalls, seasonal demand variation, and system adequacy under high electrification. Global assessments indicate that batteries are not suitable for very long durations, necessitating mechanical and chemical options such as pumped hydro and hydrogen storage[286]. System analyses further note that increasing electrification and RE penetration create flexibility requirements across all time scales, with seasonal variation requiring dedicated planning beyond short-term balancing. Figure 137[58] illustrates discharge durations of different ESS relative to power system events.

For planning purposes, long-duration storage is typically defined as discharge beyond approximately 10 hours to multiple days, with value linked primarily to adequacy, seasonal balancing, and resilience rather than ancillary services. Policy and investment discussions therefore treat long-duration storage as a distinct category, emphasising the need to recognise battery limitations and adopt hybrid portfolios to manage cost and reliability risks.

286 International Energy Agency, Managing the Seasonal Variability of Electricity Demand and Supply, IEA, Paris, France, Apr. 2024.

Figure 137 Time horizon for power system phenomena and ESS discharge times



Source: G. De Carne et al.; 2024

6.3 Sector Coupling

Sector coupling refers to linking the power sector with end-use sectors such as heating, cooling, mobility, and industry to increase overall system flexibility and support higher RE penetration. Recent analyses highlight that flexibility can be mobilised across the energy system through ESS and demand-side management, with distributed resources such as EVs, heat pumps with TESS, RTS PV systems, and BTM BESS playing a central role in distribution grids. These studies also show that utilising such flexibility can defer network reinforcement and reduce losses, indicating that sector coupling functions both as a decarbonisation pathway and as a grid optimisation mechanism[287].

From an ESS perspective, sector coupling broadens value streams beyond electricity arbitrage. BESS support flexibility in mobility through smart charging and V2G operation and improve power quality and reliability for electrified industrial loads. Hydrogen enables indirect electrification and long-duration storage by linking power with industry and mobility when used as a fuel or feedstock. For hybrid ESS, this implies that battery-hydrogen configurations can deliver both grid services and cross-sector energy services, but they require clear prioritisation rules and contractual arrangements to avoid conflicts between electricity system reliability requirements and hydrogen offtake commitments[287].

287 International Renewable Energy Agency, Smart Electrification of End-Use Sectors: Benefits for Distribution Grids, IRENA, Abu Dhabi, United Arab Emirates, 2024.

6.4 Community Energy Storage Models

Community energy storage models refer to shared ESS assets that serve multiple customers and the local distribution network. These systems are typically connected at the distribution level and may be operated by a distribution operator, an aggregator, a community entity, or a hybrid partnership. The primary motivation is to extend ESS benefits to customers who cannot install BTM BESS, while also delivering network services such as peak reduction, voltage support, and improved local hosting capacity. Recent market snapshots report hundreds of proposed community BESS projects with substantial aggregate power and energy capacity, indicating rapid programme scale-up and growing involvement of both network operators and non-network proponents. Government programme descriptions similarly present community BESS as shared assets that store excess RTS PV for later use during peak periods, explicitly linking customer and network value[288].

Key design choices include ownership structure, dispatch rights, benefit sharing, tariff alignment, and metering arrangements. When dispatch prioritises network objectives, the focus is on congestion and voltage management and typically requires regulated payment mechanisms. When customer benefits are prioritised, bill reduction and improved solar self-consumption become central, subject to network and safety constraints. In practice, multi-use operation is often required, as community BESS generally need to combine market-based and network services to achieve financial viability under uncertain single-revenue outcomes.

6.5 Globally operated On-Grid Hybrid Energy Storage System projects

Globally operated on-grid HESS projects are summarised in Table 46[289].

Table 46 Globally operated HESS projects

Site name	RE source	HESS configuration	Location	Application	Year
Rankin substation hybrid energy storage project	PV	100 kW / 300 kWh lithium-ion BESS & 277 kW / 8 kWh SESS	United States	Energy time shift, power smoothing, frequency regulation	2016
AEG's German frequency control project	N/A	20 MW BESS-electrical heating system	Germany	Frequency regulation	2018
Kraftwerksgruppe Pfreimd pumped hydro storage plant	N/A	12.5 MW lithium-ion BESS & 13.7 MW PHS	Germany	Energy arbitrage, frequency regulation, black start	2018

288 Australian Government, "Community Batteries for Household Solar program," Department of Climate Change, Energy, the Environment and Water, May 2026.

289 Z. Fang, J. K. H. Shek, and W. Sun, "A review of grid-connected hybrid energy storage systems: Sizing configurations, control strategies, and future directions," Journal of Energy Storage, vol. 118, p. 116226, Mar. 2025.

Site name	RE source	HESS configuration	Location	Application	Year
Monash University microgrid project	PV	120 kW / 120 kWh lithium-ion BESS & 180 kW / 900 kWh VRFBs; 4 MW lithium-ion BESS & 1 MW FESS	Australia	Peak-shaving	2018
Shanxi Laoqianshan wind farm hybrid energy storage project	Wind	1 MW lithium-ion BESS & 1 MW FESS	China	Power smoothing, frequency regulation	2020
Bystra battery energy storage system	Wind	1 MW / 0.47 MWh lithium-ion BESS & 5 MW / 26.9 MWh lead-acid BESS	Poland	Energy time shift, energy arbitrage, voltage support	2020
Energy Superhub Oxford	N/A	50 MW / 50 MWh lithium-ion BESS & 2 MW / 5 MWh VRFB	United Kingdom	Energy arbitrage, frequency regulation	2021
Shuozhou thermal power composite frequency modulation project	N/A	5 MW / 5 MWh lithium-ion BESS & 2 MW / 0.4 MWh FESS	China	Frequency regulation	2023
Luoyuan power plant hybrid energy storage project	N/A	15 MW / 7.5 MWh lithium-ion BESS & 5 MW SESS	China	Frequency regulation	2023
Zhaoyuan hybrid energy storage project	N/A	201 MW / 402 MWh lithium-ion BESS & 3 MW / 187 kWh SESS	China	Energy arbitrage, frequency regulation, black start	2024
Dossi pumped hydro storage plant	N/A	4 MW / 8 MWh lithium-ion BESS & 43.4 MW PHS	Italy	Energy arbitrage, frequency regulation, black start	2024

07

CHAPTER 7

STANDARDS FOR ENERGY STORAGE SYSTEMS



Pexels

Summary

- Defines the standards framework required for safe, reliable, interoperable, and grid compliant ESS deployment across transmission, distribution, and behind the meter applications.
- Covers interconnection standards such as IEEE 1547, IEEE 2800, national grid codes, harmonic compliance, protection coordination, testing, certification, and model validation.
- Explains communication and interoperability requirements using IEC 61850, DNP3 or IEEE 1815, Modbus, SunSpec, OpenADR, IEEE 2030.5, SCADA integration, and time synchronised measurement frameworks.
- Highlights cybersecurity, safety, and certification requirements through NERC CIP, IEEE 1547.3, IEC 62443, UL 2900, UL 9540, UL 9540A, UL 1973, UL 1741, NFPA 855, IEC 62933, and electrical installation codes.





Pexels

With the increasing integration of ESS into power systems, comprehensive standards are required to ensure safe interconnection, reliable operation, effective communication, and resilience against cyber threats. This section addresses grid interconnection standards, including electrical connectivity requirements and grid code compliance, as well as communication protocols, interoperability frameworks, cybersecurity considerations, and applicable testing and safety standards. Adherence to these standards ensures that ESS installations operate compatibly within interconnected networks, maintain system security, and avoid adverse impacts on grid stability, equipment, or public safety.

7.1 Grid Interconnection Standards

Interconnection standards define the technical requirements for connecting ESS at both transmission and distribution levels. They address voltage regulation, frequency response, anti-islanding, fault ride through capability, power quality, protection coordination, and system stability performance.

- **IEEE 1547 series for distribution DER:** IEEE 1547-2018 establishes interconnection and interoperability requirements for distributed energy resources, including ESS, connected to distribution networks. It mandates capabilities such as voltage regulation through volt VAR and volt watt functions, defined frequency response ranges, mandatory ride through of voltage and frequency disturbances, and anti-islanding protection for feeder connected systems[290]. IEEE 1547.1-2020 specifies conformance test procedures to verify these functionalities. In practice, converter based ESS connected to medium voltage distribution systems in the United States are required to demonstrate compliance through certification pathways such as UL 1741 SB[291].
- **IEEE 2800-2022 for bulk converter based resources:** IEEE 2800 defines performance requirements for transmission connected converter based resources, including large scale ESS. It specifies adjustable droop based primary frequency response, voltage control capability in voltage and reactive power modes, and mandatory ride through during defined voltage and frequency excursions. The standard also addresses system strength considerations and oscillatory stability to ensure acceptable performance under low short circuit ratio conditions. Transmission connected ESS must demonstrate, through validated simulation studies, compliance with fault ride through requirements and dynamic reactive current injection during disturbances[292].
- **National grid codes:** Many national grid codes explicitly incorporate storage within the regulatory framework. The Indian Electricity Grid Code 2023 includes ESS within generation asset definitions and requires participation in primary frequency response during discharge, interruption or modulation of charging during frequency deviations, and defined reactive power capability and ramp rate limits. Compliance is monitored by RLDC and SLDC at the point of interconnection[293]. European network codes issued by ENTSO-E, including the Requirements for Generators, apply comparable performance criteria to large converter based units, including reactive power capability, voltage ride through performance, and responsiveness to TSO control signals.

290 "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003) , vol., no., pp.1-138, 6 April 2018

291 "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces," in IEEE Std 1547.1-2020

292 "IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," in IEEE Std 2800-2022 , vol., no., pp.1-180, 22 April 2022

293 Central Electricity Regulatory Commission, Indian Electricity Grid Code, CERC, New Delhi, India.

- **Interconnection procedures and compliance studies:** In addition to formal standards, project level interconnection procedures require detailed analytical studies, including harmonic assessments in accordance with IEEE 519[294], short circuit and protection coordination studies, and dynamic stability analysis.
- **Testing, certification, and model validation:** Compliance frameworks increasingly require type testing and certified functionality verification. Distribution level converter certification is typically conducted under UL 1741[295] SB aligned with IEEE 1547. For transmission scale ESS, validated dynamic models are required for planning studies, and model performance must align with measured field response within defined tolerances. Emerging regulatory practices extend generator model verification principles to ESS to ensure consistency between simulated and actual system behaviour.

7.2 Communication Standards

The interoperability of ESS with grid infrastructure, operators, and market platforms is fundamentally governed by communication standards that define the exchange of setpoints, status signals, and measurement data. These standards enable coordinated control, multi-vendor integration, and scalable aggregation across transmission and distribution domains.

- **IEC 61858:** It provides a comprehensive framework for substation and DER communication. IEC 61850-7-420 defines the information model for DER, including logical nodes and data objects relevant to ESS, such as SoC, charge discharge status, and available capacity. ESS integrated at substations can communicate through standardized logical nodes to SCADA or substation controllers, supporting functions such as connection control, operating mode selection, and voltage regulation commands. Adoption of IEC 61850 enables consistent data modelling and seamless integration within utility automation systems[296].
- **DNP3/ IEEE 1815:** It is standardized as IEEE 1815, remains widely used for SCADA communication in North America. The MESA alliance developed interoperability profiles that map IEC 61850 DER information models to DNP3 point structures. The MESA DER specification standardizes representation of ESS parameters, including SOC, power limits, alarms, and control commands, thereby ensuring that ESS from different vendors can integrate with utility control centres using consistent point definitions. This reduces customization effort and enhances interoperability in large scale deployments[297].
- **Modbus:** TCP and RTU are commonly used for lower level industrial communication, particularly between BMS, PCS, and local controllers[298]. The SunSpec Alliance has defined standardized Modbus register mappings for PV and storage systems, enabling third party EMS to access battery parameters without proprietary interfaces. Such profiles are prevalent in commercial and industrial ESS installations[299].

294 "IEEE Standard for Harmonic Control in Electric Power Systems," in IEEE Std 519-2022 (Revision of IEEE Std 519-2014) , vol., no., pp.1-31, 5 Aug. 2022

295 "UL launches advanced inverter testing and certification program," UL Solutions.

296 International Electrotechnical Commission, IEC 61850-7-1: Communication Networks and Systems for Power Utility Automation – Part 7-1: Basic Communication Structure – Principles and Models, Geneva, Switzerland: IEC.

297 "IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3)," in IEEE Std 1815-2012 (Revision of IEEE Std 1815-2010) , vol., no., pp.1-821, 10 Oct. 2012

298 Modbus Organization, Modbus Protocol Specification.

299 SunSpec Alliance, SunSpec Modbus IEEE 1547-2018 Profile Specification and Implementation Guide, Version 1.1.

- **OpenADR and IEEE 2030.5 (SEP2.0):** At the application layer, OpenADR[300] and IEEE 2030.5[301] facilitate DER participation in demand response and aggregation frameworks. OpenADR 2.0b supports event based dispatch instructions, while IEEE 2030.5, also known as Smart Energy Profile 2.0, enables secure IP based communication for pricing signals, scheduling, and direct control of distributed ESS. These standards are particularly relevant for virtual power plants and behind the meter aggregation, where coordinated control of large fleets of distributed ESS is required.
- **Utility Scale SCADA integration:** Utility scale ESS are typically integrated into SCADA systems using protocols such as IEC 60870-5-104[302] in Europe and Asia or DNP3[303] in North America. Standardized point lists include real and reactive power output, breaker status, SoC, and available headroom, as well as supervisory commands for output adjustment or mode switching. Interoperability profiles developed by MESA and SunSpec ensure consistent semantic interpretation across vendors, thereby minimizing integration complexity and risk.
- **Time synchronization and measurement:** While not ESS specific, IEEE C37.118 synchro phasor protocols may support fast response or oscillation damping applications where PMU feedback is incorporated into ESS control schemes[304]. Microgrid control frameworks such as IEEE 2030.7[305] and IEEE 2030.8[306] further define hierarchical communication structures that include storage coordination.

Hence, standardized communication frameworks such as IEC 61850, IEEE 1815 with MESA profiles, Modbus with SunSpec mappings, and OpenADR or IEEE 2030.5 are essential for scalable and vendor neutral ESS integration. They reduce engineering overhead, mitigate interoperability risks, and enable coordinated operation of heterogeneous ESS fleets within evolving market structures and aggregated DER participation frameworks.

7.3 Cybersecurity in ESS Systems

With increasing digitalisation and remote controllability, cybersecurity has become a critical requirement for ESS. Compromise of ESS control systems can result in asset damage, loss of availability, or coordinated misoperation with potential grid stability implications. Modern ESS are software managed through on site SCADA or EMS platforms and increasingly through cloud based interfaces, thereby expanding exposure to cyber threats. The potential threat landscape related to ESS is mentioned below:

- Unauthorised control commands, including malicious dispatch instructions that force abrupt charge or discharge, potentially causing grid disturbances or equipment stress.
- Data manipulation, such as falsified SOC, power limits, or temperature readings, leading to unsafe operation or incorrect dispatch decisions.

300 OpenADR Alliance, OpenADR for Distributed Energy Resources (DER), OpenADR Alliance, 2021.
301 "IEEE Standard for Smart Energy Profile Application Protocol," in IEEE Std 2030.5-2023 (Revision of IEEE Std 2030.5-2018/ Incorporates IEEE Std 2030.5-2023/Cor1-2024) , vol., no., pp.1-398, 11 Dec. 2024
302 ABB, IEC 60870-5-104 Communication Protocol Manual: SSC600, ABB Ability™ Smart Substation Control and Protection for Electrical Systems, Nov. 2020.
303 ABB, Relion® 615 Series: DNP3 Communication Protocol Manual, Doc. ID 756709, ABB.
304 "IEEE Standard for Synchrophasor Measurements for Power Systems," in IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005) , vol., no., pp.1-61, 28 Dec. 2011
305 "IEEE Standard for the Specification of Microgrid Controllers," in IEEE Std 2030.7-2017 , vol., no., pp.1-43, 23 April 2018.
306 "IEEE Standard for the Testing of Microgrid Controllers," in IEEE Std 2030.8-2018 , vol., no., pp.1-42, 24 Aug. 2018

- Malware or ransomware targeting BMS or EMS platforms, potentially disabling protection functions or interrupting grid services.
- Exploitation of remote access gateways and cloud connected fleet management systems, increasing the attack surface compared to isolated legacy systems.

The applicable standards and guidelines that needs to be implemented by ESS are:

- **NERC CIP:** Transmission connected ESS forming part of the Bulk Electric System in North America may qualify as BES Cyber Systems and are subject to NERC CIP[307] requirements, including asset identification, access control, configuration management, monitoring, and incident response. ESS control systems are treated comparably to substation automation systems for security hardening and compliance.
- **IEEE 1547.3-2023:** Provides cybersecurity guidance for DER, including encryption, authentication, secure configuration, firmware integrity, logging, and development of cybersecurity management plans aligned with IEEE 1547 interconnection requirements[308].
- **IEC 62443:** Establishes security requirements for industrial automation and control systems[309]. ESS integrators increasingly adopt zone and conduit architectures, network segmentation, secure device development practices, and role based access control consistent with this standard.
- **UL 2900-2-2:** Defines cybersecurity certification criteria for industrial control systems, addressing secure coding practices, vulnerability assessment, and baseline encryption requirements for embedded controllers[310].

7.4 Testing, Safety, and Certification Standards

Safety is a fundamental requirement for ESS, particularly ECES that present electrical, thermal, and fire hazards. Comprehensive safety standards govern system design, component certification, installation practices, and fire mitigation to ensure reliable operation and provide confidence to utilities and authorities having jurisdiction. Compliance with these standards ensures that ESS are not only interoperable at the grid interface but also safe under normal and abnormal operating conditions. The key safety and testing standards are summarised below:

- **UL 9540:** This is the primary system level safety standard for ESS in North America[311] It evaluates the complete system, including battery modules, PCS, enclosure, thermal management, and control systems. The standard addresses electrical isolation, fault protection, fire and explosion risks, and thermal runaway mitigation. NFPA 855 mandates UL 9540 certification for lithium ion systems above defined energy thresholds, making it central to regulatory approval[312].

307 North American Electric Reliability Corporation, CIP-002-5.1a – Cyber Security: BES Cyber System Categorization, NERC Reliability Standard, Atlanta, GA, USA.

308 "IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems," in IEEE Std 1547.3-2023 (Revision of IEEE Std 1547.3-2007) , vol., no., pp.1-183, 11 Dec. 2023

309 International Electrotechnical Commission, IEC 62443-3-2: Security for industrial automation and control systems – Part 3-2: Security risk assessment for system design, Ed. 1.0, Jun. 2020.

310 UL Solutions, UL 2900 Series – Software Cybersecurity for Network-Connectable Products, UL Solutions.

311 UL 9540: Energy Storage Systems and Equipment, 3rd ed., Underwriters Laboratories, ANSI approved Mar. 07, 2025, published Jun. 28, 2023.

312 UL 9540: Energy Storage Systems and Equipment, 3rd ed., Underwriters Laboratories, ANSI approved Mar. 07, 2025, published Jun. 28, 2023.

- **UL 9540A:** This is a test method used to evaluate fire propagation and thermal runaway behaviour in battery systems. Testing is conducted at cell, module, unit, and installation levels to assess fire spread, gas generation, and explosion risk. Results inform installation requirements such as spacing, ventilation, and fire suppression design. Certain jurisdictions require submission of UL 9540A test data for ESS installation approval[313]
- **UL 1973:** This standard applies to stationary battery modules and racks. It evaluates mechanical integrity, thermal stability, vibration tolerance, short circuit protection, and overcharge protection to ensure safe performance under normal and fault conditions. Most lithium ion modules deployed in ESS installations are certified to UL 1973.
- **UL 1741:** This standard governs safety and grid interaction of PCS. It verifies anti islanding protection, electrical safety, and compliance with grid support functions[314]. Supplements such as UL 1741 SB reference IEEE 1547-2018 and validate advanced converter capabilities required for distribution interconnected ESS.
- **NFPA 855:** This installation standard specifies fire safety requirements for stationary ESS. It defines allowable energy capacities per installation area, separation distances, fire suppression requirements, ventilation for off gas management, emergency shutdown provisions, and signage[312].
- **IEC 62933 series:** This international standard series addresses system safety and performance of ESS[315]. IEC 62933-5-2 specifies safety requirements for ECES systems at the system level, comparable to UL 9540.
- **Electrical installation codes:** NFPA 70 , including NEC Article 706[316], defines wiring methods, disconnect requirements, grounding, labelling, and clearances for ESS installations. IEEE C2[317], the National Electrical Safety Code, governs utility scale installations with respect to grounding, conductor clearances, and related safety provisions.
- **Environmental and reliability testing:** Standards such as IEC 60068[318] address environmental qualification under temperature, humidity, vibration, and shock conditions. Additional guidance, including IEEE 1679.1[319] and emerging industry specifications, supports evaluation of durability, cycling performance, and operational reliability under diverse environmental and loading scenarios.

Collectively, these standards establish a multilayered safety framework covering component certification, system integration, fire behaviour assessment, installation practices, and operational reliability. This framework ensures that ESS deployments meet rigorous safety and regulatory expectations across jurisdictions.

For certification, ESS products are typically evaluated by a Nationally Recognised Testing Laboratory, such as UL or TÜV. The evaluation includes compliance testing under UL 9540 at the system level, verification of component certifications such as UL 1973 for battery modules and UL 1741 for PCS,

313 Standard Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, ANSI/CAN/UL 9540A, 5th ed., Underwriters Laboratories, Mar. 2025.

314 SunSpec Alliance, SunSpec UL 1741 Supplement SA / Rule 21 Implementation Guide, Application Note, Draft ver. 0.3.

315 IEC 62933-4-3, Electrical energy storage (EES) systems – Part 4-3: Protection requirements of battery-based energy storage systems (BESS) according to environmental conditions, Ed. 1.0, Oct. 2025

316 National Fire Protection Association, NFPA 70: National Electrical Code, 2026 ed., 2026.

317 "2023 National Electrical Safety Code® (NESC®)," in 2023 National Electrical Safety Code(R) (NESC(R)) , vol., no., pp.1-365, 1 Aug. 2022

318 IEC 60068-2-42, Environmental testing – Part 2-42: Tests – Test Kc: Sulphur dioxide test for contacts and connections, 3rd ed., May 2003.

319 "IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications," in IEEE Std 1679.1-2025 (Revision of IEEE Std 1679.1-2017) , vol., no., pp.1-57, 16 May 2025.

and assessment of integrated safety functions. Upon successful completion, the system is listed and authorised to carry the UL 9540 mark. This certification facilitates approval by authorities having jurisdiction by demonstrating conformity with established electrical, fire, and system safety requirements. In Europe, ESS products achieve regulatory acceptance through CE marking, which requires compliance with applicable directives such as the Low Voltage Directive and relevant harmonised standards, including IEC 62933 for system safety. Certification is supported by type test reports and conformity assessments issued by accredited laboratories, providing assurance of compliance with electrical safety, electromagnetic compatibility, and product safety obligations.



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CHAPTER 8

08 INTERNATIONAL EXPERIENCE OF ENERGY STORAGE SYSTEM DEPLOYMENT FRAMEWORKS



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Summary

- Reviews global ESS deployment pathways from 2015 to 2025, showing how storage progressed from pilot projects to mainstream grid infrastructure through policy targets, incentives, and market reforms.
- Compares regional storage strategies across China, the United States, the United Kingdom, the European Union, and Australia, highlighting different combinations of mandates, tax credits, auctions, grants, capacity mechanisms, and regulatory reforms.
- Explains how removal of barriers such as double charging, unclear asset classification, limited market access, and inadequate revenue mechanisms has enabled ESS participation in energy, capacity, ancillary service, and flexibility markets.
- Highlights the growing policy focus on long duration storage, grid forming capability, safety regulation, domestic battery manufacturing, DER aggregation, and storage as a firm capacity and reliability resource

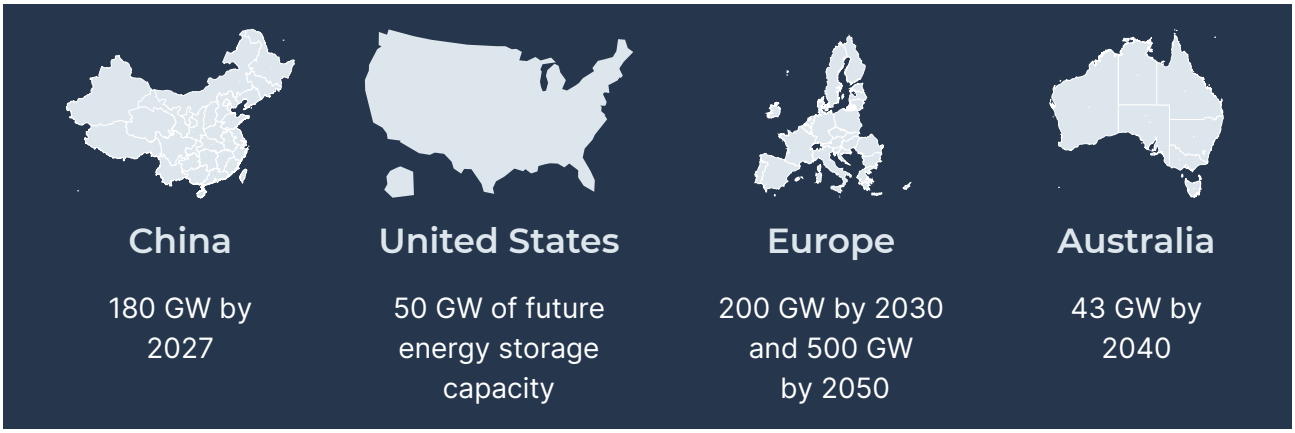




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ESS has become a key enabler of modern power systems by supporting RE integration and improving grid resilience. Between 2015 and 2025, global installed ESS capacity, led by PHS and BESS, expanded rapidly, with grid-scale BESS capacity increasing several fold in the early 2020s[31]. In parallel, governments and regulators increasingly recognised ESS as critical for grid flexibility, capacity adequacy, and ancillary services, leading to evolving policy frameworks that introduced deployment targets, financial incentives, and market reforms.

By the mid-2020s, several regions had adopted large-scale storage targets. U.S. announced more than 50 GW of future ESS capacity[320], European national plans indicated around 200 GW by 2030 and 500 GW by 2050[31], China announced 180 GW of ESS by 2027[321], and Australia announced the deployment of 43 GW by 2040[322]. BESS deployment was supported by substantial cost reductions and rising RE penetration, while PHS regained policy attention for LDES and inertia provision.



Early regulatory barriers, such as double charging and unclear market participation rules, were progressively removed during this period. Reforms clarified the regulatory status of ESS and its participation in energy, capacity, and ancillary service markets[31,323]. Governments also introduced capital subsidies, tax credits, auctions, and long-term contracts, including the U.S. investment tax credit for stand-alone ESS and European innovation and revenue stabilisation programmes[287]. Grid operators further accelerated deployment through new market products and tenders tailored to ESS, such as fast frequency response and capacity market contracts[31]. Together, these developments shifted ESS from pilot projects to a mainstream grid resource. The following sections outline how policy frameworks evolved across six regions between 2015 and 2025, highlighting common trends and region-specific approaches to enabling storage in the clean energy transition.

320 International Energy Agency, United States 2024: Energy Policy Review, IEA, Paris, France, 2024.

321 The State Council of the People's Republic of China, "China accelerates development of new-type energy storage," The State Council Information Office, Sep. 12, 2025.

322 Australian Government Department of Industry, Science and Resources, "National Battery Strategy: Introduction," Australian Government

323 International Energy Agency [IEA], "Grid-scale Storage," 2023.


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8.1 China

8.1.1 National Strategy and Targets

China has increasingly prioritised ESS to support rapid RE expansion and improve grid reliability. While PHS historically dominated installed ESS capacity, policy attention broadened in the mid-2010s to "new ESS", covering non-hydro technologies such as BESS, FESS, and CAES. A key milestone was the 2017 national guidance on ESS development, which recognised storage as a core power system technology and promoted pilot projects, clearer grid-connection rules, ancillary service compensation mechanisms, and distributed storage, despite the absence of explicit numeric targets[324].

During 2020s, policy emphasis shifted from pilot programmes to explicit deployment goals. In 2021, China announced a target of 30 GW of new non-hydro ESS by 2025, signalling a transition toward commercial-scale deployment and an intention for ESS to become largely market-driven by 2030 alongside substantial cost reductions[325]. In parallel, PHS ambitions expanded, with plans to increase capacity from about 30 GW in 2020 to 62 GW by 2025 and approximately 120 GW by 2030, reflecting growing flexibility requirements to integrate large-scale wind and solar PV generation.

8.1.2 Regulatory Measures and Market Reforms

Alongside deployment targets, China introduced regulatory and market measures to accelerate ESS adoption. From 2016-2017, several provinces required new wind and solar projects to include BESS, typically 5-20 percent of installed capacity for around one hour, to smooth output and reduce curtailment. National guidance issued in 2017 reinforced this approach by promoting compensation mechanisms for storage participation in ancillary service markets[324].

Subsequently, regional market pilots enabled BESS to provide frequency regulation and ramping services in return for payment. Regions with high curtailment, such as Xinjiang and Gansu, implemented peak shaving compensation schemes that paid ESS operators to consume surplus RE generation and discharge it during peak demand[326]. From 2019-2020, shared ESS models also emerged, with large BESS stations serving multiple RE projects through service fees. While this supported early deployment, policy has generally favoured third-party ownership, and around 2020 ESS was formally recognised as a market-participating resource, procured through market mechanisms rather than treated as a regulated network asset.

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324 L. Fang, X. Huang, and S. Wang, National Survey Report of Photovoltaic Applications in China 2017, International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), Paris, France, 2018.

325 Oxford Institute of Energy Studies, "A: Hydropower," Guide to Chinese Climate Policy. 2022.

326 China Energy Storage Alliance, Official Release of Energy Storage Subsidies in Xinjiang: Capacity Compensation of 0.2 CNY/kWh, Capacity Lease of 300 CNY/kW·Year, and Peak-Shaving Compensation of 0.55 CNY/kWh.

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China scaled ESS through targets, renewable-storage mandates, and market reforms rather than direct subsidies, reaching over 70 GW of new-type storage by 2024 while positioning storage as a market-participating grid resource.

8.1.3 Financial Incentives

In contrast to many Western countries, China did not rely heavily on direct subsidies for BESS deployment after 2015. Earlier, during 2011–2015, policy support mainly took the form of research funding and a limited number of demonstration projects, such as the Zhangbei wind-solar-ESS pilot project[327]. From 2015 to 2025, the policy emphasis shifted toward mandates and market rule reforms rather than upfront grants. An important aspect has been ancillary service cost-allocation reform, under which generators contribute to funds that compensate resources providing frequency regulation or reserves. In provinces like Jiangsu and Guangdong, BESS have earned substantial revenue through participation in these markets, creating performance-based incentives. In parallel, central and provincial research funding supported cost reduction and domestic manufacturing, aligned with broader industrial policy that identified large-scale ESS as a strategic growth sector.

8.1.4 Integration with RE and Grid Planning

ESS has also been integrated into China's RE expansion and grid planning frameworks. The 13th Five-Year Energy Plan (2016-2020) implicitly emphasised PHS expansion, with targets that were largely achieved[325]. Under the 14th Five-Year Plan (2021-2025), both PHS and new energy storage technologies became explicit elements of power system planning. For example, policy directives issued in 2021 required large solar PV and wind bases in certain regions to include storage or other flexibility resources to maintain grid stability. By 2025, many provinces had released local ESS plans specifying expected capacity additions, often directly linked to RE targets.

By 2025, China's ESS landscape was characterised by rapid, government-guided scale-up. Several gigawatts of BESS were deployed across grid-side and BTM applications. National targets translated into deployment outcomes, with cumulative new-type ESS installations reported to exceed 70 GW by the end of 2024. PHS development also accelerated, with numerous projects approved or under construction to meet interim capacity goals. Key challenges remain, particularly the need for sustainable long-term revenue models once mandated targets are met. As a result, regulators are exploring capacity-based payments and deeper electricity market reforms to support multi-service participation by storage. Overall, between 2015 and 2025, China progressed from pilot projects to large-scale deployment by combining top-down targets and mandates with gradual market reforms, driving storage deployment at unprecedented scale and influencing global cost trends. The summary table comprising of ESS policy and market evolution from 2015 to 2025 is mentioned in Table 47[328].

327 Carmen, "Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project I - BESS, China," Power Technology, Aug. 31, 2021.

328 GIL Research



Table 47 Energy storage evolution in China from 2016 to 2026

Year	National initiative	Description
2016	**Launching three north pilot project**	Allowing a limited number of ESS projects to participate in peak/frequency ancillary service market mechanisms
		Early national-level opening for ESS revenue via ancillary services in specific regions
2017	**Guiding opinions on promoting ESS technology and industry development**	Establishes first national framework for ESS technology and industry development
		Emphasizes demonstration, standardization, and commercialization pathways
		Positions ESS as supporting a "clean, low-carbon, safe, efficient" energy system
2019	**2019–2020 Action plan to implement the 2017 guiding opinions**	Converts the 2017 framework into near-term deliverables (R&D, demos, standards, applications)
		Calls for advancing major demonstration projects and improving supportive mechanisms
		Strengthens cross-ministry coordination for ESS implementation
2021	**Guiding opinions on accelerating the development of new-type ESS**	Elevates "new-type ESS" as a strategic flexibility resource for the modern power system
		Sets staged development goals
		Pushes market mechanisms and policy environment to move from pilots to scale deployments
2021	**Medium & long-term PHS development plan**	Provides national medium/long-term planning basis for PHS establishment
		Frames PHS as a key mature flexibility resource for large-scale RE integration
		Guides project layout and development sequencing till 2035
2022	**Strengthening safety management of ECES**	Establishes national safety management requirements for ECES
		Strengthens responsibilities across planning/design, equipment selection, construction, commissioning, and O&M
		Safety becomes an explicit compliance focus with deployment
2022	**Further promoting new-type ESS participation in electricity markets and dispatch utilization**	Explicitly supports new-type ESS participating in markets
		Promotes coordinated dispatch/operation frameworks to improve utilization
		Requires local implementation plans and strengthens oversight for fair dispatch
2023	**Strengthening safety operation risk monitoring for generation-side and grid-side ECES**	Requires building risk monitoring, analysis, and early-warning capability for electrochemical storage stations
		Tightens data management & industry reporting/analysis mechanisms

Year	National initiative	Description
2024	**Promoting grid connection and dispatch utilization of new-type ESS**	Standardizes grid-connection management and dispatch operation mechanisms for new-type ESS
		Clarifies dispatch principles: market-clearing where markets exist or dispatch instructions otherwise
		Improves operational integration and utilization governance
2025	**NEA press conference / briefing on new-type ESS development**	Provides official, nationwide status update on new-type ESS development
		Publicly states 2024 installed capacity surpassed 70 million kW
2026	**New-type ESS (except PHS) into capacity pricing mechanism**	Officially included new-type ESS in its generation-side capacity pricing mechanism, recognizing ESS as a firm capacity resource
		Policy enables stable capacity-based revenue streams for ESS projects, improving project bankability and accelerating large-scale deployment.

8.2 United States

In the United States, ESS policy has evolved through a combination of federal regulatory actions, primarily affecting wholesale market access and tax incentives, and state-level initiatives such as procurement targets, pilot programmes, and inclusion of ESS in resource planning. This layered governance structure has produced uneven regional progress, with early adopters such as California and New York advancing rapidly, while initial federal policy focused on enabling market participation. Over time, Federal Energy Regulatory Commission (FERC) actions removed barriers for ESS participation in wholesale markets, and subsequent federal legislation strengthened investment incentives. By 2025, the United States had established robust mechanisms to support ESS deployment and market access, contributing to its position as one of the leading global markets for BESS additions[320].

8.2.1 Early State Mandates and Pilot Projects

State governments led early ESS deployment in the United States during the mid-2010s, prior to the introduction of comprehensive federal incentives. California played a pioneering role through Assembly Bill 2514, enacted in 2010, which mandated investor-owned utilities to procure 1.325 GW of ESS by 2020, positioning the state as a national testbed for ESS technologies, regulation, and market integration[329].

Following California, several states introduced quantitative ESS targets. Oregon mandated 5 MWh by 2020 to gain operational experience, Massachusetts set a 200 MWh target for 2020 linked to clean energy integration, and New York established one of the most ambitious goals, initially targeting 3 GW by 2030 and later expanding this to 6 GW as part of its clean energy strategy[330]. These targets were supported by regulatory measures and financial incentives, such as California's Self-Generation Incentive Program for BTM BESS and New York's New York State Energy Research and Development Authority (NYSERDA) grants for pilot and early commercial projects. By end of 2020, at least nine U.S. states had adopted formal ESS targets, collectively amounting to more than 50 GW by around 2040. This state-level leadership was instrumental in creating early markets, reducing investment

329 California Energy Commission, "Energy Storage Targets for Publicly Owned Utilities-AB".

330 U.S. Department of Energy, U.S. Hydropower Market Report 2021, U.S. DOE, Washington, DC, USA, 2021.

risk, and laying the groundwork for large-scale ESS deployment under subsequent federal reforms and incentives[320].

8.2.2 Federal Regulatory Reforms

The U.S. Federal Energy Regulatory Commission implemented pivotal rule changes to integrate ESS into wholesale electricity markets. The most significant was FERC Order No. 841[331], issued in 2018, which required Regional Transmission Organisations (RTOs) and Independent System Operators (ISOs) to remove barriers to ESS participation and recognised them as both supply and demand assets. The order mandated dedicated participation models that allow ESS to provide energy, capacity, and ancillary services while accounting for SoC and operating constraints. This marked a major shift from earlier generator-centric market rules and was upheld in 2019, confirming FERC's authority to reform ESS participation[330]. FERC strengthened ESS through additional Order 841. Order No. 842, issued in 2018, required new resources, including ESS, to provide primary frequency response[332], while Order No. 845 improved interconnection procedures, benefiting ESS projects facing long queues and uncertain upgrade costs[333].

A further major step was Order No. 2222 in 2020, which enabled aggregated DERs, including BTM BESS and EVs, to participate directly in wholesale markets[334]. This reform allowed aggregators to combine smaller resources and support new models such as virtual power plants. Together, Orders 841 and 2222 modernised U.S. wholesale markets by recognising ESS and aggregated DERs as core system resources. By 2025, all major U.S. RTOs and ISOs had implemented compliance tariffs, supporting rapid growth in both FTM and BTM ESS.

8.2.3 Incentives and Funding

The Inflation Reduction Act (IRA) had an immediate and significant impact on U.S. ESS markets by improving project economics, reducing revenue risk, and expanding viable locations for stand-alone BESS projects. As a result, analysts expect sustained growth across grid-scale, community, and distributed ESS. This outlook is supported by market data showing U.S. BESS additions exceeding 8 GW in 2023, roughly double the previous year[323].

331 Federal Energy Regulatory Commission, Order No. 841: Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators.

332 Federal Energy Regulatory Commission, Order No. 842: Primary Frequency Response, FERC, Washington, DC, USA, 2018.

333 Federal Energy Regulatory Commission, Order No. 845: Reform of Generator Interconnection Procedures and Agreements, FERC, Washington, DC, USA, 2018.

334 Federal Energy Regulatory Commission, Order No. 842: Primary Frequency Response, FERC, Washington, DC, USA, 2018.



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Alongside fiscal incentives, federal support expanded through research, development, and demonstration programmes. The U.S. Department of Energy (DOE) launched the Energy Storage Grand Challenge in 2020 and published an ESS Roadmap, increasing funding for innovation across the value chain with emphasis on long-duration and non-lithium technologies[335]. This was reinforced by the LDES Shot in 2021, which targets a 90 percent cost reduction for ESSs with durations of 10 hours or more by 2030[336], and by the Bipartisan Infrastructure Law, which allocated substantial funding for grid resilience and large-scale ESS demonstrations[337]. This direction is further supported by the U.S. DOE's Storage Innovations 2030, which highlights pathways for rapid scale-up, commercialization, and cost competitiveness of diverse energy storage technologies[338]. Together, long-term tax incentives under the IRA and expanded federal Research, Development and Demonstration funding reshaped the U.S. ESS policy landscape. Hence, ESS has shifted from reliance on niche or state-level support to a technology underpinned by durable federal policy, providing a stable foundation for large-scale private investment and integration into the evolving U.S. power system.

8.2.4 Market Participation and Revenue Mechanisms

Following compliance with FERC Order 841, all major U.S. RTOs and ISOs had established explicit participation models for ESS in wholesale markets by the early 2020s. These frameworks removed structural barriers and enabled ESS to participate across energy, capacity, and ancillary services. For example, California Independent System Operator (CAISO) updated its Non-Generator Resource model to align with Order 841, PJM introduced a dedicated storage classification, and ISO New England modified capacity market rules to account for limited-duration resources[339, 340]

These reforms supported rapid growth of grid-scale BESS, initially driven by frequency regulation markets such as PJM's fast regulation product. As these markets matured, developers increasingly shifted toward capacity markets and multi-service value stacking. By the mid-2020s, ESS had become a routine capacity resource, with more than 2.2 GW of BESS clearing Pennsylvania-New Jersey-Maryland Interconnection's (PJM) 2024/25 capacity auction[341]. RTOs also refined dispatch rules to reflect SoC constraints, including SoC-aware dispatch in PJM and New York Independent System Operator (NYISO) and a formal stored energy resource category in Midcontinent Independent System Operator (MISO). In parallel, aggregated BTM ESS emerged as a grid resource under FERC Order 2222. Pilot projects demonstrated aggregation of customer-sited BESS, supported by state policies such as the Massachusetts Clean Peak Standard. Together, these developments mark the transition of ESS from a niche service provider to a multi-product, capacity-relevant resource within U.S. wholesale electricity markets.

The summary table comprising of ESS policy and market evolution from 2015 to 2025 is mentioned in Table 48[342]:

335 U.S. Department of Energy, Energy Storage Grand Challenge.
336 U.S. Department of Energy, Long Duration Storage Shot: An Introduction, Energy Earthshots Initiative, U.S. DOE, Washington, DC, USA, Jul. 2021.
337 U.S. Department of Energy, Bipartisan Infrastructure Law and Inflation Reduction Act Funding-Spring 2024 Progress Update.
338 U.S. Department of Energy, "Storage Innovations 2030: Technology Liftoff," Office of Electricity, U.S. DOE.
339 California Independent System Operator, Business Requirements Specification: FERC 841 – Non-Generator Resource Model, California ISO, Folsom, CA, USA, 2019.
340 PCI Energy Solutions, Understanding Capacity Resource Obligations in ISO New England.
341 PJM Interconnection, "PJM capacity auction procures adequate resources." Inside Lines, PJM Interconnection.
342 GIL Research

Table 48 Energy storage policy and market evolution in United States from 2015 to 2025

Year	National initiative	Description
2015	State-level initiatives	California implemented AB 2514 with 1.325 GW ESS mandate by 2020
		Self Generation Incentive Program incentives cover up to 50% system cost for BESS
		Oregon becomes second state with mandatory ESS target
		Early utility pilots validate BESS-based grid services
2016	FERC technical conferences and PJM fast response	FERC initiates groundwork for ESS market integration
		PJM RegD market proves commercial viability of BESS
		250 MW batteries deployed in PJM by 2016
		Aliso Canyon crisis triggers rapid utility-scale ESS procurement
2017	State targets expand and DOE engagement	Massachusetts sets 200 MWh ESS target
		New York proposes 1.5 GW by 2025 under REV framework
		Multiple states begin planning GW-scale ESS goals
		DOE reports and funding raise policy confidence in ESS
2018	FERC Order 841 issued	Order 841 mandates ESS participation in all ISO/RTO markets
		Enables ESS access to energy, capacity, and ancillary services
		States expand targets aligned with clean energy goals
		Federal momentum builds for standalone ESS tax credits
2019	Order 841 upheld and State investments	Federal court upholds FERC authority over ESS markets
		All ISOs submit market rule compliance filings
		New York and Virginia adopt multi-GW ESS mandates
		Utilities include storage as firm capacity in IRPs
2020	FERC Order 2222 and DOE Energy Storage Grand Challenge	Order 2222 enables DER and ESS aggregation
		DOE launches Storage Grand Challenge and LDES cost targets
		Federal R&D funding expanded via stimulus measures
		Extreme events highlight reliability value of ESS
2021	Infrastructure act and large projects online	IIJA allocates funding for long-duration storage demos
		Supply chain investments support domestic battery manufacturing
		Moss Landing 300 MW BESS marks deployment milestone
		ERCOT and California see rapid post-event ESS growth

Year	National initiative	Description
2022	Inflation reduction act and record growth	IRA introduces 30% ITC for standalone ESS at least through 2033
		Bonus credits improve project economics significantly
		Grid-scale installations of ESS reach 4 GW in one year
		Aggregated ESS begins providing capacity services
2023	Rapid scale-up and capacity market entry	Annual additions reach 8–9 GW, fastest growth to date
		BESS clear capacity auctions in PJM and MISO
		ESS supplies advanced ancillary and flexibility services
		U.S. supports global 150 GW ESS by 2030 goal
2024	Continued expansion and long-duration focus	Federal funds support long-duration storage demonstrations
		Equity and resilience programs target community-scale ESS
		Markets refine rules for hybrid and aggregated resources
		Interconnection reform addresses project backlogs
2025	Mainstream resource status	ESS established as core grid resource nationwide
		Standardization of capacity accreditation advances
		Policy focuses shifts to reliability, safety, and fleet coordination
		Long-term planning aligns with hundreds of GW by 2040



Shimatonis, Public domain, via Wikimedia Commons

8.3 United Kingdom

The United Kingdom's ESS landscape over 2015-2025 evolved in two phases: early removal of regulatory barriers and support for demonstrations, followed by deeper market integration and targeted support. The government and The Office of Gas and Electricity Markets (Ofgem) identified ESS early as a key enabler of a flexible, low-carbon power system, particularly given rapid growth in wind and solar. By 2025, the UK had developed one of Europe's most mature BESS markets, supported by clear policy direction, defined market access rules, and procurement by National Grid ESO. This enabled ESS to transition from pilot projects to a commercial grid asset providing balancing, ancillary, and capacity services[320].

A central policy focus was clarifying the legal and regulatory status of ESS, which had previously been treated ambiguously as generation. This exposed projects to double charging of network fees and licensing uncertainty. These barriers were addressed through the 2017 Smart Systems and Flexibility Plan, which identified ESS as a core flexibility resource and set out reforms to modernise regulation. Subsequent changes during 2019-2020 formally recognised ESS for licensing purposes, simplified grid connection, and restructured charging arrangements to remove double charging, including exemptions from certain levies and adjustments to transmission charges such as Balancing Services Use of System (BSUoS)[343,344]. Together, these reforms removed long-standing distortions and significantly improved the commercial viability of ESS in the UK.

8.3.1 Market Mechanisms and Procurement

The UK electricity market is largely privatised, so ESS deployment was driven mainly by market access and competitive procurement rather than direct subsidies. A key early intervention was National Grid ESO's Enhanced Frequency Response tender in 2016, which procured 200 MW of sub-second frequency services under four-year contracts. The auction was oversubscribed, with eight BESS projects securing contracts at competitive prices, demonstrating the technical and commercial viability of BESS based frequency control and catalysing private investment[345].

All Enhanced Frequency Response (EFR) projects were delivered by 2018, after which additional ancillary service markets were opened to BESS, including dynamic frequency response and reserve products. By 2018–2019, BESS were routinely participating in Firm Frequency Response, though revenues declined as competition increased[346]. The UK Capacity Market also provided an important revenue stream, initially allowing short-duration BESS to secure capacity contracts. However, post-2018 reforms revised de-rating factors to better reflect duration, reducing the adequacy value of shorter-duration ESS assets[347].

343 Office of Gas and Electricity Markets, Electricity Storage: Licensing Statutory Consultation – Decision, Ofgem, London, U.K., 2020.
344 National Energy System Operator, Balancing Services Use of System (BSUoS) Charges
345 National Grid, Enhanced Frequency Response (EFR), National Grid Electricity System Operator, London, U.K.
346 National Grid, Firm Frequency Response: Frequently Asked Questions, National Grid Electricity Transmission, Warwick, U.K., Aug. 2017.
347 Energy Storage Association, Intelligence for Europe's Biggest Storage Project: Leighton Buzzard Battery Park (UK).



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8.3.2 Targets and Strategy

UK did not set a central government mandated ESS deployment target until recently. Instead, policy focused on creating an enabling market and regulatory environment. As the net zero 2050 agenda advanced, the scale of ESS required became clearer. In 2021, the government updated the Smart Systems and Flexibility Plan (SSFP) 2021, reaffirming the objective of removing barriers to flexibility and introducing measures such as mandating smart EV chargers and expanding flexibility markets. Within this framework, ESS was identified as a critical enabler for achieving around 30 GW of low carbon flexibility by 2030[348]. By 2022, government signalling shifted toward more explicit ambition. The British Energy Security Strategy published in April 2022 highlighted the importance of system flexibility, and official statements indicated that tens of gigawatts of ESS and flexibility would be required by 2035 to support a RE dominated power system. This marked a transition from a purely enabling approach toward stronger policy direction[349]. In this context, Clean Power 2030 Action Plan was launched which highlighted the addition of 23-27 GW of BESS capacity and 4-6 GW of LDES by 2030[350].

8.3.3 Long-Duration Storage Support

One limitation of the UK's largely market-driven approach was the limited investment in LDES covering multi-hour to multi-day time scales. These assets are capital intensive and difficult to finance using merchant revenues alone. PHS is the primary technology in this category, and the UK had not commissioned a new large PHS plant since the 1980s, apart from a small unit added in 2012. Recognising this gap, the government initiated the design of a dedicated support mechanism.

In 2023, the UK government consulted on a "Cap and Floor" regime for large-scale LDES, modelled on the framework used for electricity interconnectors. Under this approach, projects receive a minimum revenue guarantee (the floor) and an upper limit on returns (the cap), reducing investment risk while protecting consumers[351]. The mechanism effectively functions as a contract-based revenue stabilisation framework tailored for ESS. Following consultation from several stakeholders, in 2025 the government announced the formal launch of an LDES cap-and-floor scheme, with Ofgem appointed as the regulator and the first application window expected in 2025. This policy directly targets the commercial barriers facing new PHS projects such as the proposed 1500 MW Coire Glas scheme in Scotland, as well as emerging long-duration technologies including CAES and liquid air energy storage[352].

The objective is to enable the first new LDES projects to become operational in the early 2030s, strengthening system resilience during extended periods of low RE output. As of 2025, Britain has approximately 2.8 GW of existing PHS capacity across four plants, with several additional projects in development that are contingent on the implementation of this support framework.

The summary table comprising of ESS policy and market evolution from 2015 to 2025 is mentioned in Table 49:

348 U.K. Department for Business, Energy & Industrial Strategy, Smart Systems and Flexibility Plan 2021, HM Government, London, U.K., 2021.

349 U.K. Department for Business, Energy & Industrial Strategy, British Energy Security Strategy, HM Government, London, U.K., 2022

350 UK Department for Energy Security and Net Zero, Clean Power 2030 Action Plan: Main Report, Dec. 2024.

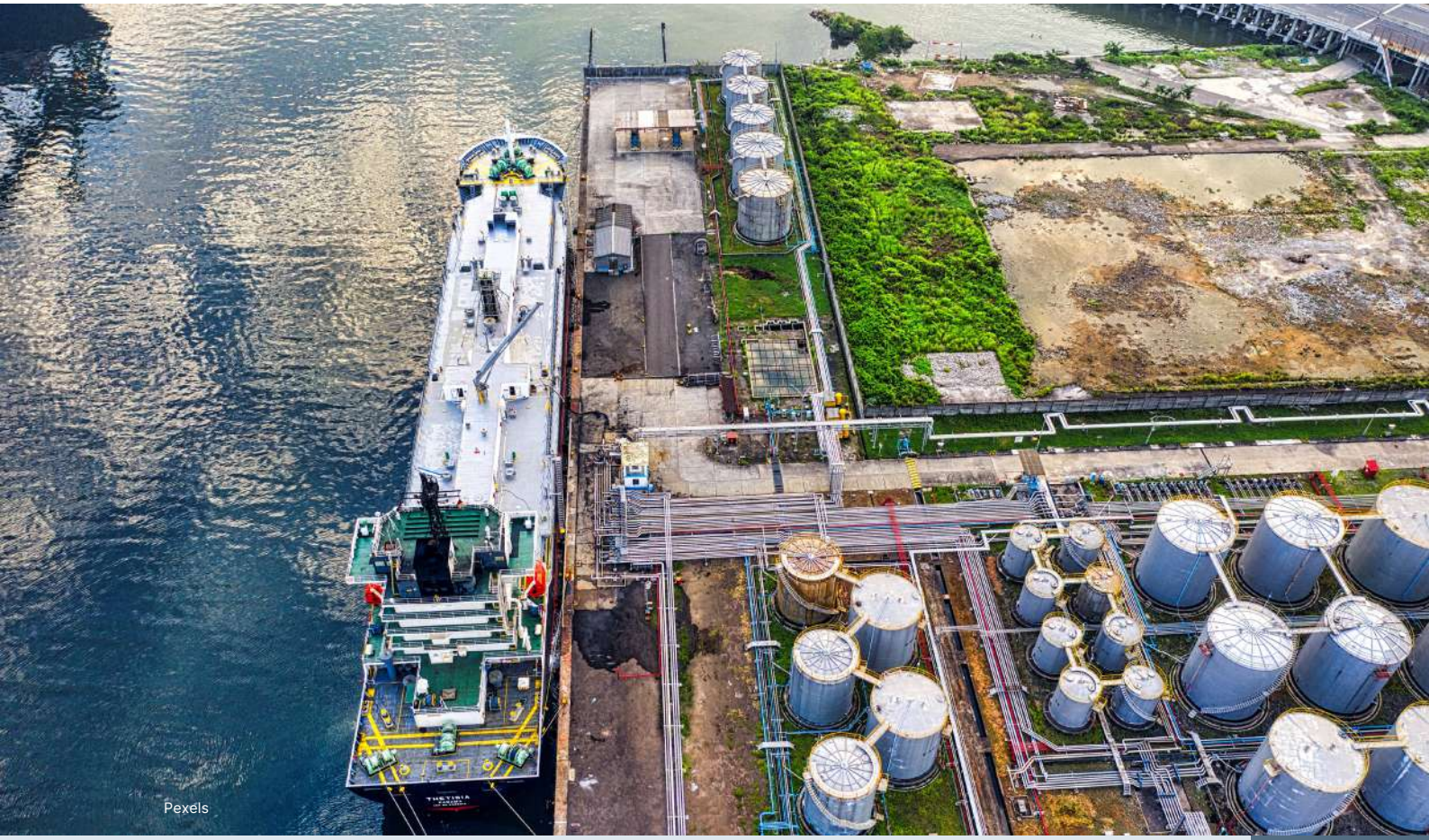
351 U.K. Parliament, Energy Act 2023, c. 52, HM Government, London, U.K., Dec. 2023.

352 U.K. Department for Energy Security and Net Zero, Long Duration Electricity Storage: Cap and Floor Scheme – Design, HM Government, London, U.K., 2024.

Table 49 Energy storage policy and market evolution in United Kingdom from 2015 to 2025

Year	National initiative	Description
2015	Early demonstrations and studies	First grid-scale BESS pilots (e.g. Leighton Buzzard 6 MW) commissioned
		National Grid identifies need for fast-response flexibility
		ESS considered within Whole System Smart Grid strategy
2016	Enhanced requency Response (EFR) auction	National Grid procures 200 MW sub-second response from BESS
		4-year EFR contracts validate battery technical capability
		Auction triggers private investment pipeline
		Ofgem acknowledges double charging issue
2017	Smart systems and flexibility plan	ESS formally addressed in national flexibility reforms
		Commitment to remove double charging barriers
		Licensing and planning rules for ESS clarified
		Co-located RE and ESS enabled without CfD penalty
2018	Legal definition and charging reforms	ESS legally defined as a subset of generation
		Decision to remove ESS from demand residual charges
		Frequency response prices decline as supply increases
		BESS diversify into balancing and wholesale markets
2019	Removal of double charges and planning reform	Final consumption levies for ESS eliminated
		Transmission demand charges for ESS removed
		Planning cap of 50 MW lifted for BESS projects
		Large-scale ESS deployment accelerated
2020	Capacity market and ancillary evolution	ESS re-enters capacity market with updated de-rating
		Dynamic containment service launched for fast BESS
		ESS secures long-term CM contracts despite short duration
		Net Zero strategy highlights flexible assets
2021	Smart systems plan update and net zero strategy	Reinforced commitment to large-scale storage deployment
		Net Zero Strategy signals need for 30 GW flexibility by 2030
		Stability pathfinder awards include BESS inertia trials
		GFM capabilities tested

Year	National initiative	Description
2022	Storage target signalling and LDES policy	Energy Security Strategy emphasizes ESS for system balance
		Indicative ambition of 30 GW flexibility by 2030
		Cap-and-Floor model proposed for long-duration ESS
		GFM converters for BESS procured for stability services
2023	ESS targets legislated and market shift	First statutory targets set: 2.6 GW (2030), 6.3 GW (2035)
		Cap-and-Floor scheme confirmed for LDES
		Market revenues shift toward wholesale and energy arbitrage
		Operational ESS reaches 1.7 GW
2024	LDES support launch and flexibility markets	Cap-and-Floor scheme opened for >4 h ESS projects
		PHS projects advance toward FID
		Local flexibility markets approved by Ofgem
		Updated safety and regulatory guidance issued
2025	ESS as core grid asset	UK reaches 4 GW operational ESS
		BESS routinely provide frequency, reserve, and capacity
		GFM and black-start trials expand
		Policy shifts toward long-term flexibility markets



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8.4 European Union

The European Union (EU) has increasingly recognised ESS as a key enabler of the clean energy transition and grid reliability. EU-level policy has focused on establishing a supportive regulatory framework across member states and facilitating investment through research funding and market integration. While deployment targets are primarily defined in national energy plans, the EU has provided overarching directives, notably through the 2019 Clean Energy for All Europeans package, to ensure ESS can participate on equal terms in electricity markets[353]. By 2025, Europe had established a continent-wide regulatory baseline for ESS, including a legal definition of ESS, widespread removal of double grid charging mechanisms, restrictions on transmission and distribution operator ownership except in specific cases, and inclusion of ESS in capacity market mechanisms and related schemes in several countries. These measures, together with declining technology costs, have driven significant growth in BESS projects and renewed interest in PHS across Europe.

8.4.1 EU Legislative Framework (Clean Energy Package 2019)

A major milestone was the adoption of the Electricity Directive (EU) 2019/944 and Electricity Regulation (EU) 2019/943, which for the first time explicitly addressed ESS in EU law. Key provisions in the law included[356]:

- **Definition of ESS:** The Directive introduced a clear legal definition of ESS as "deferring the final use of electricity to a later moment than when it was generated, or the conversion of electricity to another energy carrier and the subsequent reconversion of that energy carrier to electricity".
- **Market access rights:** Member States required to ensure that ESS facilities can access all electricity markets, including energy, capacity, and ancillary services, without discrimination. This established EU-wide market access similar to the role of FERC Order 841 in the United States.
- **Network charging:** The Directive required that stored energy is not subject to double network charges when electricity is withdrawn from and later reinjected into the grid, avoiding double payment of transmission and distribution tariffs. Several countries, including Italy, Spain, Germany, and Sweden, implemented tariff reforms to reflect this, reducing grid-related costs for ESS.
- **TSO/DSO ownership restrictions:** Transmission and distribution system operators are generally prohibited from owning or operating ESS assets to avoid conflicts of interest and market distortion, except where no market-based solutions exist and subject to regulatory

353 European Commission, Clean Energy for All Europeans Package Completed: Good for Consumers, Good for Growth and Jobs, and Good for the Planet.

☼ KEY INSIGHT

The EU has enabled ESS scale-up by legally defining ESS, ensuring non-discriminatory market access, removing double charging, and linking ESS deployment with national flexibility planning.

approval, typically limited until 2024 unless extended. Limited exemptions were applied in specific cases like Cyprus or island systems, to support grid stability.

- **Flexibility assessment and planning:** Member States must assess flexibility needs, including ESS, within their National Energy and Climate Plans and remove barriers to the deployment of such resources.

These provisions entered into force in 2020 and have since been transposed into national legislation. They established a more level playing field for ESS across the EU, replacing earlier frameworks in which some countries applied unfavourable treatments, such as double grid fees or levies on charging energy.

8.4.2 National Targets and Supports

Under the EU Governance Regulation, National Energy and Climate Plans (NECP) for 2021-2030 outlined expected ESS deployment across EU27 countries. Collectively, these plans indicated that around 42.5 percent of new non-PHS capacity by 2030 would consist mainly of BESS, with smaller contributions from CAES and TESS[354]. NECP reflected broad ambition, with Germany, Italy, Spain, and Greece each setting multi-gigawatt ESS goals, although these targets were indicative rather than binding at EU level.

To support deployment, many countries introduced auctions and dedicated support schemes. Italy enabled ESS participation through its capacity market and fast frequency reserve auctions. Greece launched one of the EU's first large-scale stand-alone BESS tenders, awarding substantial grants and long-term contracts in 2023. Spain, Portugal, and Ireland integrated ESS into RE tenders or system service programmes, while Germany relied more on market signals and co-location with solar. At EU level, state aid rules were adapted to permit NECP, with the EU approving several large programmes in 2022 and formally recognising ESS as essential for grid reliability[355].

8.4.3 Research and Innovation Funding

The EU, through Horizon 2020 and Horizon Europe, has invested heavily in storage R&D. The Battery 2030+ initiative and the European Battery Alliance, launched in 2017, aimed mainly to build BESS manufacturing capacity and support deployment cost reductions[356]. The Innovation Fund, launched in 2020 and funded by ETS carbon allowance revenues, provided grants to selected large ESS related projects; for example, innovative molten salt storage in Denmark and a CAES project in Germany were finalists. The Recovery and Resilience Facility after Covid also earmarked funds for ESS in some national recovery plans, including Greece's BESS tender and Italy's hydrogen storage pilot. In addition, IEA and EU collaboration supported knowledge sharing, including an EU Strategic Energy Technology Plan action on ESS[357].

354 European Commission, "Renewable Energy Targets", Energy, Climate change, Environment.
355 European Parliamentary Research Service, EU Electricity grids, European Parliament, Brussels, Belgium, 2025.
356 European Commission, "European Battery Alliance," Business, Economy, Euro
357 European Commission, "Recovery and Resilience Facility for Clean Energy," Energy, Climate change, Environment.

8.4.4 Integration in Electricity Markets

By 2025, ESS, particularly BESS, had become a significant participant in several European ancillary service markets. Services provided by BESS in Europe are mentioned below:

- **Frequency regulation:** After 2017, most Continental European TSOs opened primary frequency response markets to ESS. In Germany, Benelux, and Switzerland, BESS provided up to 40 percent of FCR by 2020, contributing to a price reduction of around 30 percent. Similar developments occurred in Great Britain[358].
- **Balancing and reserves:** Several countries introduced fast reserve products or adapted secondary reserve rules to enable ESS participation. Finland and Estonia procured fast frequency reserve largely from new BESS projects by 2022[359].
- **Capacity mechanisms:** ESS was included in capacity markets in multiple EU countries. In addition to Italy and Great Britain, France allowed BESS to participate, although low clearing prices limited uptake until 2022. Poland's 2020 capacity auction saw 11 MW of BESS clear.
- **Day-ahead and intra-day trading:** The transition to 15-minute intra-day markets across the EU by 2021 improved arbitrage opportunities for ESS. During the high price volatility of 2022, BESS in countries such as Germany captured substantial revenues from intra-day trading linked to RE intermittency[360].
- **Cross-border and regional planning:** The EU increasingly considered ESS in a regional context. The Trans-European Networks for Energy policy was revised in 2022 to include ESS, enabling selected projects to qualify as Projects of Common Interest with access to streamlined permitting and funding[361].

8.4.5 Long-Duration ESS and Hydrogen Storage

The EU also began addressing longer-duration storage and sector coupling. The emphasis on Power-to-X pathways, including power-to-gas, reflects the use of hydrogen as a form of seasonal ESS. The EU Hydrogen Strategy adopted in 2020 promotes green hydrogen production from surplus RE energy, effectively treating hydrogen as chemical ESS[362]. Several member states, including Austria and Spain, supported PHS expansion, while EU funding instruments such as the Connecting Europe Facility co-financed selected PHS projects between 2018 and 2024, including in Portugal and the Czech Republic. According to the EU Hydropower Roadmap, PHS capacity is projected to increase to around 50 GW by 2030, up from approximately 33 GW in 2015, as part of broader system flexibility assessments rather than an explicit EU-wide target[363].

358 ENTSOE - Connecting Europe, Electrifying the Future, "Frequency Containment Reserves (FCR)," ENTSOE.
359 Fingrid, Fingrid Transmission System Operator's Magazine, no. 2, Fingrid, Helsinki, Finland, 2022.
360 European Commission, EU Electricity Trading in Day-Ahead Markets Becomes More Dynamic.
361 European Commission, Commission Collects Views on Preparation of the European Grids Package.
362 European Commission, "Hydrogen," Energy, Climate change, Environment.
363 European Commission, "Commission Presents the European Grids Package," Energy, Climate change, Environment

Photo by American Public Power Association on Unsplash



8.4.6 Regional Cooperation

EU initiatives such as the European Battery Alliance, aimed at building a domestic BESS value chain, indirectly support ESS by strengthening supply chains and reducing costs. Cross-border projects have also progressed through new interconnectors, for example Nordic flexibility where Norway's PHS effectively provides ESS for wind generation in Denmark and Germany[356].

Overall, by 2025 the EU approach has focused on establishing enabling framework conditions, with member states and markets driving deployment. Several countries are moving from pilot projects to large-scale ESS procurement, supported by EU rules on market access and funding. The outlook indicates the EU could reach on the order of at least around 50 GW of cumulative ESS by 2030, including existing PHS plants. The final mix will depend on market signals, technology maturity, and the pace at which support schemes such as those in Italy and Greece scale across the block[364].

The summary table comprising of ESS policy and market evolution from 2015 to 2025 is mentioned in Table 50[365].

Table 50 Energy storage policy and market evolution in EU from 2015 to 2025

Year	National initiative	Description
2015	Horizon 2020 ESS R&D and early national actions	Horizon 2020 funds early ESS R&D and demonstrations
		Germany expands PV-BESS subsidies via KfW program
		Denmark pilots TESS for CHP
		EU lacks explicit ESS regulation
2016	Commission draft legislation and innovation initiatives	Clean Energy Package drafts propose ESS definition and no double charging
		"Batteries Europe" initiative launched for BESS innovation
		National fast-frequency pilots (e.g. UK EFR) influence EU TSOs
2017	European Battery Alliance (EBA) and Strategic Energy Technology (SET)-Plan Action 7	EBA launched to build EU BESS value chain
		SET-Plan Action 7 coordinates ESS R&D targets
		Italy and Ireland integrate BESS in system services
2018	EU electricity market reform agreed	ESS friendly rules finalized (adopted 2019)
		Principles: no double network charges, fair market access
		Horizon 2020 funds island and TESS demos
		First commercial grid scale BESS deployed
2019	Clean Energy Package enters force	Electricity Directive/Regulation formally adopted
		TSOs/DSOs plan compliance with ownership restrictions
		NECPs indicate 45 GW ESS by 2030
		Ancillary market reforms benefit fast ESS

364 International Renewable Energy Agency, Tripling Renewable Power and Doubling Energy Efficiency by 2030, IRENA, Abu Dhabi, United Arab Emirates, 2023.

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Year	National initiative	Description
2020	Member state transposition and recovery measures	National laws updated to define ESS and remove double billing
		Recovery and Resilience Facility open funding for ESS
		Energy System Integration Strategy highlights ESS role
		Island and high-RE grids deploy BESS
2021	Implementation and first EU-funded auctions	Grid codes clarify ESS as generation for connection
		Transmission fee exemptions enacted
		Large ESS projects supported via Recovery Plans
		High power prices validate arbitrage value of ESS
2022	Energy crisis response and storage recommendations	REPowerEU stresses ESS for gas displacement
		Italy and Greece launch BESS capacity auctions
		Cap-and-contract models tested for flexibility
		Political momentum for faster ESS deployment
2023	Commission storage guidance and market design reform	European Commission (EC) issues formal Energy Storage Recommendation
		Proposes tariff reform, faster permitting, revenue certainty
		NECP drafts raise national ESS targets
		ENTSO-E scenarios include high ESS deployment in future
2023	Life cycle standards on battery	Producers are responsible for entire BESS life cycle, including safe collection and recycling
		Mandatory recovery of critical materials like lithium, cobalt, and nickel
		Battery passport enables lifecycle tracking, transparency, and supports reuse/recycling
2024	NECP updates and EU flexibility package	Member States revise NECPs with higher ESS ambitions
		EU considers flexibility targets or procurement mandates
		Dedicated national ESS auctions expand (e.g. Italy)
		Cross-border capacity participation begins
2025	Consolidation and outlook	EC reviews ESS progress and need for EU-wide targets
		EU ESS capacity roughly doubles vs 2022
		Focus shifts to seasonal and LDES
		Harmonized regulatory framework largely established

8.5 Australia

Australia has emerged as a leader in deploying ESS, particularly BESS, driven by rapid RE growth and the need for grid stability across a vast and sparsely populated network. Over 2015–2025, federal and state governments, together with market bodies such as Australian Energy Market Operator (AEMO) and Australian Energy Market Commission (AEMC), implemented policies and mechanisms to support ESS. These ranged from early project funding to major market rule changes, including faster dispatch and new participant categories, to integrate storage into the National Electricity Market (NEM). By 2025, Australia had introduced ambitious state-level storage targets, provided substantial public funding for large BESS and PHS, and updated regulations to recognise ESS as an essential power system asset[366].

8.5.1 Early Projects and State Leadership

The catalyst for modern BESS in Australia was the 2016 state-wide blackout in South Australia, which triggered an urgent focus on grid stability[367]. In 2017, the South Australian government partnered with Tesla and Neoen to deliver the Hornsdale Power Reserve, a 100 MW/129 MWh lithium-ion BESS that was the world's largest at the time[368]. Supported by state funding and an ARENA grant for later expansion, the project demonstrated the effectiveness of large BESS in providing fast frequency response and reserves, reportedly saving around A$40 million in grid services in its first year. Its success established proof of concept for large-scale BESS and accelerated wider deployment.

South Australia positioned ESS as central to its net 100 percent RE by 2030 target[369]. It implemented the Home BESS Scheme between 2018 and 2022, allocating AU$100 million in subsidies of up to AU$6,000 per system, resulting in more than 15,000 residential BESS and substantial aggregated capacity. The state also advanced Virtual Power Plant (VPP) trials, notably with Tesla, demonstrating coordinated operation of thousands of home BESS[370]. New South Wales, through its 2020 Electricity Infrastructure Roadmap, set a target of 2 GW of LDES by 2030 alongside major RE build-out. It introduced the Emerging Energy Program to support novel ESS projects and, by 2022, committed funding to the 700 MW/1400 MWh Waratah Super BESS. Scheduled to be operational by 2025, this project is designed as a state-funded reliability asset to support Sydney and Newcastle load centres following the retirement of the Eraring coal plant. Queensland's 2022 Energy Plan announced around 7 GW of new PHS by 2035, including the 5 GW Scenic Rim project, and at least 3 GW of BESS. The state has also deployed grid-scale BESS such as the 100 MW/150 MWh Wandoan system and piloted community BESS. Outside the NEM, Western Australia and the Northern Territory pursued ESS mainly for remote and off-grid reliability, including community PowerBanks in WA and a 35 MW BESS commissioned in 2023 on the Darwin–Katherine system.

8.5.2 Federal Policies and Market Reforms

At the federal level, Australia did not initially set a unified ESS target, but the Australian Renewable Energy Agency (ARENA) and the Clean Energy Finance Corporation provided critical financial support. ARENA, established in 2012, funded early ESS demonstrations. It co-funded the Hornsdale

366 Australian Energy Market Commission, Integrating Energy Storage Systems into the National Electricity Market.
367 Australian Energy Market Operator, Integrated Final Report: South Australian Black System, 28 September 2016, AEMO, Melbourne, VIC, Australia, 2017.
368 Neoen, Australia: The World's Largest Battery Storage System.
369 Clean Energy Investor Group, South Australia: The Denmark Down Under, Clean Energy Investor Group, Nov. 2025.
370 Australian Government, Department of Climate Change, Energy, the Environment and Water, Cheaper Home Batteries Program.

BESS expansion in 2019 to test GFM PCS functionality and supported projects such as the 25 MW Gannawarra BESS and the 30 MW Ballarat BESS in 2018 to demonstrate wholesale market participation. In December 2022, ARENA announced A$176 million for eight grid-scale BESS totalling 2 GW/4.2 GWh with advanced PCS, leveraging public funding to unlock A$2.7 billion of investment. This programme aimed to enable BESS to provide inertia and system strength services traditionally supplied by thermal plants[371].

On the regulatory side, the Australian Energy Market Commission and AEMO introduced major reforms. Five-Minute Settlement, implemented in October 2021, reduced dispatch and settlement intervals from 30 minutes to 5 minutes, improving opportunities for fast-responding resources such as BESS. Australia's Frequency Control Ancillary Services market, with eight products, enabled BESS to capture significant shares of regulation services by 2020 despite their limited capacity. In December 2021, the AEMC approved the Integrating ESS into the NEM rule, creating the Integrated Resource Provider category to simplify registration of ESS and hybrid units and remove double charging[372]. Regulators also addressed inertia and system strength. From 2020, AEMO identified minimum inertia requirements in regions such as South Australia, and by 2023 enabled BESS with GFM capability to receive payments for specific network services. The 2022 System Strength Mitigation Requirement further encouraged deployment of advanced converters, which several new large BESS projects are now implementing. To strengthen the BESS manufacturing capabilities and enable commercialization, Battery Breakthrough Initiative was launched by ARENA in 2025. The focus area of this initiative applies to ECES including FBESS[373].

8.5.3 Targets and Strategies

The federal government's targets are net zero by 2050 and 82 percent RE by 2030 for the NEM, which implies a substantial need for ESS. In 2023, the federal government introduced the Capacity Investment Scheme to underwrite new firming capacity, including ESS, to maintain reliability as coal retires. The scheme operates in a Contracts-for-Difference style for RE and ESS investment. Initial auctions are planned in New South Wales and Victoria for 2024, aiming to contract hundreds of MW of LDES, typically 8 to 12 hours, through floor prices for capacity and revenue support[372].

AEMO's Integrated System Plan, updated in 2022 and 2024, projected a requirement of around 45 GW and 620 GWh of ESS by 2050 under the optimal development pathway, including large volumes of utility BESS and PHS[372]. These projections have guided government planning and prioritisation of ESS. This context also includes major PHS developments such as the 2,000 MW Snowy 2.0 project led by Snowy Hydro, although it has experienced delays.

371 Australian Renewable Energy Agency, ARENA Backs Eight Grid-Scale Batteries Worth $2.7 Billion.
372 International Energy Agency, Australia 2023 Energy Policy Review, IEA, Paris, France, 2023.
373 Australian Renewable Energy Agency, Battery Breakthrough Initiative – Focus Areas 2025, Aug. 2025.



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The summary table comprising of energy storage policy and market evolution from 2015 to 2025 is mentioned in Table 51[374].

Table 51 Energy storage policy and market evolution in Australia from 2015 to 2025

Year	National initiative	Description
2015	ARENA storage R&D and early trials	ARENA funds network BESS pilots and CSIRO research
		Early off-grid mining BESS reduce diesel dependence
		Market discussions begin on flexible resource participation
2016	South Australia blackout – catalyst for ESS deployment	Statewide blackout drives focus on reliability solutions
		South Australia government initiates plan for grid-scale BESS
		AEMO explores fast frequency response procurement
		Home BESS uptake accelerates with high RTS PV penetration
2017	Hornsdale power reserve and rule reforms	100 MW Hornsdale BESS commissioned, proving fast response
		FCAS costs in South Australia drop sharply due to BESS participation
		Demand response pilots test non-generator flexibility
		Five-Minute Settlement rule finalized (effective 2021)
2018	Big BESS, VPPs, home schemes	ARENA/Clean Energy Finance Corporation co-fund multiple 30 MW-class BESS
		Virtual Power Plant trials launched in South Australia
		SA Home BESS Scheme offers household grants
		BESS validated as critical frequency stabilizers
2019	Regulatory integration and PHS	New converter standards mandate smart BESS behaviour
		Snowy 2.0 and Queensland PHS plans advance
		Wholesale Demand Response reform progresses
		First BESS with islanding capability commissioned
2020	NSW roadmap and GFM trials	New South Wales sets 2 GW firming target under infrastructure roadmap
		Five-Minute Settlement implementation prepared
		ARENA funds GFM converter upgrades
		ESS highlighted in federal technology roadmap
2021	Five-Minute settlement and storage rules	Five-Minute Settlement boosts BESS market advantage
		Integrated resource provider category created
		Victorian Big BESS (300 MW) commissioned
		AEMO contracts BESS for virtual inertia

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Year	National initiative	Description
2022	**ARENA scale-up and capacity investment scheme**	ARENA funds 2 GW advanced BESS with GFM converters
		Capacity Investment Scheme launched for firming resources
		System strength procurement enables BESS contracts
		NEM power crisis highlights ESS reliability value
2023	**Legislated targets and mega BESS**	Victoria legislates binding ESS targets (2030/2035)
		700 MW Waratah Super BESS progresses
		Fast Frequency Response market introduced
		Large PHS projects advanced for long-duration needs
2024	**CIS auctions and market redesign**	First CIS ESS auctions expected to award contracts
		Market redesign supports 100% RE operation
		ESS embedded in system planning and reliability models
2025	**Battery breakthrough initiative by ARENA**	Program supports projects that advance BESS manufacturing and enable commercialization
2025	**Main streaming** ESS **and expansion**	Utility-scale ESS exceeds 3 GW, distributed >5 GW
		ESS treated as critical grid infrastructure
		Bipartisan support solidifies long-term deployment
		BESS routinely provide inertia, Frequency Control Ancillary Services, and reserves



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09

CHAPTER 9

ECONOMIC ASPECTS OF ENERGY STORAGE SYSTEMS



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Summary

- Establishes an integrated techno economic framework for ESS by linking capital cost, operating cost, degradation, financing, market access, system value, and project level feasibility.
- Explains the ESS valuation framework through service identification, technology mapping, system level value assessment, operational simulation, revenue stacking, and financial viability assessment.
- Discusses LCOS as a useful cost benchmarking metric, while highlighting its limitations in capturing revenue streams, system benefits, value stacking, external costs, and market specific profitability.
- Reviews ESS revenue generation across energy, capacity, ancillary, transmission, distribution, and behind the meter services, showing that bankability increasingly depends on multi service value stacking.





U.S. Department of Energy from United States, Public domain, via Wikimedia Commons

9.1 Economics of Energy Storage Systems

The economics of ESS cannot be assessed using a single upfront cost metric, as ESS does not operate as a conventional generation asset that converts fuel into electricity. Its value depends on charge and discharge timing, the range of services provided, cycling frequency, degradation characteristics, and the applicable market and regulatory framework. Accordingly, the cost and pricing of ESS are best evaluated through an integrated techno-economic framework that incorporates capital cost, operating cost, operational value, degradation, financing, and market access.

At a fundamental level, the cost of an ESS reflects the expenditure required to procure, install, connect, operate, maintain, and eventually replace or decommission the entire system. The pricing or revenue aspects reflects the compensation that an ESS asset can earn through multiple use cases, including energy arbitrage, peak shaving, RE firming, capacity adequacy, ancillary services, transmission and distribution deferral, resilience, BTM bill management, and many more. Viability is therefore determined not only by cost minimisation, but by the ability of the ESS asset to capture a sufficient and durable value stacking over its technical and economic life. This is particularly important as ESS is increasingly evaluated as a multi service flexibility resource rather than only a single purpose asset. Therefore, it is also emphasised that ESS should be assessed based on its use case, system location, and modelling approach, and that different analytical tools are required depending on whether the asset operates as a price taker or is large enough to influence system dispatch and prices[375]. A structured examination of ESS economics is therefore presented through an assessment of valuation frameworks, LCOS, and key techno-economic factors governing cost and pricing.

9.1.1 Valuation Framework for Energy Storage Systems

A comprehensive valuation framework for ESS should explicitly distinguish between cost metrics, benefit metrics, and decision metrics, while capturing the multi service and time dependent nature of value derived from ESS. Unlike conventional assets, valuation of ESS is inherently sequential, and model driven, requiring a structured workflow that links system level planning with feasibility of the project. This detailed structured approach is illustrated in Figure 138[376], which outlines a five phase methodology progressing from service identification to project viability assessment. As described below, each phase builds on outputs from the previous stage, ensuring that technical suitability and economic performance are consistently evaluated.

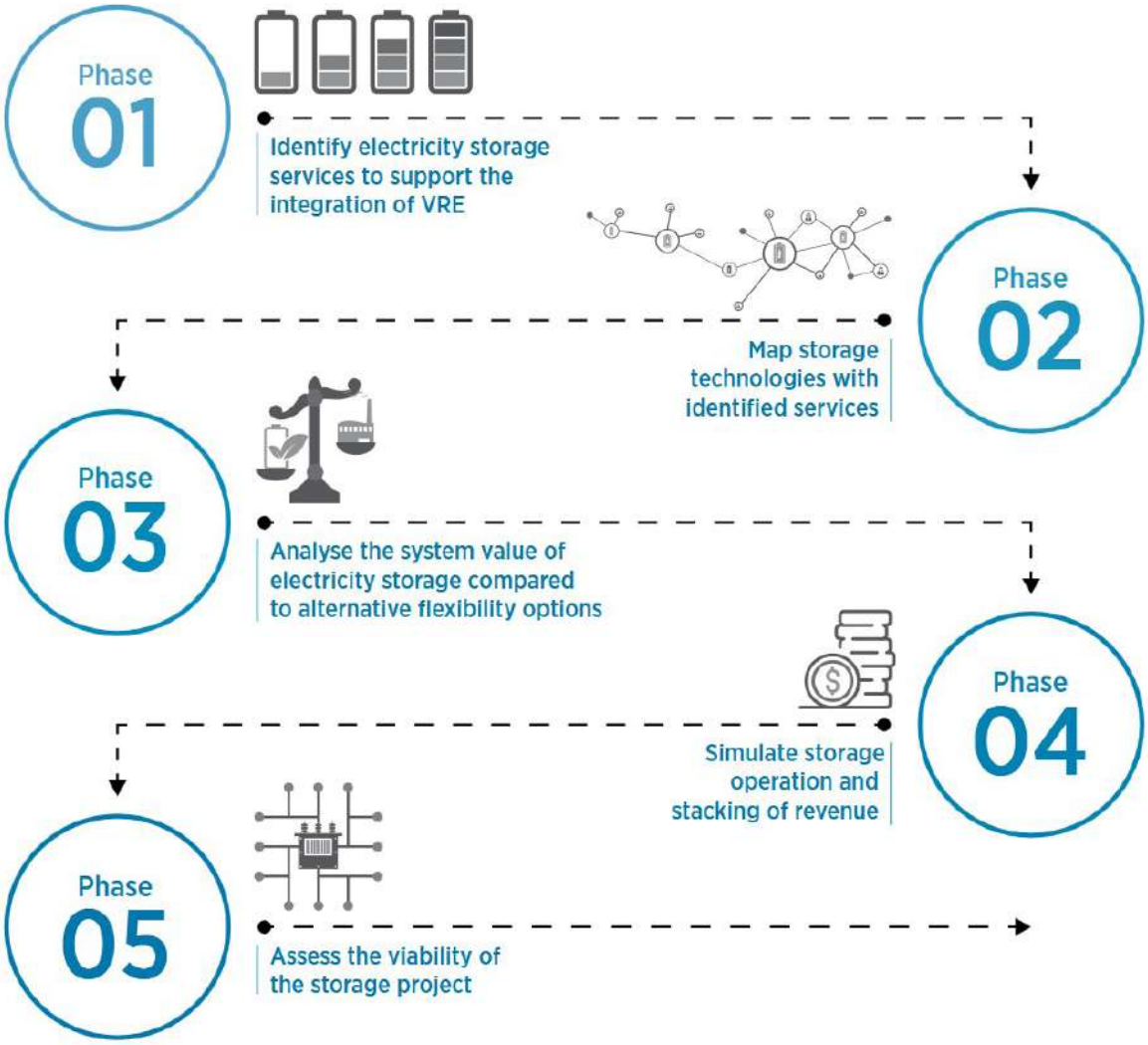
Phase 1: Identification of ESS services

The first phase defines the specific services that ESS can provide to support fundamental power system requirements, particularly the integration of variable RE. These services include energy arbitrage, frequency regulation, reserve provision, peak shaving, and network support. At this stage, detailed modelling is not required as the focus is on establishing the functional role of storage within the system.

375 V. Siberry, D. Wu, D. Wang, and X. Ma, Energy Storage Valuation: A Review of Use Cases and Modeling Tools, Tech. Rep. DOE/OE-0029, U.S. Department of Energy, Jun. 2022.

376 IRENA et al., "Electricity Storage Valuation Framework: Assessing system value and ensuring project viability," 2020.

Figure 138 ESS valuation framework



Source: IRENA

Phase 2: Technology mapping and suitability assessment

Once services are identified, ESS technologies are mapped against these services based on their technical characteristics. This step incorporates key techno-economic parameters, as summarised in Table 52[376]. This phase ensures that only technically viable and context appropriate ESS technologies are considered for further analysis.

Table 52 Techo-economic parameters for ESS suitability assessment

Parameter	Range
Technical	Efficiency (AC-to-AC) (%)
	Minimum and Maximum C rate
	Maximum DOD (%)
	Maximum operating temperature
	Safety (thermal stability)

Parameter	Range
Economic	ESS CAPEX (USD/kWh)
	Power Converter CAPEX (USD/kWh)
	Development and construction lead time
	Operating cost (USD/kWh)
	Energy density (Wh/kg)
	Power density (kWh/kg)

Phase 3: System level value assessment

In this phase, the system wide value of ESS is evaluated relative to alternative flexibility options such as flexible generation, demand response, or network expansion. This stage typically employs capacity expansion models coupled with production cost models. These models quantify the impact of ESS on system operation, including reductions in generation costs, curtailment, and ancillary service requirements. The output of this phase includes system level benefits such as avoided costs and improved operational efficiency.

Phase 4: Operational simulation and value stacking

The fourth phase focuses on detailed operational modelling of ESS assets using dispatch optimisation tools. A price taker storage dispatch model is typically used to simulate charge discharge behaviour at high temporal resolution, such as hourly or sub hourly intervals. This enables quantification of stacked revenues across multiple services. The outputs of this phase include detailed operational profiles, revenue streams, and performance metrics such as SoC cycling and utilisation rates.

Phase 5: Project level feasibility assessment

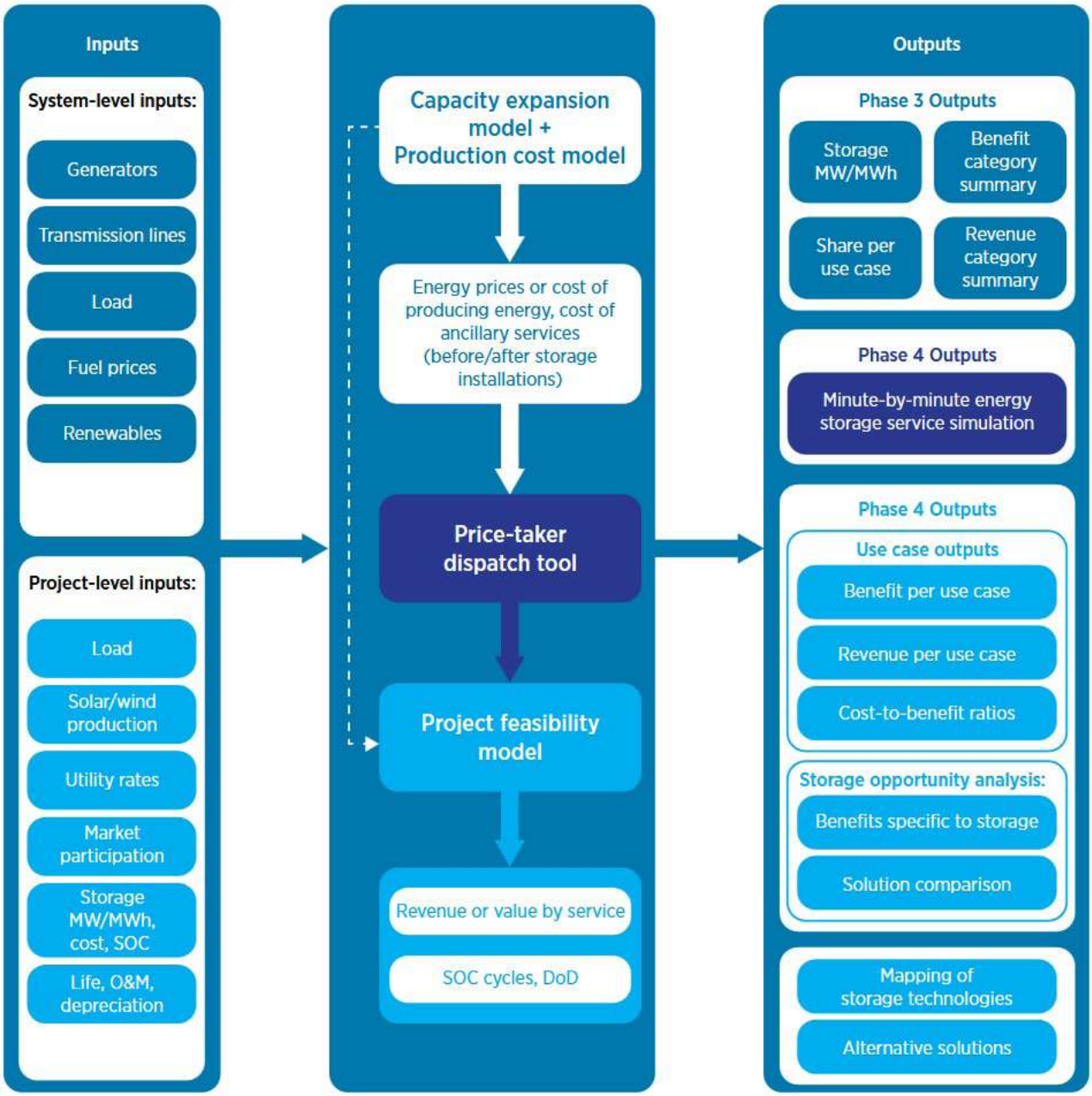
The final phase evaluates the financial viability of ESS projects using project level models. This involves a project feasibility model that integrates costs and monetizable revenues to assess investment performance using metrics such as net present value, internal rate of return, and payback period. This phase also identifies gaps between system value and investor returns that may require regulatory or market interventions.

9.1.1.1 Information Flow and Model Integration

The interaction between the modelling stages is further detailed in Figure 139[375]. The framework integrates system level inputs, such as generation mix, transmission constraints, demand profiles, fuel prices, and RE penetration, with project level inputs, including load profiles, RE characteristics, tariff structures, capital costs, and operational parameters.

These inputs feed into a sequential modelling chain that links system level planning with project level evaluation. Capacity expansion and production cost models are first used to determine optimal system configurations and quantify system wide benefits of ESS. The outputs from this stage inform a price taker dispatch model, which simulates operational strategies and captures revenue stacking across multiple services. These operational results are then integrated into a project feasibility model to assess financial viability and investment attractiveness.

Figure 139 Information flow between modelling based phases



Source: IRENA

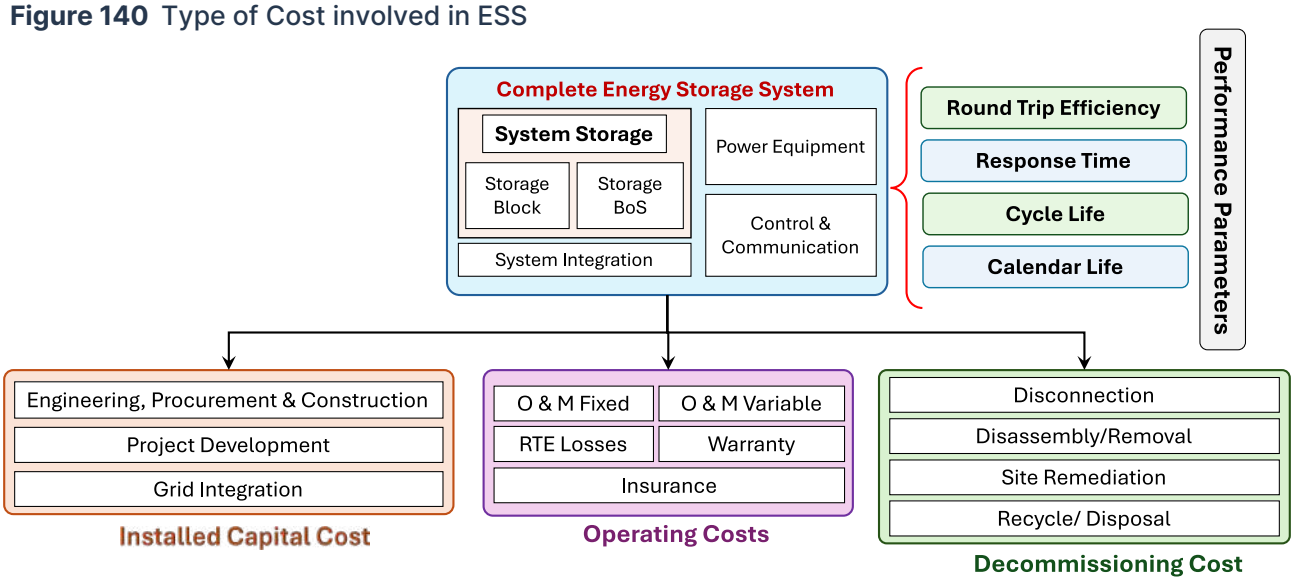
Across these stages, key outputs include ESS value metrics such as avoided system costs and benefit categories, detailed revenue breakdowns by service and use case, cost benefit ratios, and comparative assessments against alternative solutions. This integrated modelling framework ensures consistency between system level insights and project level economics, thereby reducing the risk of misaligned or suboptimal investment decisions.

Overall, the ESS valuation framework provides a multi layered, model driven methodology that links technical performance, system value, and financial viability. By progressing from service identification to detailed feasibility analysis, and integrating techno-economic parameters with system level modelling, the framework ensures that ESS investments are evaluated in a manner consistent with their operational complexity and multi service capability.

9.2 Generalised Cost and Performance Parameters for Energy Storage Systems

A comprehensive understanding of ESS economics requires integrating system architecture with lifecycle cost components. As illustrated in Figure 140, an ESS comprises ESS blocks, Balance of System (BoS), PCS, and control and communication systems, all contributing to overall cost formation. Technical performance parameters such as RTE, response time, cycle life, and calendar life are closely linked to economic outcomes, as they determine usable energy throughput, operational reliability, and asset lifetime, thereby influencing metrics such as LCOS and project returns.

Figure 140 Type of Cost involved in ESS



Installed Capital Cost (CAPEX) represents the most significant upfront investment and includes Engineering, Procurement and Construction (EPC), project development, and grid integration. These costs depend on system configuration, technology selection, and site specific conditions such as interconnection requirements and land availability. Operating Expenditure (OPEX) includes fixed and variable components such as routine O&M, efficiency related energy losses, warranty coverage, and insurance. RTE losses directly affect net delivered energy and revenue potential, while degradation related factors such as cycle life and calendar life influence maintenance requirements, augmentation, and long term replacement costs.

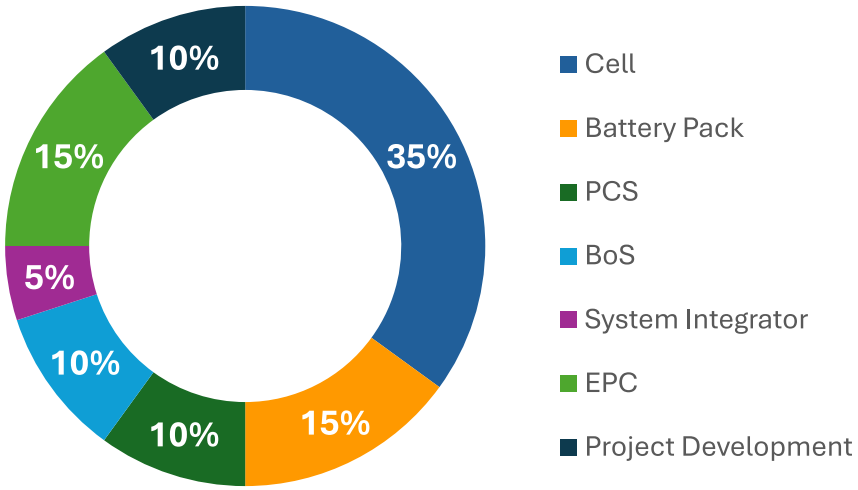
In addition to CAPEX and OPEX, decommissioning costs are an important component of lifecycle economic assessment. These include system disconnection, dismantling, site remediation, and recycling or disposal of components, gaining importance with increasing regulatory focus on sustainability and end of life management. These cost layers are interdependent with system performance characteristics, highlighting the need for a holistic evaluation framework that captures upfront investment, operational efficiency, degradation behaviour, and end of life liabilities to assess the financial viability of ESS.

The cost distribution for a typical lithium ion BESS highlights the dominance of core system components within total project expenditure. As indicated in Figure 141[377], battery packs constitute the largest share, around 35 percent, followed by PCS at approximately 15 percent and balance

377 O. Schmidt and I. Staffell, Monetizing Energy Storage - A Toolkit to Assess Future Cost and Value. Oxford University Press, 2023.

of system components, including structural, thermal, and electrical infrastructure. Additional contributions arise from engineering and integration, control and communication systems, and other auxiliary components, each accounting for smaller but significant portions of total cost.

Figure 141 Cost components of lithium ion BESS



Source: O. Schmidt et al.; 2023

This breakdown shows that while battery cell costs remain the primary driver, non-cell components collectively represent a substantial share and play a critical role in overall system performance and reliability. These proportions are technology specific and vary depending on ESS technology, system configuration, duration, and application, particularly for non-lithium ion systems where balance of plant or mechanical components may contribute a higher share of cost.

9.3 Levelised Cost of Storage by Technology

LCOS is a unit cost metric, typically expressed in $/kWh or $/MWh discharged, that estimates the average revenue an ESS must earn per unit of delivered energy to recover its lifetime costs. These costs include CAPEX recovery, fixed O&M, component replacements, financing, and charging energy costs, adjusted for efficiency losses. LCOS is most useful for technology screening when the use case and underlying assumptions are clearly defined. However, it is not a value metric and does not capture system benefits such as reliability, capacity adequacy, or ancillary service value, which must be assessed separately. LCOS can be also formalised as a cost-per-unit energy metric to compare technologies with different calendar life, cycle life, DoD limits, O&M, and replacement schedules, and notes that these attributes determine total lifetime cost[378].

9.3.1 LCOS Formulation

A common LCOS formulation uses a discounted cash-flow approach converted into an equivalent unit cost. LCOS can be also defined as a break-even sale price per unit of discharged energy, based on a fixed charge rate framework and explicitly including electricity charging costs adjusted for RTE. LCOS is determined by the below mentioned formula[379]:

378 V. Viswanathan, K. Mongird, R. Franks, X. Li, V. Sprenkle, and R. Baxter, 2022 Grid Energy Storage Technology Cost and Performance Assessment, Pacific Northwest National Laboratory, Richland, USA, Tech. Rep. PNNL-33283, Aug. 2022.

379 L. Friedel, J. Grenz, and C. Hagist, "A comparison of long duration energy storage technologies based on levelized cost of storage," J. Energy Storage, vol. 153, no. 120679, p. 120679, 2026.

$$LCOS = \frac{CAPEX_{PV} + \sum_{t=0}^{T} \frac{OPEX \times (1+\pi)^t}{(1+WACC)^t} + \sum_{t=0}^{T} \frac{\frac{E_{out,t}}{RTE} \times ccost}{(1+WACC)^t} + \sum_{t=0}^{T} \frac{\frac{E_{out,t}}{RTE} \times GridF \times \left(1+esc_{gridf,t}\right)^t}{(1+WACC)^t}}{\sum_{t=0}^{T} \frac{E_{out,t}}{(1+WACC)^t}}$$

where,

$CAPEX_{PV}$: Capital expenditures ($)

OPEX: Operational expenditures per year ($)

π: Inflation index (%)

$E_{(out,t)}$: Electricity discharged per year (MWh)

RTE: Round-trip efficiency (%)

ccost: Electricity charging cost ($/MWh)

GridF: Grid fees ($/MWh)

$esc_{(gridf,t)}$: Grid fees escalation factor (%)

WACC: Weighted average cost of capital (%)

T: Repayment period, starting at COD, with t = 0, 1, 2, …, T (years)

There are several reasons for increase in LCOS. Some of the reasons are mentioned below:

- Capital expenditures rise, including PCS, balance-of-plant, civil works, permitting, interconnection, and owner's costs
- Financing costs increase, due to higher discount rates, lower debt fractions, or more conservative debt terms
- Utilisation decreases, reflected in fewer cycles per year or fewer discharged hours per year, which is particularly critical for long-duration assets with low duty cycles
- RTE declines, as more charging energy is required per delivered kWh and losses reduce marketable output
- Augmentation or replacement needs increase, especially for lithium ion BESS where capacity fade can necessitate periodic augmentation to maintain contracted discharge capability

9.3.2 LCOS Evaluation Criteria and Reporting Framework

LCOS formulations are often compared based on how accurately they represent real project economics and how consistently they can be applied across different storage technologies. Key considerations include whether all relevant life-cycle costs are captured, whether assumptions are transparent and based on accessible inputs, and whether the methodology accounts for financing structure, taxes, inflation, and differences in asset lifetime. The main criteria, associated metrics, and their rationale are summarised in Table 53[380].

380 W. Hill Balliet, P. Balducci, V. Durvasulu, and T. Mosier, "Determining the profitability of energy storage over its life cycle using levelized cost of storage," Energy Econ., vol. 142, no. 108174, p. 108174, 2025.

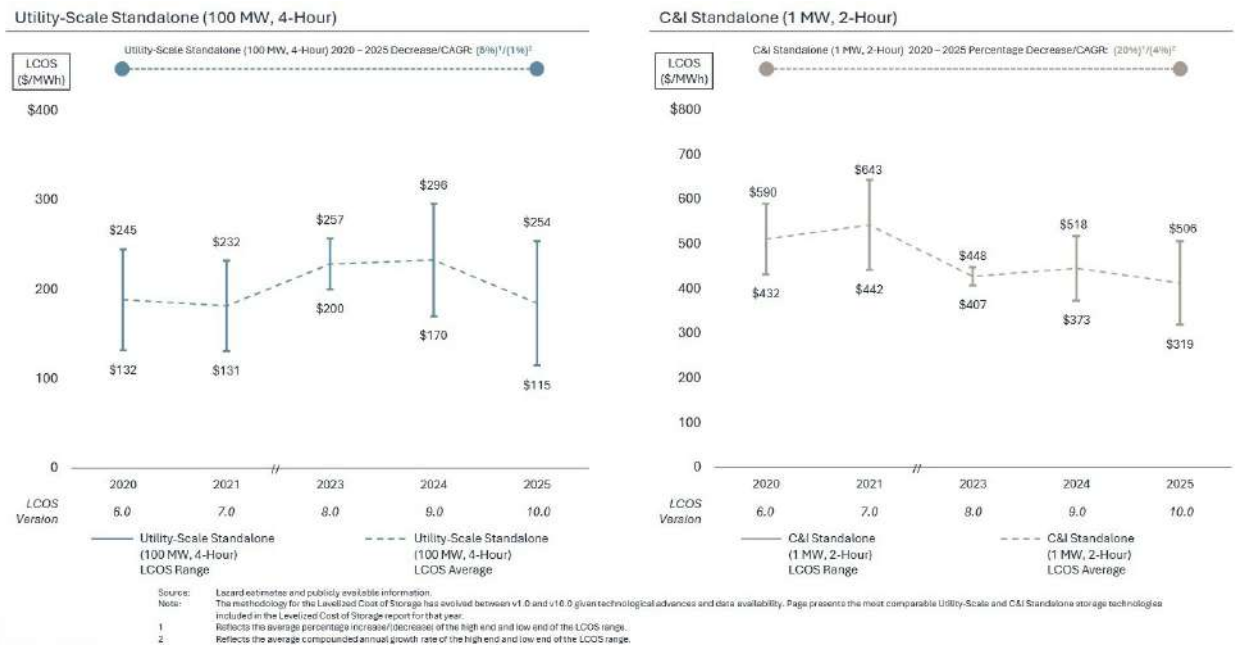
Table 53 LCOS criteria, metrics, and rationale

No.	Recommended LCOS design criterion	Key Metrics / Requirements	Rationale / Purpose
1	**Cost added to electricity by storing it in ESS**	Units should be in $/kWh discharged; includes design, construction, and operational costs; excludes charging electricity cost but includes round-trip efficiency losses	Ensures LCOS remains analogous to LCOE and provides a clear, intuitive, and usable cost metric
2	**Use of readily available data**	Publicly available CAPEX, OPEX, and performance data sources	Improves transparency, reproducibility, and practical usability
3	**Simple and understandable formulation**	Fewer variables, simpler equations, and reduced computational complexity	Enhances accessibility and adoption across organisations
4	**Inclusion of time value of money and inflation**	Discounting of future costs and benefits; inflation-adjusted future prices	Reflects standard financial practice and avoids unrealistic assumptions
5	**Inclusion of tax impacts**	Taxes treated as operational costs	Prevents underestimation of actual project costs
6	**Inclusion of financing costs**	Debt payments and financing structure incorporated into lifecycle costs	Captures the effect of capital structure and debt servicing
7	**Consideration of incentives such as ITC**	Incentive mechanisms treated as user-defined inputs	Reflects project- and region-specific policy conditions
8	**Applicability to all bidirectional ESS technologies**	Residual asset value, refurbishment schedules, and replacement assumptions	Enables fair comparison across technologies with different lifetimes
9	**Unambiguous inputs**	Clear definition of normalisation basis and cost boundaries	Reduces inconsistent interpretation and improves comparability
10	**Inclusion of full project lifecycle**	Pre-construction, end-of-life, disposal, and residual value considerations	Prevents underestimation of lifecycle costs
11	**Amortisation over the longest practical project lifetime**	Subsystem augmentation and replacement schedules	Better reflects real project operation
12	**Easy application across ESS technologies**	Closed-form equations compatible with spreadsheets and code-based tools	Improves usability and integration into modelling workflows

9.3.3 Historical Trends in Levelised Cost of BESS

Historical LCOS estimates for utility-scale and Commercial and Industrial (C&I) standalone BESS are examined to illustrate cost evolution from 2020 to 2025. Figure 142[381] show both LCOS ranges and average values for consistent system configurations, capturing the effects of technological advancement and market conditions. Declining costs over time reflect improvements in storage energy density, system integration, and recent supply–demand dynamics in BESS manufacturing.

Figure 142 Comparison of levelised cost for utility-scale and C&I standalone BESS



Source: Lazard

The plots show a sustained decline in LCOS for both utility-scale and C&I standalone BESS between 2020 and 2025, with the average LCOS trending downward despite year-to-year variability in the cost range . Utility-scale systems exhibit lower absolute LCOS values and a narrower spread compared to C&I systems, reflecting stronger economies of scale. The widening and subsequent narrowing of the LCOS ranges over time highlights the combined effects of market volatility and ongoing technology maturation.

9.3.4 Limitations of LCOS

While the LCOS is widely used as a benchmarking metric for comparing different ESS technologies, it has important limitations when applied to real world investment decisions and system level planning. These limitations arise primarily from its cost centric formulation, simplifying assumptions, and lack of standardisation.

- **Lack of value representation:** LCOS reflects only the cost per unit of discharged energy and does not account for revenue streams or value stacking. ESS generate value through multiple services such as energy arbitrage, capacity provision, and ancillary services, including frequency regulation and voltage support, which are not captured in LCOS. For arbitrage applications, profitability depends on price spreads rather than absolute costs, making LCOS insufficient to represent true economic value.

381 Lazard, LCOE (Levelized Cost of Energy), Jun. 2025.

☀ KEY INSIGHT

LCOS can benchmark ESS cost, but it underestimates ESS value because it excludes revenue stacking, grid benefits, reliability contribution, and market-specific operation.

- **Sensitivity to operational assumptions:** LCOS is highly sensitive to assumptions such as cycle frequency, DoD, and degradation rates. Systems with higher assumed utilisation, such as daily cycling, exhibit lower LCOS compared to those used intermittently. Variations in degradation and operational profiles can significantly affect lifecycle costs, limiting the reliability of LCOS under real world conditions.
- **Exclusion of system level and external costs:** LCOS is typically evaluated at the asset level and excludes broader system impacts. It does not account for grid integration costs such as transmission and distribution upgrades, or system benefits such as avoided capacity and reduced curtailment. Environmental and safety requirements are also generally omitted, resulting in an incomplete economic assessment.
- **Methodological inconsistency:** There is no standardised approach for LCOS calculation, leading to variability across studies. Differences in the treatment of charging costs, discount rates, project lifetime, and financing assumptions can significantly alter results. This lack of consistency reduces comparability and may lead to misleading conclusions.

LCOS is a useful benchmarking indicator but should not be used in isolation. A comprehensive evaluation requires combining LCOS with value based and system level assessment frameworks.

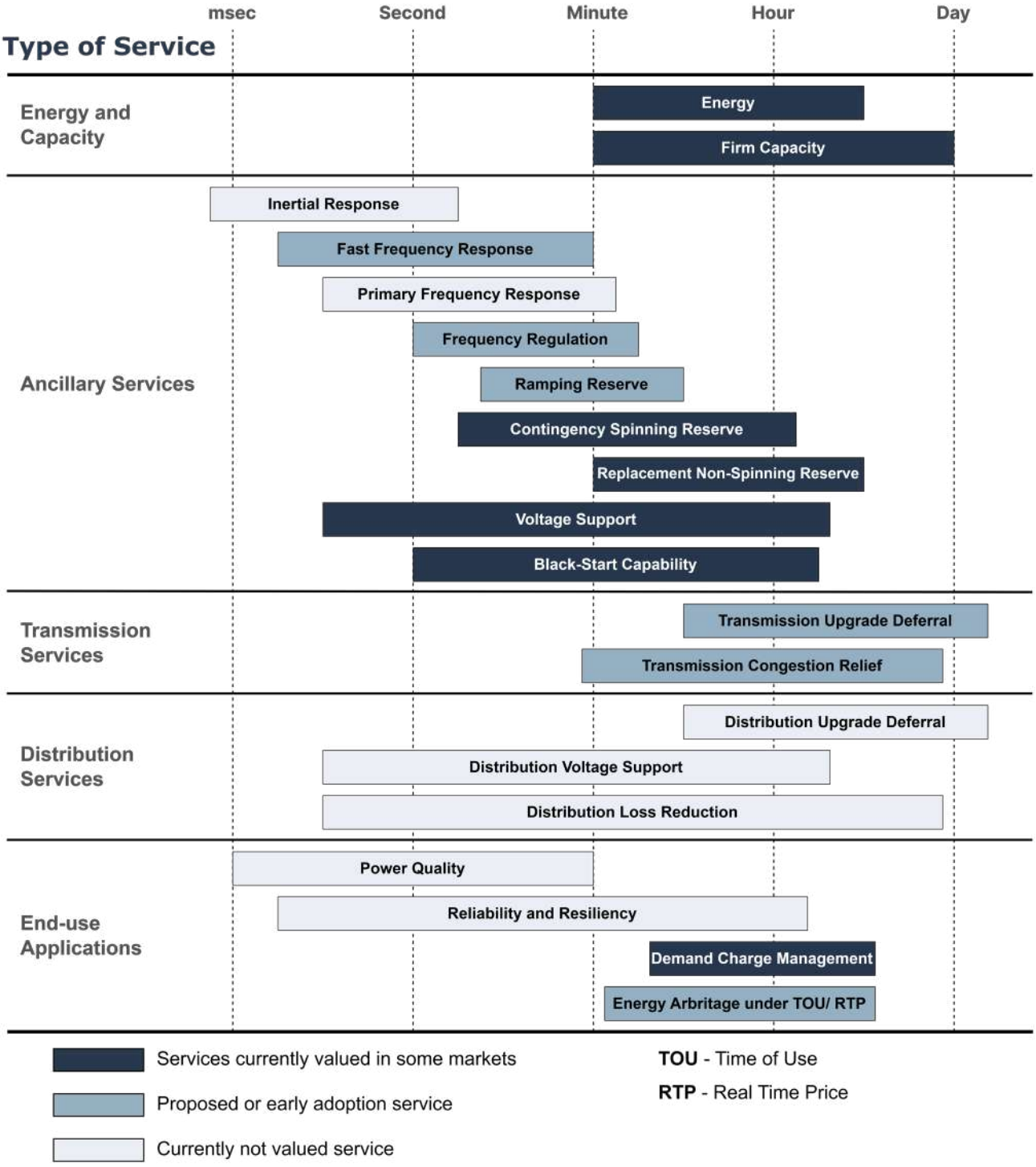
9.4 Potential Revenue Streams from Energy Storage Systems

ESS offer a wide range of services and generate revenue across multiple segments of the energy market. Figure 143 provides an overview of these services, highlighting their variation by response time, service category, and market maturity. It distinguishes between services that are already monetised, those in early stages of adoption, and those that remain largely unvalued. These services span multiple time scales, from milliseconds to days, and include energy and capacity provision, ancillary services such as inertial response, fast frequency response, frequency regulation, ramping reserves, and contingency reserves, as well as transmission and distribution support. ESS also supports end use applications such as demand charge management, reliability and resiliency, power quality, and energy arbitrage[382].

The fast response services, including inertial response, fast frequency response, voltage support, and power quality, operate over millisecond to minute time scales and are generally suited to high power storage technologies. In contrast, energy arbitrage, firm capacity, transmission deferral, congestion relief, and distribution upgrade deferral require longer discharge durations and stronger alignment with market or planning mechanisms. This indicates that revenue generation from ESS is highly application specific and depends on matching technology capability with service duration, response speed, and monetisation pathway.

382 Clean Energy Ministerial, Battery Storage Unlocked: Lessons Learned from Emerging Economies, Nov. 2024.

Figure 143 Time-scale classification and market maturity of potential revenue generation streams from ESS





AI Image

10

CHAPTER 10

SUSTAINABILITY, RECYCLING, AND CIRCULAR ECONOMY



AI Image

Summary

- Presents sustainability assessment of ESS through full lifecycle impacts, including raw material extraction, manufacturing, operation, second life use, recycling, and end of life management.
- Compares lifecycle characteristics of major storage technologies, including Li-ion batteries, VRFB, sodium-ion batteries, supercapacitors, and pumped hydro, with emphasis on dominant impact stages and lifetime utilisation.
- Discusses second life battery pathways for retired EV batteries, covering SOH based screening, repurposing, safety, BMS requirements, application suitability, and final retirement thresholds.
- Highlights recycling, circular economy models, and critical mineral risks as key factors shaping sustainable and secure global ESS deployment.




Brandgefa
ple der Lithium-Batterien mit
dem Klebeband abkleben.

Pexels

The sustainability of ESS must be assessed over the full life cycle, from raw material extraction and manufacturing to operation and end-of-life management. As ESS becomes central to RE-dominated power systems, sustainability increasingly influences technology choice, procurement, regulation, and system planning. Unlike conventional generation, ESS relies on material-intensive components and global supply chains, making environmental and social impacts sensitive to mineral sourcing, energy-intensive processing, and waste management. Different ESS technologies exhibit distinct sustainability profiles. ECES are material and manufacturing intensive but provide high flexibility and modularity. PHS involves significant upfront civil impacts but offers very long asset lifetimes and low marginal environmental impact during operation. Electrical ESS technologies such as SESS have low material toxicity and long cycle life but limited energy capacity, which constrains their range of applications.

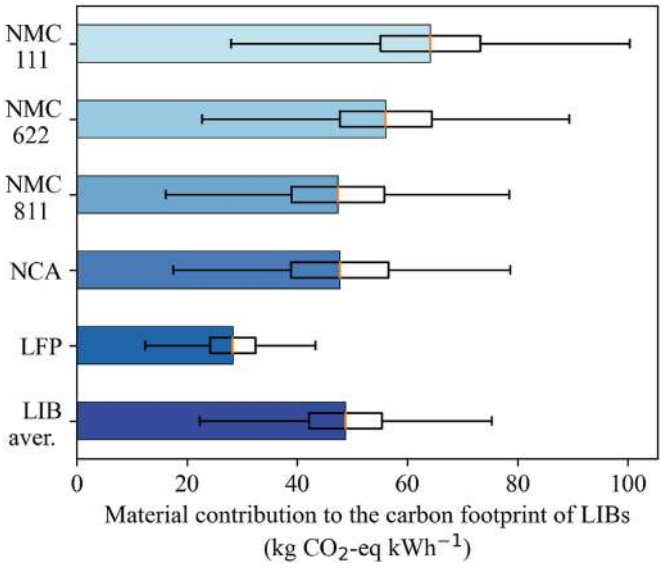
10.1 Life Cycle Assessment of ESS

Life Cycle Assessment (LCA) is the primary method used to quantify environmental impacts of ESS in a consistent and transparent way. Standardised under ISO 14040 and ISO 14044, LCA requires clear definition of the functional unit, system boundaries, data sources, and impact categories[257]. For ESS, most commonly used functional units include kilograms of CO_2 equivalent per kWh of installed ESS capacity, per kWh delivered over the asset lifetime, or per MW-year of firm capacity provided.

10.1.1 Technology Specific LCA Characteristics

Lithium-ion BESS typically exhibit manufacturing-dominated life-cycle impacts, driven by energy-intensive cathode production, electrolyte synthesis, and cell assembly. A cradle-to-gate emissions of approximately 60 to 100 kg CO_2 eq per kWh of capacity, depending on chemistry, factory energy mix, and production scale as shown in Figure 144[383]. When amortised over lifetime energy throughput, emissions per delivered kWh decline substantially for high-cycle applications such as frequency regulation or daily cycling.

Figure 144 Carbon footprint of lithium ion BESS



Source: E. Kallitsis et al.; 2024

383 E. Kallitsis, J. J. Lindsay, M. Chordia, B. Wu, G. J. Offer, and J. S. Edge, "Think global act local: The dependency of global lithium-ion battery emissions on production location and material sources," J. Clean. Prod., vol. 449, no. 141725, p. 141725, 2024.

VRFB show a distinct life-cycle profile. The vanadium electrolyte accounts for a large share of material mass and embodied emissions, but it does not significantly degrade and can be reused across multiple system lifetimes. As a result, over multi-decade operation, VRFBs can achieve competitive life-cycle emissions per delivered kWh, particularly in long-duration applications[384].

Sodium ion BESS share many manufacturing processes with lithium ion systems but rely on more abundant raw materials. Although current sodium ion cells exhibit lower energy density and higher material intensity per kWh, emerging assessments indicate that life-cycle emissions could become comparable to, or lower than, those of lithium ion BESS as manufacturing matures and scales[385].

SESS offer extremely high cycle life, often exceeding one million cycles, which reduces per-cycle environmental impact. However, their low energy density results in high embodied emissions per unit of stored energy, limiting sustainability advantages to applications requiring very frequent cycling[386].

PHS has construction-dominated life-cycle impacts, primarily from concrete, steel, and excavation. With operational lifetimes of 50 to 80 years or longer, it achieves among the lowest life-cycle emissions per delivered kWh of all storage technologies when assessed on a system basis[386,387].

LCA characteristics of major ESS technologies are summarised in Table 54[388].

Table 54 Life cycle characteristics of major ESS

Storage technology	Dominant LCA stage	Typical lifetime	Key LCA sensitivity
Lithium ion BESS	Cell manufacturing	10–15 years	Electricity mix, cathode chemistry
VRFB	Electrolyte production	20–30 years	Vanadium sourcing, reuse rate
Sodium ion BESS	Manufacturing	10–15 years	Process maturity, energy density
SESS	Electrode production	>20 years	Activated carbon source
PHS	Civil construction	>50 years	Site geology, land use

LCA of ESS shows that environmental impacts depend strongly on technology type, dominant lifecycle stage, and operational characteristics. Lithium ion and sodium ion BESS are largely manufacturing intensive, with emissions influenced by material sourcing, energy mix, and process maturity, while VRFB shift impacts towards electrolyte production but benefit from long lifetimes and reuse potential. In contrast, SESS and PHS exhibit lower per cycle or per kWh impacts due to long lifetimes, although construction and material constraints remain significant. Overall, lifetime utilisation, cycle frequency, and system longevity are key determinants of emissions per unit of

384 N. Blume, M. Becker, T. Turek, and C. Minke, “Life cycle assessment of an industrial-scale vanadium flow battery,” J. Ind. Ecol., vol. 26, no. 5, pp. 1796–1808, 2022.

385 W. Guo, T. Feng, W. Li, L. Hua, Z. Meng, and K. Li, “Comparative life cycle assessment of sodium-ion and lithium iron phosphate batteries in the context of carbon neutrality,” J. Energy Storage, vol. 72, no. 108589, p. 108589, 2023.

386 M. Cossutta, V. Vretenar, T. A. Centeno, P. Kotrusz, J. McKechnie, and S. J. Pickering, “A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application,” J. Clean. Prod., vol. 242, no. 118468, p. 118468, 2020.

387 Z. Guo, S. Ge, X. Yao, H. Li, and X. Li, “Life cycle sustainability assessment of pumped hydro energy storage,” Int. J. Energy Res., vol. 44, no. 1, pp. 192–204, 2020.

388 GIL Research

delivered energy. These findings highlight the importance of considering full lifecycle performance rather than only upfront impacts when evaluating ESS technologies.

10.2 Environmental Impacts

10.2.1 Climate Change and Air Emissions

Greenhouse gas emissions are the most commonly reported environmental metric for ESS. Lithium-ion BESS can deliver net system-level emission reductions by enabling higher RE penetration, reducing curtailment, and displacing fossil-based peaking generation. System-level modelling consistently shows that, under low-carbon charging conditions, avoided emissions exceed embedded emissions over the BESS lifetime[389]. VRFB and PHS further reduce curtailment and provide firm capacity, lowering reliance on fossil backup during prolonged RE shortfalls. These indirect system benefits often exceed direct life-cycle emissions and should be included in sustainability assessments[387].

10.2.2 Water Use and Ecosystem Impacts

Lithium extraction from brines involves high water consumption, particularly in arid regions, raising concerns about competition with agriculture and local communities. Hard-rock lithium mining lowers water intensity but introduces land disturbance and tailings management impacts[390]. Vanadium mining and processing can generate toxic byproducts if controls are inadequate, though recycling and electrolyte reuse can mitigate impacts[384]. PHS can affect local hydrology and ecosystems during construction, but operational impacts typically stabilise over time, with water losses mainly from evaporation[127].

10.2.3 Toxicity and Safety

Toxicity and safety are critical considerations in the deployment of ESS because different storage technologies involve varying levels of chemical, thermal, electrical, and environmental risk. ECES systems, particularly lithium ion BESS, are susceptible to thermal runaway caused by overcharging, internal short circuits, mechanical damage, or elevated temperatures, which can lead to fire, toxic gas release, and explosion hazards[391]. Certain battery chemistries also involve hazardous materials such as cobalt, nickel, lead, vanadium electrolytes, or corrosive compounds that require controlled handling, transportation, and disposal. Mechanical systems such as PHS and CAES generally present lower chemical toxicity but may involve high-pressure, geotechnical, or environmental risks. Similarly, hydrogen storage introduces flammability and leakage concerns due to its low ignition energy and high diffusivity. Consequently, ESS deployment increasingly depends on integrated safety frameworks involving BMS, thermal management, fire suppression, gas detection, fault isolation, ventilation, and compliance with standards such as UL 9540, UL 9540A, NFPA 855, and IEC 62933.

389 G. Harper et al., “Recycling lithium-ion batteries from electric vehicles,” Nature, vol. 575, no. 7781, pp. 75–86, 2019.

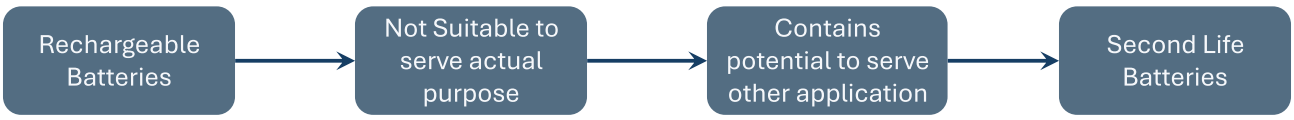
390 S. Bawankar et al., “Environmental impact assessment of lithium ion battery employing cradle to grave,” Sustain. Energy Technol. Assessments, vol. 60, no. 103530, p. 103530, 2023.

391 Y. Wang, T. Yu, J. Chen, B. Gao, M. Yu, and J. Zhu, “Advances in safety of lithium-ion batteries for energy storage: Hazard characteristics and active suppression techniques,” Energy Reviews, vol. 4, no. 1, p. 100117, 2025.

10.3 Second Life Battery

SLB storage refers to the repurposing of retired rechargeable batteries, mainly lithium-ion batteries from EVs, for stationary ESS applications once they no longer meet automotive performance requirements. Batteries are typically retired from vehicle use when state of health declines to around 70 to 80 percent of nominal capacity, driven by range, power, and safety constraints rather than complete functional failure. Despite retirement, these batteries retain significant residual electrochemical capability that can be used effectively in stationary applications with lower power density, slower dynamics, and less stringent volumetric constraints[392].

Figure 145 Conceptual transition of rechargeable batteries to SLBs



*Instead of being discarded or recycled immediately, batteries are given a **"second life"** in less demanding energy storage roles*

The transition of rechargeable batteries from primary use to SLB deployment is illustrated in Figure 145. Rather than immediate recycling or disposal, retired batteries are redirected to stationary ESS, extending functional life and deferring end-of-life processing. EVs are expected to be the main future source of retired lithium-ion batteries due to rapid global EV adoption. Although no longer suitable for traction use, these batteries remain viable for stationary ESS, where cycling requirements, thermal stresses, and safety margins can be managed more conservatively[392].

10.3.1 Motivation and Drivers for Second Life Battery

The motivation for SLB deployment arises from environmental, economic, and energy transition considerations. Environmentally, the growing volume of retired lithium-ion batteries creates a waste management challenge. Extending battery use through second life applications can reduce life-cycle greenhouse gas emissions by about 15 to 30 percent compared to immediate recycling, mainly by deferring energy-intensive material recovery and lowering demand for virgin mineral extraction[393]. This directly reduces upstream mining of lithium, cobalt, and nickel, which have significant environmental and social impacts.

From an economic perspective, new BESS manufacturing remains capital and energy intensive. Repurposed SLBs are typically reported to cost 30 to 70 percent less than new lithium-ion systems on a usable capacity basis, depending on screening, remaining life, and system integration requirements. This cost advantage supports more affordable ESS for applications such as residential backup, community ESS, and RE integration, particularly in cost-sensitive markets[393]. SLBs also contribute to energy transition goals by bridging the period between EV retirement and final recycling. This intermediate use improves resource efficiency and supports circular economy principles by extracting additional functional value from battery assets before material recovery.

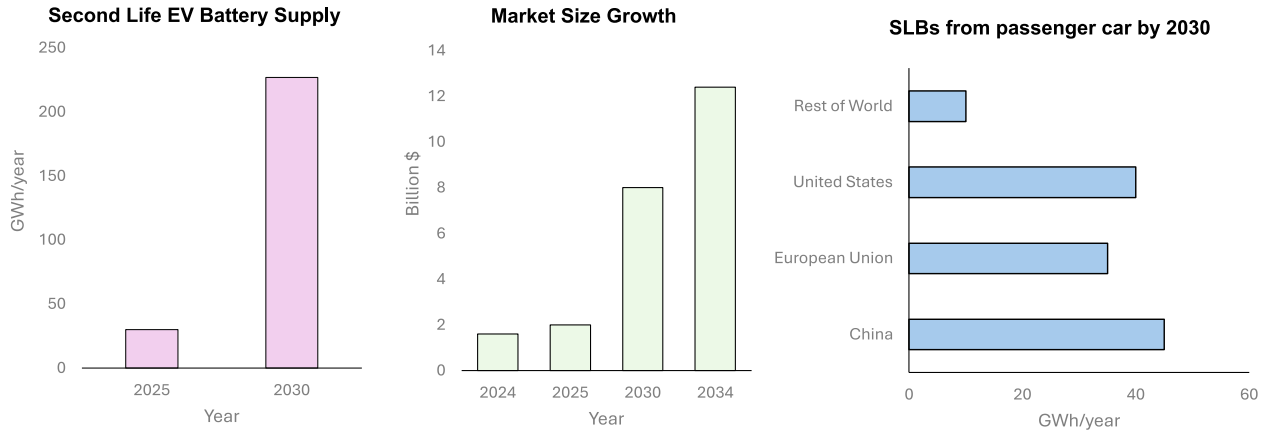
392 M. F. Roslan, P. R. Satpathy, T. Prasankumar, V. K. Ramachandaramurthy, M. Mansor, and S. L. Walker, "Second-life battery energy storage system for energy sustainability: Recent advancements, key takeaways and future perspectives," J. Energy Storage, vol. 123, no. 116808, p. 116808, 2025.

393 X. Hu et al., "A review of second-life lithium-ion batteries for stationary energy storage applications," Proc. IEEE Inst. Electr. Electron. Eng., vol. 110, no. 6, pp. 735–753, 2022.

10.3.2 Market Evolution

The global market for SLB storage remains at an early commercial stage but is expanding rapidly, as illustrated in Figure 146[394,395]. Projections show a sharp rise in available SLB supply, reaching several hundred gigawatt-hours per year by 2030 as early EV fleets retire. Market assessments indicate a compound annual growth rate above 26 percent into the early 2030s, driven by growing supply and rising demand for low-cost stationary ESS.

Figure 146 Market evolution trends of SLBs



Source: GIL Research *Data Source: McKinsy & Company*

10.3.3 Global Deployment

The global SLB deployment projects is summarised in Table 55[394]. These include grid-scale systems such as the BMW Energy Storage Farm in Germany, community and residential applications like Nissan xStorage Home in Europe, and hybrid RE-integrated projects such as the Johan Cruijff Arena installation in the Netherlands. Together, these examples demonstrate the technical feasibility of SLBs across diverse scales and applications, while also indicating that deployments remain largely at pilot and early commercial stages.

394 GIL Research

395 H. Engel, P. Hertzke, and G. Siccardo, "Second-life EV batteries: The newest value pool in energy storage," McKinsey & Company, Apr. 2019.



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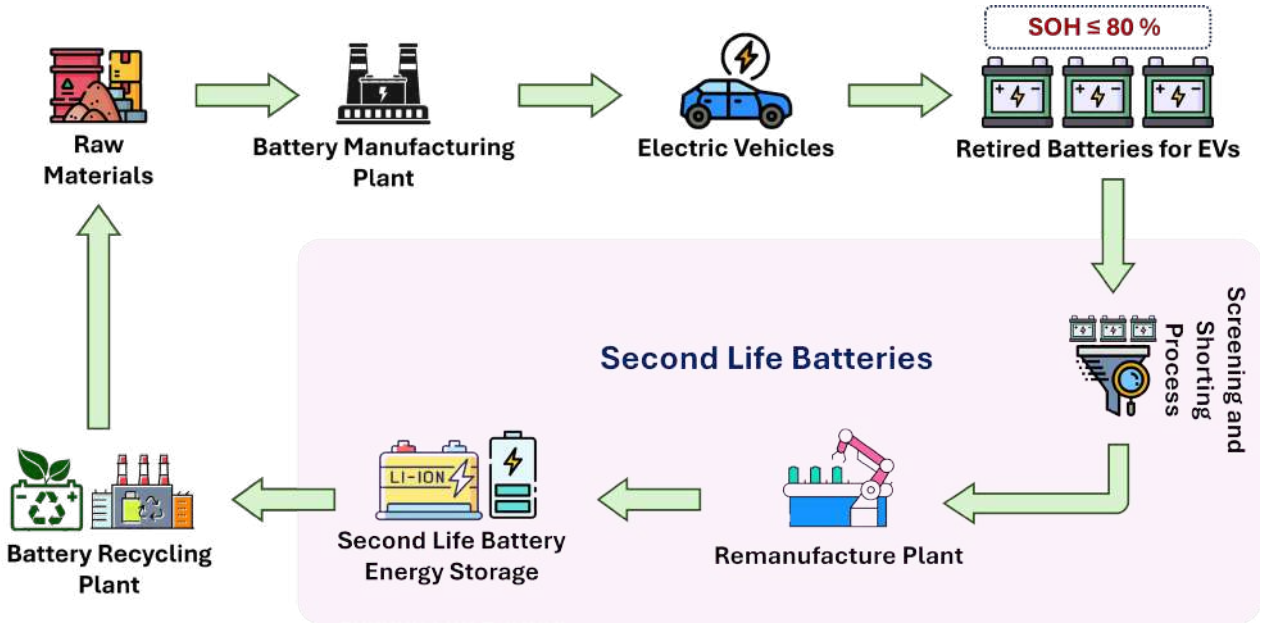
Table 55 Global deployment of SLBs

Project / Initiative	Location	Capacity	Battery source	Launch / Status	Notes
BMW Energy Storage Farm	Leipzig, Germany	10 MWh	BMW i3 batteries (700 modules)	2017	Stores surplus wind power, supports grid stability
BMW Group UK + Off Grid Energy	UK	40–180 kWh	BMW & MINI EV batteries	2020	Mobile power units for events replace diesel gensets
Nissan LEAF Johan Cruijff ArenA	Amsterdam, Netherlands	2.8–3 MW / 2.8 MWh	148 Nissan LEAF batteries	2018	Powers stadium & 7,000 households for approx. 1 hr
Nissan xStorage Home	Various locations (Europe)	4.2–10.08 kWh	Nissan LEAF batteries	2016	Residential PV integration & backup
Nissan +Enel	Melilla, Spain	1.7 kWh	Nissan LEAF batteries	2022	Power plant backup
Audi + RWE Energy Storage	Herdecke, Germany	4.5 MWh	Audi e-tron test car batteries	2022	Part of EUREF Campus stabilizes grid
PIONEER Airport Sustainability	Rome, Italy	2.5–10 MWh	Mixed OEM EV batteries	2022	Linked to 30 MW PV plant 1st multi-OEM SLB system
Toyota Yellowstone Project	Lamar Buffalo Ranch, USA	85 kWh	208 Toyota Camry hybrid NiMH packs	2015	Supports 40 kW PV system in off-grid setting
ABB + GM Demo	San Francisco, USA	25 kW / 25 kWh	Chevrolet Volt batteries	2013	Early prototype for SLB feasibility
BMW–Vattenfall–Bosch Project	Hamburg, Germany	2 MW/ 2800 kWh	100+ BMW EV batteries	2016	Grid support system
Daimler Stationary Projects (Mercedes-Benz Group)	Hannover (15 MWh), Lünen (13 MWh), Germany	EV bus batteries	Mercedes-Benz eCitaro City Bus	2021	Compensating for load peaks and providing uninterrupted power
Volkswagen Berlin Pilot	Berlin, Germany	10 kWh	VW EV batteries	2016	Small-scale test
Renault & Mitsubishi Pilots	UK, Paris	Various	Various EV batteries	Mid-2010s	Early pilots
University of California, Davis	Davis, USA	Winery Microgrid	Nissan LEAF packs	Ongoing	Academic microgrid project
UC San Diego & RIT Projects	USA	Various	Nissan / other EV packs	Ongoing	Academic SLB R&D

10.3.4 Battery Life Cycle with SLB Integration

The life cycle of the lithium-ion battery with second life use is shown in Figure 147. After initial deployment in EVs, such batteries having SoH in a range of 70 to 80 percent are directed to SLBs manufacturing following assessment and remanufacturing. Batteries with advanced degradation and unstable operation that no longer meet performance and safety criteria are sent directly to recycling[393]. IEEE Std 2993-2025 and GB/T 34015.3-2021 specify that repurposed cells must deliver at least 55% of their rated capacity when discharged at a C/5 rate at room temperature[396,397]. Retired EV batteries that meet these criteria are remanufactured for second-life applications, a process often referred to as Echelon utilization.

Figure 147 Life cycle of lithium ion battery for second life usage



10.3.5 Lithium ion Battery Chemistries for Second Life Usage

Not all lithium-ion chemistries are equally suitable for SLB applications. Table 56 summarises the suitability of common chemistries based on thermal stability, degradation behaviour, and residual capacity retention. LFP battery shows very high suitability due to long cycle life, strong thermal stability, and lower safety risk, making it well suited for stationary grid and residential use. NMC battery chemistries are also commonly deployed in SLB systems because of their widespread use in EV fleets. In contrast, NCA and LMO battery chemistries show more limited suitability for second life use due to greater sensitivity to thermal stress and ageing-related degradation. As a result, these chemistries require stricter screening, control, and operational constraints when deployed in second life systems[392].

396 "IEEE Recommended Practice for Energy Storage System Design using Second-Life Electric Vehicle Batteries," in IEEE Std 2993-2025, vol., no., pp.1-31, 6 June 2025.

397 "Recycling and Secondary Utilization of Vehicle Power Batteries - Part 3: Requirements for Secondary Utilization," GB/T 34015.3-2021, March 2022.

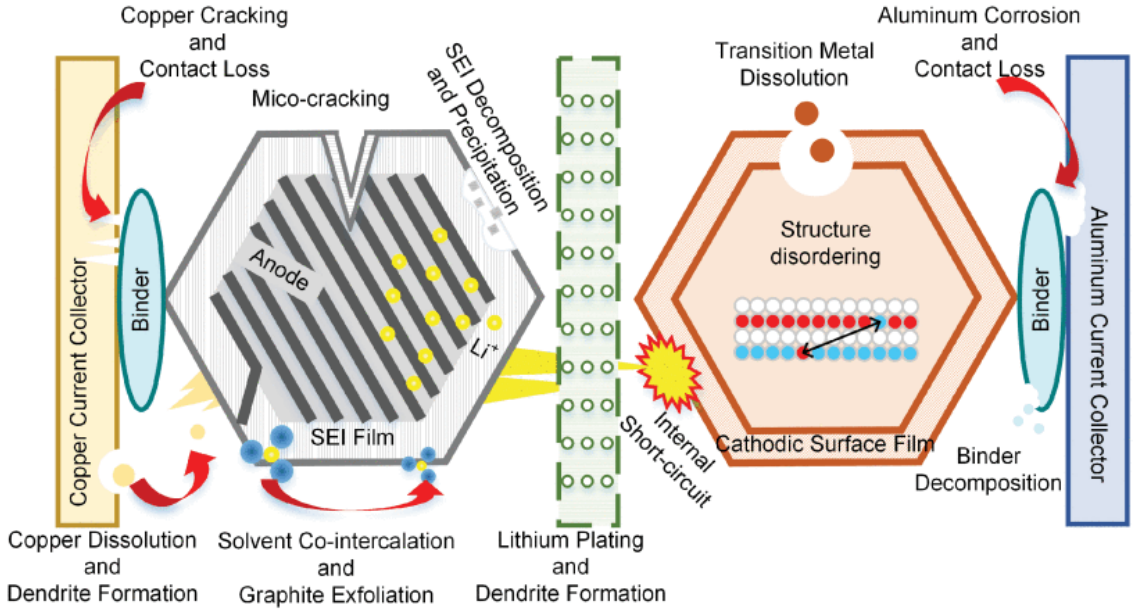
Table 56 Suitability of lithium ion batteries for SLB usage

Chemistry	Suitability for SLB	Reason	Applications
LFP	Very High	Long cycle life, high thermal stability, safe	Grid storage, RE firming, residential backup
NMC	High	Widely available from EVs, retains 70–80% capacity	Stationary storage, C&I systems
NCA	Moderate	High energy density but safety-sensitive	Low–medium demand stationary systems
LMO	Limited	Cheaper, good power, but shorter lifespan	Hybrid use (NMC–LMO blends), short-duration storage

10.3.6 Degradation Mechanism and Screen Criteria

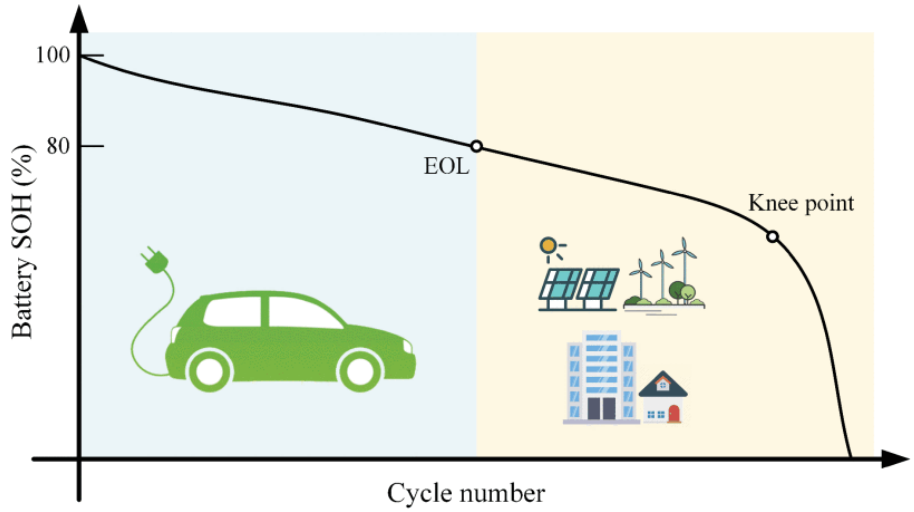
SLB performance and safety are governed by electrochemical and mechanical degradation accumulated during first life operation. As shown in Figure 148[393] key mechanisms include capacity fade from loss of cyclable lithium and active material, increased internal resistance due to electrode and electrolyte ageing, solid electrolyte interphase growth, lithium plating under high-rate or low-temperature conditions, and structural disordering of electrode materials. Together, these processes determine residual SoH and directly affect thermal stability and power capability in SLB applications. A critical concern is the nonlinear ageing knee as shown in Figure 149, where degradation accelerates sharply beyond a threshold, making accurate screening and Remaining Useful Life (RUL) estimation essential to prevent premature failure and safety risks in repurposed systems.

Figure 148 Key factors degrading lithium ion battery



Source: X. Hu et al.; 2022

Figure 149 Aging trajectory and knee point of lithium ion battery



Source: X. Hu et al.; 2022

Screening criteria for SLBs rely on a combination of electrical, thermal, and diagnostic indicators, including minimum SoH thresholds, limits on resistance growth, voltage imbalance, self-discharge behaviour, and abnormal thermal response under load. This multi-parameter approach ensures that only BESS with predictable ageing behaviour and adequate safety margins are repurposed for stationary use, reducing operational uncertainty, limiting maintenance needs, and improving overall system reliability. Some of the technical aspects associated with lithium ion battery aging are summarized in Table 57.

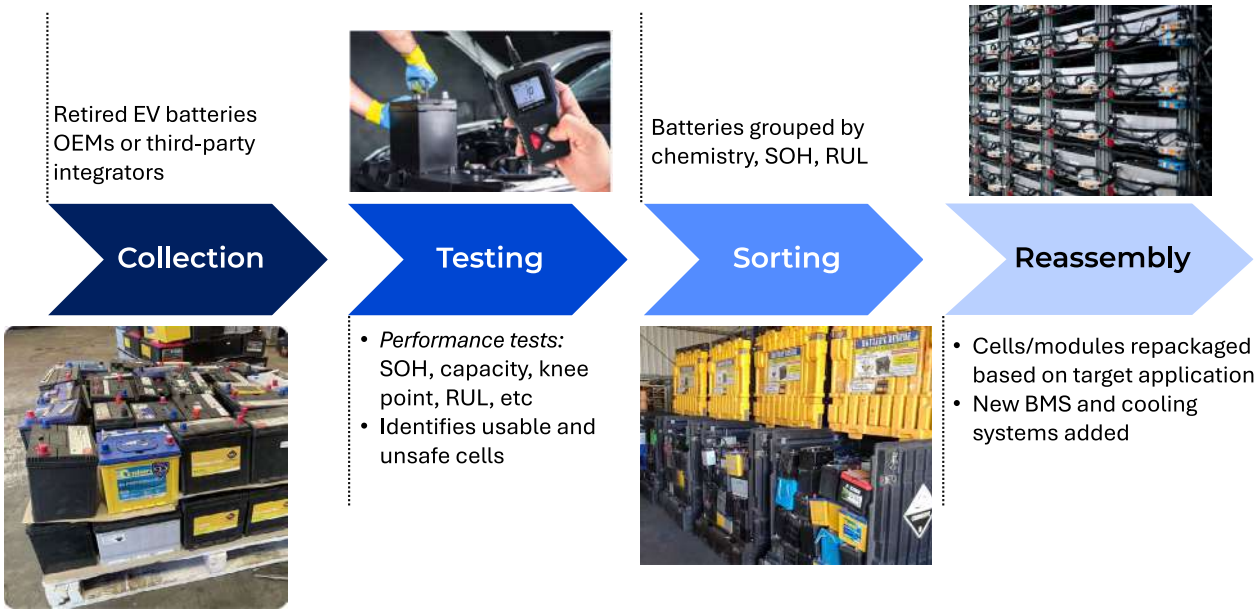
Table 57 Technical aspects for lithium ion battery aging

Technical aspect	Impact on SLB performance
SoH	Defines when EV batteries are retired (75–80%)
	Accurate estimation ensures only safe and reliable cells are repurposed
Resistance rise	Increases heat generation & lowers efficiency
	Affects power delivery and safety
Aging knee	Sudden transition from gradual to rapid degradation
	Accurate prediction avoids sudden failures and plan maintenance
Solid Electrolyte Interface (SEI) growth	Consumes lithium and raises internal resistance
	Impacts long-term performance stability
Lithium plating	Causes capacity loss and dendrite growth
	Critical for reliability of large SLB systems

10.3.7 Repurposing Process for SLBs

The repurposing workflow illustrated in Figure 150 consists of four main stages: collection, testing, sorting, and reassembly. Retired batteries are obtained from original equipment manufacturers or third-party aggregators and undergo diagnostic testing to evaluate capacity, resistance, and safety condition. Based on test results, batteries are classified by chemistry, SoH, and expected remaining life, and then reassembled into stationary storage systems using new battery management and thermal control architectures[398].

Figure 150 SLB repurposing process



This workflow is labour and time intensive and currently represents a key cost and scalability constraint for large-scale SLB deployment. Improvements in automated testing and data-driven screening are therefore essential to reduce repurposing costs and enable wider adoption.

10.3.8 Battery Management, Safety, and Operational Considerations

Effective battery management is critical for safe and reliable SLB operation. Table 58 summarises key BMS functions for SLBs, including SoC and SoH estimation, thermal management, cell balancing, and fault protection. Aged cells have higher internal resistance and greater thermal sensitivity, which requires conservative operating limits and robust monitoring to ensure safe performance[73].

398 J. P. Manaia, G. Pedreiro, J. P. Dias, J. Santos, A. Alves, and A. Pardal, "Sustainable repurposing of EV batteries: A methodology for certification in the EU," Future Batteries, vol. 7, no. 100101, p. 100101, 2025.



Table 58 Key BMS functions required for SLB

Function	Description	Impact on SLB
SOC estimation	Tracks remaining charge relative to full capacity	Prevents overcharge/discharge of aged cell
		Extends usable second life
SOH estimation	Measures degradation (capacity fade, resistance rise)	Ensures only healthy modules are reused
		Predicts remaining lifespan
Thermal management	Maintains safe operating temperatures via cooling/heating	Aged cells generate more heat
		Reduces risk of thermal runaway
Balancing	Equalizes charge across cells/ modules	Mitigates inconsistencies in retired cells
		Improves performance & safety
Fault detection & protection	Detects abnormal voltage, current, or temperature	Prevents catastrophic failure in SLB packs

Safety considerations specific to SLBs are summarised in Table 59. Key challenges include thermal runaway risk, electrical imbalance, mechanical integrity, and the evolution of applicable safety standards. Existing standards such as UL 1974 and IEC 62660 are being updated to address repurposed battery systems, although regulatory harmonisation across jurisdictions remains incomplete[391].

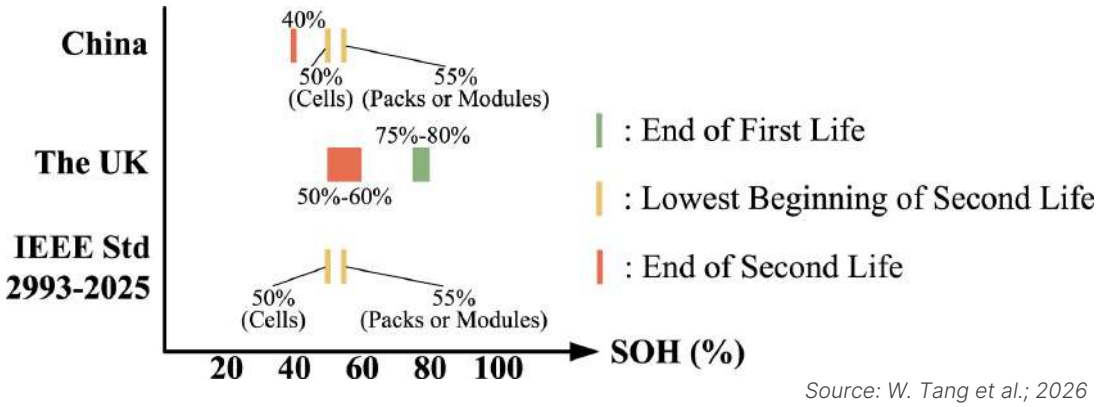
Table 59 Safety aspects for SLB

Aspect	Description	SLB implication
Thermal runaway risk	Uncontrolled heating can cause fire/explosion	Aged cells prone to overheating due to high resistance
	Triggered by lithium plating, dendrites, or short circuits	Strict monitoring & cooling needed
Electrical safety	Overcharge, deep discharge, or short-circuit events	Repurposed packs have inconsistent cells, raising voltage imbalance risk
		Requires robust BMS
Mechanical integrity	Physical damage, swelling, or leakage from aged cells	SLBs often dismantled & repacked
		Higher chance of damage during handling
Standards & regulations	SAE J2997, UL 1974, IEC 62660 evolving for repurposed batteries	Ensures uniform safety testing before SLB deployment
Fire protection & emergency response	Fire suppression systems, isolation switches, venting design	Essential for large-scale SLB systems (grid, community ESS)

10.3.9 Retirement of SLBs

The recommended retirement thresholds for SLBs are only formally proposed by IEEE Std 2993-2025, China and the UK as shown in Figure 151[399]. However, several studies consider the threshold SOH value between 40 to 60 percent as the end of second life operation. A SLB is generally considered to have reached its final end of life when it enters an accelerated degradation phase, characterised by a rapid decline in available capacity and increased safety risks. However, accurately identifying the onset of this degradation knee point remains challenging, creating uncertainty in predicting the transition. This limitation complicates the development of consistent and standardised criteria for defining the end of SLB use.

Figure 151 Thresholds of SOH for SLBs



Source: W. Tang et al.; 2026

10.3.10 Applications of SLBs

SLBs are deployed in stationary applications where energy-centric operation, moderate power requirements, and predictable cycling dominate performance needs. Application suitability depends mainly on residual SoH, degradation variability, thermal behaviour, and acceptable risk levels[393].

- **Grid-connected RE firming:** SLBs are used for distribution-level RE firming, smoothing short-term solar and wind variability. These energy-oriented applications allow SLBs with reduced capacity to provide ramp-rate control, intra-hour balancing, and limited time shifting. However, frequent cycling accelerates ageing, requiring conservative operating limits and effective thermal management.
- **Peak shaving and energy arbitrage:** SLBs can shift consumption from high- to low-tariff periods in residential, commercial, and light industrial settings. Economic viability is application-specific due to daily cycling stress and declining efficiency with ageing, making this use case more suitable for small to medium systems were lower capital cost offsets lifetime uncertainty.
- **Residential storage systems:** Residential systems, typically below 10 kWh and paired with RTS PV, use SLBs to increase self-consumption, provide limited backup, and improve energy autonomy. Low power demands and flexible schedules make this a suitable application when strict safety controls, conservative DoD, and certified enclosures are applied.
- **Light commercial and industrial applications:** Small commercial and industrial users deploy

399 W. Tang, Y. Huang, T. Qian, X. Xie, C. Wei, and J. Wu, "Unlocking the value of retired EV batteries: Technologies, application, and commercial models for second-life energy storage in power systems," Appl. Energy, vol. 404, no. 127151, p. 127151, 2026.

SLBs for demand charge reduction, backup power, and power quality support. Predictable load profiles and narrow operating ranges limit degradation, and higher system budgets allow improved battery management and thermal control compared to residential use.

- **Community microgrids and distributed backup power:** SLBs are well suited for community microgrids, campuses, and backup systems where resilience and energy availability are prioritised over high power. Their modularity and lower cost enable scalable deployment in remote or resource-constrained settings.
- **Transmission-level and high-power grid services:** Frequency regulation and fast reserves require high power density and rapid response. Due to increased resistance, ageing variability, and thermal limits, SLBs are generally unsuitable, with deployment largely confined to pilot-scale demonstrations.

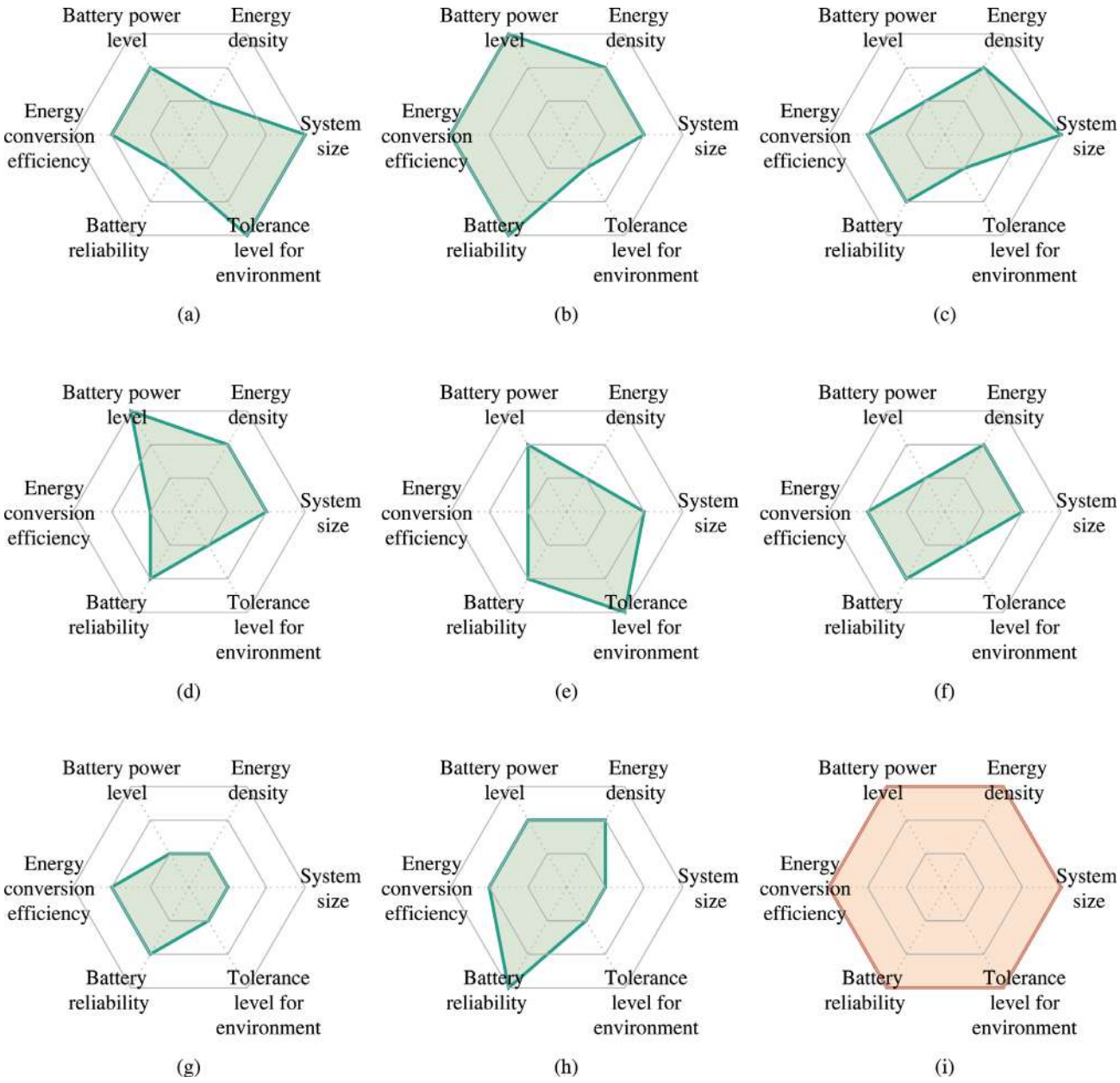
Table 60 summarises representative SLB use cases, highlighting application scale, suitability, ageing behaviour, thermal management needs, and market potential. The table consolidates observed deployment patterns and links them to the technical constraints of repurposed BESS.

Table 60 SLB use case in stable power system operation

Application	Size	SLB suitability	Ageing	Thermal management	Market potential
RE Firming	MWh	High	Frequent cycling → high stress	Essential	High (driven by RE integration & carbon neutrality)
Peak Shaving / Energy Arbitrage	kWh - MWh	Moderate	Daily cycling → high stress	Needed for long discharges	Growing, but debated at large-scale applications
Transmission Support	MWh	Low	Calendar aging dominates	Critical due to size	Small
Light Commercial / Industrial	kWh–MWh	High	Daily use → high concern	Less demanding (small size)	High
Residential	< 10 kWh	High	Daily cycling major concern	Less demanding, but safety critical	Strong (bill savings, PV + ESS)

A qualitative multi-dimension suitability evaluation of SLB for different power system applications is highlighted in Figure 152[399]. Each requirement is categorised as “High”, “Medium”, and “Low” evaluation points. The higher the requirement level of a given application, the greater the technical and economic challenges in the SLB application.

Figure 152 Suitability evaluation for SLB across power system applications. (a) Integration with RE, (b) Frequency regulation, (c) Peak shaving, (d) Backup power, (e) microgrid, (f) Commercial and industrial ESS, (g) ESS in Buildings, (h) EV Charging station, (i) EVs



Source: W. Tang et al.; 2026

10.3.11 Challenges and Future Prospects

Despite the environmental and economic potential of SLB storage, large-scale deployment faces technical, economic, and regulatory constraints. A key technical challenge is uncertainty in remaining useful life, as degradation histories vary widely with first-life usage, operating conditions, and thermal exposure. This heterogeneity complicates reliable SOH estimation and increases the risk of premature failure, requiring conservative operating margins and advanced diagnostics. In addition, the lack of standardised battery management system architectures for repurposed batteries limits interoperability and increases integration complexity, especially when aggregating batteries from different manufacturers and chemistries[392].

☼ KEY INSIGHT

SLBs can reduce cost and waste, but large-scale use depends on reliable SoH screening, safety certification, recycling pathways, and clear end-of-life accountability.

Economic barriers further constrain scalability where costs associated with collection, transport, testing, sorting, and repackaging can be significant and are sensitive to labour intensity and automation. In many cases, these costs reduce the apparent capital cost advantage of SLB systems, particularly for smaller projects. Uncertainty around performance warranties, liability, and insurance also reduces investor confidence and complicates bankability assessments[400].

Regulatory and institutional challenges remain important. Safety standards, certification pathways, and grid interconnection requirements for SLBs are still fragmented across jurisdictions. The absence of harmonised regulations creates uncertainty for manufacturers, integrators, and utilities, slowing commercialisation and limiting cross-border deployment. Unclear responsibilities at the end of second life, especially for recycling and producer responsibility, add further compliance risk[401].

Despite these challenges, future prospects remain positive. Advances in data-driven diagnostics, including artificial intelligence and machine learning for SoH and RUL prediction, are expected to improve screening accuracy and reliability. Digital battery passports and lifecycle tracking frameworks are emerging to enhance transparency and information exchange across value chains, supporting safer and more scalable second life deployment. These developments are expected to reduce uncertainty, improve economic viability, and support integration of SLBs into circular economy-oriented ESS.

10.4 Battery Recycling

Recycling is essential to reduce environmental impacts and material supply risks associated with ESS deployment, with maturity differing across technologies. Lithium-ion battery recycling is progressing rapidly, driven by regulation and the economic value of cobalt and nickel. Commercial processes mainly use hydrometallurgical routes, achieving high recovery of lithium, nickel, cobalt, and manganese, but requiring careful management of chemical waste streams[402]. VRFB have a distinct advantage, as the electrolyte remains chemically stable and can be recovered with near-complete efficiency. This enables leasing models in which vanadium remains an asset rather than a consumable, improving circularity[403]. Sodium-ion batteries offer fewer recycling incentives due to lower material value, although reliance on abundant materials reduces disposal risk. Supercapacitor recycling is limited for similar reasons, but associated environmental risks are relatively low[404]. Recycling pathways for major storage technologies are summarised in Table 61.

400 S. Prenner et al., “Barriers and framework conditions for the market entry of second-life lithium-ion batteries from electric vehicles,” Heliyon, vol. 10, no. 18, p. e37423, 2024.

401 Z. Alam and S. H. Gheewala, “Recharging the planet: The sustainability potential of second-life electric vehicle batteries,” J. Energy Storage, vol. 144, no. 119720, p. 119720, 2026.

402 Z. Dobó, T. Dinh, and T. Kulcsár, “A review on recycling of spent lithium-ion batteries,” Energy Rep., vol. 9, pp. 6362–6395, 2023.

403 Z. Yong et al., “Sustainable recycling and regeneration of redox flow battery components,” Future Batteries, no. 100044, p. 100044, 2025.

404 Y. Zhao et al., “Recycling of sodium-ion batteries,” Nat. Rev. Mater., vol. 8, no. 9, pp. 623–634, 2023.

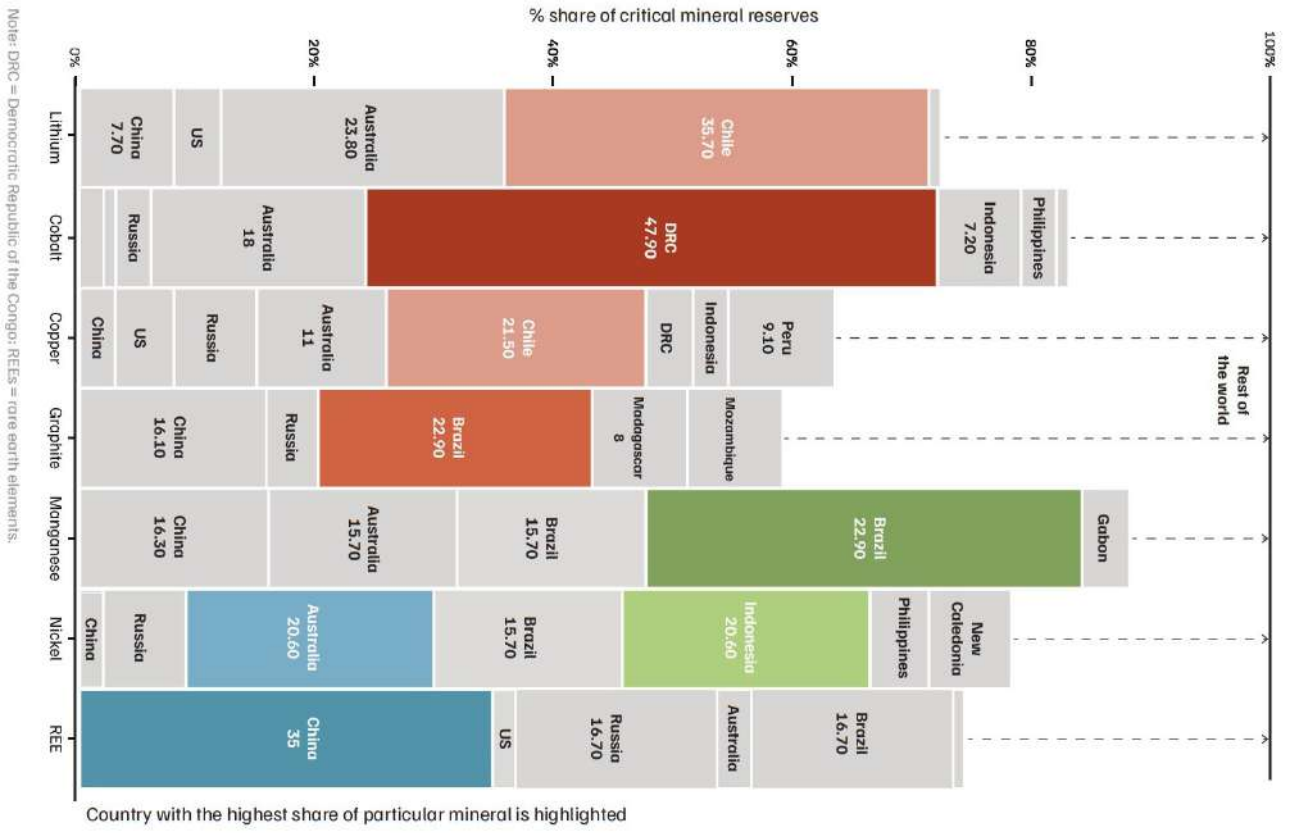
Table 61 Recycling pathways for major storage technologies

Technology	Recycling maturity	Recovery efficiency	Circularity potential
Lithium-ion	Commercial	High	Medium–High
Vanadium flow	Commercial	Very high	Very high
Sodium-ion	Emerging	Moderate	Medium
Supercapacitor	Limited	Low	Medium
PHS	Mature	High (structural)	High

10.5 Critical Minerals

ESS rely on a range of critical minerals with differing supply risks. Lithium, cobalt, nickel, and vanadium are especially important for ECES. Concentrated supply chains, long project development timelines, and environmental permitting constraints create vulnerabilities that extend beyond environmental impacts to energy security and industrial policy considerations[66]. The countries with highest share of particular minerals are highlighted in Figure 156[405].

Figure 153 Country wise critical mineral availability



Source: CEEW

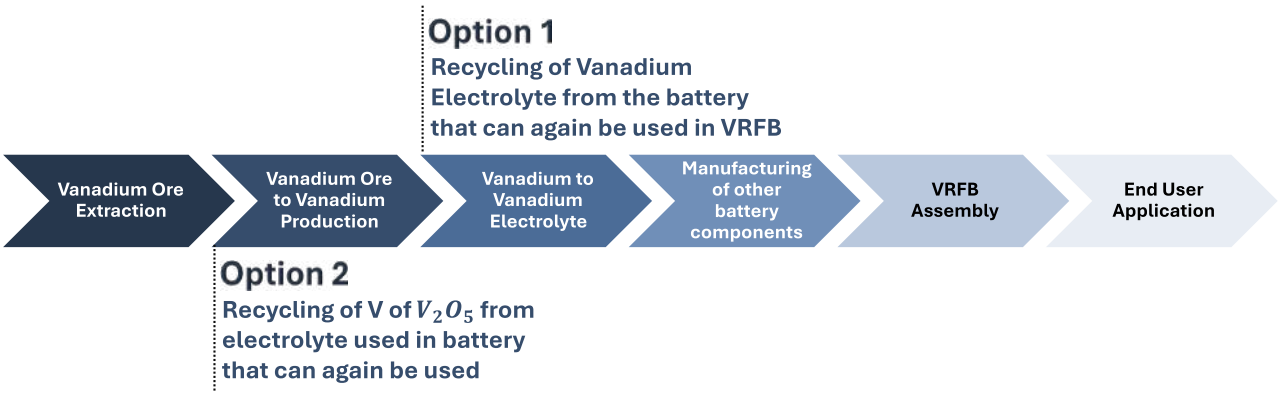
405 P. Tiwari, N. Majumdar, and A. Ghosh, "Local Grids to Global Power," Council on Energy, Environment and Water (CEEW), 2025.

Lithium-ion battery chemistries with reduced cobalt content, such as LFP, lower human toxicity and geopolitical risk but increase reliance on lithium supply. Sodium-ion batteries eliminate lithium dependence, providing strategic diversification. VRFB depend on vanadium supply, which is geographically concentrated, but risks are partly mitigated through electrolyte reuse and secondary sourcing from steel industry by-products.

10.6 Circular Economy Models

Circular economy integration seeks to reduce primary resource extraction while maintaining energy system services, with ESS technologies showing different levels of inherent circularity. Lithium-ion BESS systems depend on policy-driven measures such as extended producer responsibility, recycled content requirements, and battery passports to enable effective material recovery and traceability. In contrast, VRFB offer intrinsic circularity through electrolyte reuse and leasing models, which decouple storage service provision from continuous raw material extraction. The circular economy model for VRFB is illustrated in the Figure 154.

Figure 154 Circular economy model for VRFB



PHS achieves circularity mainly through long operational lifetimes and refurbishment rather than active material cycling. SESS benefit from very long cycle life but face challenges in developing economically viable recycling pathways. Circular economy alignment of storage technologies is summarised in Table 62.

Table 62 Circular economy of different storage technologies

Technology	Circular economy strength	Dominant mechanism
Lithium-ion	Medium	Recycling mandates
Vanadium flow	High	Electrolyte reuse
Sodium-ion	Medium–High	Material abundance
Supercapacitor	Medium	Long cycle life
PHS	High	Long asset life

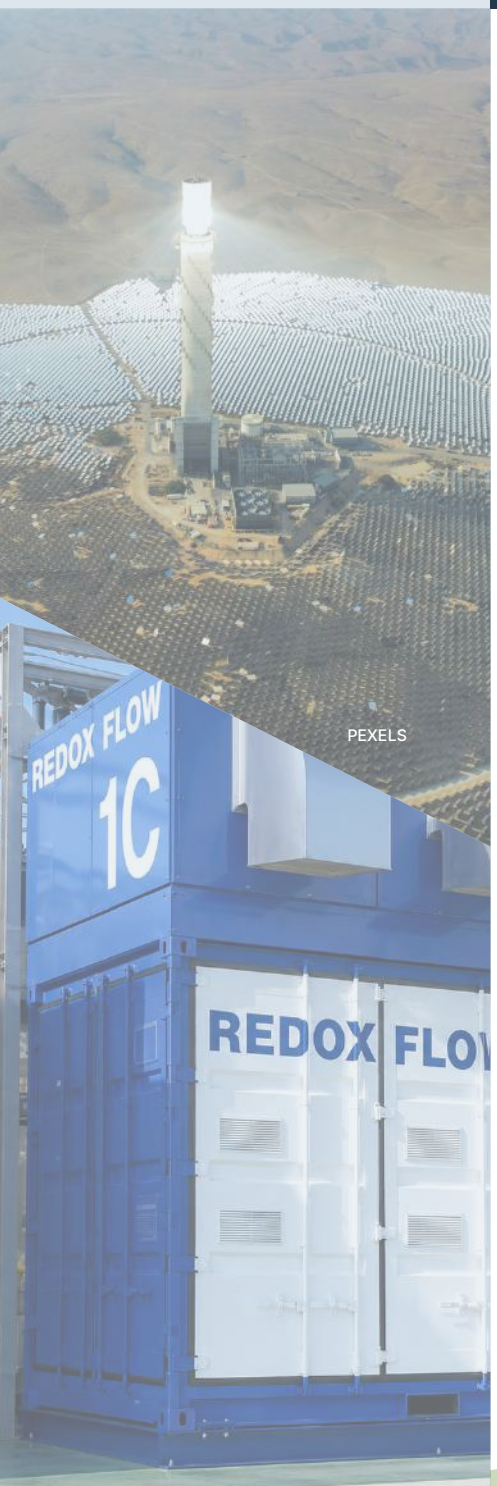


Photo by Dominik Vanyi on Unsplash

11

CHAPTER 11

GLOBAL CASE STUDIES



PEXELS

PV Magazine

Summary

- Presents global ESS case studies across pumped hydro, lithium-ion BESS, VRFB, CAES, flywheel, gravity storage, supercapacitors, residential storage, virtual power plants, and revenue stacking models.
- Demonstrates how different ESS technologies provide distinct grid services, including bulk energy shifting, resource adequacy, renewable firming, frequency regulation, voltage support, inertia, black start, and fast frequency response.
- Highlights practical deployment lessons from major projects such as Bath County PHS, La Muela PHS, Moss Landing BESS, Rongke VRFB, Jiangsu CAES, Dinglun flywheel storage, Energy Vault EVx, and South Australia VPP.
- Shows that ESS project value depends on technology capability, system location, market design, safety engineering, interconnection infrastructure, and the ability to combine multiple revenue streams





Pexels

11.1 Bath County Pumped Storage Station

The Bath County PHS Station as seen from Figure 155[406] and Figure 156[407], located in Virginia, United States, is widely recognised as one of the largest PHS facilities globally. Commissioned between 1985 and 1989 and owned by Dominion Energy in partnership with Allegheny Power, the plant has an installed capacity of approximately 3,000 MW, making it a major bulk energy storage asset within the PJM Interconnection. It was developed to enhance system reliability, manage peak demand, and increase operational flexibility in a large, interconnected transmission network historically dominated by thermal and nuclear baseload generation.

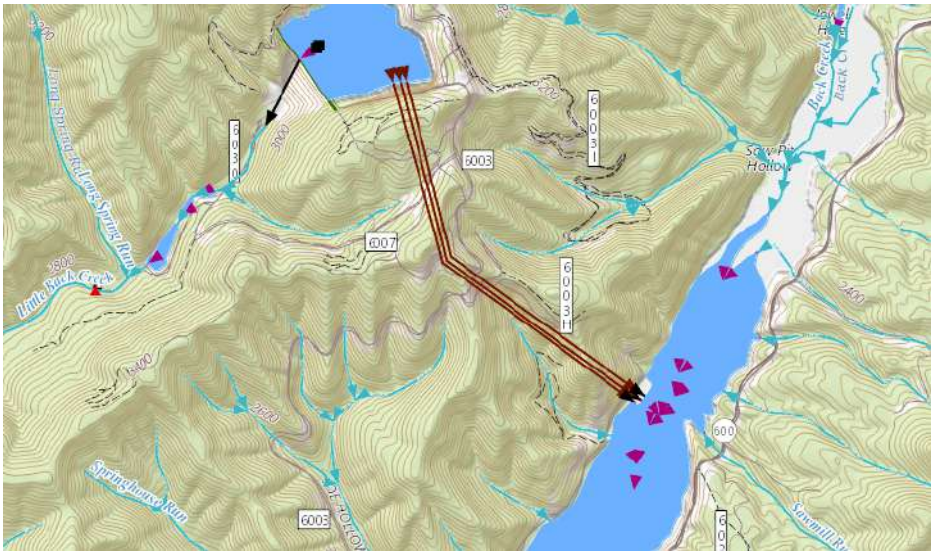
Figure 155 Bath county PHS



Bath County is a conventional PHS facility comprising an upper and lower reservoir connected through underground water conveyance systems to a powerhouse housing six reversible pump turbine units coupled with synchronous motor generators. Each unit is rated at approximately 500 MW. During off peak conditions, surplus grid electricity is used in pumping mode to transfer water to the upper reservoir. During peak demand periods, water is released through the turbines to generate electricity. The plant provides approximately 8 to 10 hours of full load discharge, with a RTE in the range of 75 to 80 percent. It features an underground powerhouse cavern designed for structural stability and operational resilience. The use of synchronous motor generators enables the provision of both active and reactive power support, along with inherent short circuit current contribution and rotational inertia, thereby strengthening the transmission grid.

406 "Bath County Pumped Storage Station," Dominion Energy.
407 "Bath County Pumped Storage Facility," Virginia Places.

Figure 156 Penstocks carrying water down to lower reservoir and then back to upper reservoir



Source: Virginia Places

Operationally, Bath County functions as a bulk energy shifting resource, absorbing low cost off peak energy and delivering it during periods of high demand. While historically charged by coal and nuclear generation, it increasingly supports RE integration by utilising surplus wind and solar output. In addition to energy arbitrage, the facility provides frequency regulation, primary response, spinning reserve, contingency support, voltage regulation, inertia contribution, and black start capability. Its large capacity and rapid ramping characteristics allow it to respond effectively to generation outages and load fluctuations, contributing significantly to resource adequacy within the PJM system.

With rising penetration of variable RE energy resources, the strategic value of large scale PHS has increased. Bath County supports RE integration by consuming excess generation during low demand intervals, compensating for variability through rapid output adjustment, and stabilising system frequency through governor action and physical inertia. Unlike converter based systems that provide synthetic inertia, synchronous PHS delivers real rotational inertia, improving frequency nadir performance during disturbances and reinforcing system strength under low inertia conditions. The facility is capable of black start operation, enabling it to initiate generation independently during system wide outages and energise transmission corridors to support restoration sequencing. This capability enhances grid resilience and provides a reliable anchor resource for system recovery in large, interconnected networks.

From an economic and strategic perspective, Bath County demonstrates the long term viability of PHS as a transmission level storage solution. Although capital intensive, its operational life exceeding four decades, high durability, and low marginal operating costs support favourable lifecycle economics. It exemplifies the suitability of PHS for bulk energy management, multi hour LDES, high capacity grid support, and reliability oriented system planning. The Bath County PHS Station illustrates that large scale synchronous ESS assets provide system wide flexibility extending beyond market arbitrage. They enhance grid strength through fault current and inertia contribution, support long duration adequacy, and reinforce resilience in high RE systems. As power systems evolve toward converter dominated generation, facilities of this nature continue to function as backbone stability resources while complementing emerging BESS and hydrogen based ESS technologies.

11.2 Grid Support Services from Pumped Hydro Storage

PHS plays a critical role in providing multiple grid support services, particularly in systems with high RE energy penetration. One key functionality is load shifting and RE curtailment reduction, as demonstrated by the La Muela PHS facility in Spain as shown in Figure 157[408].

Figure 157 La Muela PHS facility in Spain



Source: International Hydropower Association

As shown in Figure 157[409], the plant operates by pumping water to the upper reservoir during periods of low demand and high wind generation and generating electricity during peak demand periods when wind output declines. This complementary operation smooths wind variability and aligns supply with demand, improving system efficiency and reducing RE energy curtailment. The daily operational pattern illustrates how PHS acts as a buffer between variable generation and demand, with benefits extending over longer time horizons such as weeks and months.

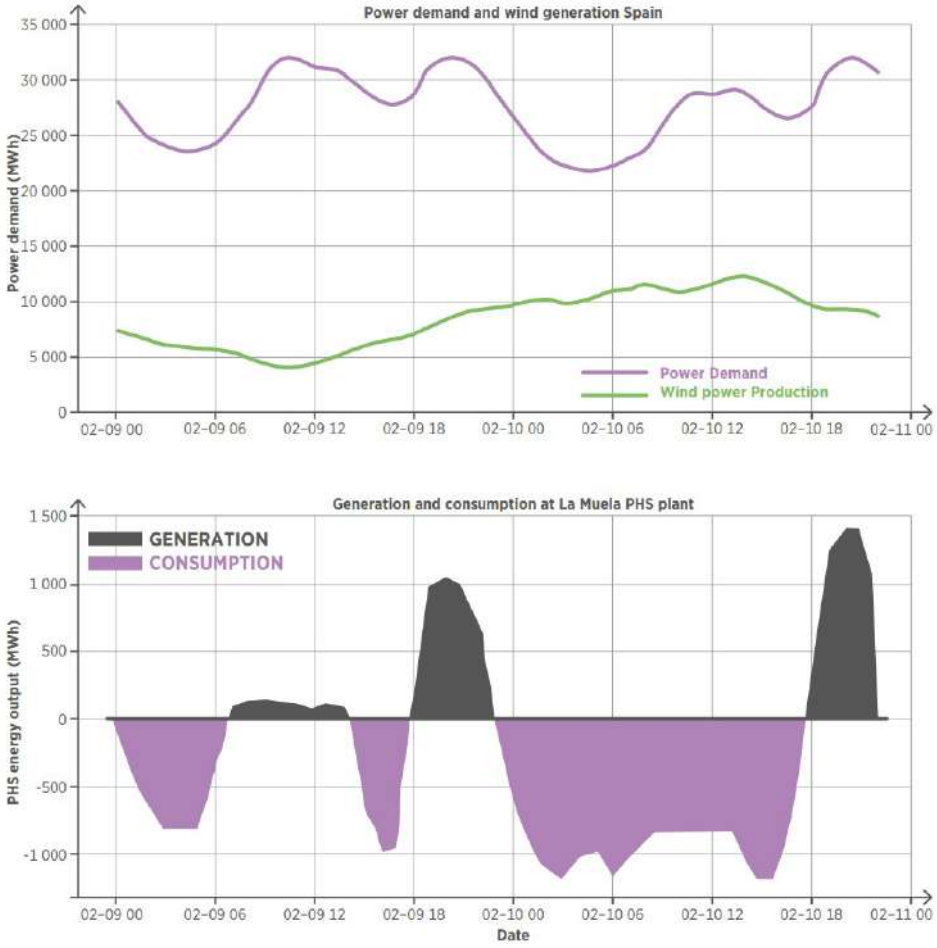
During the Iberian blackout of 28 April 2025, La Muela PHS contributed primarily to post disturbance system restoration. Following partial re energisation of the local network and restoration of auxiliary services, La Muela PHS was synchronised to support the Mediterranean restoration corridor by injecting dispatchable active power, reportedly delivering about 4.7 GWh by the end of 28 April 2025. As shown in the pumped storage fleet operation profile in Figure 159[408], comparing 21 April 2025 with the blackout day of 28 April 2025, the event day exhibited loss of pumping or charging operation during the midday period and increased turbine mode generation during the evening restoration window, indicating a transition from scheduled storage cycling to emergency system

408 "Unlocking the value of Hydro Pumped Storage after the Iberian blackout," International Hydro Power Association.

409 IRENA, "Innovation landscape brief: Innovative operation of pumped hydropower storage," International Renewable Energy Agency, 2020.

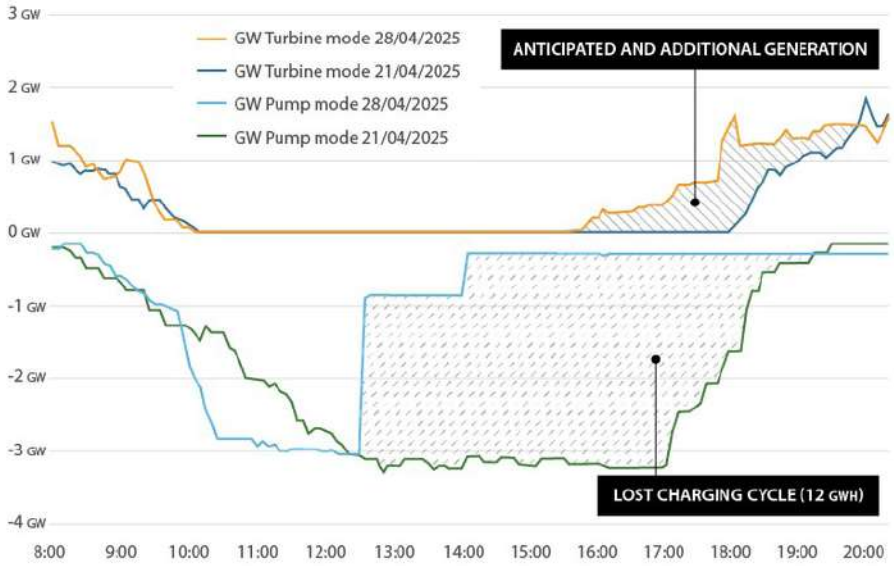
support operation. As a large synchronous generation asset, La Muela also contributed short circuit strength, voltage regulation through reactive power capability, inertial response, and frequency support during the vulnerable grid restoration phase.

Figure 158 Flexibility service provision from La Muela PHS, Spain



Source: IRENA

Figure 159 Hourly generation and consumption of La Muela PHS- 21/04/25 vs 28/04/25



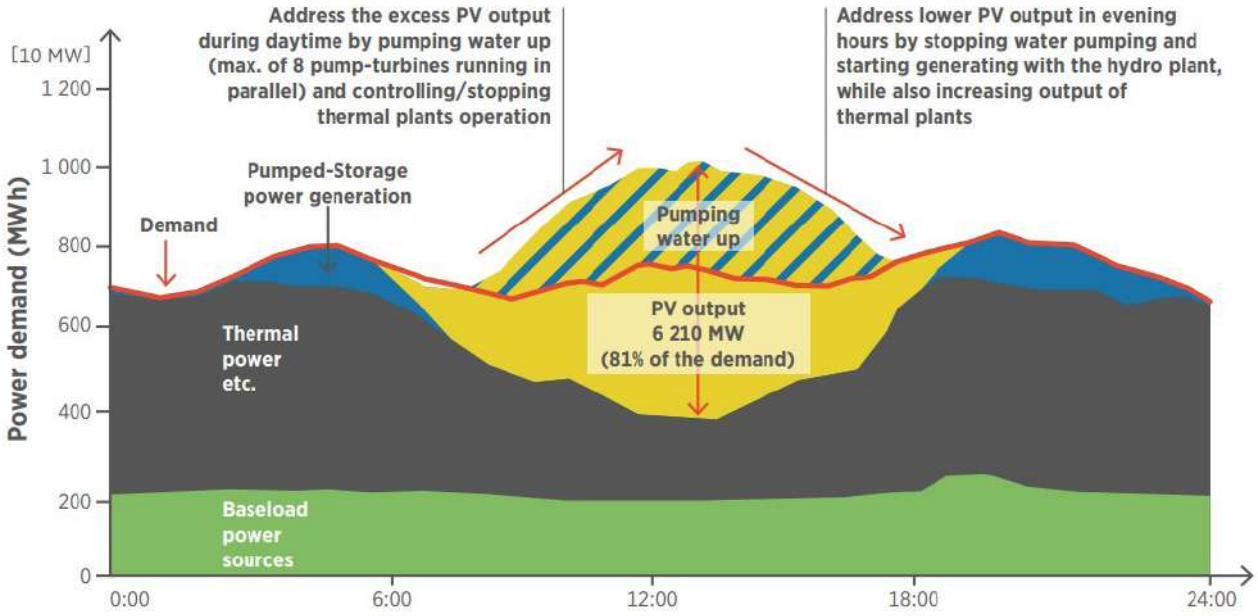
Source: International Hydropower Association

☀ KEY INSIGHT

PHS remains uniquely valuable because it combines bulk energy shifting with synchronous grid support, enabling both RE curtailment management and post-disturbance restoration in high-RE systems.

Another important application of PHS is balancing and flexibility provision in high VRE systems, as demonstrated in the Kyushu region in Japan. With high solar PV penetration, the system experiences significant midday surplus generation. Figure 160[409] shows how PHS consumes excess solar output during the day by operating in pumping mode and later supplies energy during evening demand peaks. This reduces curtailment and dependence on thermal generation while maintaining system efficiency and stability. In addition, advanced PHS configurations, such as variable speed turbines and ternary systems, enable enhanced frequency regulation by allowing simultaneous pumping and generation, providing finer control of system frequency and improving dynamic response.

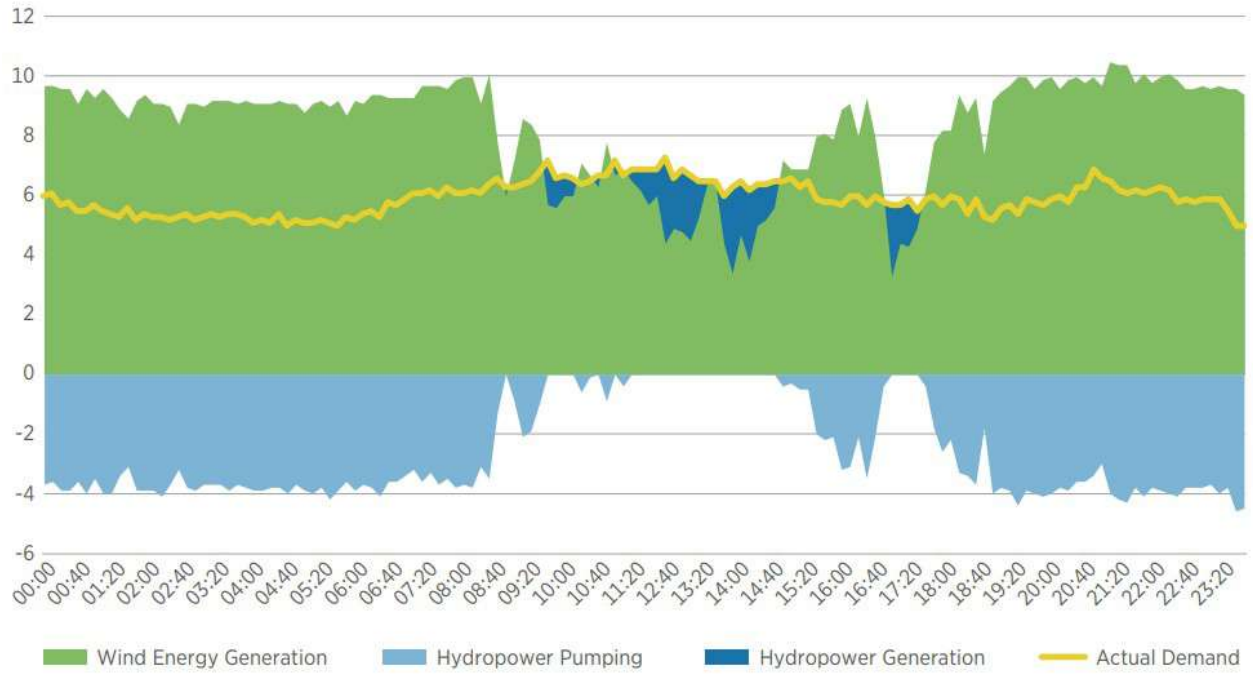
Figure 160 Supply demand balance from Kyushu Electric Power Company PHS, Japan



Source: IRENA

PHS also supports capacity firming and reliability enhancement when integrated with RE energy sources. The Gorona del Viento project in El Hierro, Spain, demonstrates how wind energy can be coupled with PHS to ensure stable and reliable supply. As illustrated in Figure 161[409], excess wind generation is stored through pumping, while stored energy is dispatched during periods of low wind output, reducing dependence on diesel generation. This configuration enables extended periods of high RE penetration, including near 100 percent RE operation. Such hybrid systems highlight the role of PHS in mitigating intermittency, ensuring supply adequacy, and enabling higher RE integration without compromising grid stability.

Figure 161 RE firming through Gorona del Viento wind-PHS hybrid power plant



Source: IRENA

11.3 Vistra Moss Landing Lithium-ion BESS Project

The Vistra Moss Landing ESS Facility, located at the Moss Landing Power Plant site in Monterey County, California, is among the largest grid scale lithium ion BESS installations globally as shown in Figure 162. Developed by Vistra Energy beginning in 2020, the project repurposed existing turbine halls of a retired natural gas facility and interconnected through the existing high voltage switchyard[410]. This approach leveraged established transmission infrastructure within the CAISO network, reduced development timelines, and enabled rapid grid integration.

The project was implemented in multiple phases. Phase I, commissioned in 2020, provided 300 MW and 1,200 MWh of lithium ion BESS. Phase II in 2021 added 100 MW and 400 MWh. Subsequent expansions increased the total installed capacity to approximately 750 MW and 3,000 MWh. The facility employs modular lithium ion battery racks housed within former turbine buildings. Battery blocks are connected through DC combiners to bidirectional PCS, interfacing through medium voltage transformers to the 230 kV transmission system. The plant is designed primarily as a four hour duration resource, consistent with California's Resource Adequacy requirements.

Interconnected to the CAISO transmission network at 230 kV, Moss Landing is strategically positioned near major load centres and transmission corridors, enabling delivery of system level services. Its principal operational functions include resource adequacy capacity provision, energy arbitrage in CAISO day ahead and real time markets, frequency regulation, fast ramping support, and mitigation of midday solar over generation associated with the duck curve phenomenon. The facility charges during periods of high solar output and low market prices and discharges during evening peak demand when net load increases sharply. Its response time, on the order of milliseconds to seconds, exceeds the ramping capability of conventional thermal generation.

410 Vistra Corp., "Vistra Completes Milestone Expansion of Flagship California Energy Storage System," Press Release, 2023.

Figure 162 Vistra Moss Landing BESS facility



At the plant level, operations are coordinated through a centralised EMS integrated with CAISO dispatch and AGC signals. The control hierarchy includes market dispatch interfaces, active and reactive power control loops, PCS level current regulation, and BMS oversight to enforce thermal and operational constraints. The plant operates in grid following mode in accordance with CAISO interconnection requirements, providing frequency regulation through active power modulation and reactive power support within converter capability limits to assist local voltage control.

A defining aspect of the Moss Landing case is the occurrence of battery thermal events, as shown in Figure 163.

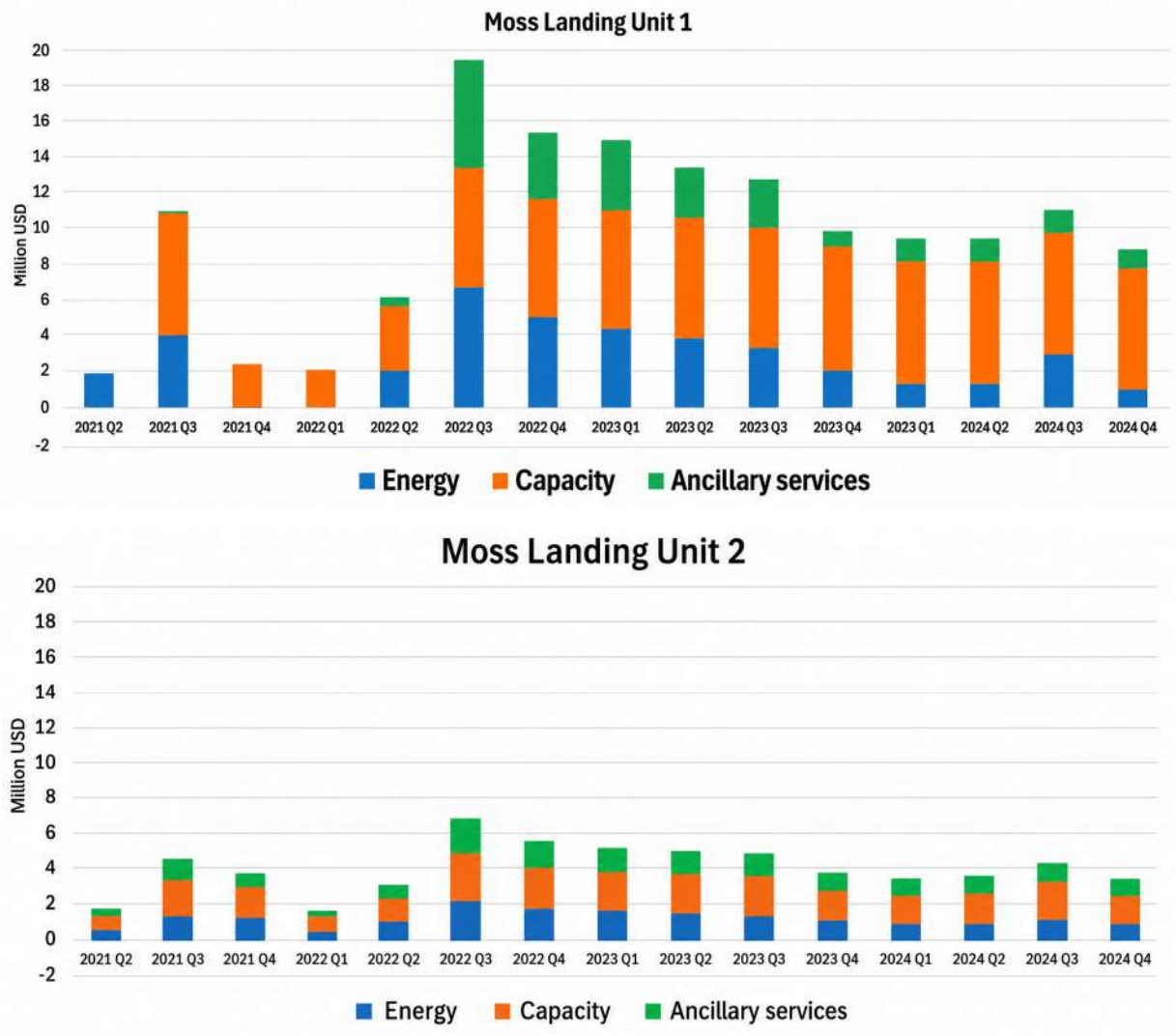
Figure 163 Moss BESS thermal events



In September 2021, a smoke and overheating incident in Phase I resulted in a temporary shutdown, followed by another thermal event in February 2022 requiring partial module isolation[411]. During 2023 and 2024, safety upgrades were implemented, including enhanced fire detection, improved gas monitoring, compartmentalisation, and revised operational protocols. These events highlighted thermal runaway propagation risk, fire suppression design challenges, and the need for effective module isolation and emergency coordination. Subsequent modifications strengthened plant level safety engineering and monitoring systems.

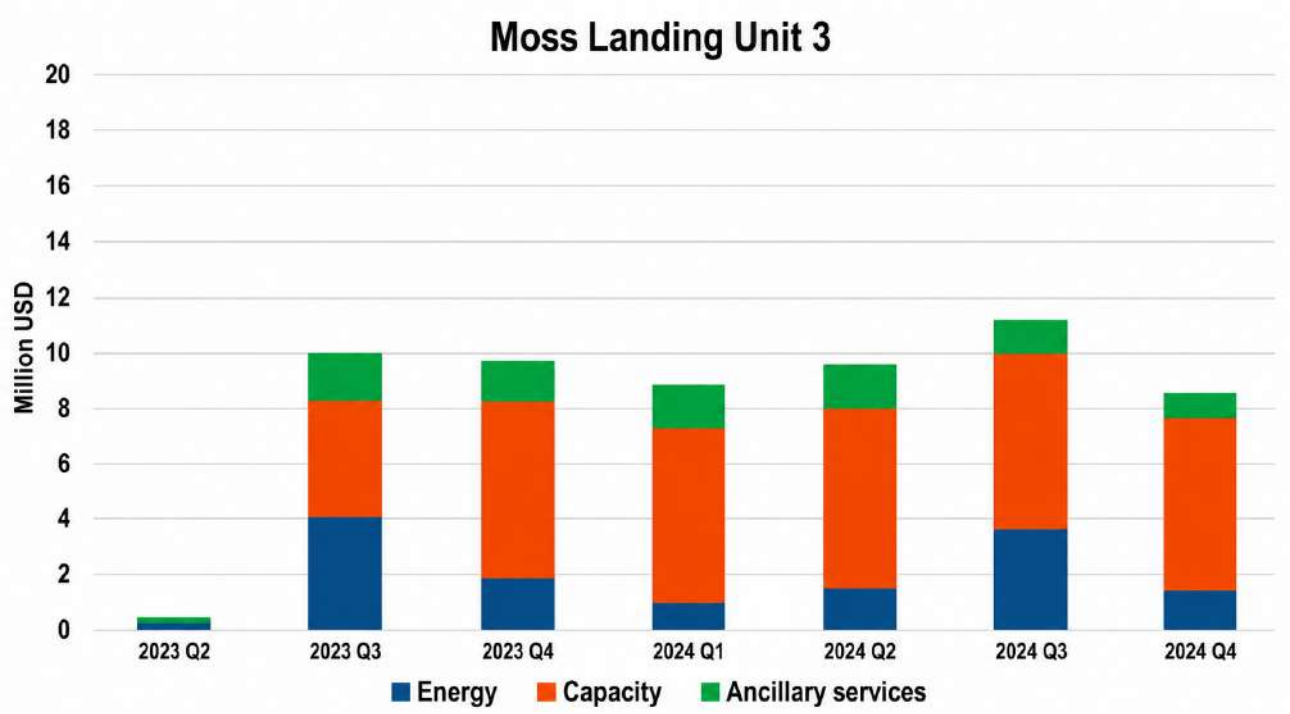
Despite these incidents, Moss Landing has demonstrated substantial operational value within CAISO. It has provided rapid frequency regulation, supported evening ramp management, reduced reliance on gas fired peaking units, and enhanced grid flexibility during high stress conditions such as heat waves. Its fast dispatch capability has contributed to maintaining reliability margins during periods of constrained supply and elevated demand. Economically, the facility participates in energy arbitrage markets, ancillary service markets including regulation up and down, and resource adequacy capacity contracts as seen from Figure 164[412]. This multi-use revenue stacking model aligns with California's policy framework aimed at replacing retiring thermal generation with ESS resources capable of providing firm capacity and grid services.

Figure 164 Market participation of Moss Landing BESS unit 1



411 United States Environmental Protection Agency, "Moss Landing Vistra Battery Fire Response," Jul. 17, 2025.

412 A. Dai, X. Cui, and J. Gordon, "Financing Battery Storage in China: Insights from California's Practices", California-China Climate Institute, University of California, Berkeley, Aug. 2025.



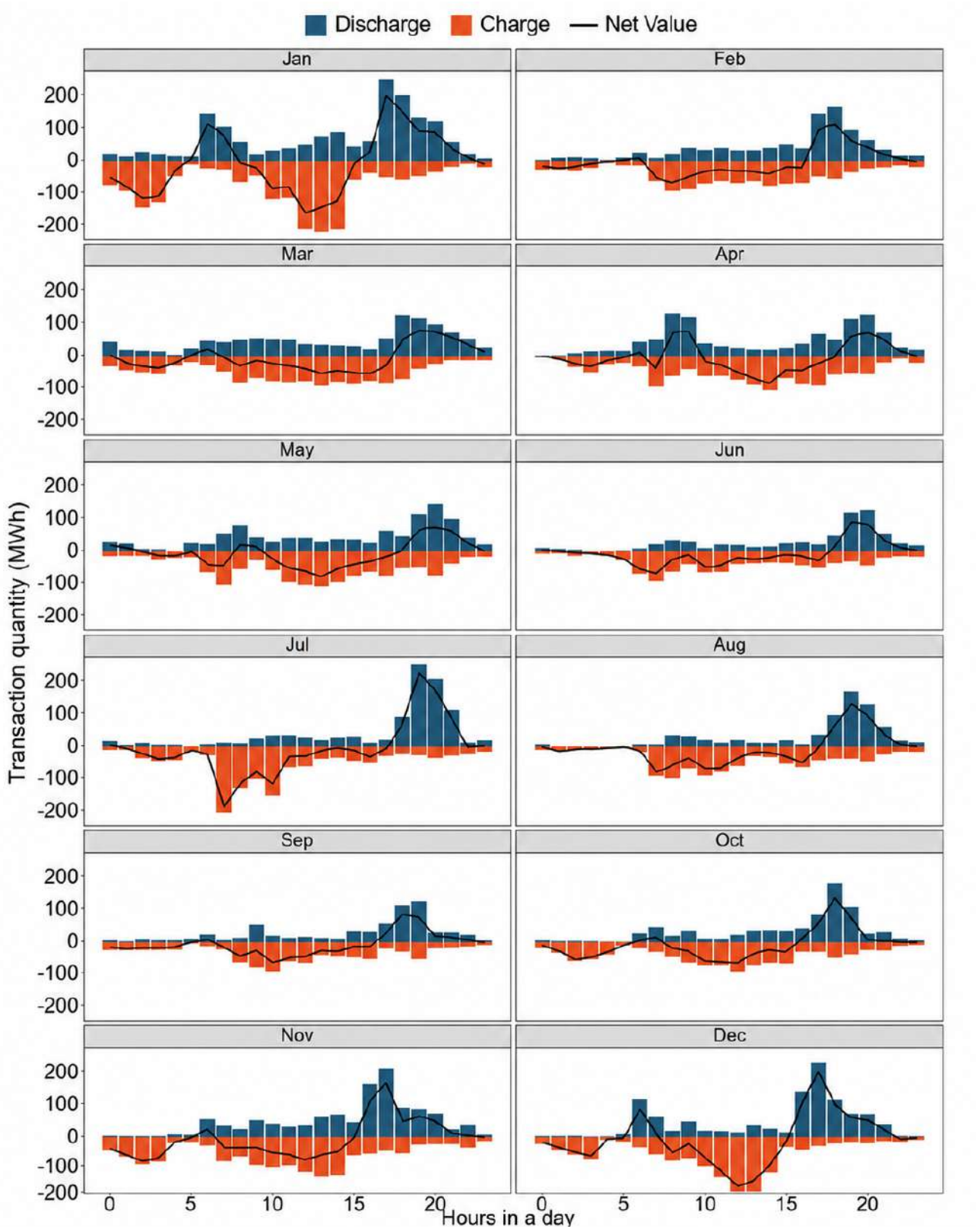
Source: University of California

The revenue breakdown for Moss Landing Units 1, 2, and 3 indicates that capacity payments consistently constitute the dominant share of total earnings, with energy arbitrage and ancillary services providing secondary contributions. Unit 1 records the highest overall revenues, peaking in 2022 before stabilising at lower but steady levels during 2023-2024. Unit 2 demonstrates comparatively moderate and stable revenue streams across all categories. Unit 3, commissioned later, exhibits strong capacity driven revenues with increased energy market participation during 2023-2024.

As observed from Figure 165, hourly energy transactions across the year, showing a consistent operational pattern. Charging predominantly occurs between 9:00-14:00 hours, with magnitudes reaching approximately -150 to -200 MWh during high activity months such as July and December. Discharging is concentrated in the evening peak window of approximately 16:00-20:00 hours, with peak discharge volumes reaching 200-250 MWh in summer and winter months. Shoulder months such as March and May exhibit more moderate discharge levels in the range of 80- 20 MWh. The net operational profile demonstrates a consistent four hour discharge strategy aligned with evening peak demand[412].

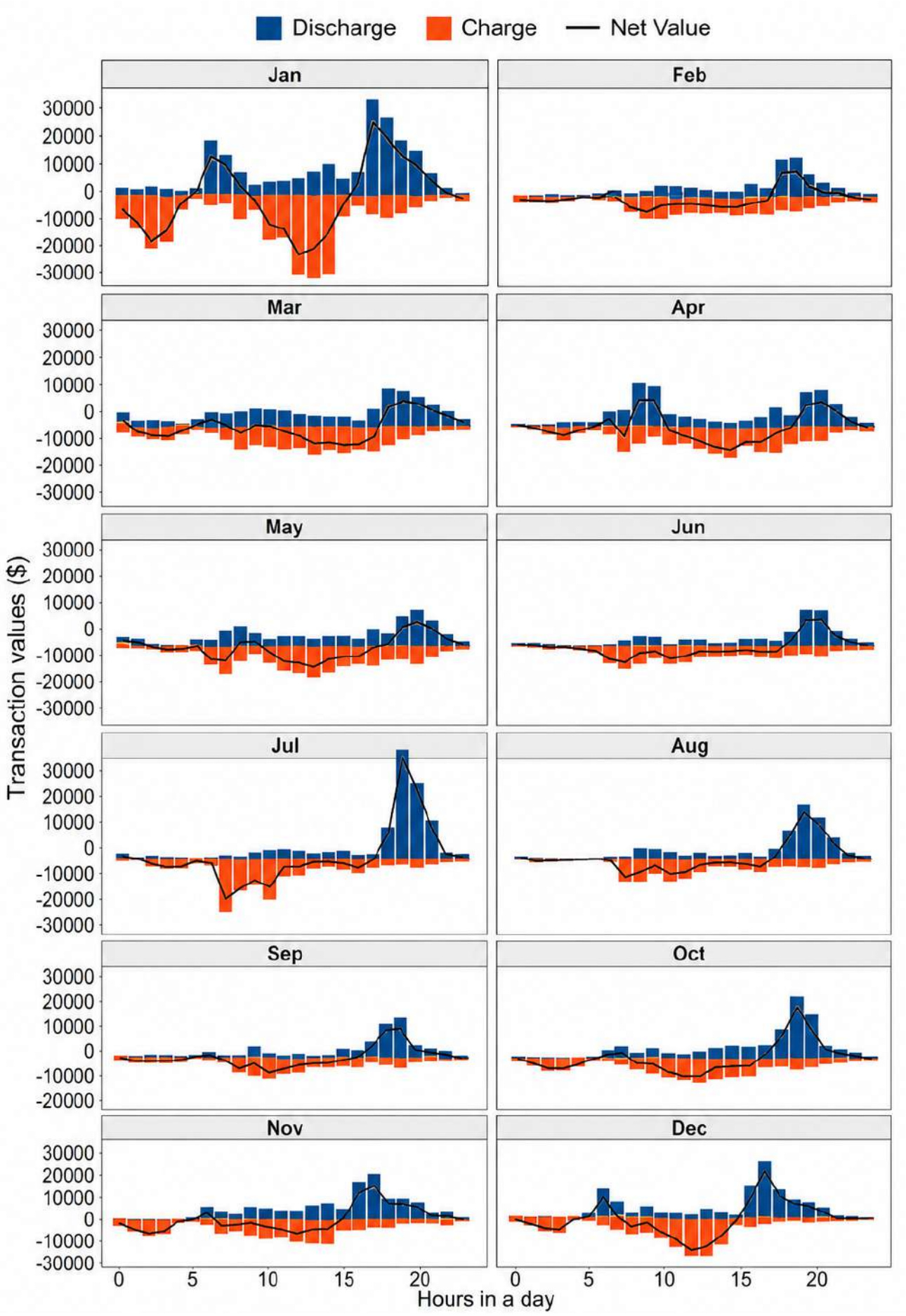
The corresponding revenue trends as shown in Figure 166 indicate that evening discharge hours generate the highest economic returns. Summer peaks, particularly in July, reach approximately $30,000-$35,000 per hour, while winter peaks such as December range between $10,000-$15,000 per hour. Charging costs during midday typically remain within -$5,000 to -$12,000 per hour, resulting in strong positive net value during periods of wide price spreads. February and spring months exhibit comparatively lower spreads, with peak revenues generally below $10,000 per hour, reflecting seasonal price sensitivity. Overall, the data confirms that value creation is concentrated in high volatility summer and winter peak periods[412].

Figure 165 Hourly average transaction quantity in 2024



Source: University of California

Figure 166 Hourly transaction charge in 2024



Source: University of California

The Moss Landing deployment offers several strategic insights. Repurposing existing thermal plant infrastructure can accelerate project development and optimise interconnection costs. However, large scale lithium ion BESS installations require rigorous thermal management, fire mitigation design, and continuous operational monitoring. Multi-phase expansion demands careful system integration to maintain safety and performance consistency across installations. The project illustrates the technical capability of multi hundred megawatt BESS to function as firm capacity resources in RE dominated systems, as well as the operational complexity inherent in high energy density storage facilities. It underscores the necessity of robust safety engineering, validated control architectures, and disciplined operational governance in utility scale BESS deployments.

11.4 Rongke Power Vanadium Redox Flow Battery

The VRFB ESS Peak-shaving Power Station, developed by Rongke Power Co., Ltd., is among the largest VRFB installations globally. Located in Dalian, Liaoning Province, China, the project represents a landmark deployment of long duration ECES at the transmission level. The first phase was commissioned with a rated capacity of 100 MW and 400 MWh, with planned expansion of 200 MW and 800 MWh, positioning it as a flagship demonstration of grid scale FBES technology[413].

The Dalian VRFB station as seen from Figure 167 is connected to the high voltage transmission network and operates primarily as a peak shaving and load levelling asset. Its principal objectives include managing peak demand fluctuations, smoothing RE generation variability, providing frequency regulation support, and enhancing grid stability in Northeast China. The project was developed in response to increasing wind penetration in Liaoning Province, where curtailment and variability created operational challenges. By consuming surplus RE generation during low demand periods and discharging during peak intervals, the facility improves RE integration and reduces curtailment risk[414].

Figure 167 Rongke Power VRFB deployment



413 Rongke Power Co., Ltd., “Rongke Power Delivers the World’s First GWh-Scale Vanadium Flow Battery Energy Storage Project Now in Operation,” Dec. 31, 2025.

414 Chinese Academy of Sciences, “100 MW/400 MWh All-Vanadium Redox Flow Battery Energy Storage Power Station Connected to the Grid,” 2024.

Figure 168 Electrolyte tanks and power modules of VRFB at Rongke Power





Operationally, the VRFB system provides seconds scale active power modulation in response to dispatch signals, stable voltage and frequency support through converter based control, and flexible charge discharge scheduling aligned with system operator requirements. Although FBESS do not provide mechanical inertia, they can participate effectively in frequency regulation and ramping services through fast converter control. Strategically, the Dalian installation represents a significant demonstration of long duration ECES bridging the gap between short duration lithium ion BESS and infrastructure scale mechanical storage such as PHS. It supports China's RE integration objectives, advances domestic vanadium supply chain development, and reduces reliance on fossil fuel based peaking generation. The project is referenced as a benchmark for multi hundred megawatt flow BESS deployment and provides a practical pathway toward diversified ESS portfolios combining lithium ion, PHS, and FBESS technologies[415].

The Dalian VRFB project demonstrates that VRFB technology can be deployed at transmission scale to deliver peak shaving, RE integration, and system stability services. It represents an important milestone in the commercialisation of long duration ECES and reinforces the role of diversified storage technologies in supporting high RE penetration power systems.

11.5 Guoxin Suyan Huai'an Salt Cavern Compressed Air Energy Storage Project

The 600 MW and 2,400 MWh CAES facility in Jiangsu Province is among the largest advanced CAES installations globally as shown in Figure 169[416]. Developed as a utility scale LDES asset, the project reflects China's strategic focus on bulk energy storage to support high RE penetration. With a nominal discharge duration of approximately four hours at full output, the plant operates as a transmission level flexibility resource within the regional power system.

The Jiangsu project represents an advanced CAES configuration incorporating efficiency improvements over conventional diabatic designs. Traditional CAES plants rely on natural gas combustion during discharge to reheat compressed air prior to expansion. In contrast, advanced systems integrate thermal management and heat recovery subsystems to improve overall efficiency. The facility includes multistage compressors driven by synchronous motor generators during charging, underground cavern storage for high pressure air, intercooling and thermal recovery

415 D. Reber, S. R. Jarvis, and M. P. Marshak, "Beyond energy density: flow battery design driven by safety and location," Energy Adv., vol. 2, no. 9, pp. 1357–1365, 2023.

416 Energy Institute, "China commissions the 'world's largest' compressed-air storage plant," Feb.2026.

components, air expanders coupled to synchronous generators during discharge, and high voltage transformers for grid interconnection. Surplus grid electricity is used to compress and store air underground, which is later expanded through turbines to generate electricity.

Figure 169 Guoxin Suyan Huai'an CAES project



Interconnected at transmission voltage, the plant functions as a bulk system asset providing peak shaving, RE integration support, resource adequacy, frequency regulation, and contingency reserves. In Jiangsu's system, where wind and solar penetration have increased, the CAES facility consumes surplus RE generation during low demand periods and dispatches stored energy during peak intervals. Its 600 MW rating enables material system level contribution during extended high demand conditions. The plant delivers approximately four hours of full load discharge, with round trip efficiency of 71 percent depending on configuration. Startup time is on the order of several minutes, faster than conventional coal fired units. The use of synchronous generators as depicted in Figure 168 enables short circuit current contribution, reactive power support, and mechanical inertia. Unlike converter based ESS, CAES contributes inherent system strength through physical inertia and fault current capability[417].

Compared with lithium ion BESS, CAES is better suited for high power multi hour bulk shifting, although it has slower ramp rates and lower round trip efficiency. Relative to pumped hydro storage, CAES offers large scale mechanical storage without strict topographic constraints but requires suitable geological formations for underground air storage, limiting site availability. Overall, the Jiangsu 600 MW and 2,400 MWh CAES project represent a significant milestone in mechanical long duration storage deployment. By combining bulk energy shifting with grid strengthening characteristics of synchronous generation, the facility enhances system adequacy, supports RE integration, and reinforces the role of mechanical storage technologies in decarbonising power systems.

417 Enerdata, "China Switches On 2.4 GWh Compressed Air Storage Plant in Jiangsu," Daily Energy News, January 202.

Figure 170 Synchronous machines used in CAES plant



11.6 Dinglun Flywheel Energy Storage Power Station

The Dinglun FES Power Station, located in Shanxi Province, China, is among the largest grid scale flywheel installations worldwide and represents a significant deployment of high power, short duration mechanical storage technology as seen from Figure 171[418]. Commissioned in phases beginning around 2023, the facility has an installed capacity of approximately 30 MW and is designed to deliver frequency regulation services to the regional transmission network. Unlike long duration storage assets intended for bulk energy shifting, the Dinglun project is optimised for rapid power modulation, high ramp rates, and very high cycle operation.

The plant comprises multiple flywheel modules connected in parallel to achieve the aggregate power rating. Each group of ten flywheels is integrated to form a single energy storage and frequency regulation unit. Twelve such units are then aggregated into a larger array, and the complete array is interconnected to the power grid at the 110 kV voltage level[419]. Each module includes a high speed rotating mass enclosed in a vacuum chamber to minimise aerodynamic losses, supported by magnetic or advanced mechanical bearings to reduce friction and maintenance requirements. A bidirectional motor generator is coupled to a power electronic converter, enabling controlled energy exchange with the grid. Kinetic energy is stored in the rotor proportional to the square of rotational speed. During charging, electrical energy accelerates the rotor, and during discharge, the rotor decelerates to drive the generator and inject power into the network. The converter interface enables precise and rapid bidirectional active power control.

Operationally, the Dinglun station functions primarily as a frequency regulation and fast frequency response resource within the transmission system. It participates in automatic generation control

418 Energy Storage News, “World’s largest 30MW flywheel energy storage project connects to grid in China.” Sept 2024
419 pv magazine, “China connects its first large-scale flywheel storage project to grid,” Sept. 13, 2024.

and provides rapid power adjustments in response to frequency deviations and RoCoF events. Its high ramp rate supports frequency arrest and stabilisation, particularly in systems with declining inertia due to increasing RE penetration. The facility is not intended for multi hour peak shaving or energy arbitrage because of its limited energy capacity. Instead, it reduces regulation burden on thermal units, enhances system response speed, and provides high precision tracking of dispatch signals.

Figure 171 Dinglun FESS power station



At the plant level, operations are coordinated through a centralised supervisory control system integrated with grid operator dispatch. The control architecture includes converter level active power loops, real time frequency measurement and response algorithms, and protection and monitoring systems for rotor speed, vibration, and mechanical integrity. The power electronic interface enables operation in grid following mode for frequency services and provision of reactive power support within converter capability limits.

The Dinglun project with efficiency of nearly 90% demonstrates advantages of flywheel technology, including minimal performance degradation due to the absence of electrochemical ageing mechanisms, high cycle durability, rapid response suited to performance based regulation markets, and reduced fire risk relative to lithium ion systems. However, the inherently short duration of storage limits its application to high power ancillary services rather than long duration adequacy or bulk energy management. Strategically, the facility underscores the role of specialised high power storage technologies in modern power systems. As RE penetration increases and aggregate system inertia declines, fast acting resources are essential to maintain frequency stability. The deployment of a 30 MW class transmission connected flywheel installation illustrates how mechanical storage can complement battery energy storage systems and conventional generation by delivering high quality frequency control tailored to short duration stability services.

11.7 Energy Vault EVx Gravitational Energy Storage

Energy Vault has commissioned a 25 MW and 100 MWh GESS adjacent to a wind power facility at Rudong, China as shown in Figure 172. The project represents an early commercial scale deployment of modular gravity based storage directly integrated with RE generation. With RTE of 80% and nominal discharge duration of approximately four hours at rated power, the facility is configured to provide medium duration services including RE smoothing, peak shifting, and grid support[420].

The system operates on the principle of gravitational potential ESS. The installation comprises a multi storey tower equipped with composite or concrete blocks acting as storage masses, motor generators integrated with lifting mechanisms, power electronic converters for grid interfacing, and automated control systems. During charging, surplus wind generation powers motors that lift the blocks, storing energy as gravitational potential energy. During discharge, the blocks are lowered in a controlled manner, converting potential energy into electrical energy. The 25 MW rating is defined by mechanical lifting and generator capacity, while the 100 MWh capacity is determined by block mass and elevation range. Co-located with a wind plant, the facility absorbs excess generation that might otherwise be curtailed. Operational objectives include output smoothing, intraday energy shifting, peak support, and provision of frequency and voltage services through converter based control. Interconnection via power electronic converters enables controlled active and reactive power exchange in line with transmission level requirements.

Figure 172 GESS deployment



420 Energy Vault Holdings, Inc., “Rudong EVx™ Gravity Energy Storage System Project,” Project Profile.

Technically, the system offers seconds scale ramping capability and is designed for long mechanical service life with limited performance degradation. GESS avoids chemical ageing mechanisms and reduces intrinsic fire risk relative to lithium ion systems. Mechanical wear is managed through structural optimisation and condition monitoring. From a planning perspective, the installation occupies an intermediate position between short duration battery storage and large scale pumped hydro. It offers enhanced intrinsic safety and potentially longer lifetime than lithium ion BESS, though with lower energy density per land footprint. Unlike PHS, it does not require specific topographic or hydrological conditions and can be deployed on relatively flat terrain with modular scalability. Overall, the 25 MW and 100 MWh GESS project demonstrate the commercial emergence of modular gravity based systems within diversified storage portfolios. By integrating directly with wind generation, it supports RE firming, curtailment reduction, and local grid stability, highlighting the expanding technological diversity of utility scale ESS.

11.8 Supercapacitor Energy Storage with Hydro Power Plant

The Kurkiaska hydropower plant in Finland, with a generation capacity of 27 MW, integrates a 2 MW / 44 kWh supercapacitor ESS to support grid stability in the Nordic power system as shown in Figure 173[421]. The Nordic grid is characterised by low inertia conditions due to high RE penetration and strong interconnections, creating a need for ultra-fast frequency control solutions. The deployed SCES system is designed to provide rapid frequency containment and power balancing, responding within milliseconds to frequency deviations and supporting stringent Nordic grid code requirements.

From a SESS perspective, this application highlights suitability for high power, short duration services such as fast frequency response and synthetic inertia. By managing rapid fluctuations, the SESS reduces mechanical stress on hydropower turbines, enabling more efficient and flexible plant operation. This enhances the plant's participation in ancillary service markets, creating additional revenue streams while maintaining compliance with grid standards. The high cycle life and minimal degradation of supercapacitors make them effective for continuous high frequency operation required in the Nordic system. Overall, the Kurkiaska project demonstrates how supercapacitors enhance hydropower dynamic performance while enabling value stacking through advanced grid support services[422].

421 Skeleton Technologies, "Supercapacitors empower hydropower plants for grid stabilization and revenue generation," Skeleton Blog

422 S. Lieskoski, O. Koskinen, J. Tuuf, and M. Björklund-Sänkiaho, "A review of the current status of energy storage in Finland and future development prospects," J. Energy Storage, vol. 93, no. 112327, p. 112327, 2024.



Figure 173 Supercapacitor energy storage deployment in Finland



11.9 BTM and Residential Storage Pilots

11.9.1 Germany – Residential PV + Battery Expansion and Sonnen Community

Germany represents the largest residential BESS market in Europe, with more than 1.2 million installed PV BESS corresponding to approximately 12.6 GWh of cumulative ESS capacity. By 2023, nearly 77 percent of newly installed RTS PV systems were paired with BESS, typically in the 5-15 kWh range. These systems are predominantly based on lithium ion chemistries, particularly LFP and NMC based BESS, combined with hybrid or AC coupled converters rated between 5 and 10 kW. Operationally, BESS charge during daytime PV surplus and discharge during evening demand to maximise on site utilisation[423]. Primary objectives include increasing RTS PV self-consumption, reducing grid imports, and enabling aggregated participation in balancing markets. Self-consumption levels have increased from approximately 30 percent to 60-80 percent with BESS integration.

423 Bundesverband Solarwirtschaft e.V. (BSW-Solar), "The German PV and Battery Storage Market." 2024.

The Sonnen Community initiative aggregates thousands of residential systems through digital platforms, enabling participation in primary frequency control markets and demonstrating the feasibility of distributed ESS as a grid resource[424]. Building upon this aggregation model, the commercial structure of the pooling concept is implemented through the Sonnen Community membership framework. Participation requires a monthly fee of €19.99, enabling members to purchase electricity from the community at a reduced tariff of €0.23 per kWh. Compared to the average German household electricity price of €0.2916 per kWh in 2017, this represents a saving of €0.0616 per kWh. Membership also provides a gross discount of €1,875 on the BESS, thereby lowering upfront capital cost barriers[425]. Participation is not limited to only prosumers. Customers without RTS PV installations may also install the BESS and join the pooling mechanism. Within this structure, residential BESS operate as distributed temporary ESS for electricity marketing and balancing services, while PV equipped households remain the primary focus of the distributed aggregation model.

11.9.2 South Australia Virtual Power Plant

The South Australia Virtual Power Plant (SAVPP), led by Tesla and supported by the ARENA, is among the largest residential aggregation programmes globally as shown in Figure 174. The target deployment includes up to 50,000 homes equipped with 5 kW PCS capacity and 13.5 kWh lithium ion BESS, with several thousand already deployed. Phase 3A focused on the initial deployment of approximately 500 systems within a broader 3,000 system rollout[426]. Each installation integrates RTS PV with Tesla Powerwall BESS.

Figure 174 A suburb in Adelaide (South Australia) which is part of VPP



424 J. Barnes, P. Hansen, S. Darby, S. Sommer, and M. Andor, New Clean Energy Communities in a Changing European Energy System (NEWCOMERS) – Summary Case Study Report: The sonnenCommunity, NEWCOMERS Project, Horizon 2020 Grant Agreement No. 837752, Feb. 9, 2022.

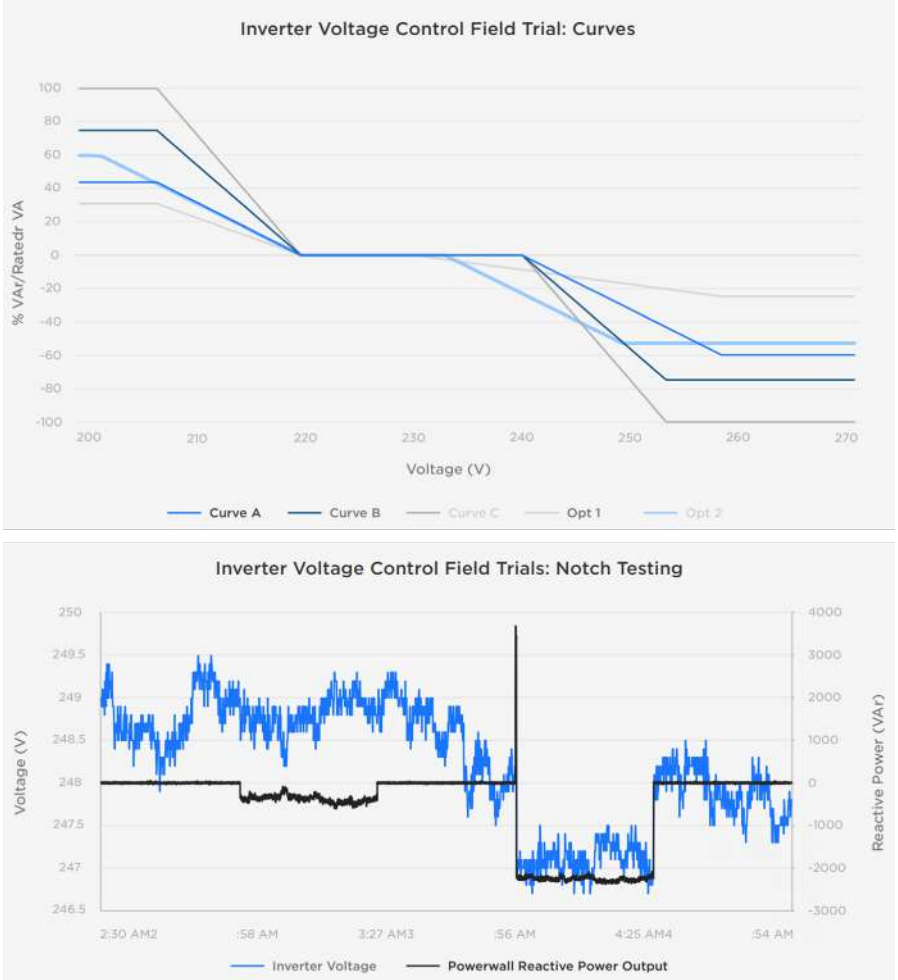
425 S. Vonsien and R. Madlener, "Li-ion battery storage in private households with PV systems: Analyzing the economic impacts of battery aging and pooling," J. Energy Storage, vol. 29, no. 101407, p. 101407, 2020.

426 Australian Renewable Energy Agency (ARENA), Tesla Virtual Power Plant – Lessons Learnt, Aug. 2021.

BESS aggregation is coordinated through a cloud based platform, enabling operation as a unified resource within the NEM. From a system operator perspective, the aggregated fleet functions comparably to a conventional power plant, capable of dispatching active power, participating in ancillary service markets, and responding dynamically to grid events. This architecture demonstrates the transition of DER from passive BTM assets to actively managed grid interactive resources.

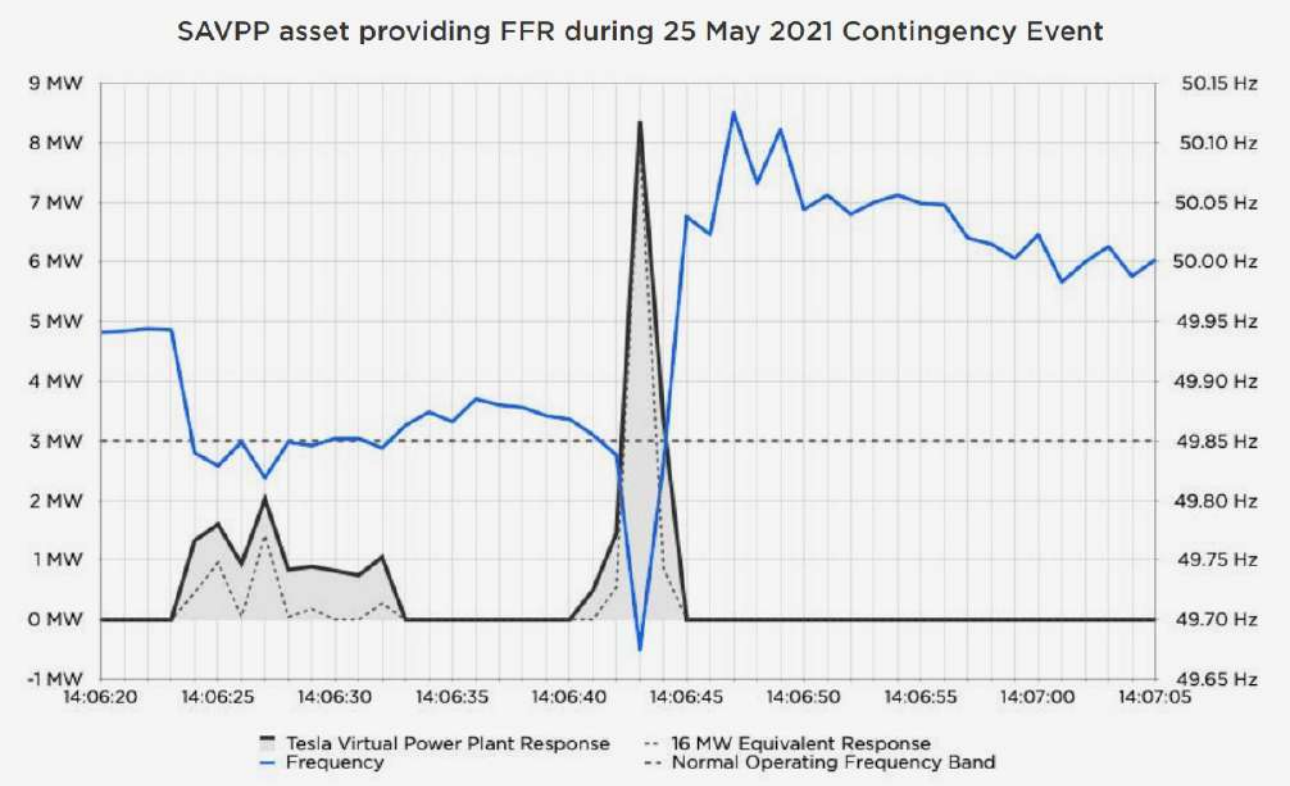
From a grid support perspective, the SAVPP is registered with the AEMO to provide energy and contingency Frequency Control Ancillary Services (FCAS), including raise and lower services across 6 second, 60 second, and 5 minute markets. The distributed batteries have demonstrated rapid response capability, enabling participation in FCAS markets traditionally dominated by synchronous generators and utility scale storage. Under the South Australian Government's Grid Scale Storage Fund (GSSF), the VPP has also trialled advanced services such as fast frequency response, synthetic inertia, and distribution level voltage support. Volt var control curves as shown in Figure 175[426] are implemented to provide localised reactive power support at feeder level, contributing to voltage stabilisation in high solar penetration environments. All SA VPP Phase 2 installations are actively delivering fast frequency response with sub second response capability. Ten selected sites operate with high speed logging at 100 millisecond resolution to accurately capture fleet performance during contingency events. Following the May 2021 Callide C power station incident, the aggregated SAVPP fleet injected approximately 16 MW of active power within one second, contributing to rapid frequency stabilisation as seen from Figure 176[426].

Figure 175 Fast Frequency response delivery following Callide C contingency event



Source: Tesla Virtual Power Plant

Figure 176 Fast frequency response delivery following Callide C contingency event



Source: Tesla Virtual Power Plant

Economically, the project demonstrates the importance of revenue stacking for distributed BESS fleets. Participation in energy arbitrage and contingency FCAS markets forms a core component of the commercial model, with FCAS revenues contributing significantly to early stage viability. Tesla's Autobidder platform optimises bidding and dispatch decisions to capture high price events in energy and ancillary markets. Aggregation enables the fleet to meet minimum market thresholds, unlocking wholesale revenues that individual households cannot access independently. These revenues support the retail offering to customers while maintaining commercial sustainability.

The Phase 3A experience also highlights financing and risk management considerations associated with large scale DER aggregation. Institutional financing support indicates increasing confidence in VPP models, although early challenges included limited insurance products and evolving regulatory frameworks for distributed assets participating in wholesale markets. Overall, the SAVPP confirms that aggregated residential BESS can deliver high quality frequency control, fast response, and voltage support while generating diversified revenue streams. The project serves as a significant technical and commercial reference for integrating distributed BESS into competitive markets with high RE penetration.

11.10 EnTEC Study: Revenue Stacking in Energy Storage Projects

ESS projects rarely depend on a single source of value. Depending on the market structure, ESS technology, grid requirements, and regulatory provisions, ESS may generate revenue through energy arbitrage, ancillary services, capacity payments, transmission and distribution support, BTM services, or other flexibility products. The EnTEC study on ESS provides useful international evidence on how different storage technologies and projects capture value through multiple service categories. These results demonstrate the diversity of business models adopted across electricity storage projects.

The share of revenue by service group and storage technology category are highlighted in Table 63[427]. The results indicate that different storage technologies rely on different dominant revenue streams. For ECES technologies, including BESS, ancillary services account for the largest share of reported revenue. In contrast, chemical and mechanical storage technologies show greater dependence on generation support and bulk storage services. This distinction is important because the economic value of storage is strongly technology dependent. Consequently, the revenue model for a BESS cannot be assumed to be identical to that of PHS, hydrogen based storage, TESS, or other LDES technologies.

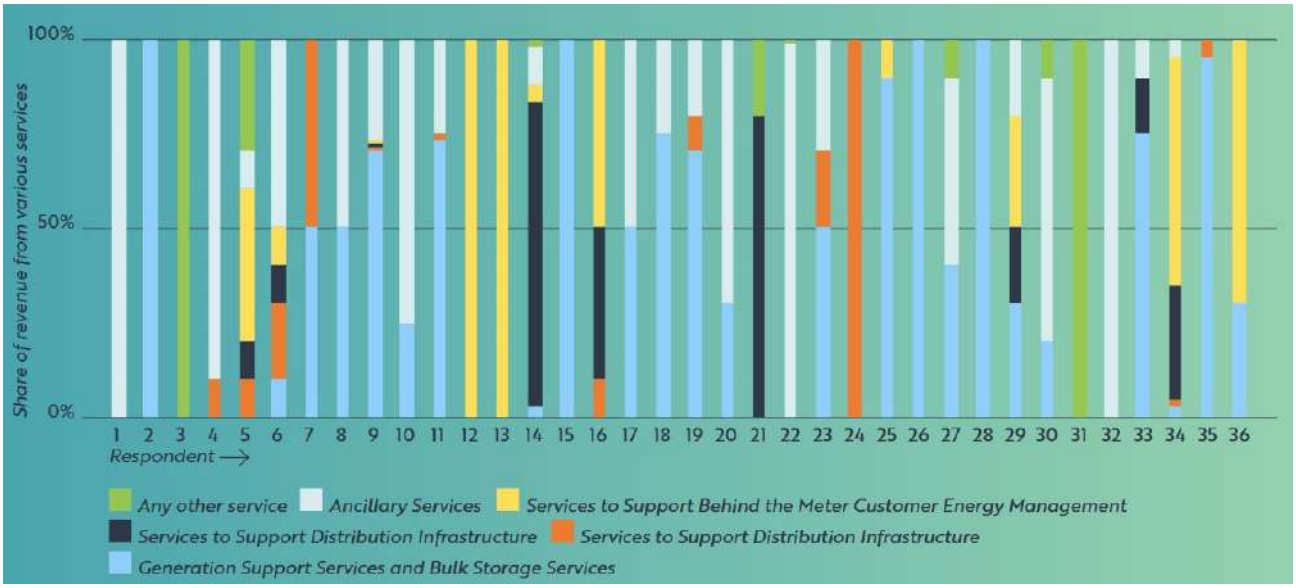
Table 63 Revenue share by ESS technologies

Technology group	Generation support services	Services to Support Transmission Network	Services to Support Distribution Network	Services to Support BTM ESS	Ancillary Services	Any other service
Chemical	59%	14%	9%	1%	3%	13%
Mechanical	49%	12%	16%	1%	21%	0%
Electro-chemical	28%	3%	4%	10%	54%	1%
Thermal	0%	5%	13%	73%	3%	8%
Mix	35%	0%	4%	9%	35%	16%

The concept of value stacking by showing the revenue composition reported by different respondents in the EnTEC study is further illustrated in Figure 177[427]. Each respondent represents a storage technology, project, or portfolio rather than a universal storage plant configuration. The figure shows that while some projects rely primarily on one service category, many combine multiple services to strengthen their business model. This demonstrates that value stacking is often necessary to improve the financial viability and revenue stability of storage projects. For BESS, this implies that project assessment should consider multiple potential revenue streams, including energy arbitrage, frequency regulation, capacity support, RE firming, and grid support services, depending on the applicable market framework.

427 Clean Energy Ministerial, Exploring the Value of Electricity Storage: A Comprehensive International Overview, White Paper, 2025.

Figure 177 Revenue through value staking strategies



Source: cem & Supercharging Battery Storage

However, the revenue shares presented in Table 63 and the patterns shown in Figure 177 should be interpreted as indicative international evidence rather than universal numerical inputs. These results are based on selected EnTEC survey responses and may vary significantly across countries, market structures, tariff mechanisms, asset locations, ESS durations, and operational strategies.



12

CHAPTER 12

CHALLENGES AND RESEARCH DIRECTIONS



AI Image

Summary

- Identifies key technical, commercial, institutional, and supply chain barriers affecting ESS bankability, safety, grid integration, and deployment scalability.
- Compares technology specific challenges associated with different ESS.
- Highlights market and policy constraints, including interconnection delays, uncertain capacity accreditation, incomplete value stacking frameworks, and weak valuation of long duration and resilience services.
- Defines priority research gaps in lifetime prediction, degradation aware control, system level safety validation, interoperability, long duration storage valuation, recycling, and distributed storage aggregation.





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The analysis synthesises non-technical barriers and technology-specific constraints that affect the bankability, safety case, and grid-operational value of ESS across distribution and transmission applications. The organising framework covers (i) technology, physics, and engineering limits, including degradation, safety, and siting; (ii) institutional and commercial constraints, including interconnection, revenue mechanisms, and capacity accreditation; and (iii) material and geopolitical factors, such as critical mineral concentration and recycling capacity. The resulting research directions focus on reducing uncertainty in lifetime, safety, and revenue streams to improve investment outcomes, while expanding the practical operating envelope of both electrochemical and non-electrochemical ESS.

12.1 Technical Barriers by Technology

Technology-specific technical barriers relevant to grid and distribution deployments are summarised in Table 64 based on safety and testing standards and hazard mitigation expectations, and on technology maturity and design constraints.

Table 64 Technology specific technical barrier

Technology	Primary technical barriers	Relevance to deployment	Key research directions
Li-ion BESS	Thermal runaway and fire propagation risk	Limits siting BESS density and indoor deployment	Propagation-resistant pack and module designs
	Accelerated degradation under high C-rate operation and service stacking	Increases insurance, safety compliance, and balance-of-plant costs	Reduced-order electro-thermal degradation models
	Temperature-sensitive ageing and capacity fade	Reduces guaranteed usable capacity over project lifetime	Data-driven SoH and RUL estimation with quantified uncertainty bounds
Sodium-ion BESS	Lower energy density than lithium-ion	Increases footprint and balance-of-system cost	Cathode and anode stability improvements
	Poor low-temperature performance	Bankability depends on demonstrated safety, durability, and cycling performance	Accelerated ageing studies for stationary duty cycles
VRFB	Vanadium electrolyte cost volatility	Suited for long-duration, high-cycle operation with low fire risk	Low-cost, durable membranes and electrolytes
	Membrane crossover and durability limitations	Electrolyte stability and contamination control are critical for long-term performance and bankability	Predictive maintenance for pumps and auxiliaries
	Electrolyte and tank contamination	Cost and auxiliary system reliability affect competitiveness	Electrolyte purification, rebalancing, and contamination monitoring techniques

Technology	Primary technical barriers	Relevance to deployment	Key research directions
SESS	Extremely low energy density	Limited to short-duration, high-power services	Hybrid DC-link and interface designs
	High self-discharge rates	Most effective when integrated into hybrid architectures	Fast and slow dynamics dispatch separation
PHS	Strong site, environment and geography dependence	Highly bankable at transmission scale	Modular or cavern-based PSH concepts
	Long permitting and construction timelines	Generally unsuitable for most distribution-level applications	Streamlined permitting and approval frameworks
Other Mechanical ESS	Geologic and site constraints	Deployment limited to specific suitable sites	Novel thermodynamic cycles
	Turbomachinery and sealing challenges	Economic viability depends on proven efficiency and O&M performance	Flexible operational control strategies
Hydrogen Storage	Low round-trip efficiency due to electrolysis	Suited for multi-day to seasonal energy storage and system adequacy	Higher-efficiency and lower-cost electrolysers and fuel cells
	High capital cost of electrolysers, and storage	Enables large-scale energy shifting and sector coupling with industry and mobility	Advanced hydrogen storage media and containment systems
	Slow dynamic response and limited part-load efficiency	Limited competitiveness for short-duration or high-cycling services due to efficiency and cost	Improved system integration and control for variable RE operation

12.2 Market and Policy Barriers

Market and policy barriers play a major role in determining the pace and scale of ESS deployment across transmission and distribution systems. Even where storage technologies are technically mature, non-technical constraints often dominate project timelines, costs, and investment risk.

Interconnection and queue delays represent a primary constraint. Large volumes of proposed generation and storage projects are awaiting grid connection, with many facing multi-year delays from application to commissioning. For ESS projects, this creates uncertainty around connection costs, network upgrade requirements, and commissioning dates, increasing financing costs and project risk. Interconnection outcomes also influence technical design choices, including converter ratings, protection schemes, and operating modes, directly linking grid processes to technology configuration.

Market design further limits the ability of ESS to realise its full system value. ESS can provide multiple services, including energy shifting, frequency and voltage support, capacity adequacy, congestion management, and resilience. However, many markets treat these services in isolation, apply restrictive qualification rules, or inadequately value long-duration and reliability attributes. This constrains revenue stacking, increases merchant risk, and often favours short-duration storage even where longer-duration systems would deliver greater system benefits. Consequently, project bankability depends strongly on stable, transparent, and durable market rules.

At the distribution level, additional challenges arise from limited visibility and coordination. BTM storage is primarily operated to meet customer objectives, while network operators typically observe only net load at the meter. In the absence of appropriate tariffs, data access, and coordination mechanisms, the ability of distributed ESS to support voltage control, congestion relief, and local reliability is difficult to capture. At the transmission level, uncertainty around capacity accreditation, duration requirements, and performance testing affects how storage competes with conventional resources in adequacy and reserve markets.

Material and supply chain factors further influence deployment. Dependence on critical minerals, exposure to price volatility, and uncertainty around recycling and end-of-life regulation affect technology choice and long-term cost trajectories. These considerations increasingly interact with industrial policy and sustainability requirements, adding another layer of investment risk.

Policy responses are beginning to address these barriers. Interconnection reforms are moving toward clustered studies, clearer readiness requirements, and more standardised cost allocation. Market reforms are gradually expanding service definitions, enabling aggregation, and improving compensation for flexibility and reliability. Together, these developments reflect a shift toward treating energy storage as a core grid resource that requires coordinated treatment across technology design, grid integration, market structures, and supply chains.

12.3 Supply Chain and Geopolitical Risks

Supply chain and geopolitical risks are an important constraint on large-scale ESS deployment, particularly for battery-based systems. Critical materials such as lithium, nickel, cobalt, and graphite are highly concentrated geographically, especially at the refining and processing stages. In many cases, processing capacity is more concentrated than mining, increasing exposure to trade restrictions, price volatility, and supply disruptions. These risks directly affect battery costs, warranty terms, and EPC contracts, and therefore influence project finance and investment decisions.

Domestic mineral resources do not automatically reduce supply risk. Even where local reserves exist, storage supply chains often depend on imported refined materials, battery precursors, and cells due to limited domestic processing and manufacturing capacity. This dependence increases procurement lead times and delivery risk, encouraging developers and policymakers to consider technology diversification, including sodium-ion batteries, flow batteries, and non-battery storage options, to reduce reliance on constrained materials.

Regulatory frameworks are increasingly linking storage deployment to sustainability and supply chain requirements, including material traceability, environmental reporting, recycled content obligations, and end-of-life responsibility. While these measures can increase near-term costs and compliance effort, they also support the development of recycling capacity and secondary material markets. Over time, this can reduce supply risk, improve material security, and influence the long-term economics and technology selection of energy storage systems.

12.4 Research Gaps

Research gaps can be grouped into two broad categories: uncertainty reduction, which improves confidence in performance, safety, and revenues, and operating envelope expansion, which enables new duty cycles, services, and deployment contexts. Addressing these gaps is essential to make energy storage more bankable, scalable, and grid relevant.

- **Lifetime prediction under stationary grid duty cycles:** Reliable lifetime and remaining useful life estimates are critical for financing storage assets that operate under multi-service dispatch, combining high cycling with long calendar exposure. Key gaps include the lack of standardised accelerated ageing protocols representative of grid applications, limited physics-informed SoH and RUL models that generalise across chemistries and vendors, and insufficient long-term field datasets capturing temperature gradients, partial cycling, and irregular dispatch. Current data-driven approaches often fail under changing operating conditions, highlighting the need for hybrid models that combine physics, data, and uncertainty quantification.
- **Degradation-aware control and planning:** Degradation is still treated mainly as a post-processing cost rather than an explicit operational constraint. Research is needed to integrate degradation models directly into dispatch, market participation, and planning tools so that cycling limits, temperature effects, and ageing trade-offs are co-optimised with revenue and reliability objectives. This is especially important for value stacking and long-duration applications.
- **System-level safety engineering and validation:** While cell-level safety has improved, major gaps remain in predicting system-level behaviour during fault conditions. These include validated models for heat release, gas generation, thermal propagation, enclosure pressurisation, and interaction with fire suppression systems. Alignment between laboratory tests, large-scale experiments, and performance-based design criteria is still limited, making it difficult to translate test results into clear engineering margins for codes, standards, and permitting.
- **Grid integration standards and interoperability:** Progress has been made in defining terminology and safety requirements, but gaps remain in interoperable control, communication, and verification standards for grid-connected and aggregated storage. These include harmonised requirements for telemetry, dispatch response, cyber security, measurement and verification, and coordination between transmission and distribution operators. Lack of interoperability increases integration cost and limits the scalable use of distributed and aggregated storage.
- **Planning and valuation of long-duration and resilience services:** Existing market and planning frameworks are well suited to short-duration services but remain weak for long-duration, resilience, and extreme-event applications. Key gaps include probabilistic valuation methods aligned with loss-of-load metrics, consistent capacity accreditation across durations, and integrated assessment of network deferral, adequacy, and resilience benefits. Seasonal and multi-day storage needs are particularly underrepresented in current planning tools.
- **Technology and materials diversification:** Reducing dependence on constrained minerals requires continued development of alternative chemistries such as sodium-ion, flow batteries, and other non-BESS alternatives. Gaps remain in scalable manufacturing pathways, long-term stationary performance validation, system-level safety characterisation, and bankable

warranty structures. Bridging the gap between laboratory performance and commercial-scale deployment remains a key challenge.

- **Supply chain resilience and lifecycle sustainability:** More research is needed on recycling at scale, second-life applications, and integration of recycled materials into new ESS systems without compromising performance or safety. Standardised metrics linking sustainability, material recovery, and lifecycle cost are still lacking, limiting their use in procurement and policy decisions.
- **Distribution-level coordination and aggregation:** At the distribution level, research gaps remain in control architectures and market designs that align customer-operated ESS with network needs. This includes scalable aggregation strategies, real-time coordination with network constraints, and settlement mechanisms that fairly allocate value between customers, aggregators, and utilities.

Together, these research gaps highlight the need for integrated advances across materials, system design, grid integration, markets, and policy. Closing them would reduce uncertainty for investors, expand the practical operating envelope of storage technologies, and ESS to fully support reliable and cost-effective power system decarbonisation.



Pexels



Pexels

CHAPTER 13

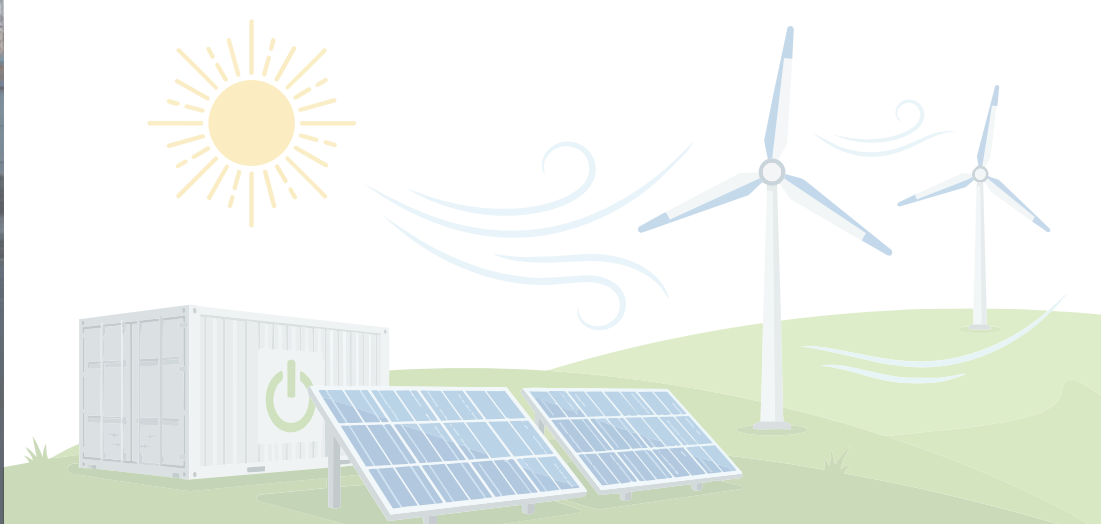
13 FUTURE OUTLOOK & ROADMAP TO 2050



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Summary

- Presents a 2050 roadmap that treats ESS as a portfolio of technologies differentiated by discharge duration, response speed, siting constraints, lifecycle sustainability, and system service capability.
- Highlights the rising role of long duration energy storage for inter day, multi day, seasonal adequacy, renewable drought management, resilience, and reduced dependence on firm fossil backup.
- Explains the growing importance of AI, machine learning, advanced BMS, digital lifecycle governance, and data driven diagnostics across the ESS value chain.
- Emphasises global collaboration for harmonised safety standards, sustainability traceability, long duration storage innovation, circularity, open datasets, and first of a kind project risk reduction.





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A forward-looking roadmap to 2050 must treat energy storage as a portfolio of assets, differentiated by discharge duration, power capability, response speed, siting constraints, and life-cycle sustainability. Over the next three decades, storage will expand from near-term flexibility roles, including diurnal shifting, operating reserves, and congestion relief, toward adequacy and resilience functions that address multi-day RE droughts, extreme weather events, and load growth driven by deep electrification. This shift implies that system planners and regulators will increasingly need: (i) duration-segmented procurement and capacity accreditation frameworks, (ii) scalable safety and interconnection pathways to reduce permitting and delivery risk, and (iii) digitalised operational and life-cycle governance, including advanced BMS, traceability, and circularity, to improve bankability and supply security.

13.1 Long Duration Energy Storage Role

LDES is increasingly treated as a distinct planning resource, as its value is driven by energy adequacy during extended scarcity periods rather than short-term balancing alone. In grid studies, long-duration storage is typically defined as having a discharge duration of at least 10 hours and is further classified into inter-day (approximately 10-36 hours), multi-day (approximately 36-160 hours), and seasonal or very-long-duration categories exceeding 160 hours. These distinctions reflect different scarcity drivers and use cases, such as weather-driven RE shortfalls versus daily ramps.

In net-zero and high-RE pathways, LDES complements short-duration batteries by supporting adequacy during prolonged periods of low RE output, reducing reliance on peaking thermal generation and emergency imports, and easing transmission and distribution constraints by shifting energy across multi-hour to multi-day horizons. As a result, planning emphasis shifts from fast, frequent cycling toward portfolios that also accommodate deep, infrequent cycling. This transition influences technology selection, warranty and degradation assumptions, and revenue design, with capacity-style mechanisms and long-horizon hedging instruments becoming increasingly important. Table 65 presents a duration-based view of storage services and representative technologies suitable for a 2050 roadmap.

While LDES is increasingly positioned as a key enabler in future low carbon power systems, this outlook is driven by evolving system requirements rather than current commercial maturity. As variable RE penetration increases, system challenges shift from short term balancing to managing prolonged supply demand mismatches, including multi day and seasonal variability. Although medium duration ESS are still progressing towards large scale commercial maturity, system level modelling indicates that short and medium duration solutions alone are insufficient to ensure reliability in deeply decarbonised grids. Consequently, LDES emerges as a necessary complement rather than a direct replacement, addressing residual flexibility needs that cannot be economically met by shorter duration assets. Global deployment trends, as illustrated in Figure 178[428] , indicate that early adoption of LDES technologies is underway across multiple regions, signalling increasing policy, market, and investment alignment. This reinforces the view that LDES represents a forward looking system requirement driven by structural grid evolution rather than immediate market dominance.

428 Long Duration Energy Storage Council, System Needs and Policy Imperatives for Long Duration Energy Storage Solutions in India, Policy White Paper, Apr. 2026.

Table 65 Storage technologies suitable for 2050 roadmap

Duration class	Dominant service window	Primary system value mechanisms	Representative technology families (Non-exhaustive)
Sub second to hour	Fast balancing	Frequency control, ramping support, power quality, converter-based grid support	Li-ion BESS, SESS/ FESS
2–10 h (daily)	Daily shaping	Solar shifting, peak shaving, congestion relief, operating reserves	Li-ion BESS (utility/ FTM and BTM), PHS (where available)
10–36 h (inter-day)	Weather-to-weather bridging	Net-load shaping across day pairs, reserve for low-wind/ low-solar periods	FBESS, CAES variants, extended long duration BESS
36–160 h (multi-day)	Prolonged scarcity	Capacity adequacy through multi-day events; reduced firm thermal dependence	FBESS/TESS/CAES/PHS expansion, emerging gravity & chemical pathways
>160 h (seasonal/ very long duration)	Seasonal mismatch	Seasonal energy shifting; resilience under extreme events	Hydrogen-to-power, power-to-heat with TESS, large seasonal reservoirs

Figure 178 Early global adoption of LDES projects worldwide



Source: Long Duration Energy Storage Council

13.2 AI-ML & Data Driven Approaches for ESS Value Chain

As storage deployment scales, constraints increasingly shift from cell cost toward operational reliability, safety assurance, and lifetime utilisation, making advanced BMS a key lever for reducing life-cycle cost and enabling higher utilisation. Next-generation BMS development focuses on (i) hybrid state estimation that combines physics-informed and data-driven methods under partial cycling, (ii) pack-level digitalisation through fleet analytics, anomaly detection, and prognostics, and (iii) closed-loop safety management that links early warning indicators with protection logic and validated propagation assumptions. Recent reviews of SOH estimation and battery management highlight the use of higher health indicators, including incremental capacity and differential voltage features, impedance-based metrics, and thermal signatures, supported by machine-learning pipelines for robust SOH and RUL estimation under field variability.

For utility-scale and distribution applications, including SLBs, BMS must also manage heterogeneity arising from cell-to-cell variation, mixed ageing histories, and differences in internal resistance. These factors directly affect usable energy, thermal margins, and protection coordination, increasing the importance of calibration discipline, model governance, cybersecurity of telemetry and control, and interoperability frameworks that enable validation across modules and vendors. In parallel, safety codes and test methods increasingly specify installation requirements, hazard mitigation measures, and propagation assumptions that BMS must support at the system level, including emergency shutdown, monitoring, and protection integration.

AI and ML are already being deployed especially across battery manufacturing to enhance production efficiency and quality control. Advanced data driven models are used for in line process monitoring, defect detection, and yield optimisation across key stages such as electrode manufacturing, cell assembly, and formation. These systems integrate sensor data, imaging techniques, and electrochemical signatures to identify process deviations, enabling real time corrective actions and reducing variability in cell performance. In addition, AI enabled analytics support end of line testing, grading, and predictive quality assessment, improving consistency and reliability at scale. This growing adoption reflects a shift towards digitalised, closed loop manufacturing environments, where continuous data feedback enhances both product quality and operational efficiency. A detailed representation of AI-ML enabled production and quality control workflows is provided in the Appendix C.

13.3 Global Collaborations

The 2050 roadmap is increasingly shaped by cross-border coordination on sustainability and life-cycle transparency, harmonised safety assurance, and innovation in long-duration storage and circularity. A key trend is the adoption of digital product traceability mechanisms, commonly referred to as battery passports, to support sustainability claims, due diligence, and end-of-life management. This direction is reflected in both global framework initiatives and binding regional regulations that specify battery information disclosure and compliance requirements. In parallel, multinational mission-oriented platforms and ministerial initiatives are coordinating research, demonstration, and best-practice exchange for energy storage deployment, including long-duration technologies and system integration. These efforts are most effective when they standardise performance and safety validation, expand first-of-a-kind risk-sharing mechanisms, and support open benchmarking datasets for forecasting, degradation, and safety modelling, thereby reducing financing uncertainty and improving project bankability.



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14

CHAPTER 14

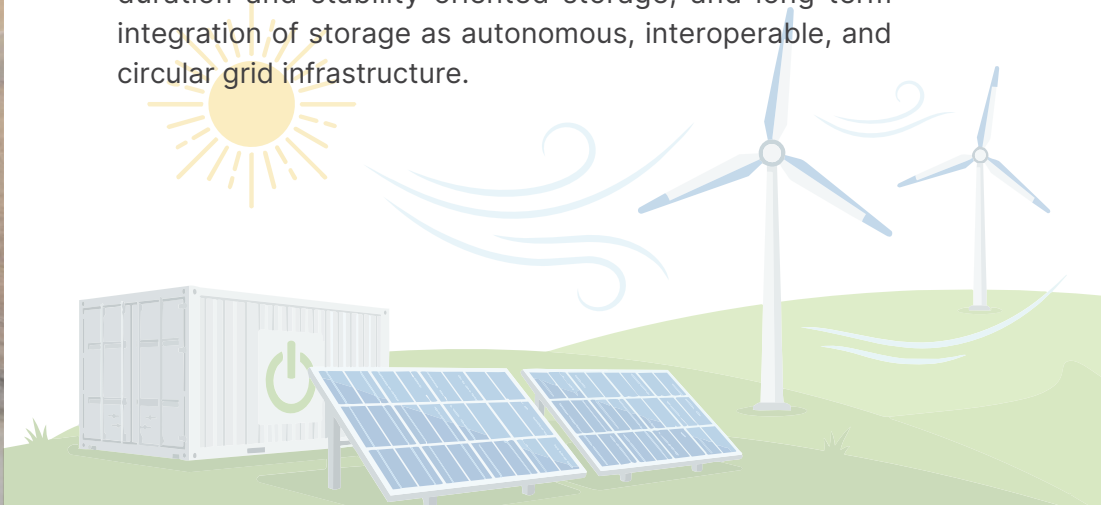
CONCLUSION



Sig. Chiocciola, CC0, via Wikimedia Commons

Summary

- Summarises the key takeaways of the report that ESS is becoming foundational infrastructure for RE dominant power systems, supporting flexibility, adequacy, stability, resilience, and secure operation.
- Establishes that future ESS planning must move from technology centric deployment to capability based procurement, where duration, response speed, deliverability, availability, ramping capability, and dynamic grid support performance are explicitly valued.
- Highlights key policy, market, and technical requirements, including revenue stacking, grid forming capability, validated modelling, interoperability, cybersecurity, lifecycle governance, and safety assurance.
- Provides a strategic roadmap covering near term deployment optimisation, medium term scaling of long duration and stability oriented storage, and long term integration of storage as autonomous, interoperable, and circular grid infrastructure.





UnSplash

This report concludes that ESS is evolving from a supplementary grid asset into a foundational infrastructure layer essential for the reliable, economic, and secure operation of renewable dominant power systems. As penetration of variable renewable energy increases, power systems are required to manage higher levels of uncertainty, steeper and more frequent net load ramps including duck curve effects, transmission congestion and RE curtailment, and an expanding set of adequacy and resilience risks. ESS is uniquely positioned to address these challenges because it can function simultaneously as a fast responding power resource and as an energy buffer across multiple temporal scales, ranging from sub second services such as frequency control and stability support, to hourly applications including energy shifting and peak shaving, and increasingly to multi day durations required for system adequacy during extreme events and prolonged low renewable periods.

One of the findings of this report is that no single storage technology can efficiently and adequately satisfy the full spectrum of system requirements. Optimal deployment therefore requires a portfolio based and capability driven approach, in which storage resources are assessed and procured based on clearly defined and measurable attributes rather than nominal capacity alone. These attributes include discharge duration, response time, ramping capability, deliverability under network constraints, availability during system stress periods, and dynamic performance in providing grid support services. This capability centric framework becomes increasingly critical as power systems transition toward converter dominant operation. With the progressive displacement of synchronous generation, services that were historically provided implicitly such as inertia, fault current contribution, and voltage strength must now be explicitly designed, validated, and procured. In this context, the future value of ESS extends beyond energy arbitrage to its role as an active grid supporting asset capable of delivering advanced ancillary services and directly contributing to system security and stability.

The report further highlights that large scale deployment of ESS is not solely an engineering challenge but equally a subject of adequate market design, governance, and digital integration. ESS project economics increasingly depend on multi service operation, where financial viability relies on effective revenue stacking across energy, capacity, and ancillary service markets. At the same time, achieving reliable and predictable performance at scale requires advanced digital capabilities, including real time monitoring, forecasting, analytics, automated control, and robust cybersecurity. Accurate modelling and dynamic simulation, supported by standardized interoperability and data frameworks, are essential to embed ESS confidently within system planning, operational decision making, and reliability assessment. Together, these technical, institutional, and digital enablers will determine the extent to which energy storage can fulfil its emerging role as a cornerstone of future power systems.

14.1 Key Insights

The synthesis across this report yields six core insights that collectively define the evolving role of energy storage in modern power systems.

- **Energy storage functions as a multi timescale system asset:** ESS supports fast acting stability services and short term balancing while also delivering mid duration flexibility and long duration adequacy. This ability to operate across multiple temporal scales is fundamental to managing renewable variability, steep net load ramps, and both routine and extreme contingency events in renewable dominant power systems.

- **A capability based portfolio approach outperforms technology centric planning:** Because grid requirements vary significantly across locations and time horizons due to congestion patterns, curtailment risk, stability requirements, peak demand characteristics, and exposure to extreme events, ESS deployment must be driven by system capabilities rather than by technology categories alone. Planning and procurement should therefore be based on measurable attributes including:
    - Duration and deliverability under network constraints
    - Dynamic response speed and ramping capability
    - Availability and reliability, including forced outage behaviour
    - Lifecycle performance under realistic operating and duty cycles
- **Converter dominant power systems require explicit stability engineering:** As synchronous generation is progressively displaced by power electronic resources, system stability can no longer be assumed as an inherent property of the grid. ESS and other converter based resources are increasingly required to provide explicitly engineered stability services, including:
    - GFM operation where system strength is limited
    - Synthetic inertia and fast frequency response
    - Fault ride through capability and dynamic reactive power support
    - Voltage control and oscillation damping

  Realizing these capabilities at scale requires validated models, standardized testing procedures, and clearly defined operational and protection frameworks.
- **Multi service revenue stacking is a structural requirement for bankability:** The economic viability of ESS projects increasingly depends on the ability to deliver multiple services over their operating life. Revenue stacking across energy shifting, capacity or availability mechanisms, and ancillary services is therefore not optional but fundamental to project bankability. Market designs must evolve to enable transparent and efficient stacking while avoiding double counting and ensuring appropriate service prioritization during periods of system stress.
- **Digitalization is decisive for both operational performance and economics:** Digital capabilities including high resolution telemetry, forecasting, degradation aware dispatch, predictive maintenance, and automated control increasingly determine realized availability, revenue capture, and lifecycle cost. As ESS deployments scale from individual projects to coordinated fleets, digital control and analytics become system level capabilities rather than plant specific features.
- **Robust modelling and standardized interoperability are prerequisites for full system value:** To unlock the full value of ESS, planning and operational frameworks must treat ESS as an active grid resource rather than a passive balancing asset. This requires consistent modelling approaches, including dynamic simulation where system conditions warrant it, together with standardized communication interfaces and data transparency. These measures reduce

uncertainty in performance and valuation, lower risk premiums, and improve both investment and system planning outcomes.

14.2 Policy Recommendations

To translate the technical insights of this report into deployable and scalable outcomes, the following policy recommendations are proposed.

- **Adopt technology neutral and capability based ESS frameworks:** Policy and regulatory frameworks should classify and value ESS according to the services it can reliably deliver, such as flexibility, adequacy contribution, and stability support, rather than by technology type. Explicit recognition of long duration and stability oriented capabilities is essential to avoid structural bias toward short duration applications that may not address system level risks.
- **Enable multi service revenue stacking with robust settlement and prioritization rules:** Market structures should explicitly permit energy storage to provide multiple services, including energy shifting, frequency regulation, voltage support, inertia emulation, contingency reserves, and congestion relief, where technically feasible. At the same time, regulators and system operators must define clear frameworks for:
  - Service prioritization during contingency and system stress conditions
  - Measurement, verification, and performance auditing standards
  - Settlement mechanisms that prevent double counting of the same physical capability
- **Standardize grid codes for converter based resources and require verified dynamic performance:** Grid codes should include clear and enforceable performance requirements for fault ride through capability, dynamic reactive power response, and, where supported by system studies, GFM operation. Compliance should be based on validated models, standardized commissioning and acceptance tests, and periodic performance verification to ensure that real world behaviour aligns with planning assumptions.
- **Support demonstrations and early commercialization pathways for emerging capabilities:** Targeted policy support is required to de risk the transition from pilot projects to commercial deployment for ESS configurations that deliver long duration capability, advanced stability services, or hybrid system value. The objective is to validate technical performance, reliability, safety, and system benefits using measurable benchmarks and replicable testing and commissioning practices.
- **Mandate digital monitoring, interoperability standards, and cybersecurity compliance:** Large grid connected ESS assets should be required to provide secure and high resolution telemetry, standardized communication interfaces, and compliance with cybersecurity requirements. Policy frameworks should embed digital event reporting and performance data transparency to support operational reliability, system planning, and continuous sector learning.
- **Treat safety and lifecycle governance as foundational infrastructure requirements:** Safety and lifecycle governance should be treated as core infrastructure obligations rather than project specific considerations. Policy should establish baseline requirements for safety cases, integration with emergency response systems, incident reporting, and full lifecycle accountability. For repurposed or second life applications of ESS, additional requirements

should include asset traceability, qualification testing, and clearly defined warranty and responsibility structures.

14.3 Industry and Academia direction

14.3.1 Priorities for Industry

The transition of ESS from a niche technology to a system critical infrastructure requires coordinated progress across industry, academia, and system operators. The following directions outline priority areas for action and collaboration.

- **Service oriented ESS solutions:** Industry development should focus on modular and configurable ESS optimized for clearly defined services, including fast frequency response, long duration energy delivery, stability support, and hybrid operational value across multiple markets and network conditions.
- **Digital ESS platforms:** Advanced digital platforms are increasingly essential to maximize both operational performance and economic returns. Priorities include predictive maintenance, market and dispatch optimisation, degradation aware control strategies, and automated bidding and dispatch systems capable of operating across multiple services and time horizons.
- **Retrofit and uprating opportunities:** Significant value can be unlocked by retrofitting existing ESS assets with advanced control functions, improved power electronics, and standardized communication interfaces. Such upgrades can expand service capability, extend asset life, and improve alignment with evolving grid and market requirements.
- **Alignment of bankability with operational reality:** Warranties, performance guarantees, and contractual structures should reflect realistic duty cycles and multi service operation rather than idealized single use cases. This alignment should be supported by verified testing protocols and transparent performance metrics to reduce risk for investors and system operators.

14.3.2 Priorities for Academia and Research Institutes

The following directions are outlined for academia and research institutes to carry out advanced R&D in ESS.

- **Control co design for multi service stability provision:** There is a critical need for control architectures that enable simultaneous provision of GFM behaviour, inertia emulation, and voltage support without adverse interactions or instability across operating conditions.
- **Lifecycle and reliability science:** Further work is required on degradation mechanisms, thermal limits, availability modelling, and uncertainty quantification, with these factors explicitly embedded into planning, dispatch, and economic assessment frameworks.
- **Cross domain system studies:** Integrated system level studies should assess the combined operation of ESS with RE generation, network infrastructure, demand response, and digital control systems to identify least cost and high reliability pathways for system operation and expansion.

14.3.3 Collaboration between Industry, Academia, and Grid Stakeholders

Pathways for collaboration between the stakeholders involved in ESS are mentioned below:

- **Utility scale pilots and living laboratories:** Collaborative demonstration projects are essential to validate end to end performance, interoperability, cybersecurity resilience, and market value under real world operating conditions.
- **Standardization and translation to practice:** Joint efforts should focus on translating research outcomes into practical standards, including grid code provisions, validated model libraries, and standardized commissioning and acceptance testing procedures.

14.4 Strategic Roadmap

Short term, 0 to 5 years: Optimise mature deployment and establish enabling foundations

In the near term, priority should be given to accelerating the deployment of ESS for system flexibility and for the reduction of congestion and RE curtailment through capability based procurement frameworks. Planning and interconnection processes should be strengthened by establishing standardized modelling approaches and consistent use of dynamic studies where system conditions warrant them. At the operational level, utilities and asset owners should implement digital monitoring, EMS upgrades, and degradation aware dispatch strategies across storage fleets to improve reliability and economic performance. Grid codes and commissioning standards must be reinforced to ensure predictable converter based performance, particularly with respect to fault ride through capability and dynamic reactive power behaviour. In parallel, cybersecurity requirements, safety governance, and transparent incident reporting should be embedded as default infrastructure practices.

Medium term, 5 to 10 years: Scaleup long duration deployment and mainstream stability oriented capabilities

Over the medium term, policy and market structures should support the scaling of long duration and resilience focused storage through bankable contracting mechanisms that explicitly value availability and deliverability during system stress periods. Grid requirements should progressively evolve toward stability capable converter behaviour, including GFM operation were supported by system studies, with compliance underpinned by verified models and field validated performance. ESS should be systematically integrated into transmission planning, congestion management, and resource adequacy assessments using probabilistic methods and realistic assumptions regarding availability and degradation. At the same time, market frameworks should be expanded to enable broader service stacking, supported by well-defined performance measurement, verification, and settlement rules that maintain system security and investment confidence.

Long term, beyond 10 years: ESS as core infrastructure with autonomous fleet level control

In the long term, energy storage should be positioned as a permanent and indispensable component of grid adequacy, stability, and flexibility in renewable dominant power systems. Large scale, interoperable ESS fleets should operate with a high degree of automation, delivering real time stability and operational services under strong cybersecurity protections and clear system operator oversight. Full coordination across ESS, RE generation, network infrastructure, flexible demand, and digital platforms should be achieved through standardized interoperability frameworks and integrated planning methodologies. At the same time, lifecycle management and circularity

governance should mature to reduce material supply risks, manage end of life pathways, and improve sustainability outcomes as storage deployment scales globally.

14.5 Final Synthesis

This report concludes that the decisive question for future power systems is no longer whether ESS is required, but how rapidly policy frameworks, market designs, technical standards, and operational practices can evolve to treat storage as a controllable and stability relevant infrastructure asset. As RE penetration increases and system inertia declines, the effectiveness of ESS deployment will be determined less by installed capacity alone and more by the extent to which ESS is integrated into planning, operations, and reliability frameworks as an active system resource.

The least cost and most reliable transition pathway are capability centric. ESS must be planned, procured, and operated based on its ability to deliver clearly defined system services, including flexibility, adequacy contribution, deliverability under network constraints, and dynamic stability support. Realising this value requires enabling foundations in the form of modern grid codes, standardized and validated dynamic modelling practices, high quality digital telemetry, interoperable control architectures, and robust cybersecurity provisions.

Over the coming decade, power systems that succeed in managing high shares of variable RE will be those that move beyond a narrow focus on energy arbitrage and instead deploy ESS as a multi service platform. In this role, ESS supports RE integration, reduces curtailment, strengthens system security in converter dominant operation, and enhances resilience under increasingly uncertain and extreme operating conditions. Treating ESS as core infrastructure rather than a supplementary asset is therefore central to achieving reliable, economic, and secure decarbonised power systems.

Appendix

Appendix A

Technology Readiness Level

TRL progression of major ESS technologies between 2020 and 2025, highlighting differences in commercial maturity, demonstration status, and deployment readiness across ESS categories is summarised in Table A1[1,2].

Table A1 TRL levels of BESS technologies

Technology name	Technology Readiness Level					
	2020	2021	2022	2023	2024	2025
Lead Acid Battery	9	9	9	9	9	9
Lithium-ion storage battery	9	9	9	9	9	9
Metal-air storage battery	4	4	4	5	6	7
Redox flow storage battery	8	8	9	9	9	9
Sodium-ion storage battery	5	7	7	7	8	9
Zinc-manganese oxide storage battery	3	4	4	4	4	4
Compressed air energy storage	8	8	8	8	8	9
Flywheel	9	9	9	9	9	9
Gravity-based storage (Excluding pumped hydro)	7	7	7	7	7	7
Liquid air energy storage	7	7	7	7	7	7
Pumped storage	9	9	9	9	9	9
BESS with grid-forming inverter	-	-	-	-	9	9
Transactive energy	4	4	4	4	4	5
Virtual inertia	-	-	7	7	7	8
Virtual net metering - community scale solar (building demand response)	8	8	9	9	9	9
Virtual power plants	-	-	-	-	-	9
Digital twins	-	-	-	-	9	9
Distributed energy resource management systems	-	-	-	-	-	8
Smart inverter	8	8	8	8	8	9

1 IEA, “ETP Clean Energy Technology Guide,” International Energy Association, Feb. 2026.
2 GIL Research

Technology name	Technology Readiness Level					
	2020	2021	2022	2023	2024	2025
High-temperature latent heat storage	6	6	6	6	6	6
Ice storage (latent heat)	9	9	9	9	9	9
Low-temperature latent heat storage	-	-	-	7	7	7
Molten metal storage	-	-	-	4	4	4
Molten salts storage	-	-	-	7	7	8
Solids storage	8	8	8	8	8	9
Combined latent and sensible storage system	8	8	8	8	8	8
Electrical storage for building systems integration	9	9	9	9	9	9
Active latent heat storage	4	4	4	4	4	4
Ice slurry thermal storage	-	-	-	-	-	9
Solid-solid thermal storage	8	8	8	8	8	8
Thermo-chemical storage	4	4	4	4	4	4
Aquifer thermal energy storage	9	9	9	9	9	9
Borehole thermal energy storage	9	9	9	9	9	9
Pit thermal energy storage	-	-	-	-	-	9
Sand thermal battery	-	-	-	-	-	8
Underground cavern thermal energy storage	-	-	-	-	-	9
Super Capacitor	-	-	-	-	-	9
Super Conducting Magnetic Energy Storage	-	-	-	-	-	6
Automatic battery recycling	3	4	4	4	4	4
EV battery reuse in BESS	4	4	4	5	5	5
Battery direct recycling	3	3	3	4	5	5
Battery passport	2	3	3	5	6	6
Electrochemical recovery systems	4	4	4	6	7	7
Virtual model of the entire recycling process	-	-	-	8	8	8

Appendix B

Global BESS Supply Chain Ecosystem

The global BESS supply chain ecosystem, highlighting major public companies with market capitalisation or valuation exceeding USD 1 billion across raw materials, materials processing, cell manufacturing, system assembly, and recycling segments is described Figure A1[3].

Figure A1 Public companies with market cap/ valuation greater then $1 Billion

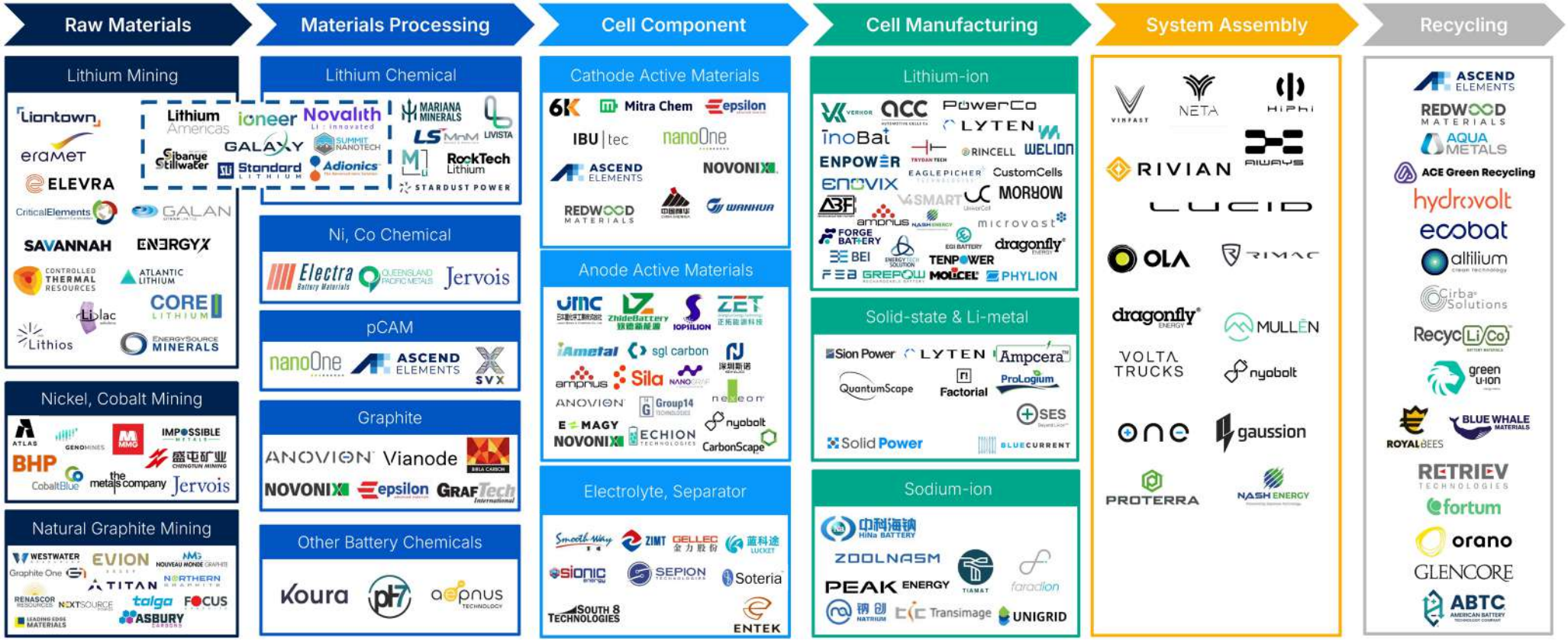


Source: Volta Foundation

3 The Battery Report 2025." Volta Foundation, 24 January 2026.

The global BESS supply chain ecosystem, highlighting major public companies with market capitalisation or valuation exceeding USD 30 million across raw materials and its processing, cell manufacturing, system assembly, and recycling segments is described Figure A2[3].

Figure A2 Public companies with market cap/ valuation greater then $1 Billion



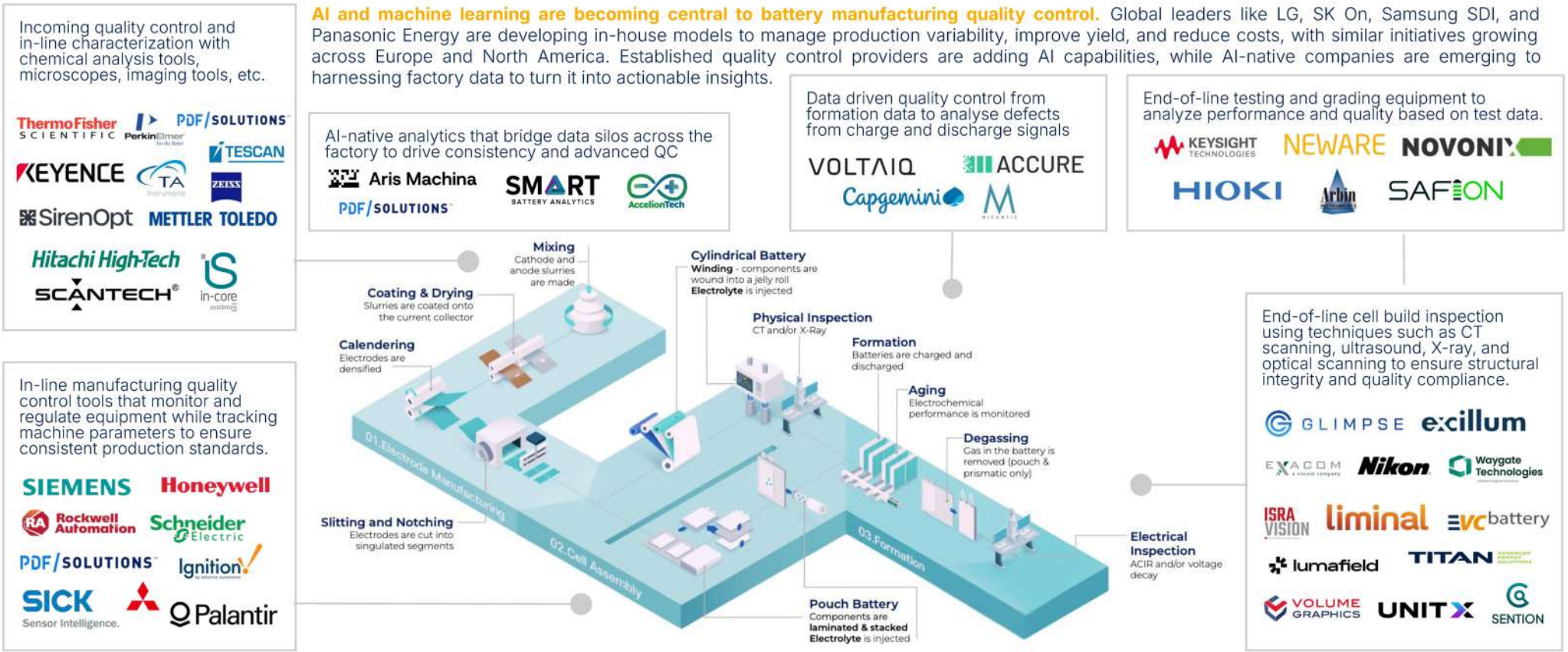
Source: Volta Foundation

Appendix C

OEM Adoption of AI/ML in BESS Manufacturing

The application of AI and machine learning across BESS manufacturing and quality control processes, highlighting major industrial participants involved in inspection, analytics, process optimisation, and end of line testing is highlighted in Figure A3[3].

Figure A3 AI/ML enhanced BESS production & quality control



Source: Volta Foundation

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