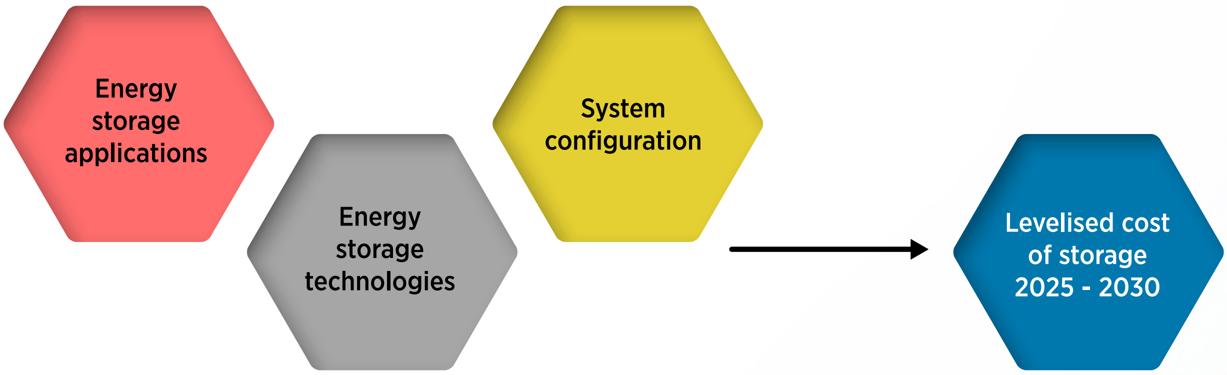
Energy Storage Cost-of-service Tool 2.0[1]

Energy storage systems (ESS) are increasingly essential for supporting a high penetration of renewables while maintaining a reliable supply of electricity. Applications vary by response speed: fast-response services support grid stability; medium-response services optimise efficiency; and long-duration storage enhances system reliability and enables the use of higher shares of renewable energy.

The tripling renewable power capacity target by 2030 will require battery storage capacity to increase between two and five times by 2030, depending on national contexts,[2] making cost assessment critical. Understanding techno-economic characteristics helps developers, policy makers and investors identify high-value storage applications and make informed decisions.

IRENA's spreadsheet-based Energy Storage Cost-of-service Tool 2.0 offers a quick and accessible means to estimate the annual cost of storage services for different technologies and applications. While not a detailed investment model, it allows users to identify potentially cost-effective options for further assessment of performance, suitability and economics.

The data, summarised in the chart below, forms the basis for the analyses.



Key messages: Energy storage[3]

System-level battery storage costs fell 93% from USD 2 571 per kilowatt hour (kWh) in 2010 to USD 192/kWh in 2024 owing to technological improvements, enhanced efficiency, manufacturing scale and increased market competition.

Energy arbitrage is the dominate use for storage globally – making up 68% of new capacity in 2024 – and helps to balance renewable generation and demand.

Lithium iron phosphate (LFP) batteries are rapidly gaining market share – from 48% in 2021 to an estimated 85% in 2024 – driven by lower costs, longer life and improved safety.

Supportive policies and regulations are critical to fully realise energy storage potential.

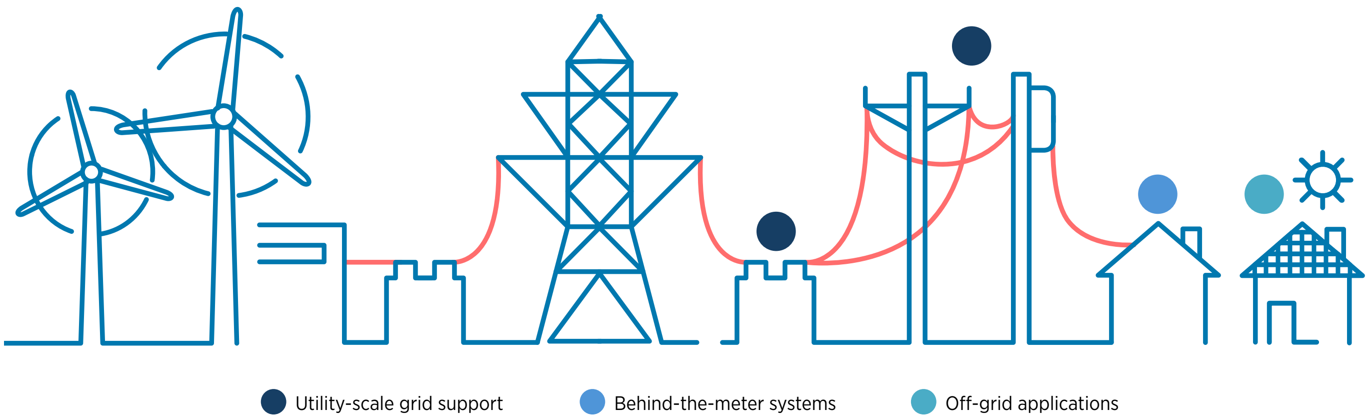
[1] *The Cost-of-service Tool has been updated by Jonas van Ouwerkerk, Lucas Koltermann and Jonas Brucksch (ISEA RWTH Aachen) and revised by Deborah Ayres, Lourdes Zamora and Yasuhiro Sakuma (IRENA).*

[2] *IRENA, COP30 and GRA (2025).*

[3] *IRENA (2025).*

Energy storage applications

Stationary energy storage systems serve three main roles: utility-scale grid support, behind-the-meter systems, and off-grid applications. All these applications are considered in the Cost-of-service Tool, and an overview of these is presented below:



Energy arbitrage

Energy price arbitrage involves responding to differences in electricity market prices. It can be conducted on day-ahead and intra-day markets, and optimised within or across them.

Co-location

Renewable generation plants and energy storage systems share the same grid connection point.

Spinning reserve, synthetic inertia and fast frequency response

These are applications designed to stabilise the grid. Available products vary by region and country. Algorithms adjust inverter output to damp rapid frequency changes.

Peak shaving

Storage is used to provide additional energy during peak load times, avoiding high peak load charges and reducing stress on the power grid.

Multi-use

Combination of two or more operating strategies.

Self-consumption

Surplus energy is stored in batteries for use in the evening and at night, lowering grid supply costs and reducing feed-in during peak PV generation.

T&D investment deferral

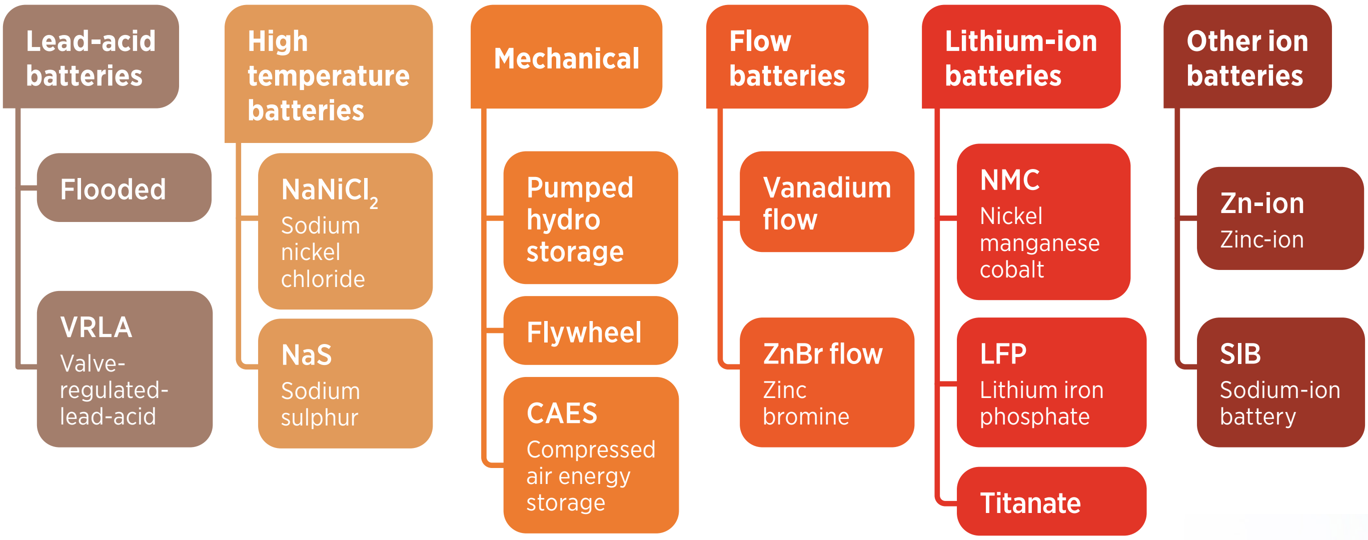
Reduce transmission and distribution investments and relieve grid constraints by installing batteries at each end of a congested line (Grid Boosters).

Island (off-grid) and mini grids

Use of battery storage to integrate renewable power generation, in off-grid and mini-grid systems, improving stability and reliability of electricity supply.

Energy storage technologies

The Tool covers a range of energy storage technologies, including electrical, electrochemical and mechanical systems. These are illustrated in the figure below, with detailed information provided in the accompanying table.



Technology	Efficiency	Calendar life	Cycle life	Typical C-rates	Self-discharge
Lead-acid	65% – 85%	5 – 15 years	500 – 2 000	<1 /hour	c. 0.3% per day
Sodium sulphur (NaS)	82% – 91%	15 – 33 years	2 500 – 10 000	0.1 – 0.25 /hour	c. 7% / day
Pumped hydro	70% – 92%	60 – 100 years	50 000 – 100 000	0.01 – 0.2	0% – 0.02% / day
Fly wheels	70% – 99%	15 – 25 years	0.2 – 2 million	2 – 200	20% – 100% / day
Compressed air energy storage (CAES)	40% – 80%	50 – 100 years	50 000 – 100 000	0.05 – 0.1	0.5% – 1% / day
Redox flow batteries	60% – 85%	5 – 32 years	10 000 – 14 000	0.05 – 0.5	0.5% – 1% / day
Lithium-ion NMC	90% – 98%	8 – 20 years	1 500 – 2 500	1 – 3 /hour	c. 0.1% / day
Lithium-ion LFP	90% – 98%	10 – 20 years	2 500 – 10 000	1 – 3 /hour	c. 0.1% / day
Sodium-ion battery (SIB)	90% – 95%	10 – 20 years	2 000 – 5 000	<4 /hour	c. 0.3% / day

Notes: LFP = lithium iron phosphate; NMC = nickel manganese cobalt.

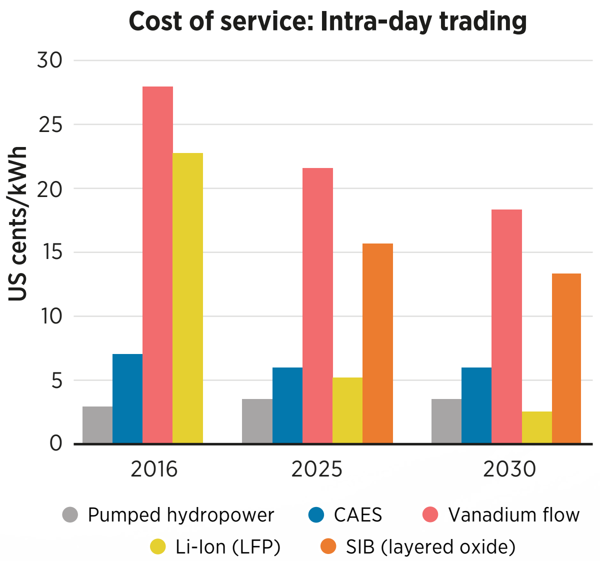
Cost drivers like lifetime, daily cycles, and balance-of-system needs are highly non-linear and depend on the system integrator's design choices. To keep system design variability manageable, the tool uses market-typical configurations or, when unavailable, well-founded estimates.

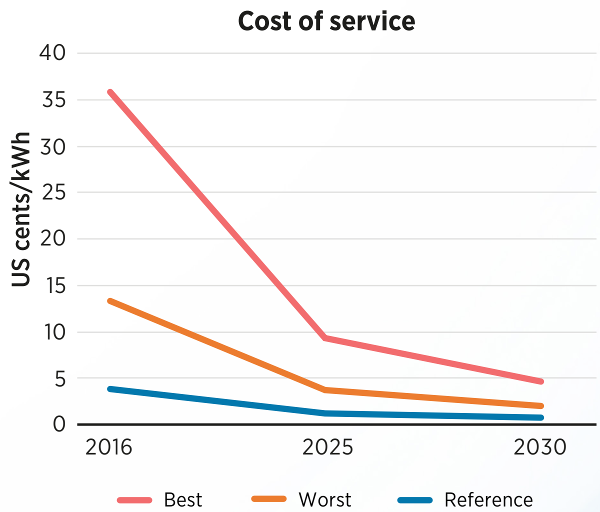
Levelised cost of storage

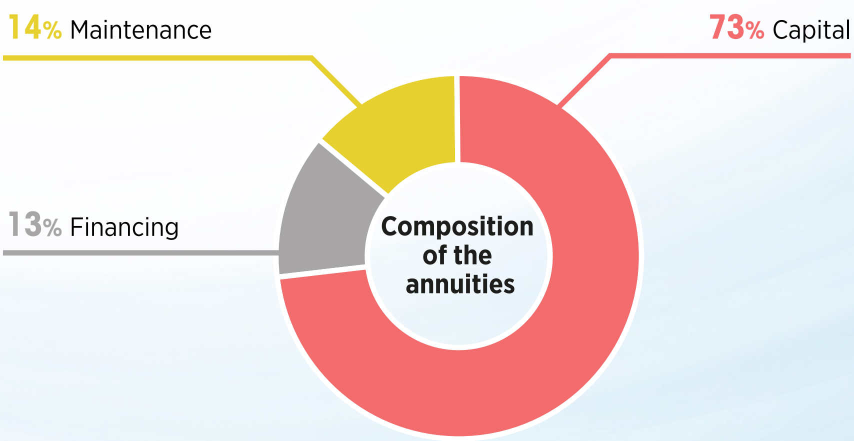
The cost development for storage systems through 2030 is calculated based on user-defined scenarios that incorporate different assumptions and parameters. For each scenario, specific design choices must be defined, with these having a significant impact on the overall cost of service. The main parameters include:

- **Power conversion unit** converts electricity between the grid and the storage system. Options: Electric machine; inverter; no inverter.
- **Grid connection** defines how the system links to the grid. Options: No grid connection; select voltage level; inclusion of transformer; and substation.
- **Storage size** specifies the capacity of the system. Options: Own storages can be integrated, or standard storages can be used.
- **Storage applications** refer to how the storage is used. Options: Utility-scale grid support; behind-the-meter systems; off-grid applications.
- **Location or country** correspond to the local conditions such as land costs, interest rates, electricity prices and maintenance factors that can be manually entered into the Tool to adjust the calculations to the local context.
- **Effect of cyclic** represents battery degradation over charge–discharge cycles. A fatigue exponent and a cycle life degradation curve are applied to determine the equivalent full cycles, depending on the depth of discharge (DOD) and the cycling characteristics of the storage technology.

Using these parameters and technology data, the Cost-of-service Tool calculates investment and operating costs (including efficiency losses, self-discharge and maintenance) for a reference plant. Based on a specific interest rate, levelised costs of storage (LCOS) are then derived on a per-kW and per-kWh basis. The resulting outputs are displayed in the form of charts accessed via the Tool's 'Visualisation' tab:







Unlocking the potential of energy storage systems

Using the Cost-of-service Tool in combination with insights on market trends, technology developments and policy frameworks facilitates more strategic energy storage deployment decisions. Some key points related to these factors are presented below:

Opportunities

- **Enhanced flexibility:** Provides frequency response, ramping, peak shaving and congestion relief, supporting higher renewable integration.
- **Rapid growth:** Global battery energy storage system (BESS) capacity nearly doubled in 2022–2024 and continues to rise.
- **Falling costs:** Lithium-ion cell and pack prices dropped by around 20% in 2024, reaching USD 115/kWh, expanding economically viable applications.
- **New revenue streams:** Mitigates negative-price exposure for renewables and captures intraday trading value.
- **Market optimisation:** Dynamic cross-market strategies are key to maximising returns.

Barriers

- **Market limitations:** Multi-service value stacking is restricted; grid codes and interconnection processes lag behind storage capabilities.
- **Revenue uncertainty:** Volatile spreads, fluctuating ancillary service prices, market saturation and future cannibalisation complicate financing.
- **Regulatory and permitting challenges:** Siting, fire codes, land use and supply-chain traceability remain inconsistent in some regions (*e.g.* Germany).
- **Long-duration costs:** Batteries exceeding 8–10 hours still face high costs limiting broad adoption.

Technology

- **LFP lithium-ion:** Dominates 1–4 hour storage; low capital costs; long cycle life; cobalt-free.
- **Sodium-ion:** Emerging alternative; lower material costs; better cold-weather performance; suited to stationary applications where moderate energy density is sufficient.
- **Long-duration solutions:** Flow batteries and CAES gaining attention; while currently limited to use-case-specific deployments, policy support and innovation efforts are targeting significant cost reductions by 2030, making them important as renewable energy penetration increases.

Policy

- **Supportive policy and regulatory framework:** Essential to unlock the full potential of energy storage systems.
- **Regulatory recognition:** Storage should be a distinct asset class with full revenue stacking across energy, ancillary services, capacity and distribution.
- **Grid integration:** Streamline interconnection with standardised grid codes, transparent queue management and firm timelines.
- **Supply and sustainability:** Invest in cell manufacturing to reduce supplier dependence. Sustainability must be embedded across the value chain, including enabling second-life applications and regulating lifecycle impacts.