Electricity storage

A booming sector of technology

September 2024

KEARNEY | Energy Transition Institute

Compiled by the Kearney Energy Transition Institute

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Robin Girard, director of the PERSEE Center at Mines PSL for this extensive review; and Claude Mandil, Adnan Shihab-Eldin, Antoine Rostand, Maria de Kleijn, and Richard Forrest, members of the board for the Kearney Energy Transition Institute. Their review does not imply endorsement of this FactBook or agreement with any specific statements herein. The review/assessment is based on own reviewers' views and opinions and does not necessarily reflect the views or positions of any entities they represent.

About the FactBook: Electricity storage

This factbook intends to cover technologies that can store electricity for future use (mainly in the form of electricity but also heat, chemicals, fuels, etc.). Based on this definition, the FactBook aims to summarize the status of the electricity storage industry, covering both current and emerging technologies. It outlines the market status and its evolution, offering insights into the costs associated with electricity storage. The report delves into the battery value chain and examines the business models surrounding electricity storage services. Additionally, it provides a global perspective on existing policies. Lastly, it discusses the environmental and social impacts of electricity storage technologies.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

Authors

Romain Debarre, Prashant Gahlot, Mark Jobson, Nathalie Ledanois, Sandy McLaughlin, Ioannis Poulopoulos, Antoine Ribière.

Executive summary

	The need for electricity storage	Achieving supply and demand balance in power systems, complicated by renewables and the phase-out of dispatchable plants, is a key driver for electricity storage. Many applications such as network reinforcement, primary reserves, etc. add further impetus to momentum for electricity storage solutions.
	Electricity storage technologies	Electricity storage encompasses five main categories: electrical, electrochemical, mechanical, thermal, and chemical storage, each with distinct advantages and limitations. Research and development aims to optimize batteries and develop new solutions for better energy density.
	Status and future market development	Global electricity storage capacity reached 276 GW by 2023, led by pumped hydro storage at 184 GW and lithium-ion batteries at 78 GW. The demand for lithium-ion batteries is driven by mobility applications, with China leading global investments, with significant growth expected.
	Costs of electricity storage	Investment costs, comprising 70–98% of overall expenditure for electricity storage, are crucial for market adoption. Experience curves show decreasing costs with increased capacity, with Li-ion cells exhibiting the fastest decrease, expected to reach USD 75–870/kWh by 2040.
	Battery value chain, from mining to recycling	The battery storage value chain, involves four main stages: mining, raw material processing, component production, and application/recycling. Increasing mineral demand, driven by EV batteries, could pose supply constraints, prompting EV and battery manufacturers to secure raw materials.
	Business models in electricity storage	Electricity storage profitability depends on diverse business models leveraging grid utilization and price arbitrage, though revenue gaps often exist due to undervalued services. Maximizing profitability involves stacking income streams from multiple applications, with revenue potential varying internationally. Electric vehicles can also participate in the electricity system through business models such as demand-side response, behind-the-meter support, and market trading.
	Policy and regulation for electricity storage	Policies supporting electricity storage include setting targets, offering financial incentives, and guiding investment through roadmaps. Globally, investment in grid-scale battery storage surged to more than USD 20 billion in 2022, with continued growth expected, fueled by governmental targets and supportive policies. Moreover, 74 countries had targets to promote electric vehicles.
	Environmental and social impact	Assessing the environmental impact of electricity storage is complex, with factors like technology and end-of-life scenarios to consider. Integrating renewables with storage can reduce greenhouse gas footprints, but various technologies have diverse impacts including land use, water consumption, and social effects, often underreported.

1. The need for electricity storage

The need for electricity storage

Scope definition:

This FactBook intends to cover technologies that are applicable in the stationary storage and mobility sectors and can store electricity for future use, mainly in the form of electricity but also heat, chemicals, fuels, etc..
The consumer electronics segment is not covered in this report.

Henceforth, “electricity storage” will be used in this FactBook instead of “energy storage” to reflect this focus.

Operating power systems requires balancing supply and **demand, which constantly fluctuates.** Traditionally, power systems are balanced by modulating the output of the power plants when in operation and demand side management. **Further, the projected phase-out of fossil fuel plants and the increase of variable power sources can pose challenges to resilient electricity supply, stable grid, etc.**

The rise of variable renewables increases system flexibility needs, as shown by residual load variations. **Other factors, like growing electricity demand and aging infrastructure, also affect supply and demand**, necessitating improved flexibility management of the power system.

Energy system transformation demands new flexibility sources, boosting the importance of electricity storage. **Storage solutions**, using electrical, electrochemical, mechanical, thermal, and chemical means, **help shift supply and demand, reduce the need for network upgrades, ensure reliable and affordable supply, and transform energy usage at the customer level.**

The transformation of energy systems is also closely linked to the growing adoption of electric vehicles, with the global **EV fleet** expected to **increase twelve-fold by 2035. EV charging patterns significantly impact the grid** by increasing demand, influencing renewable energy integration, and accelerating the need for grid reinforcement.

Smart EV charging provides power system flexibility, reduces the need for extensive grid upgrades, and supports additional electricity demand. Furthermore, the evolving relationship between EVs and electricity networks, particularly through vehicle-to-grid (bi-directional flow/smart charging) applications, enhances grid stability.

Various properties characterize the electricity storage process, which **involves withdrawing electricity from the grid, storing it, and returning it at a later stage.** It consists of two dimensions: the power capacity of the charging and discharging phases, which is the ability of the storage system to withdraw or inject electricity instantaneously from or into the grid; and the energy capacity of the storing phase, which measures how much energy can be stored and for how long.

As a consequence, **the uses of electricity storage vary, depending on the combination of the power rating and discharge time of a device, its location within the grid, and its response time.**

Electricity storage enables stationary storage, mobility, and consumer electronics applications

Scope definition:

This FactBook aims to cover electricity storage technologies applicable in **stationary storage and mobility sectors**.

Stationary storage

Stationary storage refers to **technologies connected to the power grid** (front of the meter) and **premises of the customer** (behind the meter) as well as serving off-grid standalone systems

- Energy and capacity services
- Transmission and distribution services
- Ancillary services
- Customer-level services

Mobility

Mobility applications include the use of **batteries** to store energy and allow travel through **transportation systems**.

- SUVs
- Average-size cars
- Small cars
- Buses
- Trucks
- Trains
- Boats
- Planes/ drones
- Two-/three-wheelers
- Smart charging

Consumer electronics

Consumer electronics include the use of **batteries** to store energy for portable **electronic devices**.

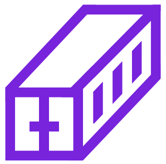
- Other electronics
- PCs
- Phones

Yearly demand of batteries storage per segment[1]

Segment	Year	Demand
Stationary storage	2017	1 GWh
Stationary storage	2023	93 GWh
Mobility	2017	71 GWh
Mobility	2023	780 GWh
Consumer electronics	2017	65 GWh
Consumer electronics	2023	212 GWh

[1] Illustrative example of battery-only demand, yearly demand reflects what comes into the market; this excludes other type of storage.
Sources: IEA, 2024, Global EV Outlook 2024; E3 Analytics, 2023, Scaling-up Energy Storage: Technology and Policy; Kearney Energy Transition Institute analysis

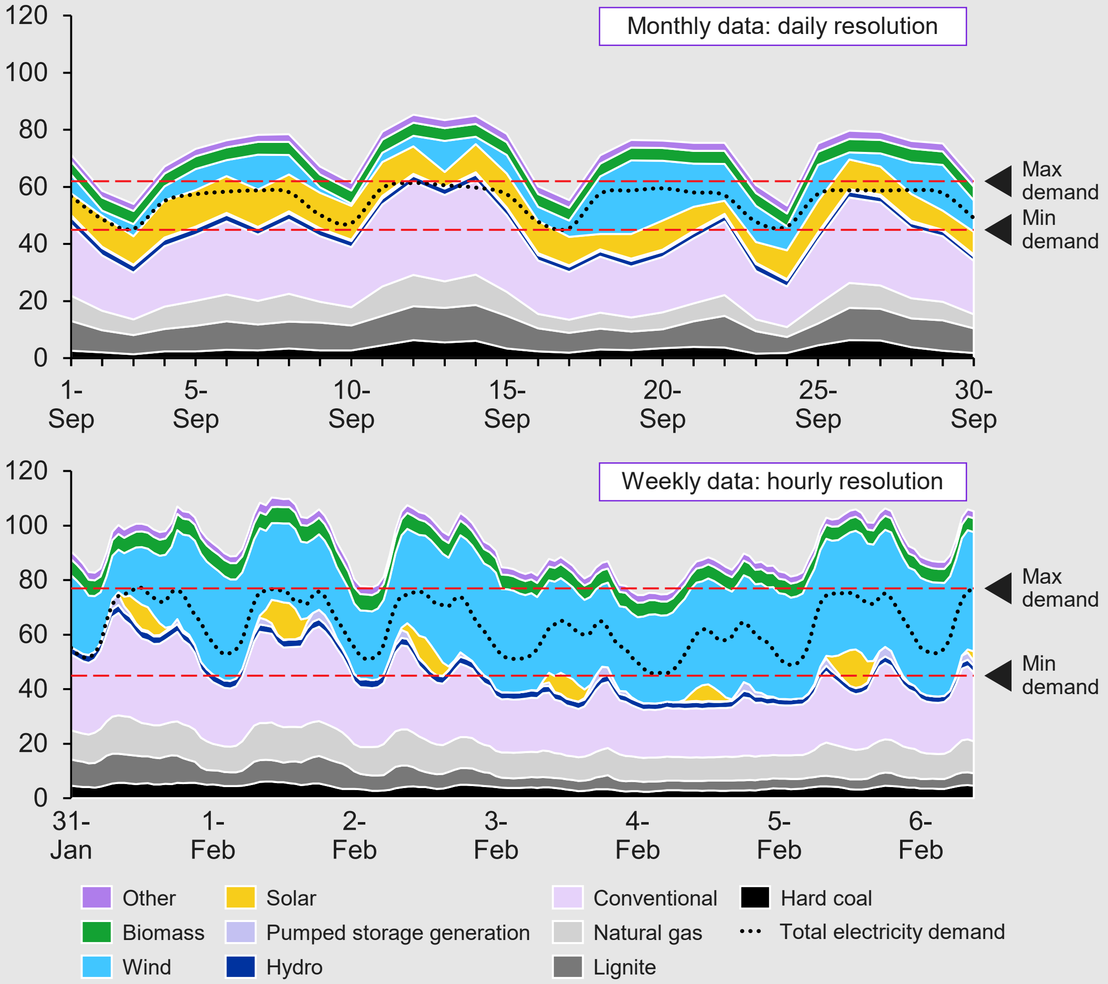
Traditionally, power systems are balanced by modulating power plants output and demand side management



1.2 Electricity systems shift

Monthly and weekly load and supply curve in Germany, by technology

GWh/h, Sept. 2023 – Feb. 2024



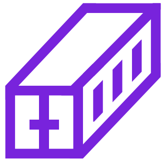
Difference between demand and generation corresponds to exports / imports

Electricity storage is crucial because of the inherent imbalance between electricity supply and demand, as depicted by the load and supply curves.

- **Matching supply with demand: Electricity storage captures excess power when supply exceeds demand and releases it when demand exceeds supply.** This balances the grid, ensuring reliable electricity supply and preventing shortages, curtailment during peak hours and blackouts.
- **Integration of renewable energy:** Solar and wind energies are variable, meaning they generate electricity according to weather conditions. **Electricity storage enables the storage of surplus renewable electricity generated during times of high production for use when production is low.** This maximizes the utilization of renewables and reduces reliance on fossil fuels.

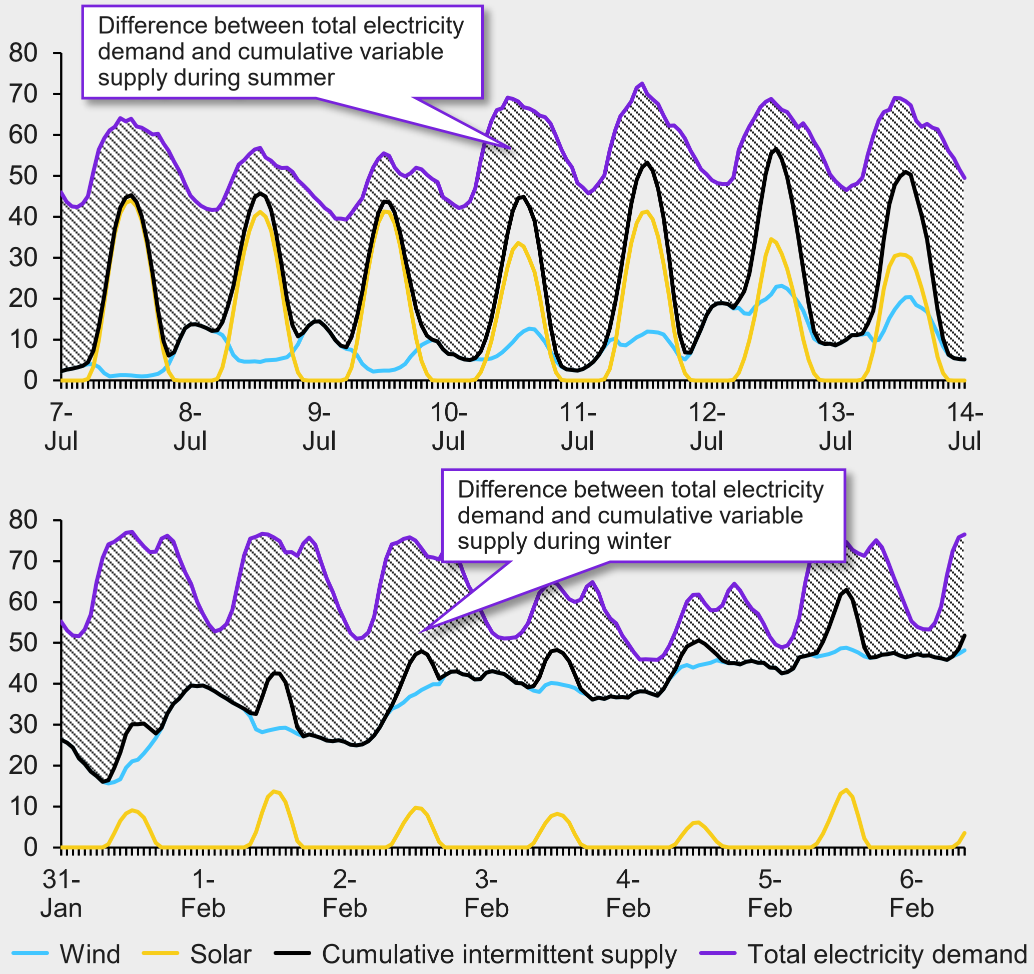
Sources: Agora Energiewende, 2024, Power generation and consumption monthly data; Agora Energiewende, 2024, Power generation and consumption weekly data; Kearney Energy Transition Institute analysis

To reach a higher penetration of wind and solar photovoltaic electricity, power and electricity flexibility are required



1.2 Electricity systems shift

Wind and solar generation vs. consumption in Germany
GWh/h, Jul. 2023 – Feb. 2024



Wind and solar introduce variability and uncertainty on the supply side. Their output varies according to daily and seasonal patterns, and weather conditions. Output is therefore:

- Less reliably predictable (notably harder to forecast than demand)
- Limited ability to ramp up production in real-time (resource availability, e.g.: wind speed, irradiance)
- Subject to steep ramp changes

The variable output of wind and solar increases the need for flexibility. The residual load variations on the graph illustrate the need for flexibility.

Wind and solar make a limited contribution to the flexibility of the power system due to uncertainty surrounding their production reliability in meeting peak demand, also known as capacity credit. The capacity credits of wind and solar range between 5% and 55%.[1]

[1] In reality, this means that of the 9,900 GW of installed wind and solar capacity predicted by 2030 (IRENA's under 1.5 °C scenario), only 495 GW will be available to power operators as part of the pool of flexibility resources. However, capacity credit varies by region and solar and wind regional grid penetration levels.

Sources: Agora Energiewende, 2024, Power generation and consumption weekly summer data, Agora Energiewende, 2024, Power generation and consumption weekly winter data; J. Ssengonzi et al., 2022, "An efficient method to estimate renewable energy capacity credit at increasing regional grid penetration levels," Renewable and Sustainable Energy Transition; Kearney Energy Transition Institute analysis

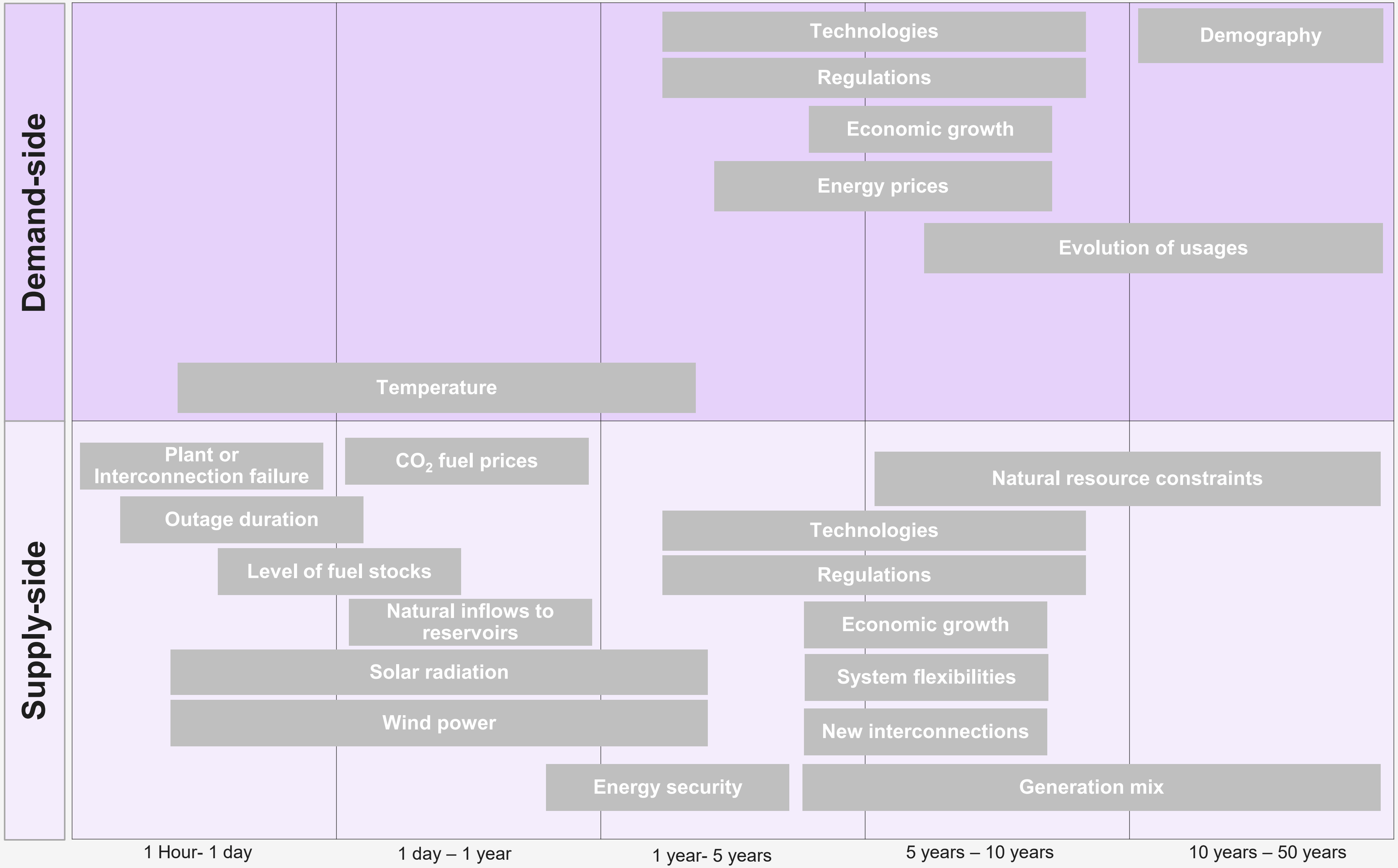
Power supply and demand is impacted by multiple factors at various time scales

Power supply and demand management faces multiple complexities and uncertainties.

1.2 Electricity systems shift

Key factors impacting supply and demand at different time scales

Illustrative



Sources: Adapted from Ecole Polytechnique, 2020, “Electrical Grid”; Kearney Energy Transition Institute analysis

Transformation of energy systems requires additional flexibility sources, driving momentum for electricity storage solutions

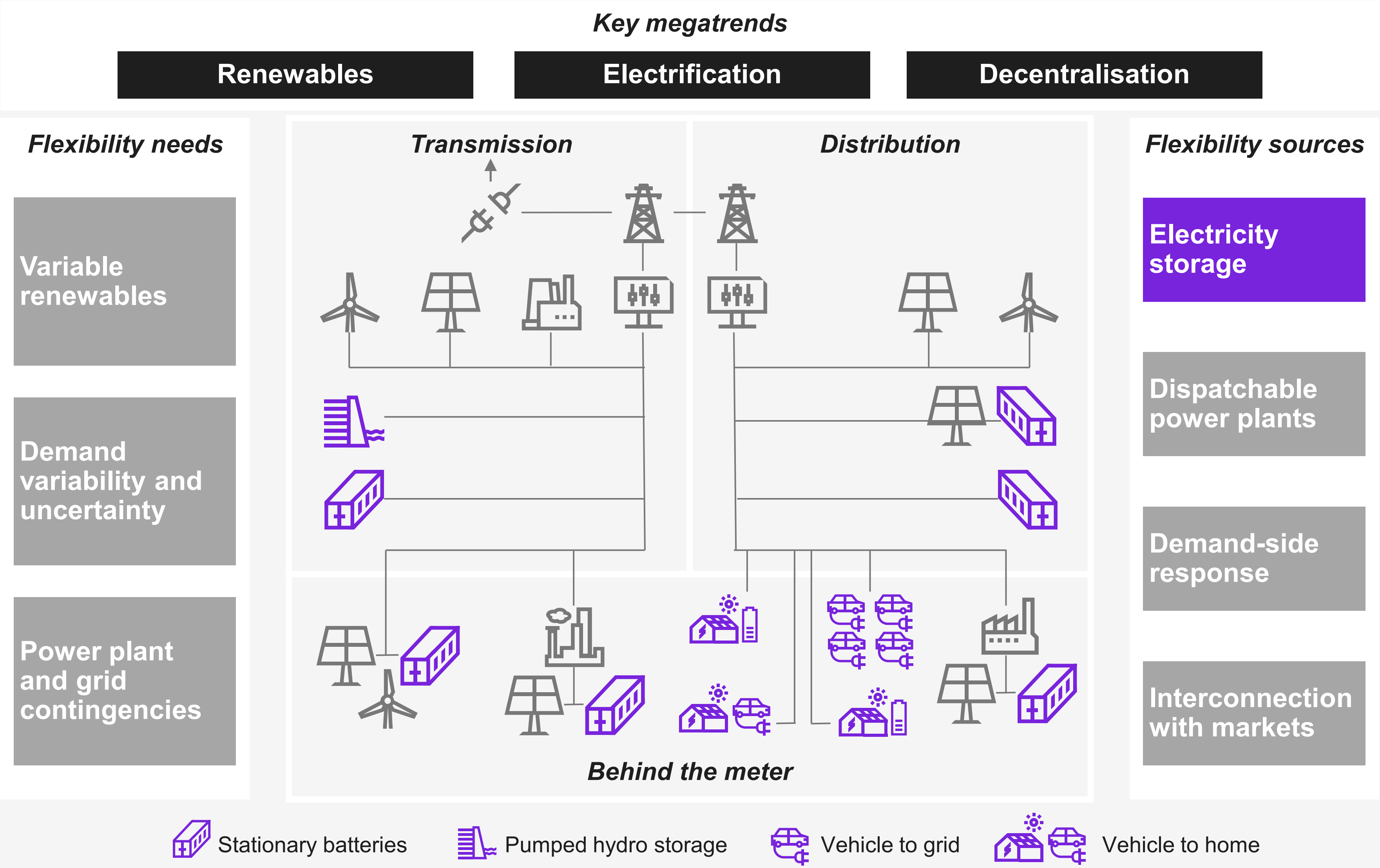
Illustrative; non-exhaustive

Power systems are under strain due to:
– Increasing electricity demand
– Widespread penetration of variable renewables
– Aging grid infrastructure

1.2 Electricity systems shift

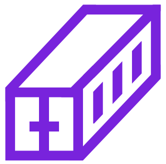
The role of electricity storage in the energy system transformation

Power system flexibility management

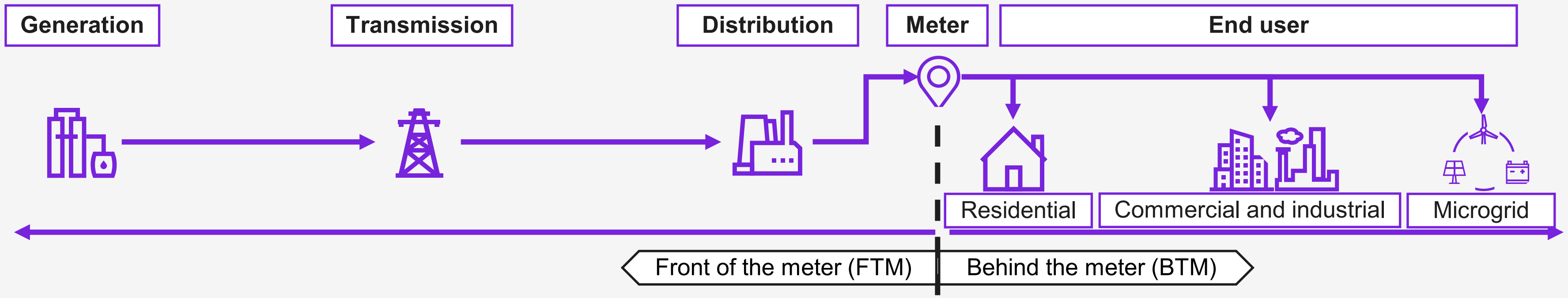


Note: Flexibility management can also be optimized by perfecting models for forecasting output from variable sources, fine-tuning market regulations and refining the design and power systems
Source: Kearney and Kearney Energy Transition Institute analysis

Electricity storage provides four main types of services to the grid and end users



The role of electricity storage projects



1 Energy and capacity services

Shift energy supply and demand over time where needed

- Capacity firming
- Energy arbitrage
- RE curtailment minimization[1]
- System electric supply capacity

2 Transmission / distribution services

Reduce / delay the need for T&D network upgrades

- Distribution loss reduction
- Distribution voltage support
- Transmission congestion relief
- Transmission/distribution upgrade deferral

4 Customer-level services

Ensure affordable, continuous, and reliable supply for end customers

- End-user peak shaving
- Power quality
- Reliability and resilience
- Time-of-use bill management
- Smart consumption maximization

3 Ancillary services

Fast and accurate shifts in supply and demand under normal and emergency operations

- Black-start capacity
- Contingency reserves
- Frequency-responsive reserves
- Ramping reserves
- Regulating reserves
- Voltage support

The definitions of different types of services, along with alternative terminologies employed in the literature, are available in Appendix.

1.3 Electricity storage role and applications

[1] Renewable energies

Note: It should be noted that the definitions can vary significantly from country to country.

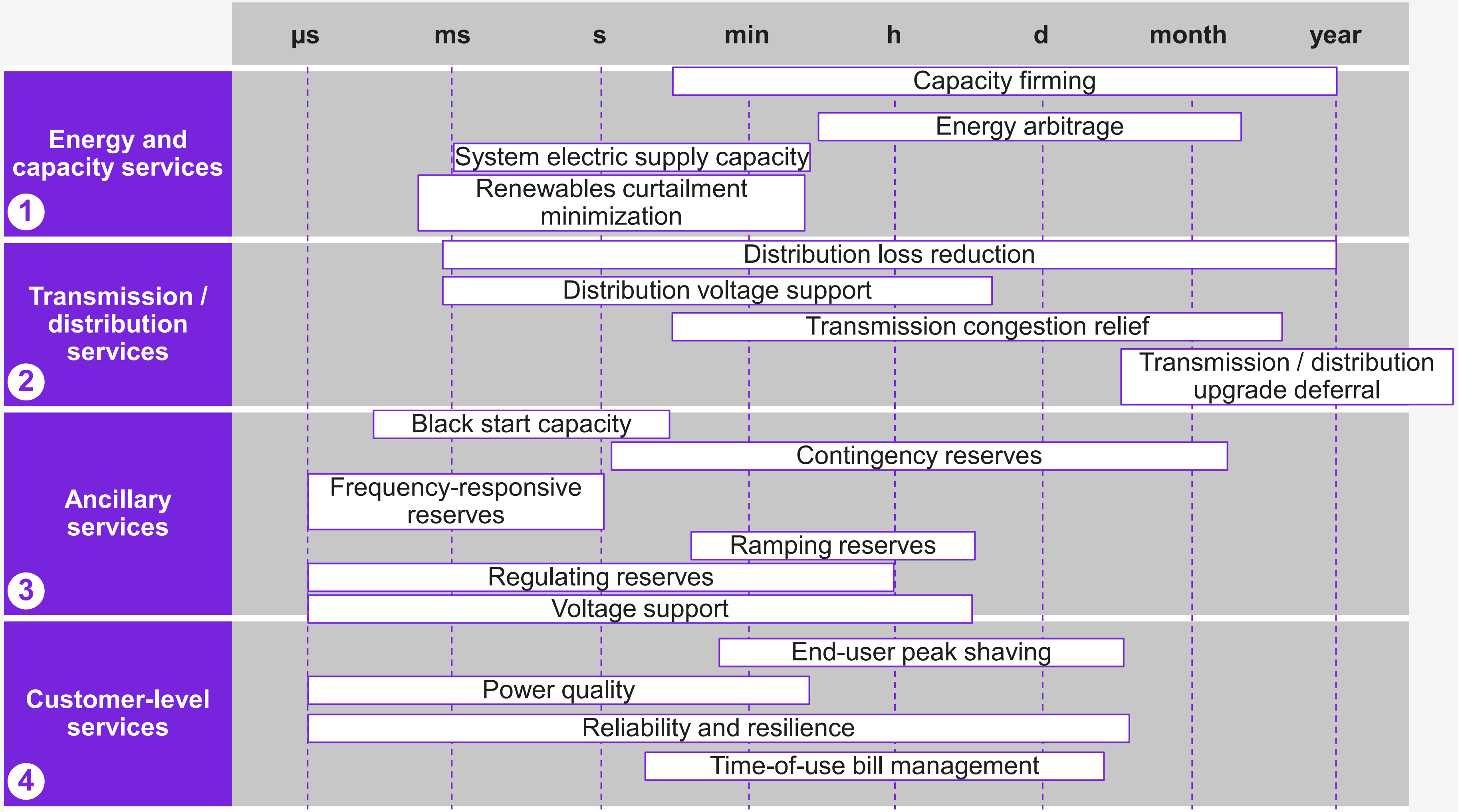
Sources: IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief; IRENA, 2020, Electricity Storage Valuation Framework: Assessing system value and ensuring project viability; NREL, 2019, An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind; E3 Analytics, 2023, Scaling-up Energy Storage: Technology and Policy; P. Wei et al., 2023, "Progress in Energy Storage Technologies and Methods for Renewable Energy Systems Application," Applied Sciences; M. Katsanevakis et al., 2016, "Aggregated applications and benefits of energy storage systems with application-specific control methods: A review," Renewable and Sustainable Energy Reviews; Kearney Energy Transition Institute analysis

Each type of service includes a variety of applications tailored to the grid's and end users' needs

Note: This is a graphical representation of a generic concept which outlines that storage solutions can address these applications in theory but may or may not be the most practical and robust solutions available at hand

1.3 Electricity storage role and applications

Applications depending on output duration and location on the grid



Note: μs corresponds to microseconds and ms to milliseconds.
Sources: IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief; E3 Analytics, 2023, Scaling-up Energy Storage: Technology and Policy; Kearney Energy Transition Institute analysis

Electricity storage technologies contribute to energy and capacity services in multiple ways

1 Energy and capacity services
2 Transmission / distribution services
3 Ancillary services
4 Customer-level services

1.3 Electricity storage role and applications

Electricity storage contribution to energy and capacity services

Electricity storage is used for load leveling over various time scales. Typically, electricity is stored during periods of low demand and discharged during peak demand periods to reduce the peak/off-peak amplitude (for daily, weekly, and seasonal demand), while limiting the need of peak plants.

Capacity firming encompasses:

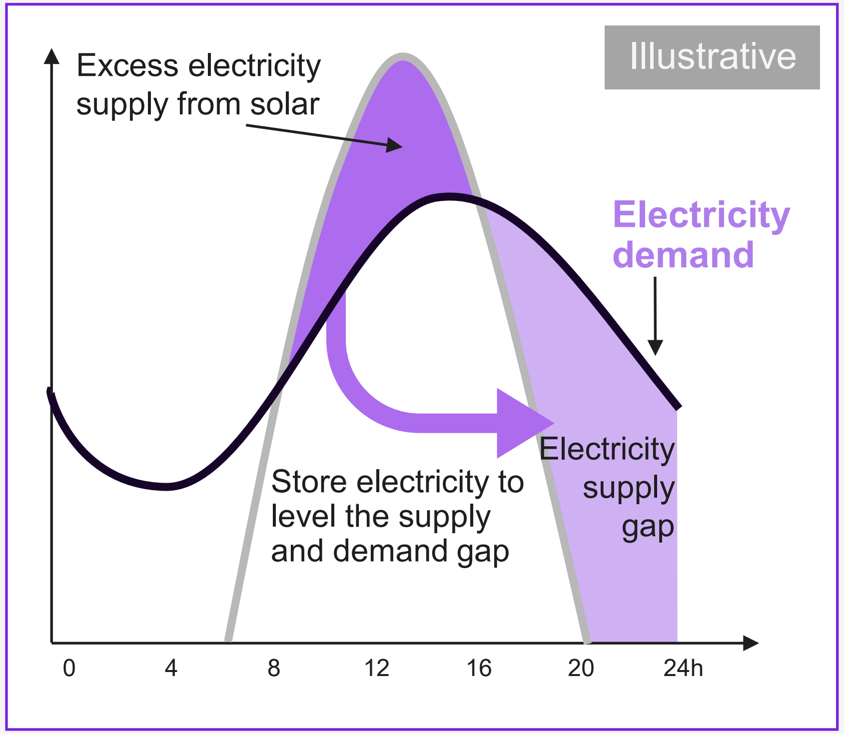
– Optimizing power fleet operations
– Deferring/avoiding transmission and distribution infrastructure upgrade
– Supplying isolated areas with electricity

Besides the capacity firming, electricity storage provides additional benefits, including:

– **Energy arbitrage:** taking advantage of an electricity price difference in the wholesale electricity to buy energy at low price and sell it at high price
– **RE curtailment minimization:** avoiding curtailment of variable RE sources[1]
– **System electric supply capacity:** providing the system with peak generation capacity.

Daily solar PV output with storage vs. demand

kW



[1] Renewable energies
Sources: Kearney Energy Transition Institute analysis

Electricity storage technologies provide various solutions to transmission and distribution services

1 Energy and capacity services

2 Transmission / distribution services

3 Ancillary services

4 Customer-level services

1.3 Electricity storage role and applications

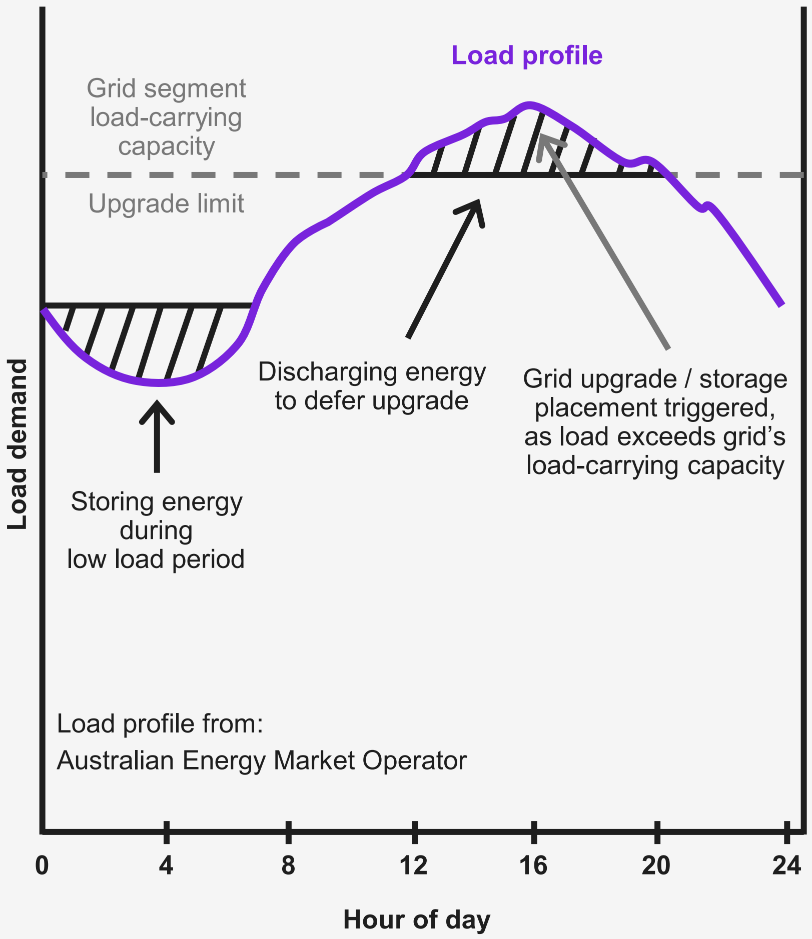
Electricity storage contribution to transmission and distribution services

Electricity storage technologies' role in T&D services consists of:[1]

- **Distribution loss reduction:** performing capacity / voltage support, reducing the impacts of the loss of a major grid component
- **Distribution voltage support:** maintaining the voltage profile within regulatory limits
- **Transmission congestion relief:** steering either the supply or demand and postponing / avoiding the necessity to increase lines in grid segments nearing capacity
- **Transmission / distribution upgrade deferral:** with EU electricity consumption projected to surge by 60% by 2030, the existing 11 million kilometers of grids are ill-prepared. **By supplying power during peak loads, these systems can delay or prevent the need to expand power transformers**, prolonging their lifespan and proving more cost-effective than alternatives. Charging should occur during low-load periods like night-time, while discharging should coincide with peak demand hours.

T&D upgrade deferral – congestion instance based on load demand[1]

kW



[1] Transmission and distribution

Sources: M. Katsanevakis et al., 2016, "Aggregated applications and benefits of energy storage systems with application-specific control methods: A review," Renewable and Sustainable Energy Reviews; Kearney Energy Transition Institute analysis

Electricity storage technologies contribute to ancillary services in various ways

1 Energy and capacity services
2 Transmission / distribution services
3 Ancillary services
4 Customer-level services

1.3 Electricity storage role and applications

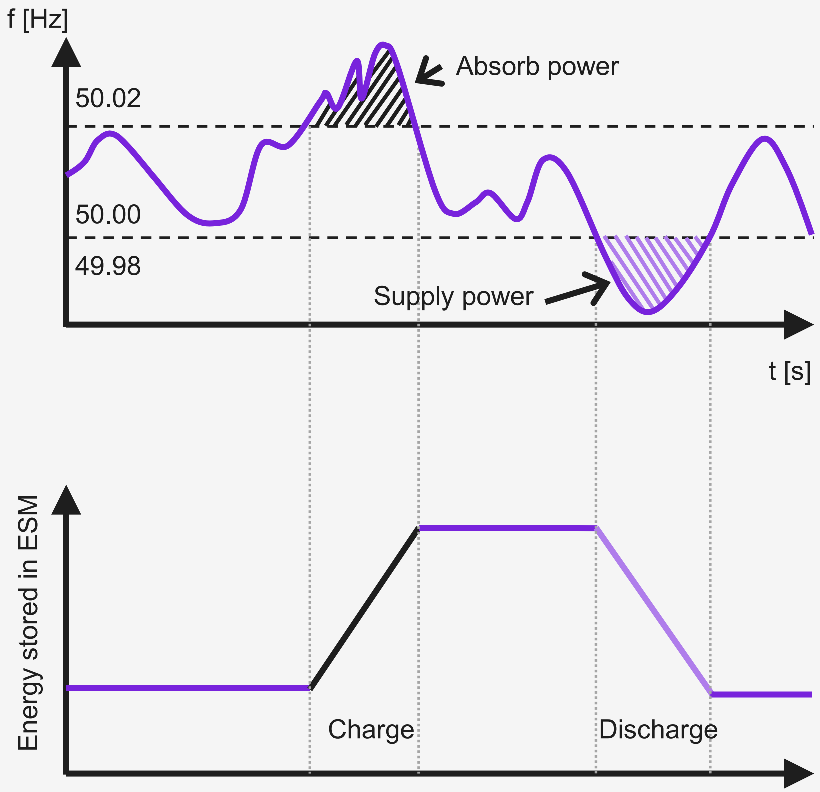
Electricity storage contribution to ancillary services

The system's frequency and voltage need to be maintained within technical limits to avoid instability and blackouts and to ensure continuous service. Ancillary services encompass:

- **Black-start capacity:** initial power supply to restart a power or gas grid after a full blackout
- **Contingency reserves:** reserves used to address power plant or transmission line failures
- **Frequency–responsive reserves:** reserves that act to slow and arrest the change in frequency via rapid and automatic responses that increase or decrease output from generators
- **Ramping reserves:** immediate or automatic mechanisms that increase or decrease output to maintain frequency and voltage continuously within electricity network standards
- **Voltage support:** Storage can be used for active and reactive power injection to sustain voltage

Frequency regulation with electricity storage

Hz, kW



The electricity storage system is charged or discharged in response to an increase or decrease, respectively, of grid frequency. This approach to frequency regulation is a particularly attractive option due to its rapid response time and emission-free operation.

Sources: E. Yosef et al., 2019, "Battery Energy Storage Applications: Two Case Studies", IEEE; Kearney Energy Transition Institute analysis

Electricity storage technologies provide multiple solutions to customer-level services

1 Energy and capacity services
2 Transmission / distribution services
3 Ancillary services
4 Customer-level services

1.3 Electricity storage role and applications

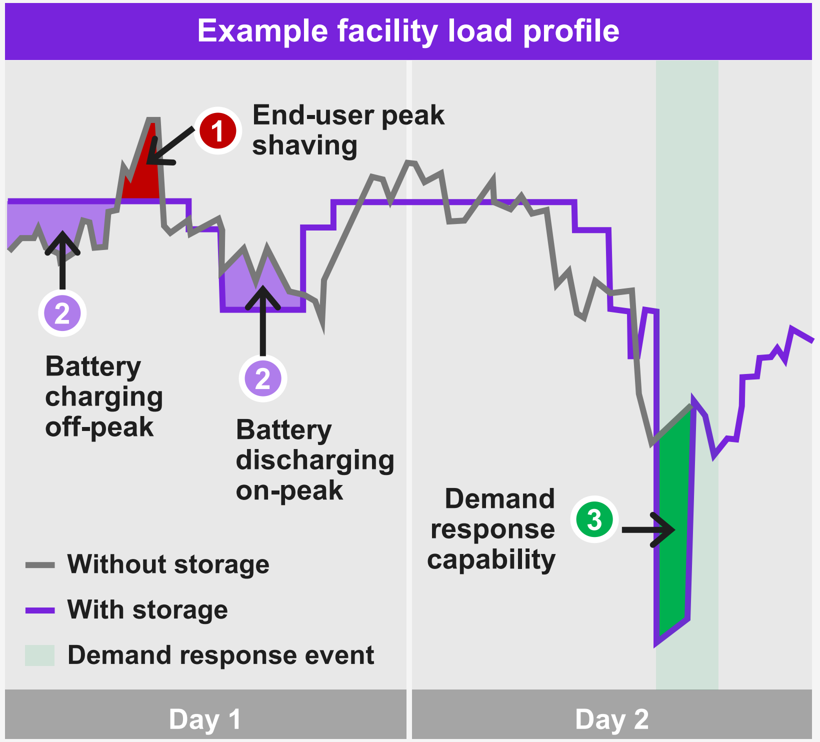
Electricity storage contribution to customer-level services

An electricity storage system can transform energy usage at a site, consisting of various services:

- **End-user peak shaving:** electricity storage systems respond effectively to market signals, enhancing flexibility, **providing solutions in demand charge management by reducing associated costs.**
- **Reliability and resilience:** substituting the network in case of interruption
- **Time-of-use bill management:** electricity storage systems **enable savings by storing power when grid prices are low and using it when prices are high, while also storing renewable energy for later use.** This can be supported by participating in demand response programs without disrupting critical equipment.[1]

Electricity storage system provides various value streams – facility load profile example

kW



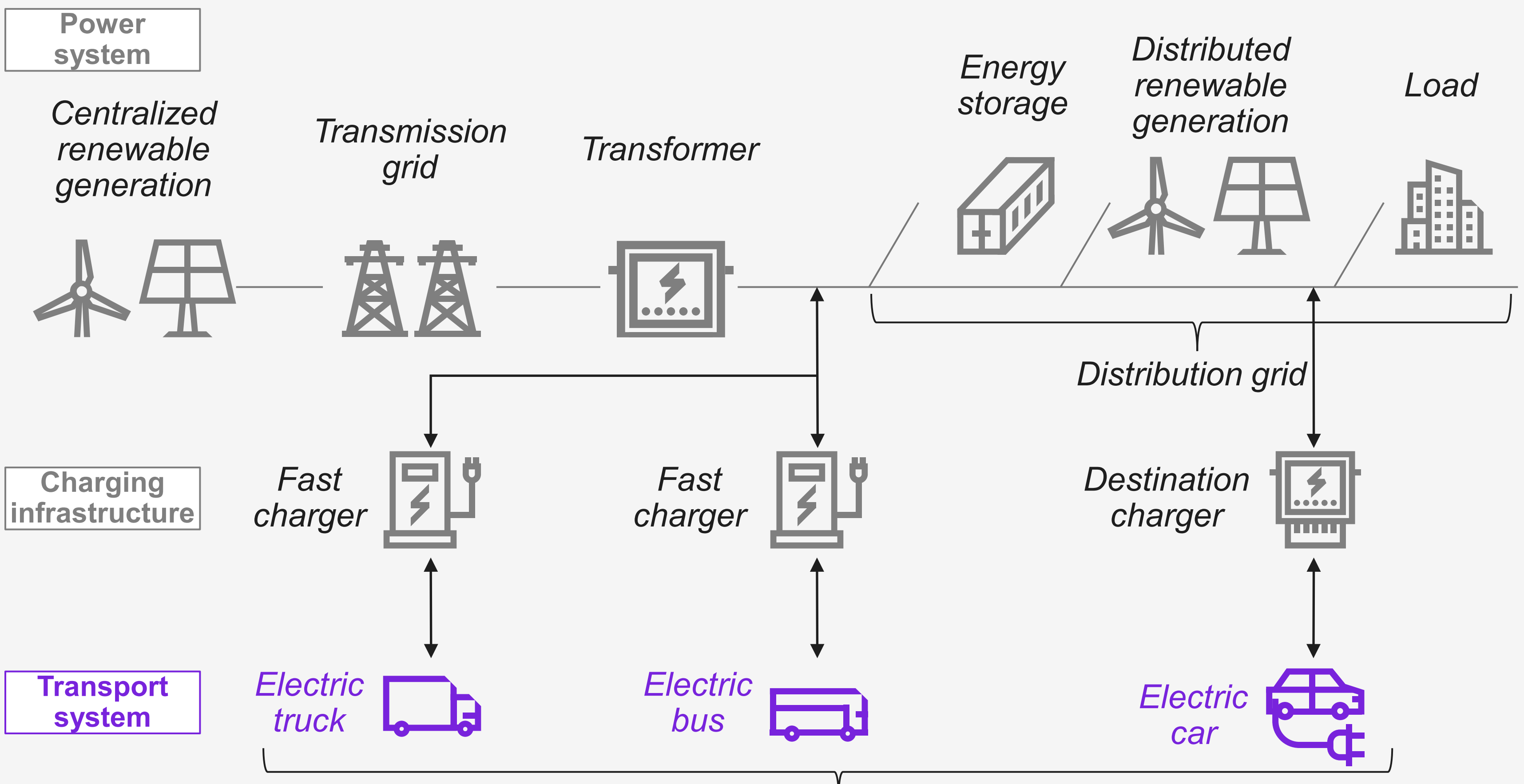
[1] Demand response programs are offered by many utilities for energy consumers to enroll in and receive money back for reducing their energy demand, at the utility's request, during peak periods of demand and under-supply. Common examples of reduction include turning up the temperature on a thermostat to reduce the air conditioning load, turning off certain lights, or shifting the time of use of some energy-consuming devices out of the peak demand period. The load avoided for a single facility may be small, but when many customers participate, it creates a meaningful energy demand reduction for the utility.
Sources: ENEL, 2023, Unlocking the full value stack for battery storage; Kearney Energy Transition Institute analysis

Growing electric vehicles adoption is intertwined with the transformation of energy systems

Vehicle-to-everything (V2X) is a term used to describe the general concept of a vehicle connected to its surrounding environment. It encompasses, among others, vehicle-to-grid (V2G) and vehicle-to-home (V2H).

1.3 Electricity storage role and applications

Integration of electric vehicles into the power and transport sectors



Functionality

Single/unidirectional charging function: Battery charging can be modulated over time, but the electricity generated cannot be fed back into the grid.

Reversible/bidirectional charging function: The battery can draw power from the grid but can also feed electricity back into the domestic supply (V2H) and/or the public grid (V2G). This functionality requires an AC/DC converter in either the vehicle or the charging station.

Sources: Zhang et al., 2024, Sustainable plug-in electric vehicle integration into power systems; RTE, 2019, Integration of electric vehicles into the power system in France; Kearney Energy Transition Institute analysis

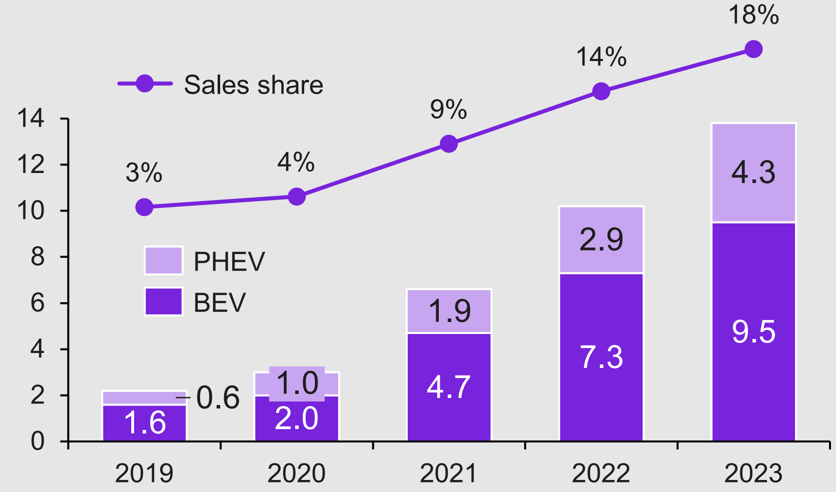
The global electric vehicle fleet is set to grow twelve-fold by 2035 under stated policies scenario of IEA

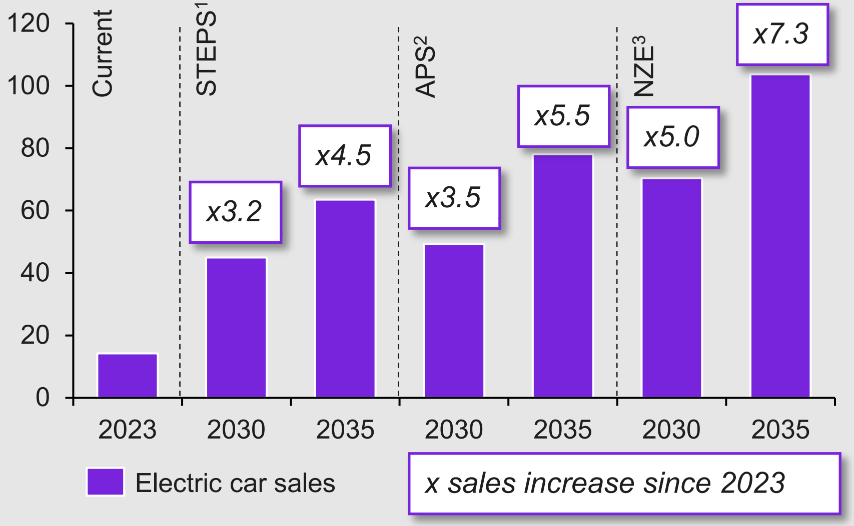
- Electric car sales neared 14 million in 2023, 95% of which were in China, Europe, and the United States.
- Nearly 1 in 5 cars sold in 2023 was electric.

1.3 Electricity storage role and applications

Electric car registrations and sales share evolution

Million, 2019–2035





[1] IEA's Stated Policies Scenario
[2] IEA's Announced Pledges Scenario
[3] IEA's Net Zero Emissions Scenario
[4] Original equipment manufacturer

Notes: PHEV to plug-in hybrid electric vehicle and BEV corresponds to battery electric vehicle. The share of sales represents the number of BEV and PHEV registrations compared to total car sales.
Sources: IEA, 2024, Global EV Outlook 2024; REN21, 2024, Renewables 2024 Global Status Report; Kearney Energy Transition Institute analysis

Main drivers of development

Growing attention of consumers for the energy transition and decarbonization:

- Consumers are increasingly adding sustainability and environmental impact criteria as a driver in their purchase decision.

Automotive OEMs fully embracing the e-mobility revolution[4]:

- A wide range of electric vehicles (EVs) is coming on the market, with growing battery power and enhanced charging speed, with the cost of batteries continuously falling.
- The largest OEMs are setting significant target (50%+) for their EV sales over the next years.

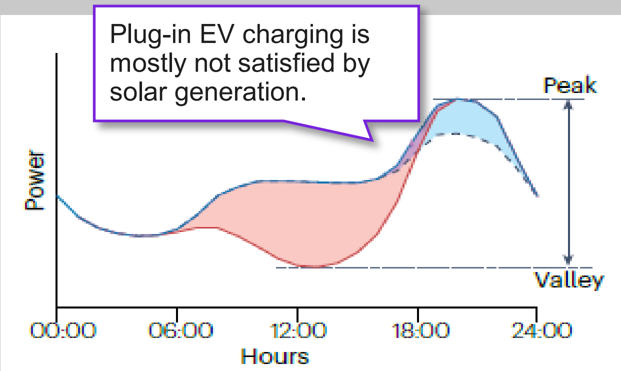
Governments' support for e-mobility with regulatory frameworks and incentives on EV purchase and infrastructure development:

- Targets promoting electric vehicles continued to lead in road transport, with a total of 74 countries with such targets by the end of 2023.
- Additionally, 18 countries announced new policies supporting EV uptake in 2023.

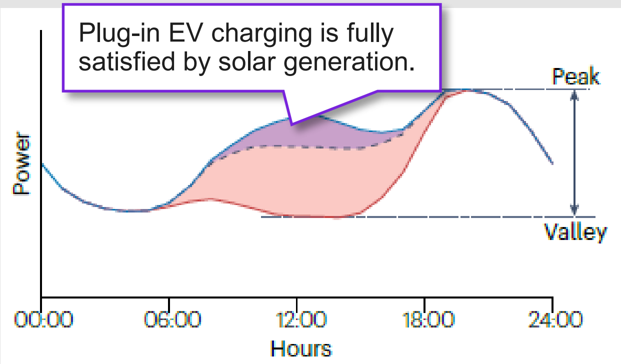
EV charging patterns have an impact on the grid, such as increasing demand, affecting renewable penetration, or accelerating grid reinforcement

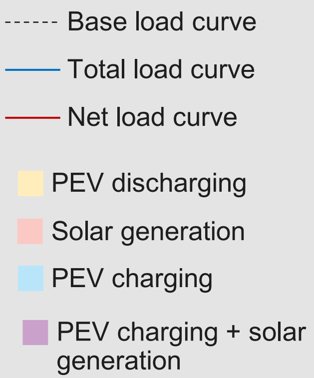
Example

In **uncoordinated charging** scheme the EV battery starts charging immediately when it is plugged in or after a fixed start delay chosen by the user.

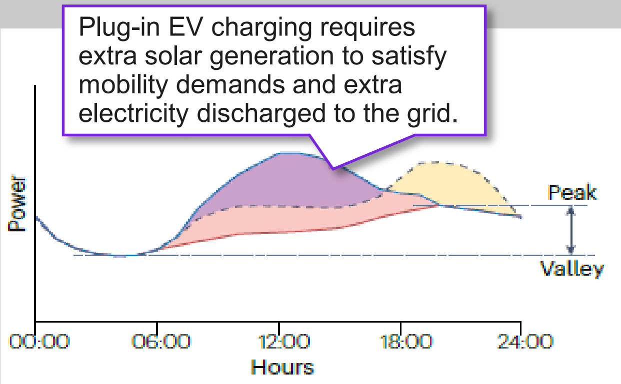


Smart charging allows plug-in electric vehicles to consume more electricity when renewable generation is high. Additional case for dynamic charging when rates are set for the time of the day (i.e. no variation on day-to-day basis)





Smart discharging can transfer electricity from time periods with high renewable generation to time periods with low renewable generation, which further flattens the net load profile and promotes renewable generation consumption.



Sources: Zhang et al., 2024, Sustainable plug-in electric vehicle integration into power systems; Kearney Energy Transition Institute analysis

1.3 Electricity storage role and applications

Smart EV charging offers power system flexibility, reduces grid reinforcement needs, and accommodates additional electricity demand

The various forms of smart charging

Simple, unidirectional, controlled time-of-use charging

Unidirectional charging with frequency balancing

Vehicle-to-home (V2H) charging, using its bidirectional function to cover household consumption without feeding power back into the grid

Vehicle-to-grid (V2G) charging with contribution to the energy market

Vehicle-to-grid (V2G) with frequency balancing

Charging management combined with self-consumption (with or without bidirectional functionality)

Simple time-of-use charging

Charging with real-time load balancing in the power grid

Dynamic charging on electricity price signals

Combined with PV self-consumption

1.3 Electricity storage role and applications

Sources: IEA, 2024, Batteries and Secure Energy Transitions; RTE, 2019, Integration of electric vehicles into the power system in France; Kearney Energy Transition Institute analysis

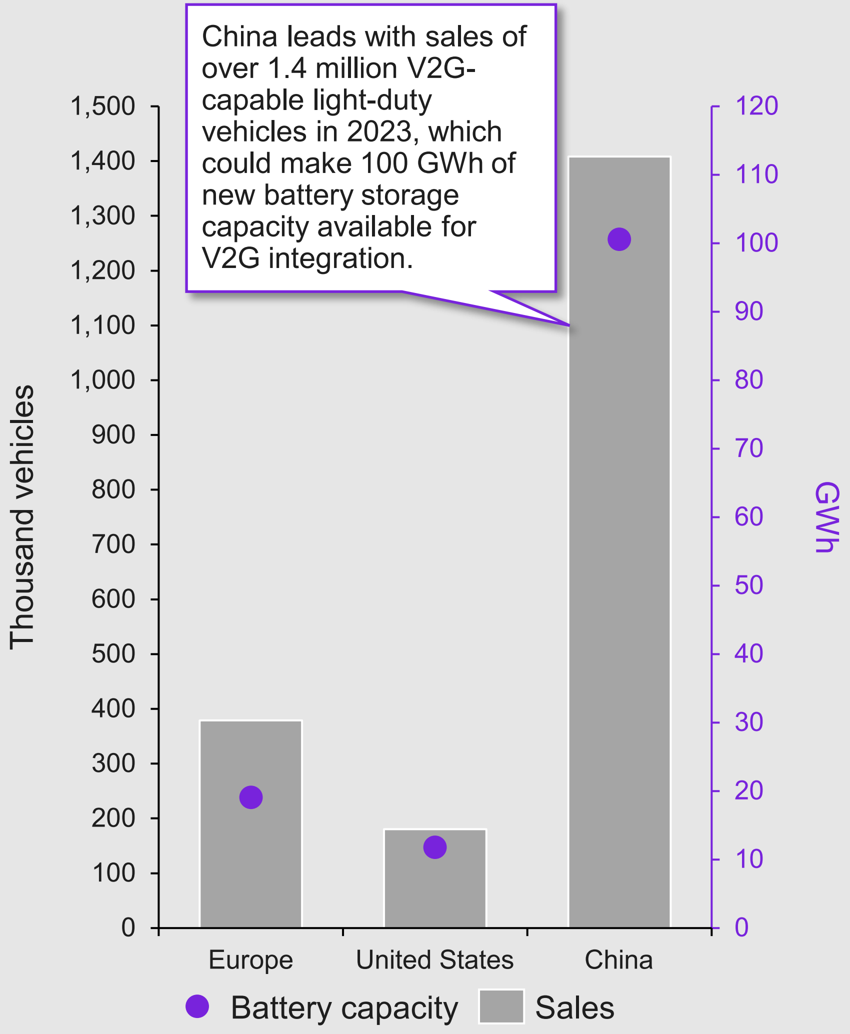
The relationship between EVs and electricity networks is evolving with vehicle-to-grid applications

The broad deployment of vehicle-to-grid (V2G) and vehicle-to-building (V2B) faces several challenges, including technical, commercial, and regulatory obstacles.

1.3 Electricity storage role and applications

V2G-capable light-duty vehicle sales by region

Thousand vehicles – GWh, 2023

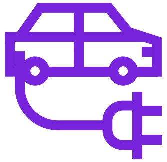


Sources: IEA, 2024, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

Challenges for V2B and V2G deployment

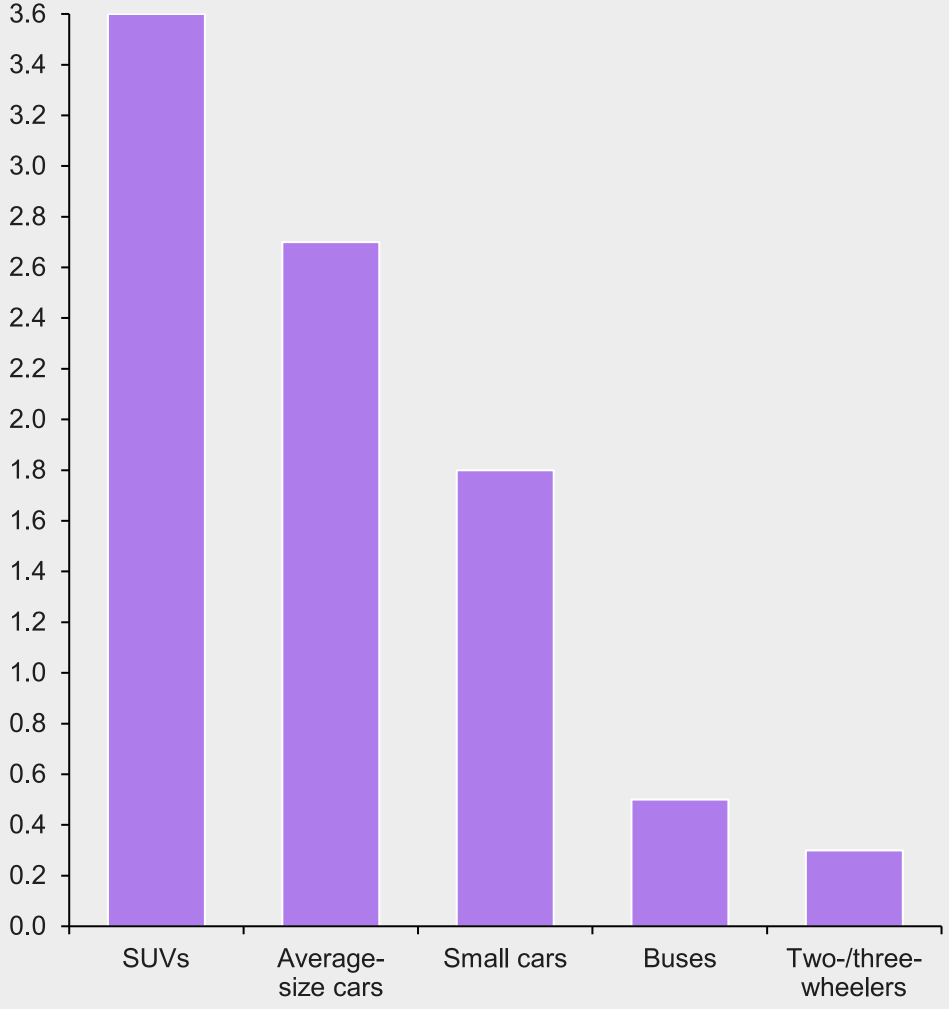
- **Electric vehicle (EV) batteries are typically designed for fewer cycles than storage batteries**, and additional cycling from V2G/V2B usage can accelerate battery degradation.
- V2G/V2B operations are usually not covered by EV battery warranties, **making these applications less attractive to consumers.**
- Although using EV batteries for V2G/V2B could support household energy needs with minimal impact on battery life, **the economic benefits for individual consumers are still limited.**
- **Coordinating mobility and storage needs makes corporate fleets a more promising market for V2G/V2B applications** due to their predictable usage patterns and larger, aggregated flexibility services.
- In **Europe, the United States and China, 7.5%, 8.7%, and 17.1%** of EV lithium-ion battery demand, respectively, is available for V2G integration.

The required battery size highly depends on the type of passenger transport and autonomy range



Customers' preference for higher autonomy and vehicle capacity also leads to associated increase in battery size

Battery capacity per passenger-kilometre of selected electric vehicle types
Wh/passenger-kilometer, 2023



Note: Analysis assumes average occupancy per vehicle type.
Sources: IEA, 2024, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

- **Two-/three-wheelers** have the highest efficiency in terms of battery capacity needs per passenger-kilometer served.
- **Buses powered by batteries** require a lower battery capacity per passenger-kilometer than **average-size cars (approximately 60 kWh)** due to higher occupancy rates.
- **SUVs (around 80 kWh)** demonstrate the least efficient performance on a passenger-kilometer basis. They require double the battery capacity per passenger-kilometer of **small EVs (40 kWh).**

1.3 Electricity storage role and applications

Electricity storage is a three-step process that is characterized by a wide range of properties

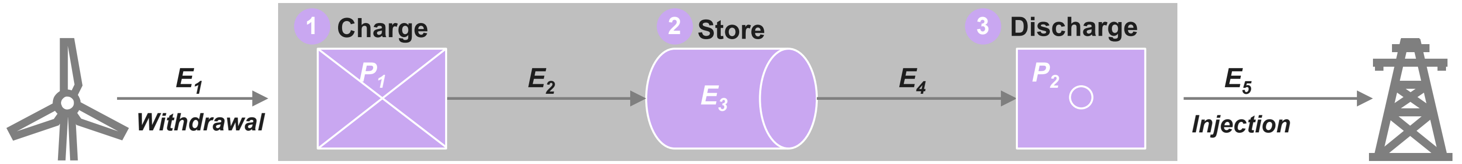
Illustrative

Electricity storage allows the storage of **energy from electricity in different ways**, including electricity, electrochemical, mechanical, thermal, or chemical storage. The **discharging phase** can be done **delivering electricity or heat**.

1.4 Electricity storage key properties

Schematic view of electricity storage principle

Key properties of electricity storage



Charging is characterized by the rate at which energy can be withdrawn (power) and the time needed to start (ramping rate).

Storing phase corresponds to the amount of energy the system can store (energy being equal to power multiplied by time).

Discharging is the rate at which electricity can be injected (power) and the time needed to start (ramping rate).

Power-to-energy ratio	Round-trip efficiency	Energy per volume or weight	Battery defining properties	
– Determines the typical storage cycling time – Cycling frequency (8 MW capacity, 48 MWh electricity storage, 6 hours charging time)	– Results form the difference between the quantities of energy withdrawn and injected – Usually, 40% to 95% depending on technologies	– **Specific energy** (kWh/kg) – **Energy density** (kWh/l) – **Power density** (kW/l)	– **Power rating** (MW) – **Storage capacity** (MWh) – **Response time** (s to min) – **Lifetime** (years)	– **Output duration** (min to h) – **Charging time** (h) – **Self-discharge** (%energy/d) – **Cycling** (#)

Note: The example above represents an electricity-storage-electricity loop, there are different possibilities. Please refer to slide 29 for other pathways with electricity storage.
Sources: Kearney Energy Transition Institute analysis

Power and energy rating are defining properties of an electricity storage system

In the context of electricity storage systems, MW (megawatts) and MWh (megawatt-hours) are two crucial specifications that describe different aspects of the system's performance.

1.4 Electricity storage key properties

Power capacity
MW

- **Measures the rate at which electricity is delivered or consumed**, indicating the maximum amount of power an electricity storage system can deliver instantaneously
- Is calculated with the current and voltage capacity (*volts x amperes*)

Energy capacity
MWh

- **Measures the total amount of energy stored or delivered over time,** indicating how long an electricity storage system can sustain power delivery
- Is calculated with the discharge power by the time of discharge (*watts x time*)

Nominal capacity
Ah

- **Specific to electrochemical systems, it measures the rate at which electric charge can be provided,** indicating how long an electricity storage system can sustain current until reaching complete discharge
- Is calculated with the discharge current by the discharge time (*amperes x time*)

Sources: MIT, 2018, A Guide to Understanding Battery Specifications; NREL, 2019, Grid-Scale Battery Storage: Frequently Asked Questions; Kearney Energy Transition Institute analysis

2. Electricity storage technologies

Electricity storage technologies

As the focus of the FactBook is electricity storage, heat has been excluded as an input and only electrothermal solutions which use electricity as an input are covered.

2.0 Chapter summary

There are five main categories of electricity storage technologies: **electrical storage, electrochemical storage, mechanical storage, thermal storage, and chemical storage.** Each technology has its own set of advantages and disadvantages defined by the constraints of the system design, chemical and physical properties of the storage medium, etc.

Electricity storage technologies' characteristics and performance encompass a wide range across key technical parameters such as energy/power capacity, response time, discharge duration, efficiency, etc. This can help in mapping different storage technologies to the different applications as per the requirements. For example, electrical storage solutions are matched with applications characterized by exceedingly fast response times and high power capacities whereas chemical storage and thermal storage offer a good match to long-duration storage needs.

Li-ion batteries dominate in the automotive and consumer electronics applications, while pumped hydropower is the only mature electricity storage technology deployed at grid-scale currently. Many technologies, however, proliferate demonstration and deployment phases highlighting high interest and rapid progress in the electricity storage domain.

Research and development priorities differ by technologies and include both **optimization of the existing** (and relatively mature) **technologies** to increase performance, reduce costs, enhance safety, and limit environmental impact, and **experimenting and developing new technologies**, exploiting new developments in material science, cross-learning and sharing from other sectors (example: utilizing oil and gas/mining assets, components, and know-how for novel pumped hydro development), innovative designs, and system combinations, etc.

Research and development activities have been focusing on batteries improvement. Their development has been primarily driven by mobility applications where energy density is of high importance. However, in stationary applications its significance is reduced. **Presently, the realized industrial energy densities are much lower than the possible theoretical energy densities** due to various reasons—inherent efficiency losses in real-world operations, high temperature and discharge rates compared to lab conditions, additional requirements for safety, faster degradation over battery life, etc. Hence, improving energy densities is a high-priority area of battery research globally. Consequently, **energy densities are expected to rise significantly over the next decade** with new chemistries (such as metal-air, metal-ion) logging appreciable gains.

Electricity storage technologies can be categorized by chemical and physical principles

1	**Electrical storage**	Electrical storage systems use electrical and electrochemical devices to store electricity.	
2	**Electrochemical storage**	Electrochemical storage systems use a series of reversible chemical reactions to store electricity in the form of chemical energy.	
3	**Mechanical storage**	Mechanical storage systems convert electricity to potential or kinetic energy for future use.	
4	**Thermal storage**	Thermal energy storage systems mainly store heat (and also electricity) as heat energy and release heat and/or electricity.	
5	**Chemical storage**	Chemical energy storage systems store electricity through the creation of chemical bonds.	

Sources: Kearney Energy Transition Institute analysis

Electricity storage is usually achieved by means of conversion into other forms of energy

Indicative

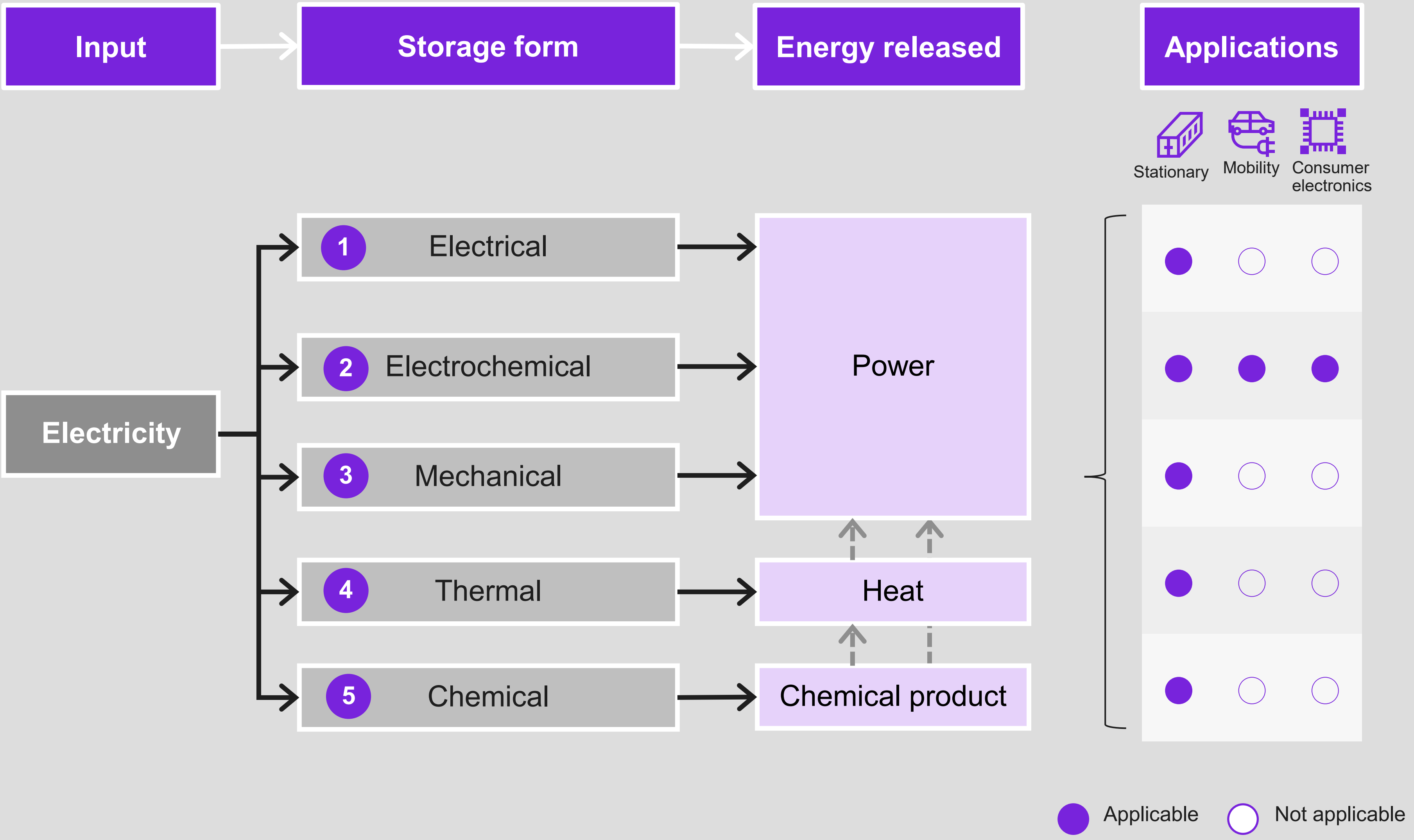
Scope definition:

This FactBook intends to cover technologies that can store electricity for future use (mainly in the form of electricity but also heat, chemicals, fuels, etc.).

Henceforth, “electricity storage” will be used in this FactBook instead of “energy storage” to reflect this focus.

2.1 Electricity storage technologies

Different electricity storage pathways



Storage form	Stationary	Mobility	Consumer electronics
1 Electrical	Applicable	Not applicable	Not applicable
2 Electrochemical	Applicable	Applicable	Applicable
3 Mechanical	Applicable	Not applicable	Not applicable
4 Thermal	Applicable	Not applicable	Not applicable
5 Chemical	Applicable	Not applicable	Not applicable

Source: Kearney Energy Transition Institute analysis

Overview of the various electricity storage technologies

Non-exhaustive

Electricity storage technologies classification tree

Main focus of this FactBook

1 Electrical
- Supercapacitor
- Superconducting magnet (SMES)

2 Electrochemical
- Classic batteries
  - Li-ion
  - Li-S
  - Na-S
  - Ni-Cd
  - Me-ion
  - Me-S
  - Lead acid
  - Na-$NiCl_2$
  - Ni-MH
  - Me-air
  - Solid-state
- Flow batteries
  - Vanadium
  - Zn-Br
  - Fe
- Hybrid supercapacitors
- Electrochemical recuperator

3 Mechanical
- Pumped hydro
- Flywheel
- Compressed air[1]
- Geomechanical pump storage
- Gravity energy storage

4 Thermal
- Sensible heat[2]
- Latent heat
- Thermochemical

A key energy storage technology with promising potential but it is not discussed in detail in this FactBook as this category of storage solutions is chiefly based on storing heat instead of electricity. However, a few emerging electrothermal technologies are profiled which use electricity as an input.

5 Chemical
- P2X (Hydrogen through water electrolysis and using it to produce electricity, chemicals, fuels, etc.)

Please refer to the Hydrogen FactBook for an in-depth analysis of these technologies.

Notes: Li = lithium, Na = sodium, S = sulphur, Ni = nickel, Na-$Nicl_2$ = sodium nickel chloride, Cd = cadmium, MH = metal hydride, Me = metal, Zn = zinc, Br = bromine, Fe = iron, Co_2 = carbon dioxide, P2X = power to X
1. Liquid air energy storage and Liquid CO_2 energy storage are based on similar thermo-mechanical dynamics; 2. Basalt, Molten salt (standalone) and Sandy battery solutions are profiled (but aren't an exhaustive set)
Sources: Kearney Energy Transition Institute analysis

Electrical storage uses capacitors and magnets to store electricity

Input

Electricity grid

Standalone renewables

Electrical storage

Key concepts utilized:

– Double layer effect develops when an electrode and a liquid solution are touching each other, causing the charges to line up and allowing electricity to be stored there.
– Some materials carry electric current with no resistive losses and the magnetic field produced by the electric current is a form of energy which can be stored.

Operating principle

Output

Electricity

Electrical storage – key categories

Supercapacitors	Superconducting magnet
Supercapacitors, commonly known as electrochemical double layer capacitors (EDLC), store electrical energy through the electric double-layer capacitance. Hence, in contrast to batteries, charges are distributed on the surfaces by physical processes involving no chemical reactions.	Devices consist of a coil of superconducting material which aids in creating a magnetic field when an electric charge is passed through it.

1

2.1 Electricity storage technologies

Sources: Kearney Energy Transition Institute analysis

Electrochemical storage includes various battery technologies that use different chemical compounds to store electricity

Input

Electricity grid

Standalone renewables

Electrochemical storage

Using a series of reversible chemical reactions to store electricity in the form of chemical energy (which is later released as electricity through electrochemical oxidation-reduction reverse chemical reactions).

– Batteries (secondary) are the most common form of electrochemical storage device consisting of metal electrodes submersed in liquid or solid electrolytes.

Operating principle

Output

Electricity

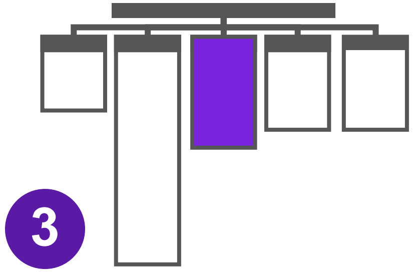
Electrochemical storage – key categories

Classic battery	Flow battery	Hybrid supercapacitors	Electromechanical recuperator
Chemical energy is stored in solid metal electrodes and is released as electrons flowing (i.e., electricity) between two electrodes (i.e., from the negative electrode/anode to the positive one/cathode) due to electrochemical reactions.	It consists of two liquid electrolyte tanks connected to a cell stack separated by an ion selective membrane. In the discharging process, the liquid electrolyte is pumped through electrodes to extract the electrons and to generate electricity.	Composed of a battery-type and a capacitive material as positive and negative electrode, which possess both high energy and power density in one electrochemical cell.	Consist in a combination of battery and supercapacitor into a single electrochemical system using a water-based electrolyte.

Sources: Kearney Energy Transition Institute analysis

2

Mechanical storage is based on converting electricity into potential or kinetic energy



2.1 Electricity storage technologies

Input

Electricity grid

Standalone renewables

Mechanical storage

These systems store energy either by:

- Forcing a mass or volume against a resistance (as a potential energy)
- Spinning a mass (as a kinetic energy)

The electricity is generated by allowing the mass or volume to work in the direction of the potential or by converting kinetic energy back into electricity

Operating principle

Output

Electricity

Mechanical storage – key categories

Pumped hydro	Flywheel	Compressed air	Geomechanical pump	Gravity based
Lifting water at an elevation	Rotational kinetic energy	Compressing and storing ambient air	Pumping sub-surface water	Lifting the storage medium

Sources: Kearney Energy Transition Institute analysis

Thermal energy storage (TES) relies on storing energy as heat and extracting the heat at a later period, either to meet heating demands directly or to generate electricity[1,2]

4

2.1 Electricity storage technologies

Input

Electricity grid

Standalone renewables

Thermal storage

Different mechanisms of electrothermal conversion:

- Creating a temperature difference within the storage medium to enable useful work to be performed later
- Manipulating phase changes of the storage medium to store and release heat
- Forming chemical bonds using a reactive storage medium

The stored electricity can then be used to harness either heat or electricity

Operating principle

Output

Electricity

Heat

Thermal storage – key categories

Sensible heat	Latent heat	Thermochemical heat
Heating or cooling a storage medium (liquid or solid) without changing its phase	Using latent heat, which is the energy required to change the phase of the material (normally solid to liquid)	Using endothermic and exothermic chemical reactions

Note: As the focus of the FactBook is electricity storage, only electrothermal solutions are covered which use electricity as an input and essentially work as a Carnot battery.[3,4]
[1] TES refers to storage of both heating and cooling energy. Heating TES usually involves using inexpensive, off-peak power to add heat to a storage medium for later use. In contrast, cool TES uses off-peak power to provide cooling capacity by extracting heat from a storage medium. Typically, a cool storage system uses refrigeration equipment at night to create a reservoir of cold material. During the day, the reservoir is tapped to provide cooling capacity. [2] TES is often combined with mechanical storage, such as CAES and LAES, to form a storage system. [3] Within electrothermal solutions' spectrum latent heat and thermochemical heat are still in preliminary R&D stages. Hence, only emerging technologies (such as standalone molten salt and sand battery) in sensible heat have been profiled. [4] The power sector has adopted TES on a commercial scale with molten-salt storage (sensible heat) used in CSP plants. However, this solution is not covered in detail as it doesn't use electricity as an input. Instead, standalone molten salt configuration is detailed which uses electricity as an input.
Sources: Kearney Energy Transition Institute analysis

Kearney XX/ID

Chemical storage is typically based on electrolysis of water to produce hydrogen

Input

Electricity grid

Standalone renewables

Chemical storage

Electricity is used to drive chemical or physical reactions which in turn yield stable chemicals that can store energy for long periods of time given the proper storage conditions.

Example: Electrolysis (i.e., using electricity to split the water molecule into hydrogen; as a storage medium) and oxygen gas. This reaction takes place in a unit called an electrolyzer and the produced hydrogen can be stored in different forms.

Operating principle

Output

H_2 Hydrogen

Chemical storage – key categories

Power- to –X (P2X)
Production (through water electrolysis), storage, and eventual reconversion of hydrogen back into electricity or other chemicals and fuels such as ammonia, methanol, synthetic jet fuel, etc.

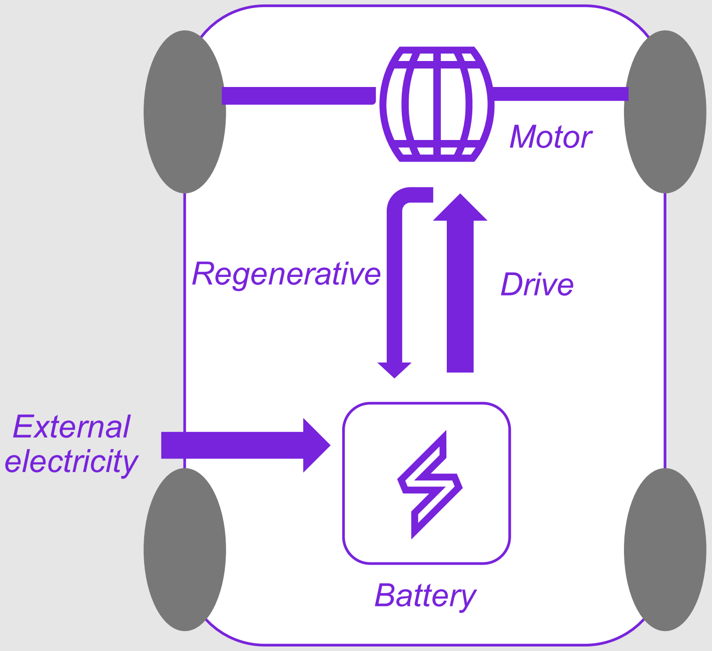
5

2.1 Electricity storage technologies

Note: As the focus of the FactBook is electricity storage, chemical storage solutions can be found in a dedicated **FactBook: Hydrogen applications and business models.**
Sources: Kearney Energy Transition Institute analysis

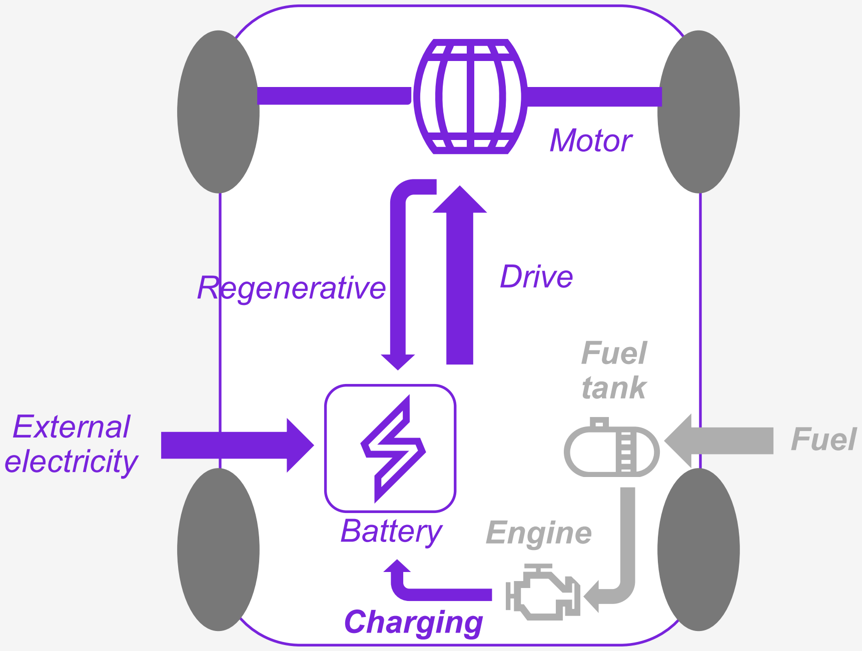
Different types of electric cars have been developed with battery-centric working principles

Working principle of battery electric vehicles (BEVs)



– Power from the DC battery is transformed into AC for the electric motor.
– The accelerator pedal sends a signal to the controller which adjusts the vehicle's speed by changing the frequency of the AC power from the inverter to the motor.
– The motor is connected to the wheels via a cog, enabling movement.
– When the brakes are applied or the car decelerates, the motor functions as an alternator, generating power that is fed back into the battery.

Working principle of plug-in hybrid electric vehicles (PHEVs)



– PHEVs usually begin in all-electric mode, running on electricity until their battery pack is drained.
– When the battery is depleted, the engine takes over, allowing the vehicle to function like a traditional non-plug-in hybrid.
– PHEV batteries can be recharged by plugging into an external power source, as well as by the internal combustion engine or through regenerative braking. During braking, the electric motor acts as a generator, capturing energy to recharge the battery.

Sources: Saldarriaga et al., 2022, Effects of the Incorporation of Electric Vehicles on Protection Coordination in Microgrids; Kearney Energy Transition Institute analysis

Even though several technologies are available for stationary electricity storage, batteries are currently gathering most of interest

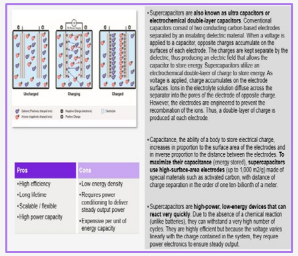
Listing of storage technologies FactCards (accessible later in the FactBook as "Appendix: FactCards")

2.2 FactCards of electricity storage technologies

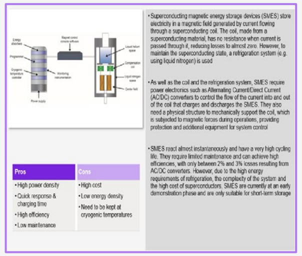
Overview and key technical parameters for the main storage technologies

1

Supercapacitors

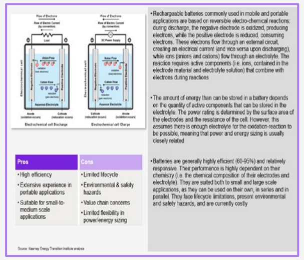


Superconducting magnet (SMES)

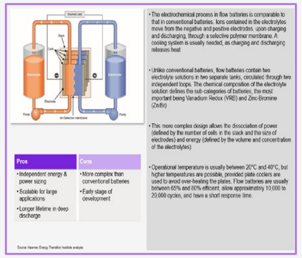


2

Classic batteries



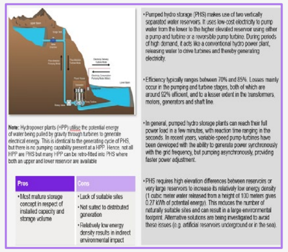
Flow batteries



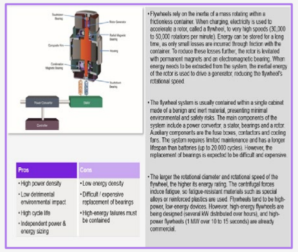
More details about **electrochemical storage** next page

3

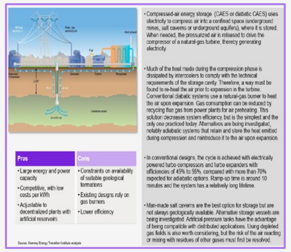
Pumped hydro (PHS)



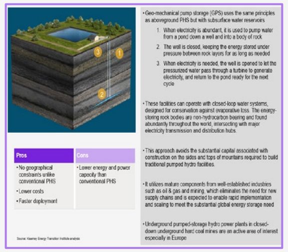
Flywheel



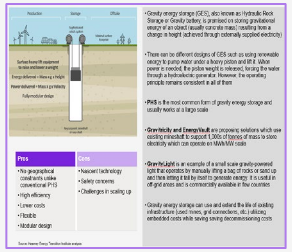
Compressed air (CAES)



Geomechanical pump (GPS)

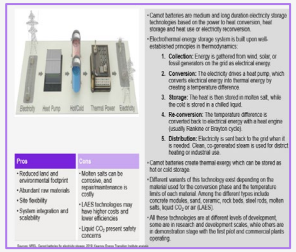


Gravity storage (GES)



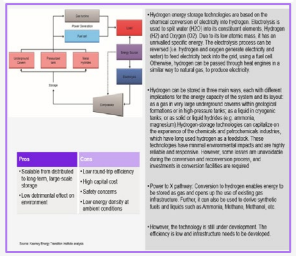
4

Sensible heat



5

Power to X



1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

Press "CTR + graphic" to directly link to the relevant FactCard

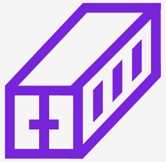
Sources: Kearney Energy Transition Institute analysis

Among electrochemical technologies, many new battery types are emerging

These technologies are mostly used for stationary storage.
Additional **emerging technologies** can be found **in the Appendix** of this FactBook.

2.2 FactCards of electricity storage technologies

For stationary applications



Classic

Lithium ion

Lithium ion (Li-ion): FactCard

Lead acid

Lead acid: FactCard

Sodium sulphur

Sodium sulphur (NaS): FactCard

Sodium nickel chloride

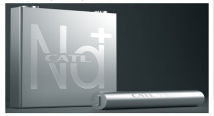
Sodium nickel chloride (ZEBRA): FactCard

Nickel based

Nickel based (Ni-Cd/Ni-MH): FactCard

Metal ion

Metal ion (Me-ion): FactCard



Metal sulphur

Metal sulphur (Me-S): FactCard

Metal air

Metal air (Me-air): FactCard

Solid-state

Solid-state (SSB): FactCard

Flow

Vanadium redox flow

Vanadium redox flow (VRB): FactCard

Zinc bromine redox flow

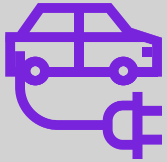
Zinc bromine redox flow: FactCard

Iron redox flow

Iron redox flow batteries: FactCard

Press “CTR + graphic” to directly link to the relevant FactCard

For mobility applications



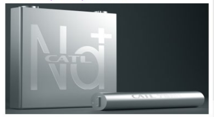
Classic

Lithium ion

Lithium ion (Li-ion): FactCard

Metal ion

Metal ion (Me-ion): FactCard



Solid-state

Solid-state (SSB): FactCard

Most mature technologies

Sources: Kearney Energy Transition Institute analysis

Summary of the main technical features of the key storage technologies

Non-Exhaustive

	Technology[1]	Energy capacity	Power capacity	Energy density (Wh/L)	Power density (W/L)	Discharge duration	Response time	Efficiency	Cycles	Lifetime
Electrical	Supercapacitor	< 1 kWh	< 300 kW	1–35	500–5,000	s–min	ms	90–95%	10,000–100,000,000	20+ years
	SMES	< 20 MWh	< 40 MW	0.2–13.8	300–4,000	ms–min	ms	90–95%	10,000	20–30 years
Electrochemical	Classic batteries	10 kWh–1 GWh	Few kW–500 MW	25–500	10-5,000	min–7 h	ms	75–90%	250–7,300	8–20 years
	Flow batteries[2]	10 kWh–800 MWh	Few kW–200 MW	10–70	0.5–34	2–12 h	ms	60–85%	2,000–10,000+	5–25 years
Mechanical	PHS	0.5–100 GWh	10 MW–3 GW	0.05–2	0.5–1.5	min–few 10 h	s–min	70–85%	20,000–100,000	50–100 years
	Flywheels	5 kWh–5 MWh	< 20 MW	20–80	800–2,000	s–min	s	85–95%	100,000–10,000,000	20+ years
	CAES	100 MWh–10 GWh	10–300 MW	0.4–20	0.5–10	h–10 h	min	42–54%	5,000–20,000	25–40 years
	LAES	10 MWh–7.8 GWh	5–650 MW	50–200	NA	2–24 h	min	45–70%	22,000–30,000	40 years
	Liquid CO_2	4–200 MWh	2–25 MW	66.7	NA	8–24 h	s	75%	NA	30+ years
	Geo-mechanical pump storage	Few MWh	0.5–10 MW	NA	NA	> 10 h	s	NA	NA	NA
	Gravity energy storage	< 100 MWh	< 25 MW	NA	NA	< 18 h	< 1 s	80%	50,000	35–50+ years
Thermal	Basalt	MWh – GWh	10 MW- 1 GW	NA	NA	Some h - days	S-min	60-70%	<10,000	30+ years
	Molten salt (standalone)	1 GWh	10–100+ MW	NA	NA	Some h–weeks	s–min	55–65%	< 10,000	30+ years
	Sand battery	1 GWh	< 100 MW	NA	NA	Some h–weeks	s–min	20–30%	1,000–10,000	50+ years
Chemical	Power to hydrogen	10 kWh–some GWh	1 kW–1 GW	600	0.2–20	Some h–weeks	s–min	20–40%	5000	5–30 years

[1] SMES: superconducting magnetic energy storage; PHS: pumped hydro storage; CAES: compressed-air energy storage; LAES: liquid air energy storage
[2] Data for vanadium redox flow battery

Sources: ENTEC - Energy Transition Expertise Centre, 2023, "Study on Energy Storage"; Kebede et. al, 2022, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration"; Behabtu et. al, 2020, "A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration"; Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Kearney XX/ID

Comparison of different electricity storage technologies –1/2

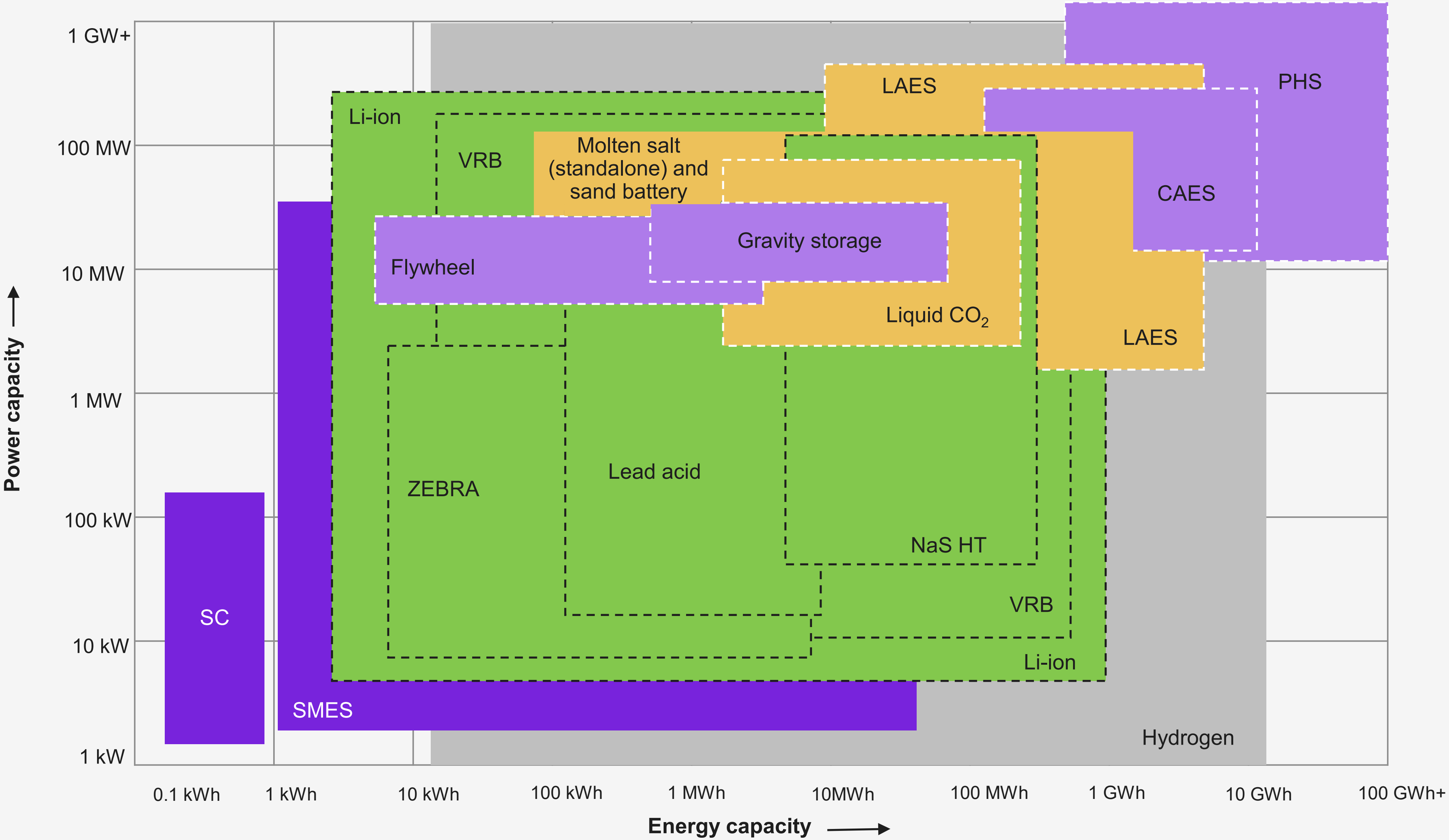
Indicative

Electrical storage
Electrochemical storage
Mechanical storage
Thermal storage
Chemical storage

2.3 Electricity technology landscape and applications

Power capacity vs. Energy capacity[1]

W vs. Wh

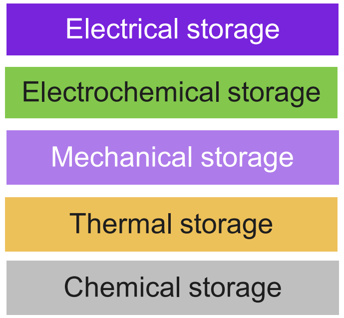


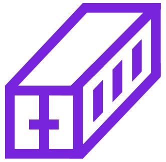
[1] PHS = pumped hydro storage, CAES = compressed air energy storage, LAES = liquid air energy storage, Li-ion = lithium-ion battery, VRB = vanadium redox flow battery, NaS HT = sodium sulphur high-temperature battery, Na-ion = sodium-ion battery, ZEBRA = sodium nickel chloride battery, SC = supercapacitor, SMES = superconducting magnetic energy storage

Sources: ENTEC - Energy Transition Expertise Centre, 2023, "Study on Energy Storage"; Kebede et. al, 2022, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration"; Behabtu et. al, 2020, "A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration"; Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Comparison of different electricity storage technologies – 2/2

Indicative

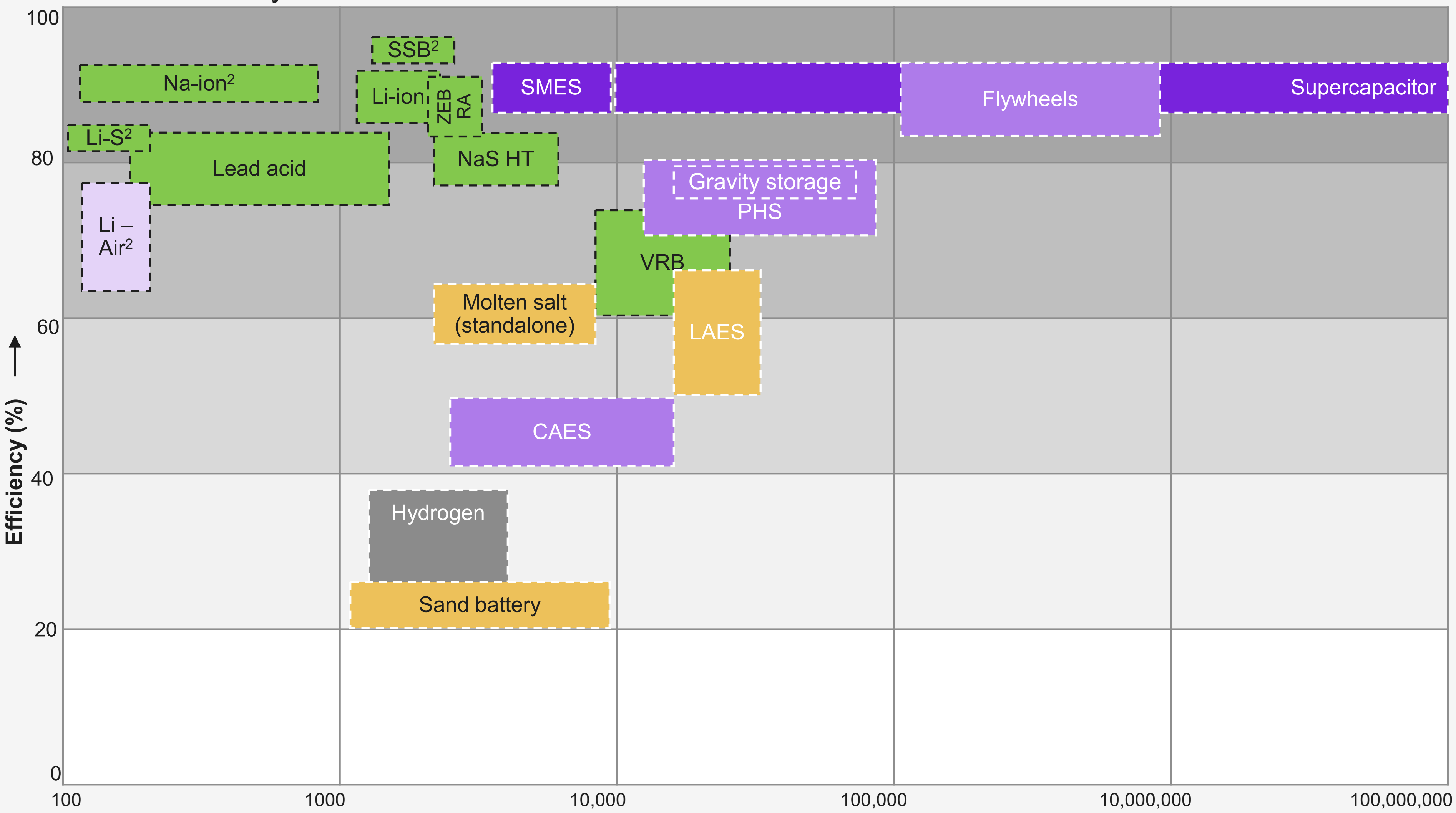




2.3 Electricity technology landscape and applications

Efficiency vs. number of cycles[1]

% vs number of cycles



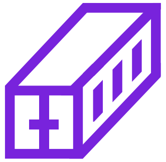
[1] PHS = pumped hydro storage, CAES = compressed air energy storage, LAES = liquid air energy storage, Li-ion = lithium-ion battery, VRB = vanadium redox flow battery, NaS HT = sodium sulphur high-temperature battery, Na-ion = sodium-ion battery), SSB = lithium polymer solid-state battery, Li-air = lithium air battery, Li-S = lithium sulphur battery, ZEBRA = sodium nickel chloride battery, SMES = superconducting magnetic energy storage

[2] Battery chemistries in R&D stage

Sources: ENTEC - Energy Transition Expertise Centre, 2023, "Study on Energy Storage"; Kebede et. al, 2022, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration"; Behabtu et. al, 2020, "A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration"; Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Kearney XX/ID

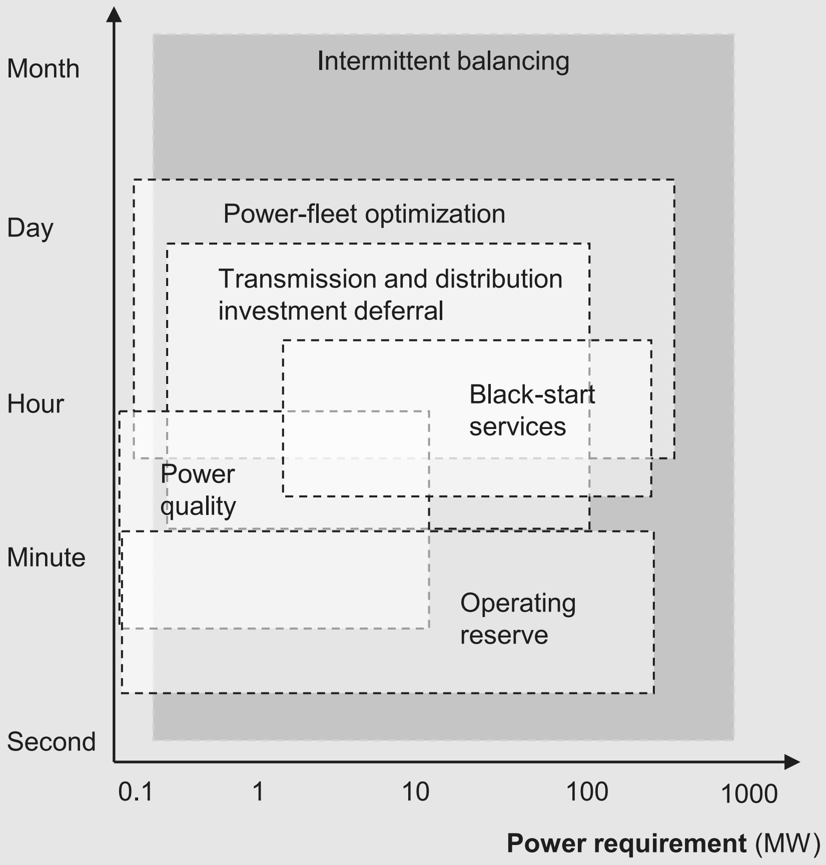
The features of storage technologies must be matched to the requirements of various applications



2.3 Electricity technology landscape and applications

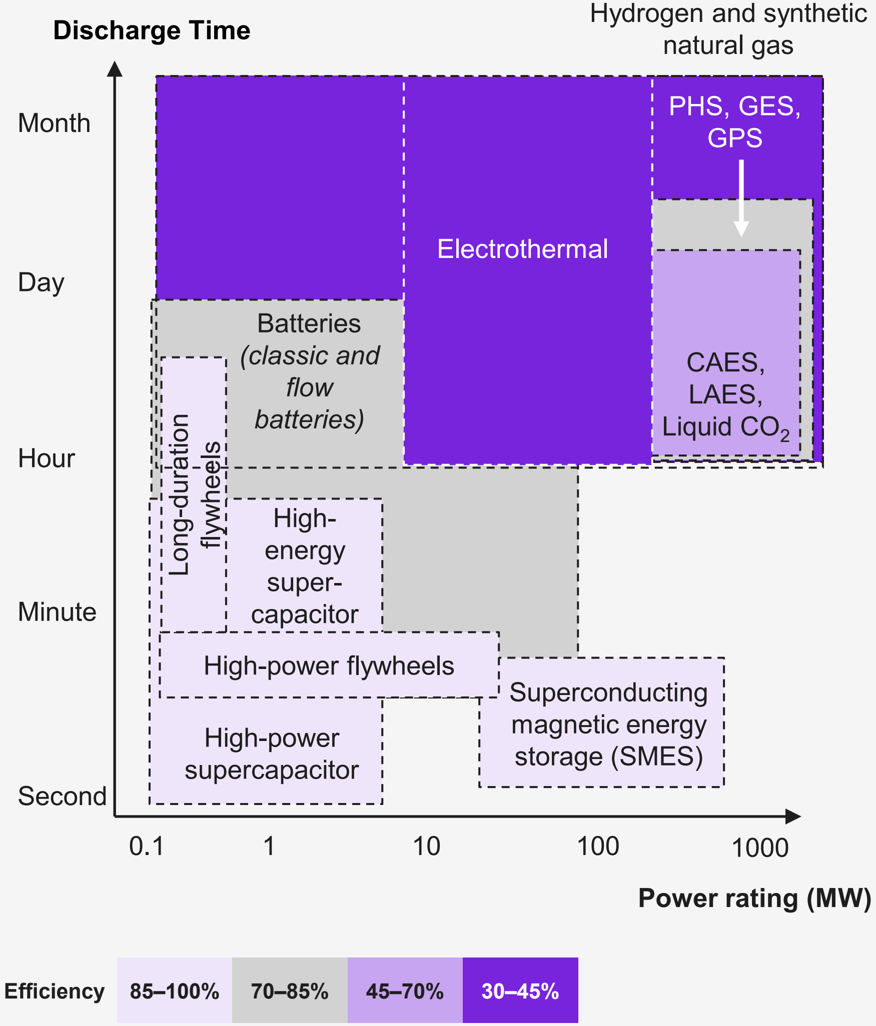
Electricity storage applications

Discharge time vs. power requirements (MW)



Electricity storage technologies[1]

Discharge time vs. power capacity (MW)



[1] PHS = pumped hydro storage, CAES = compressed air energy storage, LAES = liquid air energy storage, GPS = geomechanical pump storage, GES = gravity energy storage

Note: Supply to isolated areas has not been included as it is considered a mix of other applications. Technologies that contribute to black-start services only and serve for bridging purposes before other plants kick in have been given a low score. Technologies that balance short-term fluctuations (s-min) in renewable energy supply have been given a low score. Operating reserve does not appear on this diagram as it encompasses a large range of timeframes, capacity and response-time requirements.

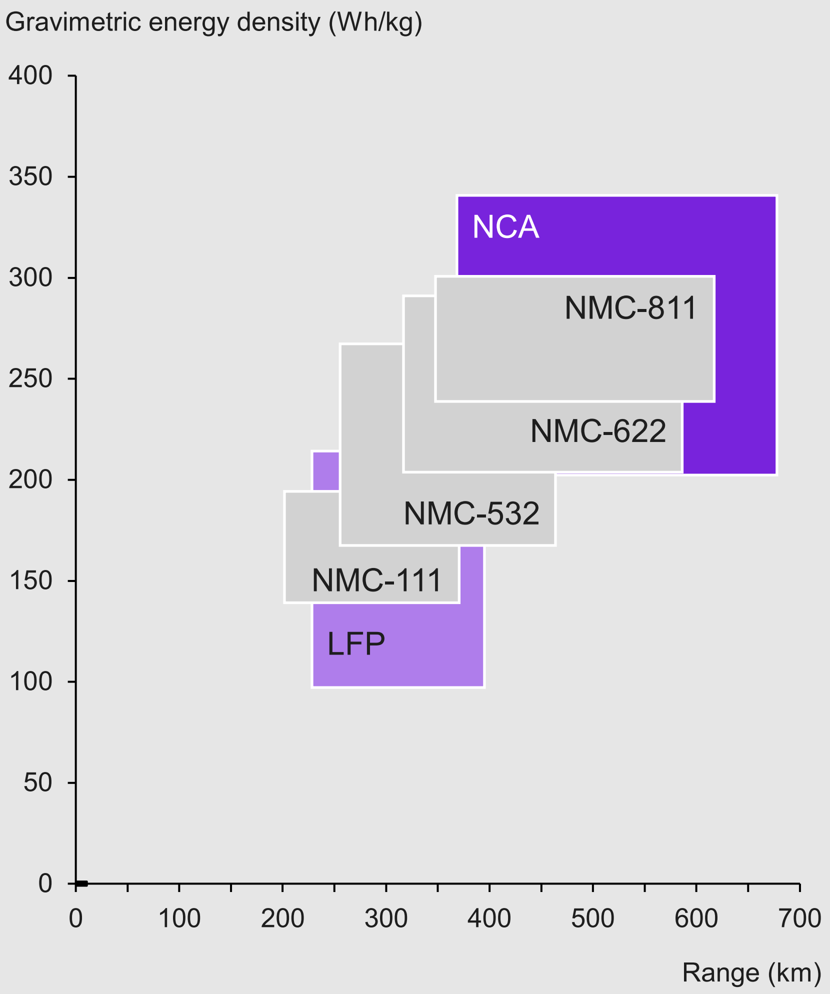
Sources: Kearney Energy Transition Institute analysis; EPRI (2010), "Electricity Energy Storage Technology Options", Bradbury (2010), "Energy Storage Technology Review"

Lithium-ion batteries dominate in the automotive applications

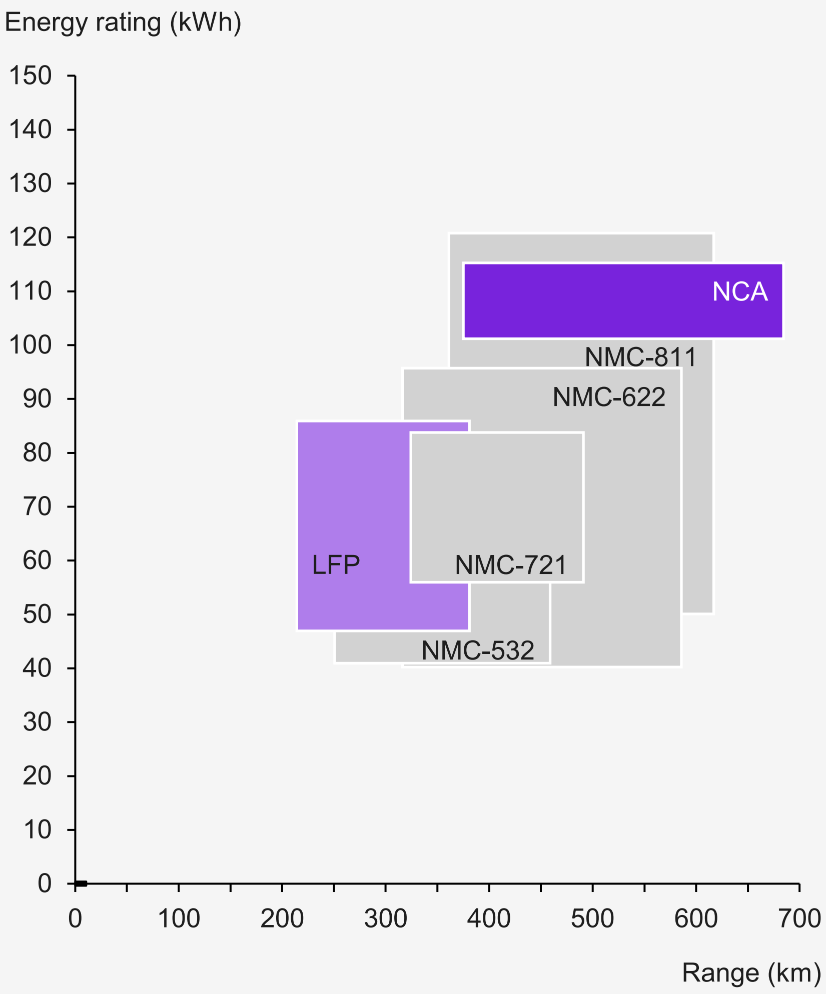
Commercial Li-ion battery types for automotive applications vary in terms of their chemistry, design (cell shape) and specifications.

2.3 Electricity technology landscape and applications

Gravimetric energy density vs. range
Wh/kg - km



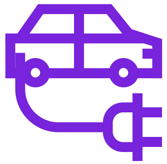
Energy rating vs. range
kWh - km



Note: LFP: Lithium iron phosphate; NMC: Lithium nickel manganese cobalt oxide; NCA: Lithium nickel cobalt aluminum oxide; The numbers after NMC denote the relative ratios of each element in the composition of the battery chemistry, i.e. NMC 111 has equal parts of nickel, manganese and cobalt
Sources: Hasselwander et al., 2023, Techno-Economic Analysis of Different Battery Cell Chemistries for the Passenger Vehicle Market; Sevdari et al., 2024, Overview of EV battery types and degradation measurement for Renault Zoe NMC batteries; Kearney Energy Transition Institute analysis

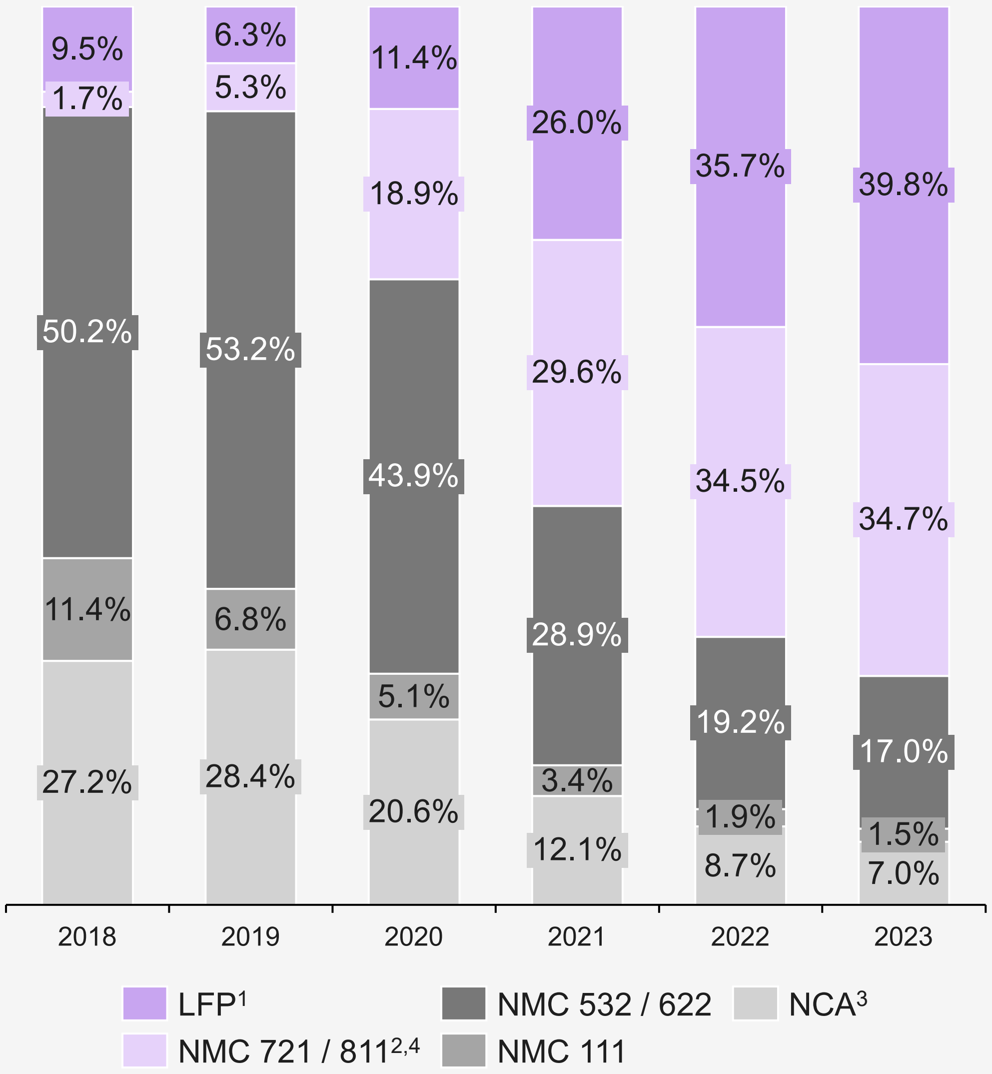
NMC remains the dominant cathode chemistry for electric cars, while the share of LFP batteries is increasing and reached record levels in 2023

Li-ion batteries have been widely used in EVs owing to their higher power and energy densities, longer cycle life, higher efficiency, and lower environmental impact compared with lead-acid and nickel-cadmium batteries.



2.3 Electricity technology landscape and applications

Battery cathode chemistry in electric car sales
2018–2023



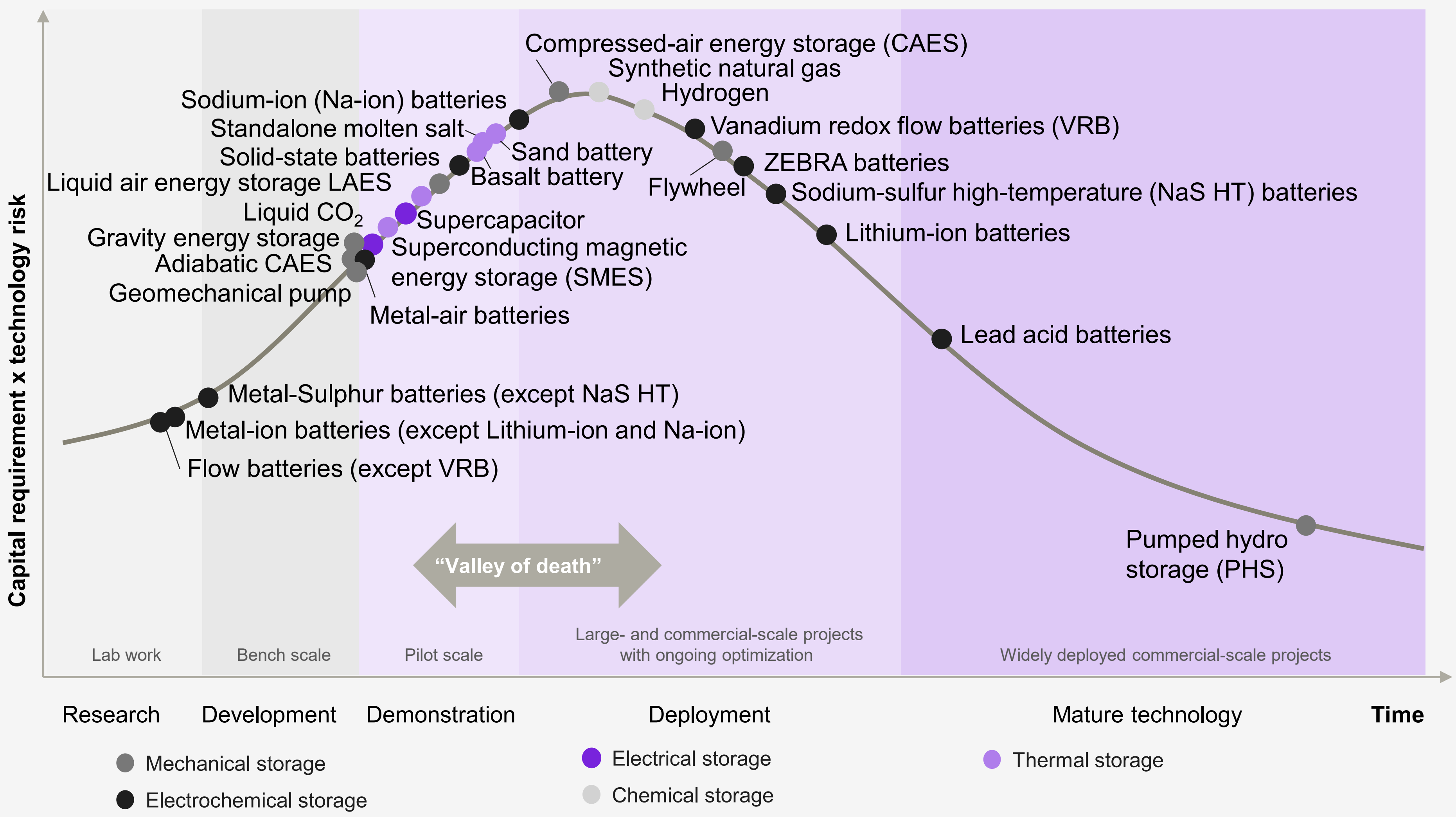
[1] LFP is lithium iron phosphate.
[2] NMC is lithium nickel manganese cobalt oxide.
[3] NCA is lithium nickel cobalt aluminum oxide.
[4] The numbers after NMC denote the relative ratios of each element in the composition of the battery chemistry, i.e., NMC 811 has eight parts of nickel, for one part of manganese and one part for cobalt.
Sources: IEA, 2024, Batteries and Secure Energy Transitions; PNNL - Lithium-ion Battery (LFP and NMC); Kearney Energy Transition Institute analysis

- Today, **NMC, NCA, and LFP** chemistries dominate the EV battery market. In recent years, alternatives to lithium-ion batteries such as **solid-state and sodium-ion batteries have gained attention.**
- **NMC and NCA** account for a large share of EV batteries because their relatively high nickel content enables higher energy densities in batteries.
- The new popularity of **LFP** chemistry is primarily driven by its lower price, longer lifespan compared to the alternatives, energy density improvements (such as the cell-to-pack configuration), and by improved thermal stability.
- As of 2023, LFP has a total installed cost of USD 452/kWh and 16-year lifespan vs USD 492/kWh and 13-year for NMC (for 10 MW and 2-hour duration).

Electricity storage technologies are spread across the maturity curve with pumped hydro storage the most mature technology deployed at scale currently

Non-exhaustive

Electricity storage maturity curve



Notes: TRL = technology readiness level, scale borrowed from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide.
Research phase corresponds to a TRL 1–3, development to a TRL 4, demonstration to a TRL 5–8, deployment to a TRL 9–10, and mature technology to a TRL 11.
Sources: IEA, Clean ETP clean energy technology guide, accessed June 2024; Kearney Energy Transition Institute analysis

Research and development priorities differ by technologies …

Non-exhaustive

2.5 Research and development

Research and development (R&D) in electricity storage technologies – summary 1/2

Technology	Sub-technology	R&D and innovation focus areas
Electrical storage	**Supercapacitors**	Material research to increase specifically by developing highly porous electrodes (such as graphene-like carbons or carbon nano tubes) vs. current activated carbon-based electrodes.
	Superconducting magnet electricity storage (SMES)	Improving performance, stability, and reliability of high-temperature superconducting materials (such as ceramics)
Electrochemical storage	**Classic batteries**	Development of new chemistries as an alternative to currently dominant Li-ion batteries – Investigate metal-ion, metal-sulphur, metal-air, and solid-state batteries to increase performance and safety as well as reduce costs. Additional motivations include reducing reliance on scarce minerals, improving environmental footprints, and diversifying supply chain to alleviate bottlenecks. Upgrading existing chemistries – Li-ion: Increasing energy density by moving toward pure lithium for cathode and adding silicon to anode – Lead acid: Increase life cycle through hybrid systems (especially supercapacitors) and carbon-modified system designs – Sodium sulphur (HT): Replacing solid beta-alumina ceramic with liquid electrolyte to reduce the operating temperature and corrosion – Sodium nickel chloride: Operations below 200°C and reduce or eliminate the use of costly nickel in the cathode, replacing nickel with iron
	Flow batteries	Development of new chemistries in addition to vanadium-based flow batteries – Such as iron-based flow batteries and organic flow batteries Upgrading existing chemistries – Vanadium: Experimentation with different chemistries to increase temperature range and lower costs – Zinc-bromine: Reduce complexity and balance-of-system costs

Sources: Kearney Energy Transition Institute analysis

… and include development of new technologies as well as refinement of the existing technologies

Non-exhaustive

2.5 Research and development

Research and development (R&D) in electricity storage technologies – summary 2/2

Technology	Sub-technology	R&D and innovation focus areas
Mechanical storage	**Pumped hydro**	Novel implementations to address geographic constraints and smaller scales effectively such as geomechanical pumped storage in existing mines, adopting sea as lower reservoir. Hybridization of hydropower turbines with batteries.
	Flywheels	Relatively mature, interest in transport applications. Experimenting with synchronous condensers for adding inertia to the grid.
	Compressed air energy storage (CAES)	– Development of adiabatic CAES that does not require the use of natural gas to reheat the air – Exploring alternative reservoirs
	Liquid air energy storage (LAES)	Integrating LAES with external thermal sources can enhance its performance.
	Liquid CO_2 energy storage	Maintaining long life of heat exchangers
	Geomechanical pump storage	Achieving higher mechanical efficiencies and reduced costs
	Gravity energy storage	Addressing technical challenges such as torques exerted by the steel cables as they untwist while lifting the weight
Thermal storage	**Molten salt (standalone)**	Corrosion mitigation in a molten salt environment
	Sand battery	Development of power-to-heat-to-power capabilities as currently it supports to heating applications
Chemical storage	**Power – to – X**	– Enhance performance and lower costs of electrolysis – Develop underground and solid storage

Sources: Kearney Energy Transition Institute analysis

Batteries' commercial energy densities are significantly lower than their theoretical potential

In mobile applications, the energy density is of particular importance because of limited space or payload. Conversely, in stationary applications, its significance is diminished.

Various factors contribute to the discrepancy between the batteries' theoretical and commercial energy densities

- **Efficiency losses:** During charging or discharging, batteries experience inherent losses from factors like resistance, heat generation, and chemical side reactions, lowering the commercial energy density.
- **Practical limitations:** Real-world battery applications face requirements in terms of performance and safety, adding weight and volume of inactive components.
- **Cycle life and degradation:** Batteries degrade over time due to factors like mechanical stress, electrode dissolution, and electrolyte decomposition, leading to reduced energy density over repeated charge cycles.
- **Operating conditions:** Battery performance and energy density are influenced by operating conditions like temperature and discharge rate.

Specific challenges for batteries' commercial energy density[1]

2023–2035

Battery type	Challenges for evolution of energy density for 2035
Li-ion	Cost reduction and alternatives to electrode materials
Na-ion	Optimizing material combinations
Mg-ion	Stable cathode–electrolyte combination
Zn-ion	Stability of electrodes and electrolyte
Al-ion	Highly corrosive electrolyte
Li-S	Cycle stability and power density
Na-S RT	Challenges on cathode and anode side
Na-S HT	Cost reduction and safety improvements
Li-air	Safety, energy efficiency, and side reactions
Zn-air	No stable planar cell design
VRB	Improved operational temperature and automated cell stacking

[1] Battery energy density is the amount of energy a battery contains compared to its weight or size. In the next slides, specific energy will refer to gravimetric energy density (Wh/kg), while energy density will refer to volumetric energy density (Wh/l).

Note: RT refers to room temperature, while HT refers to high temperature.

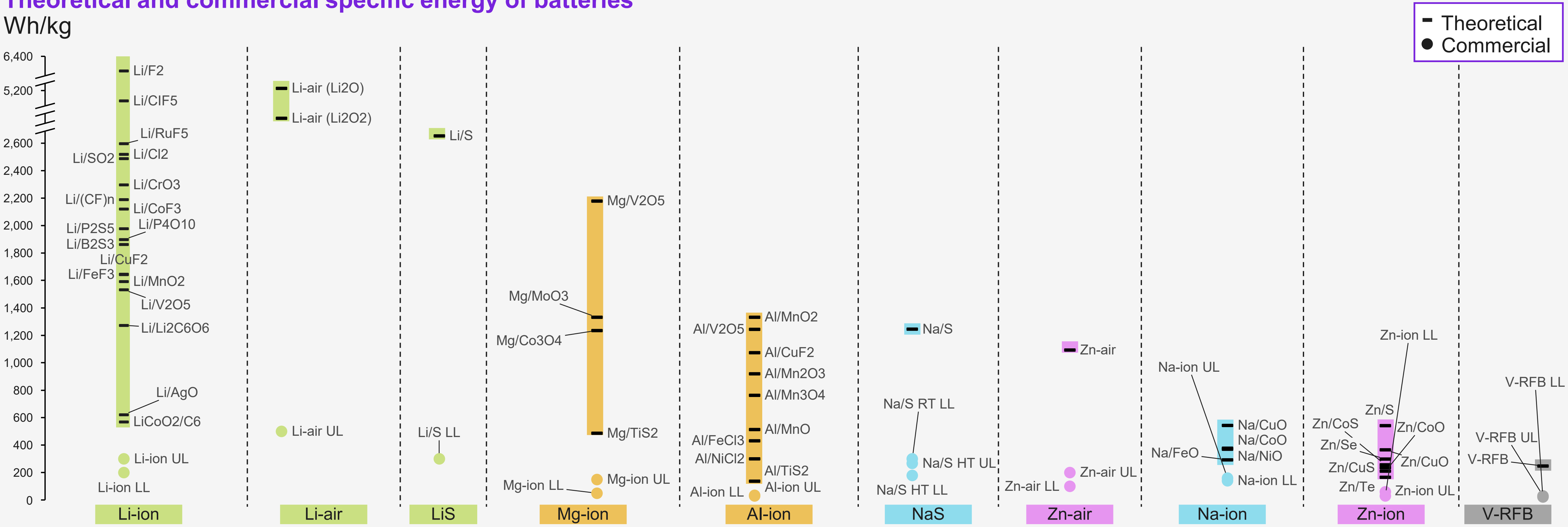
Sources: Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; J. Betz et al., 2018, "Theoretical versus Practical Energy: A Plea for More Transparency in the Energy Calculation of Different Rechargeable Battery Systems," Advanced Energy Materials; Kearney Energy Transition Institute analysis

Theoretical specific energy of batteries is up to 38 times higher than commercial

Specific energy (gravimetric energy density): The nominal battery energy per unit of mass - it determines the **battery weight** required to achieve performance parameters. High values are desirable, although limiting for consumer electronics and mobility applications due to **weight** constraints (compared to stationary storage).

Theoretical and commercial specific energy of batteries

Wh/kg



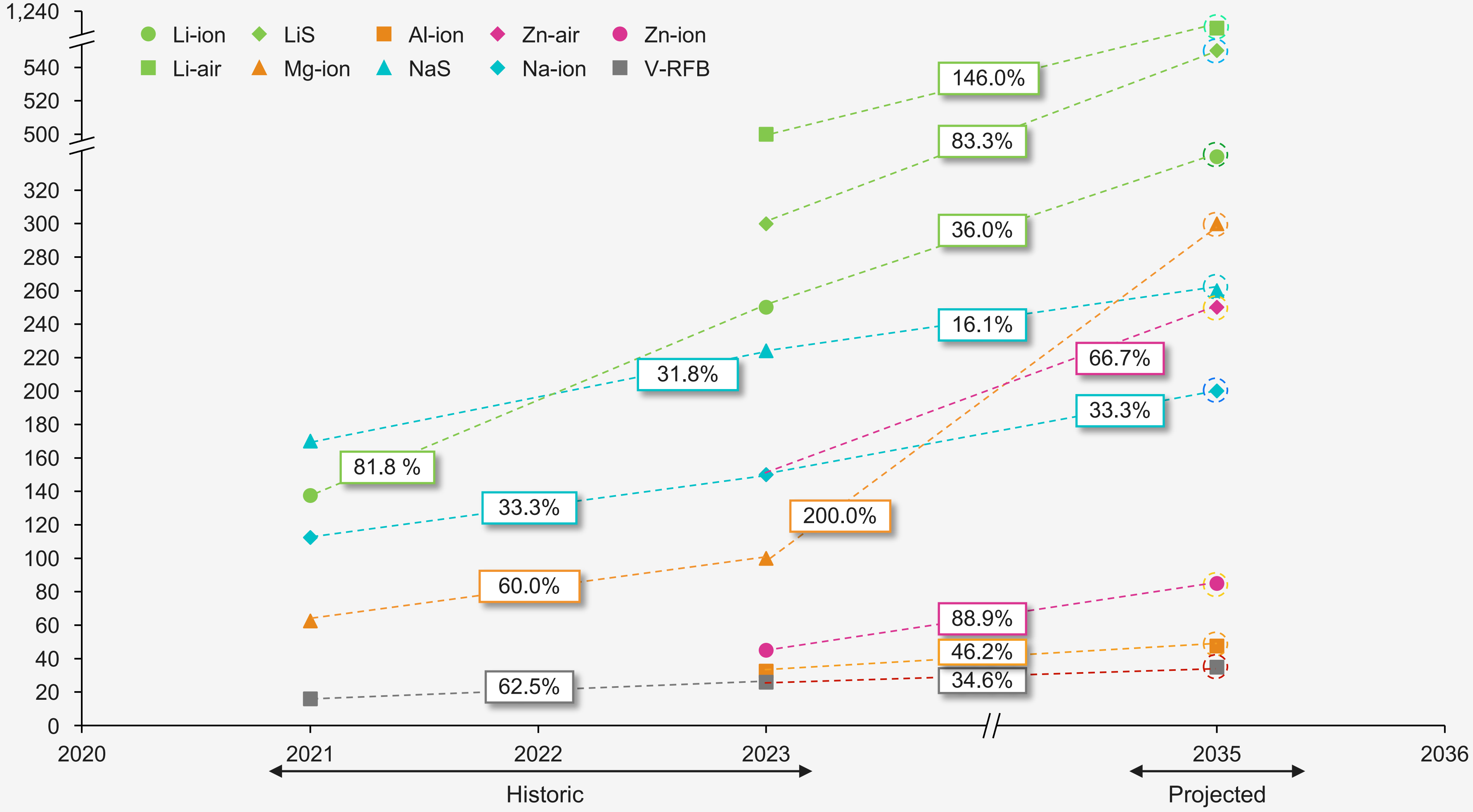
The theoretical specific energy's calculation methodology is available in Appendix.

Notes: LL refers to lower limit, while UL refers to upper limit. RT refers to room temperature, while HT refers to high temperature.
Sources: Data for Gibbs free energy of formation are taken from Engineering ToolBox; Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; J. Betz et al., 2018, "Theoretical versus Practical Energy: A Plea for More Transparency in the Energy Calculation of Different Rechargeable Battery Systems," Advanced Energy Materials; Kearney Energy Transition Institute analysis

Batteries' commercial specific energy is set to grow significantly over the next few years

Recent evolution of batteries' commercial specific energy

Wh/kg, 2021–2035



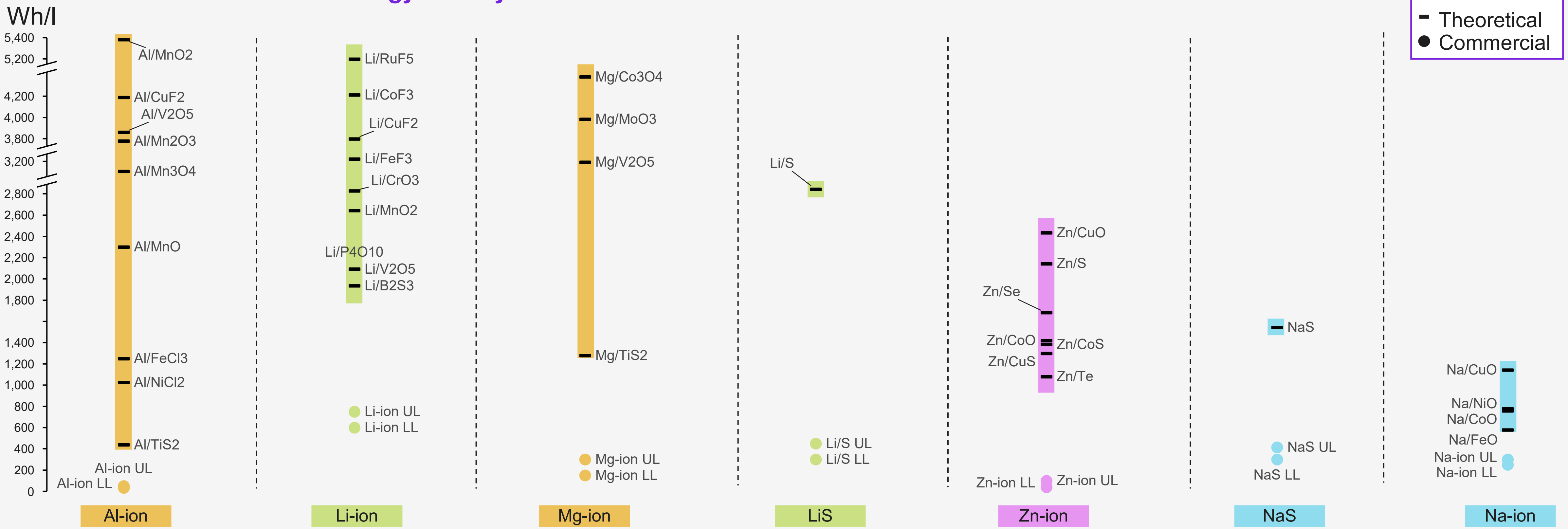
Note: LL refers to lower limit, while UL refers to upper limit. RT refers to room temperature, while HT refers to high temperature.
Sources: Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; IRENA, 2017, Electricity storage and renewables: Costs and markets to 2030; IEA, 2023, Global EV Outlook 2023 Catching up with climate ambitions; American Chemical Society, 2020, How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts?; M.Li et al., 2022, "Emerging rechargeable aqueous magnesium ion battery," Materials Report: Energy 2; Kearney Energy Transition Institute analysis.

2.6 Energy density of batteries

Theoretical energy density of batteries is up to 100 times higher than commercial

Energy density (volumetric energy density): The nominal battery energy per unit of volume - it determines the **battery size** required to achieve performance parameters. High values are desirable, although limiting for consumer electronics and mobility applications due to **size** constraints (compared to stationary storage).

Theoretical and commercial energy density of batteries



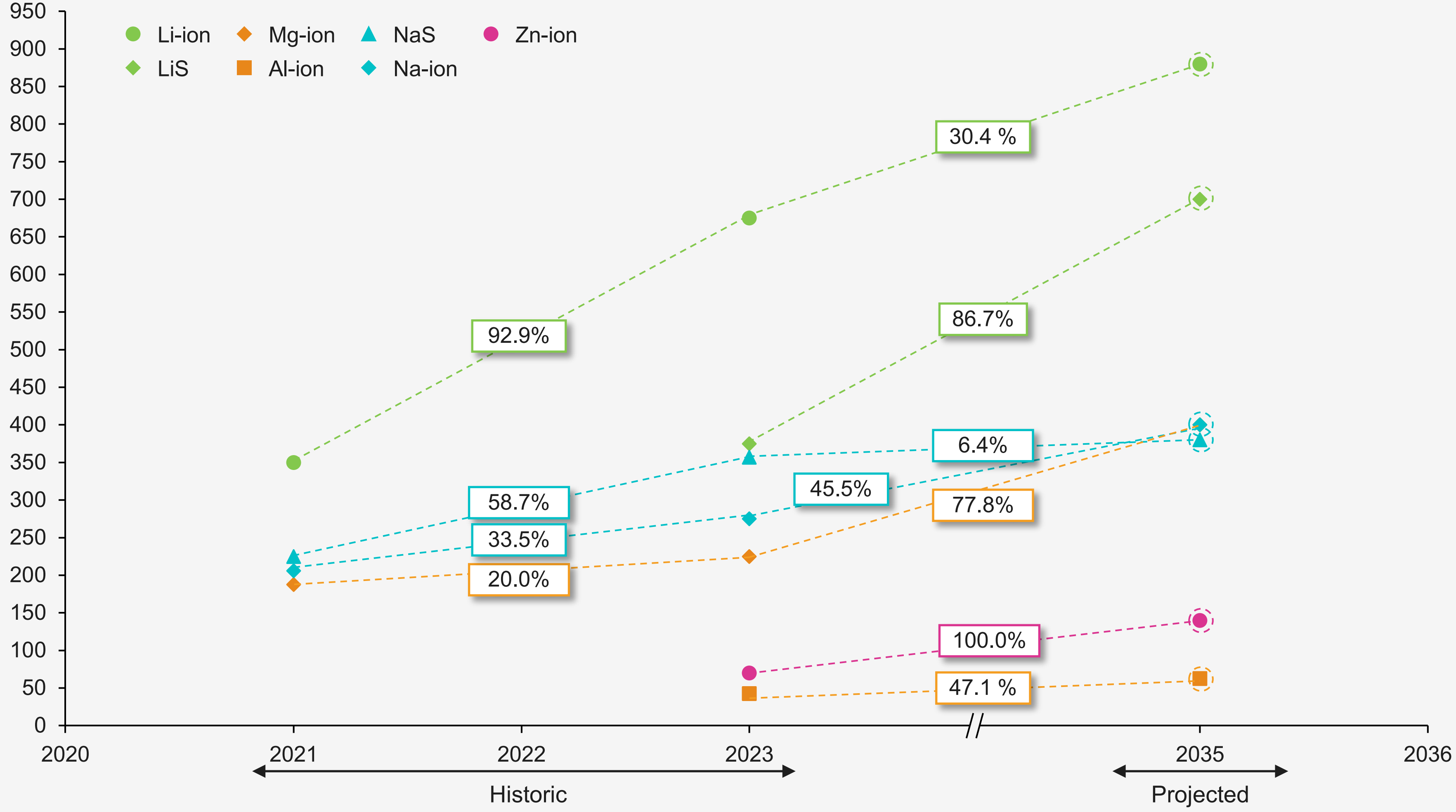
The theoretical energy density's calculation methodology is available in Appendix.

Note: LL refers to lower limit, while UL refers to upper limit. RT refers to room temperature, while HT refers to high temperature.
Sources: Data for Gibbs free energy of formation are taken from Engineering ToolBox; Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; J. Betz et al., 2018, "Theoretical versus Practical Energy: A Plea for More Transparency in the Energy Calculation of Different Rechargeable Battery Systems," Advanced Energy Materials; Kearney Energy Transition Institute analysis

Batteries' commercial energy density is set to grow significantly over the next few years

Recent evolution of batteries' commercial energy density

Wh/l, 2021–2035



Note: LL refers to lower limit, while UL refers to upper limit. RT refers to room temperature, while HT refers to high temperature.
Sources: Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; IRENA, 2017, Electricity storage and renewables: Costs and markets to 2030; IEA, 2023, Global EV Outlook 2023 Catching up with climate ambitions; American Chemical Society, 2020, How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts?; M.Li et al., 2022, "Emerging rechargeable aqueous magnesium ion battery," Materials Report: Energy 2; Kearney Energy Transition Institute analysis

2.6 Energy density of batteries

3. Status and future market development of electricity storage

Current status and future development of electricity storage

Electricity storage is not a new concept—the first electric car appeared in 1888 and the first pumped hydro storage (PHS) plants emerged during the 1890s.

Since 2017, global stationary storage capacity has surged by 58%, reaching 276 GW by the end of 2023. PHS is the leading storage technology, **with a capacity of 184 GW, while lithium-ion batteries** have shown significant growth, **experiencing a seventy-fold increase to 78 GW by 2023.** This surge has prompted a noteworthy shift in the market away from PHS toward lithium-ion batteries. These batteries have become the preferred choice for transmission and distribution services, while PHS systems remain crucial for energy capacity and ancillary services.

China (45 GW), Japan (30 GW), and the United States (23 GW) collectively account for 53% of current PHS installations. By 2030, the United States (72 GW) and China (72 GW) are projected to contribute approximately 66% of hydro storage additions. Today, battery storage installations represent 91% of the total 70 GW of non-PHS installed capacity, with flywheel and compressed air energy storage projects at a standstill.

China (35 GW) and the United States (21 GW) dominate battery storage installations, comprising 64% of total installed capacity in 2023. However, current deployment falls significantly short (between 1.5 and 3.5 times) of the projected battery capacity required to meet global climate ambitions. **The surge in lithium-ion demand is primarily driven by mobility applications and is projected to increase from 797 GWh in 2022 to around 4 TWh in 2030**, reflecting a compound annual growth rate of 23% from 2022 to 2030. Other types of batteries, such as sodium-ion and vanadium redox flow, are gaining momentum in mobility and stationary storage applications, respectively.

China is also leading the global battery storage investments with a commitment of USD 14 billion, which accounts for 39% of the global investment in batteries. In 2023, almost three-quarters of battery storage investments were directed **toward utility-scale projects**. In the IEA's net zero scenario, investment is projected to rise significantly, reaching **USD 112 billion per year in 2030**, marking a threefold increase from 2023 levels. Heading to 2040, investment continues to climb, growing by an additional 10% to **USD 123 billion per year.**

The science of storage technologies has continued to evolve since the invention of the first fuel cell in 1839

Timeline of electricity storage technologies science

1839 — **Sir William Robert Grove invents the first fuel cell** by mixing hydrogen and oxygen with an electrolyte, resulting in electricity and water production.

1859 — **Physicist Gaston Planté invents** the first practical version of a rechargeable **battery based on lead-acid chemistry.**

1883 — **The first FES is developed by John A. Howell** for military applications.[1]

1899 — **Swedish scientist Waldemar Jungner invents the Ni-Cd battery,** a rechargeable battery that has nickel and cadmium electrodes in a potassium hydroxide solution.[2]

1966 — **Ford Motor Company** develops the first **sodium-sulfur battery.**

1969 — **M. Ferrier introduces the SMES system** as a source of energy to accommodate the diurnal variations of power demands.[3]

1976 — **The first viable lithium-based battery** is patented by British chemist **Michael Stanley Whittingham.**

1977 — A 42-borehole **thermal energy storage is constructed** in Sigtuna, Sweden.

1978 — **PRI** develops the **first supercapacitor** with low internal resistance for military applications.[4]

1983 — **M. Skyllas-Kazacos and coworkers pioneer the VRB** at the University of New South Wales, Australia.[5]

2007 — **Dr. R. Linhardt, et al.** from RPI, New York first invent the **concept of paper batteries.**[6]

3.1 History of electricity storage

[1] Flywheel energy storage; [2] Nickel-cadmium battery; [3] Superconducting magnetic energy storage; [4] Pinnacle Research Institute; [5] Vanadium redox battery; [6] Rensselaer Polytechnic Institute
Sources: P. Mitali et al., 2022, "Energy storage systems: a review," Energy Storage and Saving; Kearney Energy Transition Institute analysis

Applications of electricity storage development started in the 1890s and have sped up considerably since 2021

3.1 History of electricity storage

Electricity storage development timeline: from the first application to today

1888
In 1888, the **first electric car** appeared in Germany.

1890s
First PHS plants using separate pump impellers and turbine generators **appear in Switzerland, Austria, and Italy.**[1]

1960s
Development of PHS accelerates as many countries start to envision a dominant role for nuclear and **the use of PHS for peak power.**[1]

1971
First CAES plant built in Huntorf, Germany.[2]

1985
Flywheel system built in Japan can **deliver 160 MW for 30s.**

1990s
Development of PHS declines due to a drop in gas prices.[1]

1991
Second CAES plant built in McIntosh, US.[2]

1991
Sony releases the first commercial lithium-ion battery.

2000s
New momentum for electricity storage driven by an **increase in fossil-fuel prices** and the rising penetration rate of variable electricity generation from renewables.

2007 - 2015
More than 1,500 GW of thermal storage capacity is developed to provide storage solutions for CSP plants, **principally in Spain and the US.**[3]

2015
Strong push for lithium-ion battery storage with successive announcements from **GE, Tesla, Daimler, LG Chem, and Panasonic.**

2017
World's first utility-scale hybrid wind, solar, and storage project announced in Australia.

Nanotechnology (carbon nanotube)-based batteries developed by NAWA Technology.

2021
182 GW (165 GW pumped hydro storage and 17 GW other technologies) **of energy storage** was **online at the end of 2021.**

2023
Compared with 2021, **stationary storage** capacity rose by 52% **in 2023, adding up to 276 GW.**

EV battery volumes have quadrupled over the past three years, reaching **2,225 GWh** in 2023.

[1] Pumped hydro storage
[2] Compressed air energy storage
[3] Concentrating solar power

Sources: BloombergNEF, 2022, 2H 2022 Energy Storage Market Outlook; GlobalData, 2023; US Department of Energy (DOE), 2023, Global energy storage database; IEA, 2024, Batteries and Secure Energy Transitions; IHA, 2022, Hydropower Status Report: Sector trends and insights; IHA, 2023, Pumped storage tracking tool; desktop research; Kearney Energy Transition Institute analysis

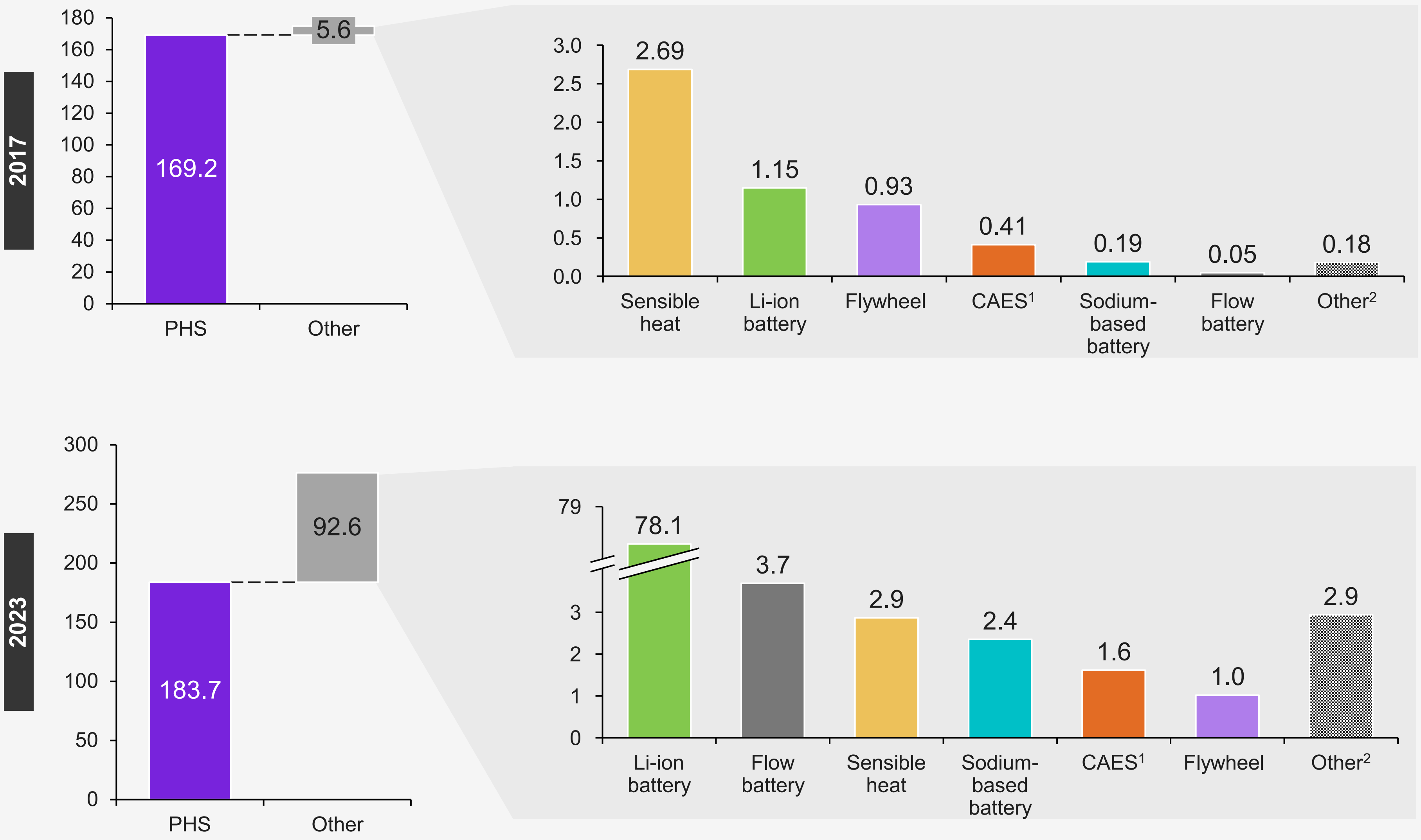
Global stationary storage capacity currently stands at 276 GW, of which 66% is pumped hydro storage (PHS)

- Global **storage capacity has increased by 58% since 2017,** currently **standing at 276 GW.**
- **Li-ion batteries'** capacity has shown **seventy-fold increase since 2017 to reach 78 GW for 2023.**
- The market is **switching from PHS to Li-ion batteries.**

3.2 Installed capacity and pipeline

Evolution of stationary storage capacity by technology

GW, 2017 and 2023

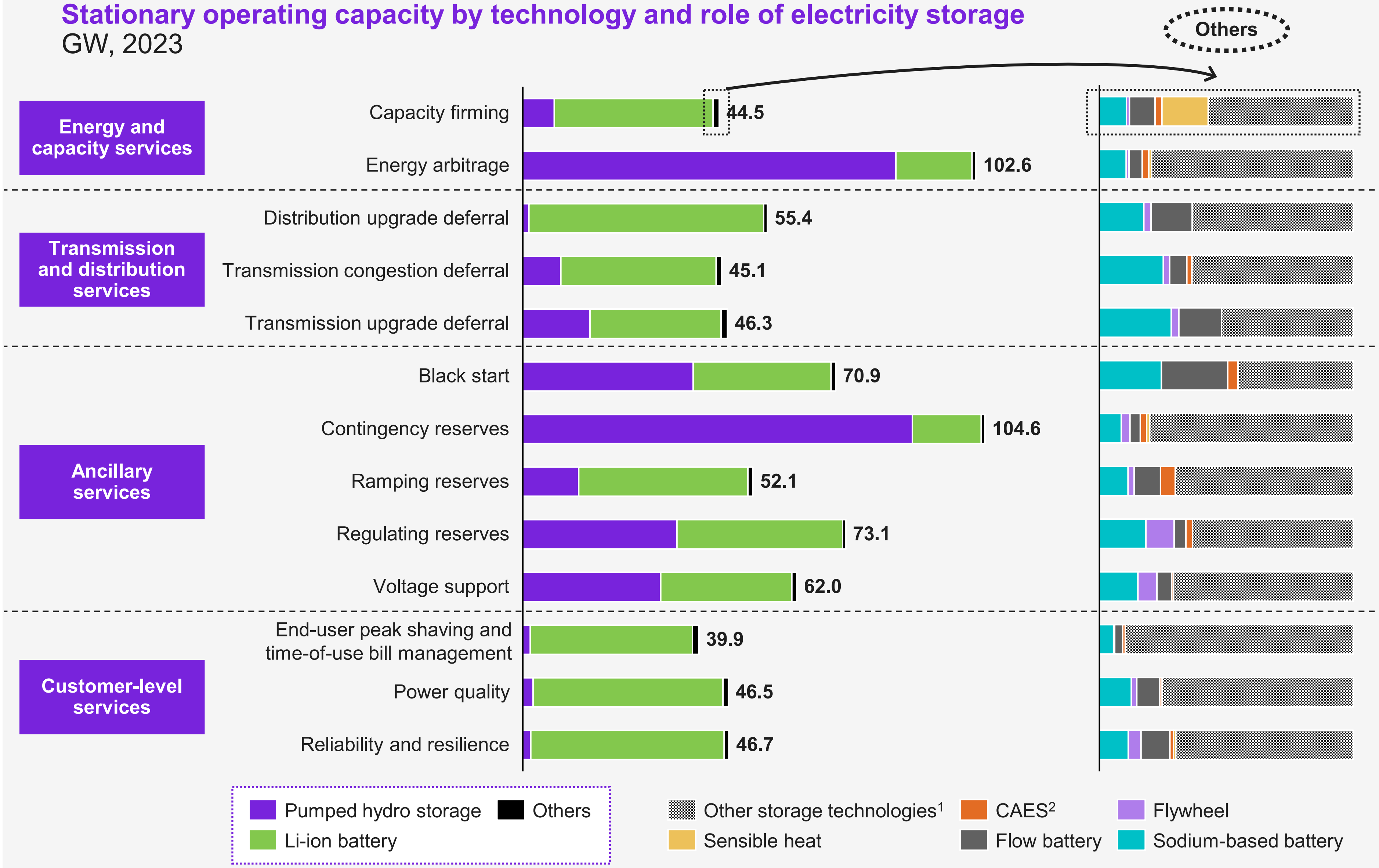


[1] Compressed air energy storage; [2] Includes heat thermal storage, latent heat, lead-acid battery, nickel-based battery, electro-chemical capacitor, hydrogen storage, zinc-based battery and unknown technologies.
Sources: GlobalData, 2023; US Department of Energy (DOE), 2023, Global energy storage database; IHA, 2023, Pumped Storage Tracking Tool; IEA, 2024, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

Li-ion batteries and pumped hydro storage are the dominating technologies in grid solutions

– **Lithium-ion batteries** are the most common storage technology used for **transmission and distribution services**.
– **Energy arbitrage and contingency reserve applications** are achieved through **pumped hydro storage systems.**

3.2 Installed capacity and pipeline

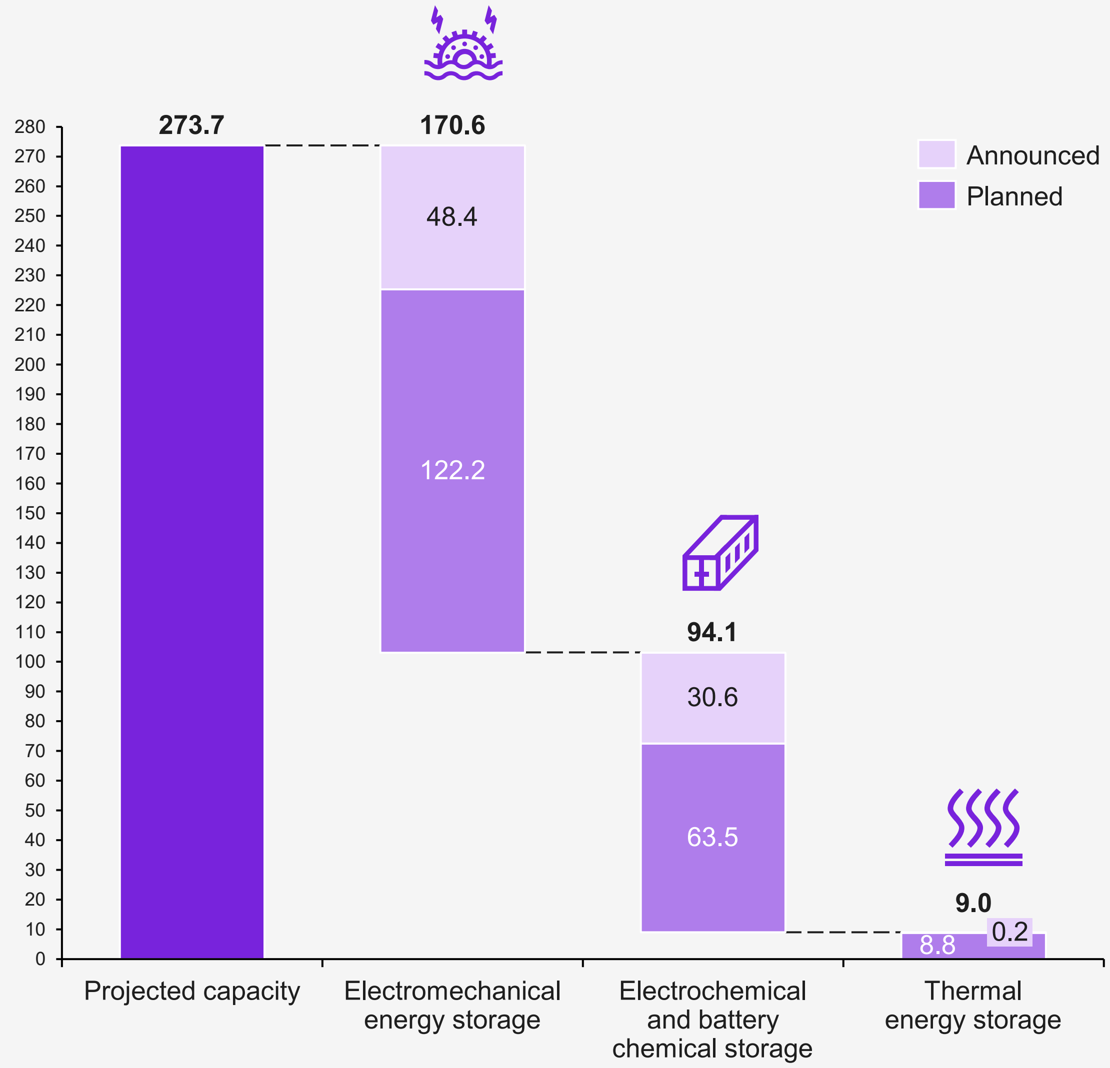


[1] Includes heat thermal storage, latent heat, lead-acid battery, nickel-based battery, electrochemical capacitor, hydrogen storage, zinc-based battery, and unknown technologies
[2] Compressed air energy storage
Note: The share of energy storage technologies deployed for each application is based on 2018 data.
Sources: GlobalData, 2023; DOE, 2023, Global energy storage database and DOE ESHB Chapter 23 Applications and grid services; IEA, 2024, Batteries and Secure Energy Transitions; IHA, 2023, Pumped storage tracking tool; Kearney Energy Transition Institute analysis

Electrochemical and chemical storage technologies register a strong growth to become the preferred alternatives to pumped hydro storage

3.2 Installed capacity and pipeline

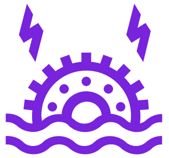
Projected stationary storage capacity additions by technology broad category
GW, 2030



- **Electromechanical energy storage:** consists of compressed air energy storage, flywheel, pumped hydro storage, and unknown technologies.
- **Electrochemical battery and chemical storage:** includes electrochemical capacitor, hydrogen storage, batteries (flow, lead-acid, lithium-ion, nickel-based, sodium-based, and zinc-based), and unknown technologies.
- **Thermal energy storage:** contains heat thermal storage, latent heat, sensible heat, and unknown technologies.

Sources: Global Data, 2023; DOE, 2023, Global energy storage database; IHA, 2023, Pumped storage tracking tool; Kearney Energy Transition Institute analysis

Pumped hydro additions are found in new geographies, but the United States and China continue to dominate growth

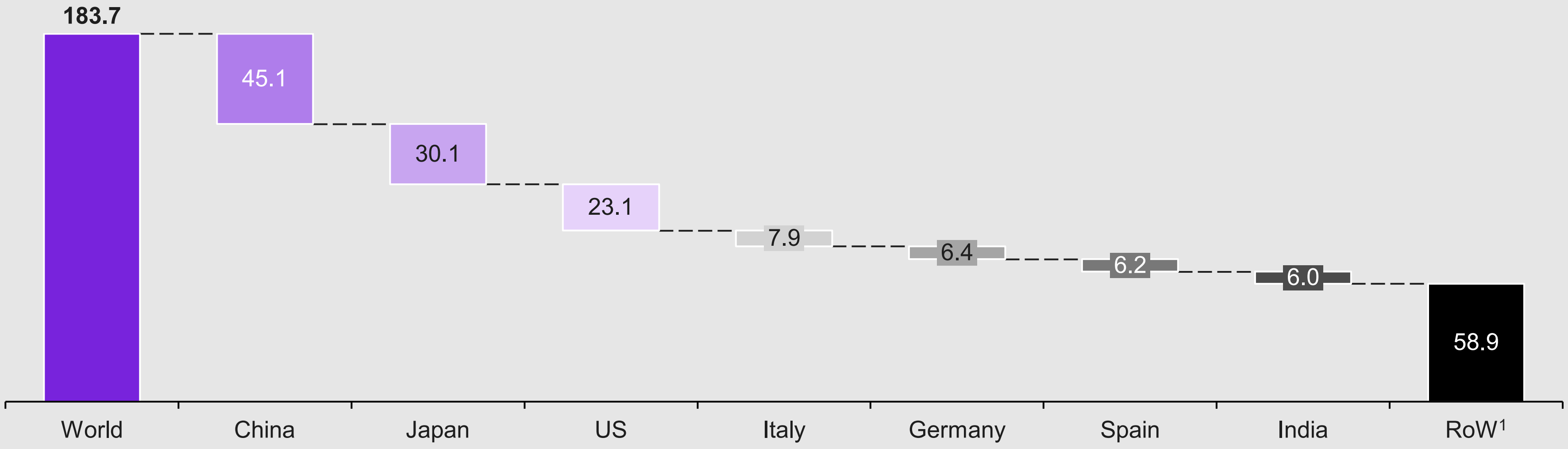


- **China, Japan, and US** hydro storage installations represent **53% of total installed capacity today.**
- **US and China** dominate growth, representing approximately **66% of hydro storage additions by 2030.**

3.3 Pumped hydro storage

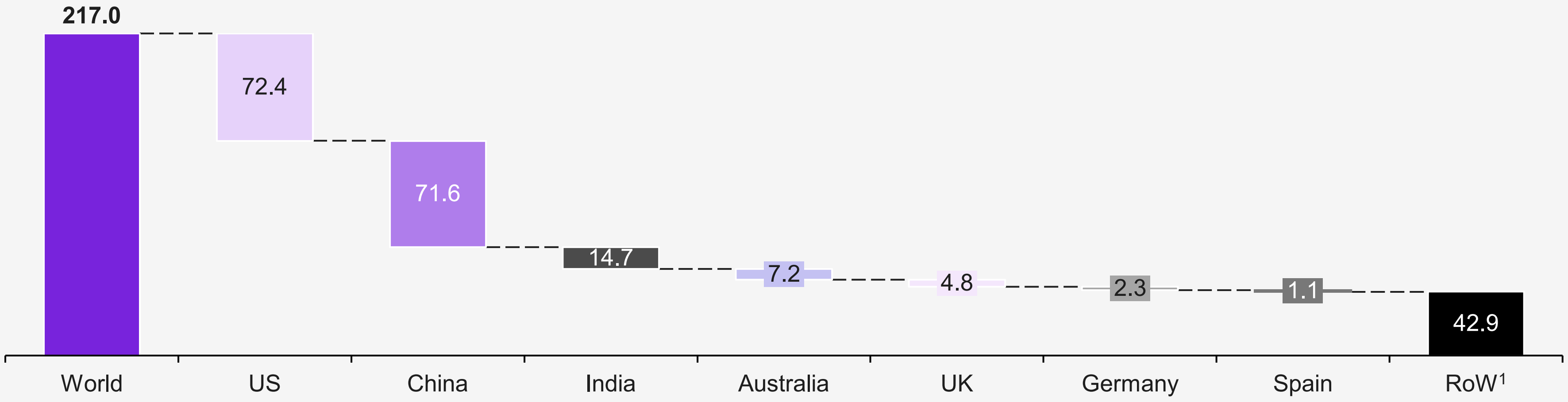
Pumped hydro storage installed capacities by country

GW, 2023



Expected pumped hydro storage additions by county

GW, 2023–2030



[1] Rest of world

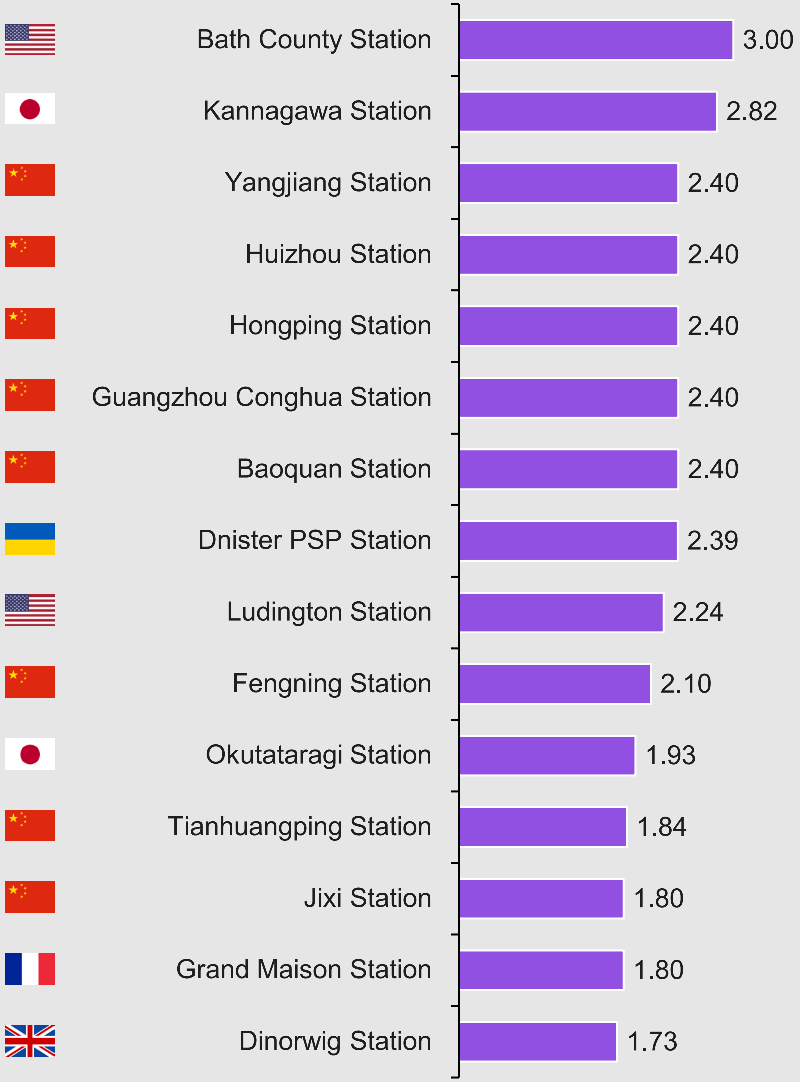
Sources: IHA, 2023, Pumped storage tracking tool; Kearney Energy Transition Institute analysis

Large PHS projects are in the pipeline for the United States, which is catching up with China and surpassing Japan

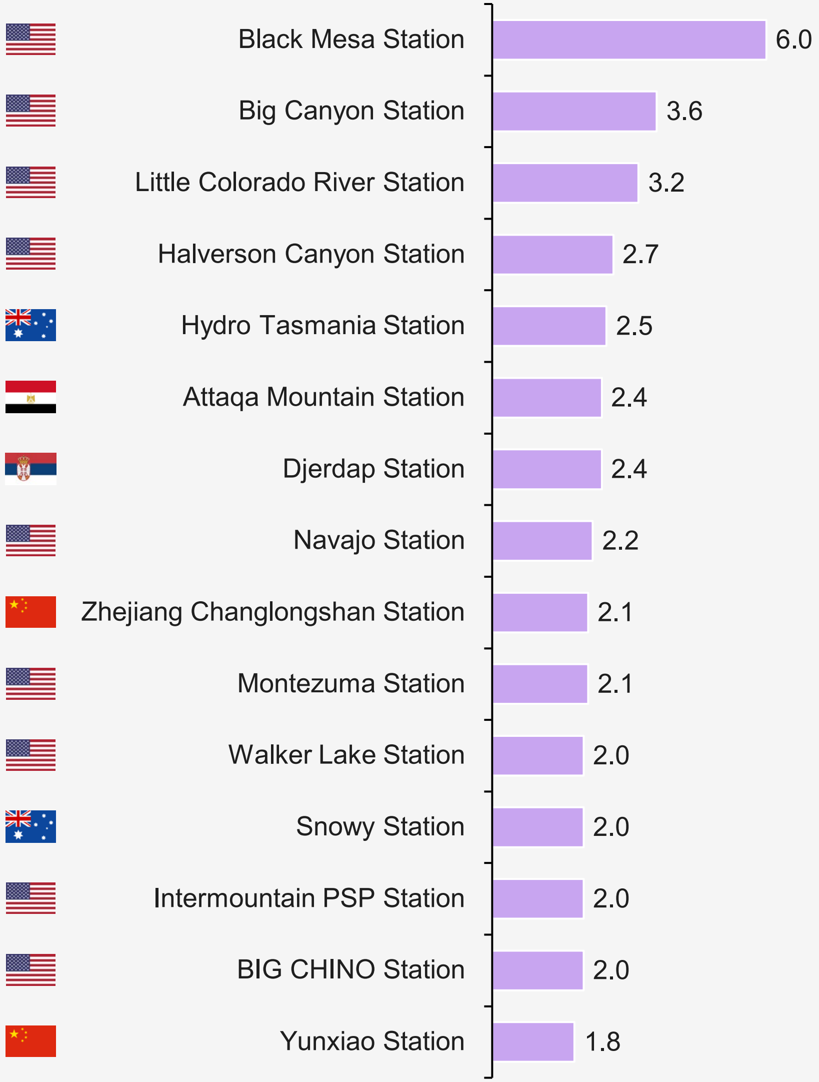
- Average capacity of the top 15 largest PHS projects **in operation is 2.24 GW**.
- Average capacity of the top 15 largest PHS projects expected to increase by **20% to 2.60 GW for the 2030 pipeline.**

3.3 Pumped hydro storage

Largest PHS installations in operation worldwide by capacity
GW, 2023



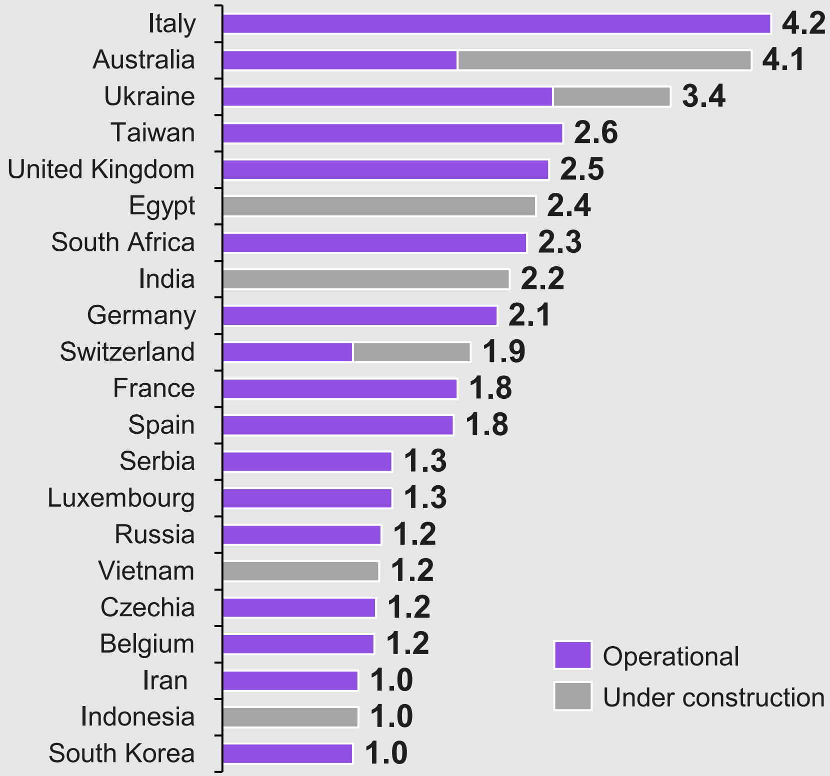
Pipeline of largest PHS projects worldwide by capacity
GW, 2024–2030



Sources: IHA, 2023, Pumped storage tracking tool; Kearney Energy Transition Institute analysis

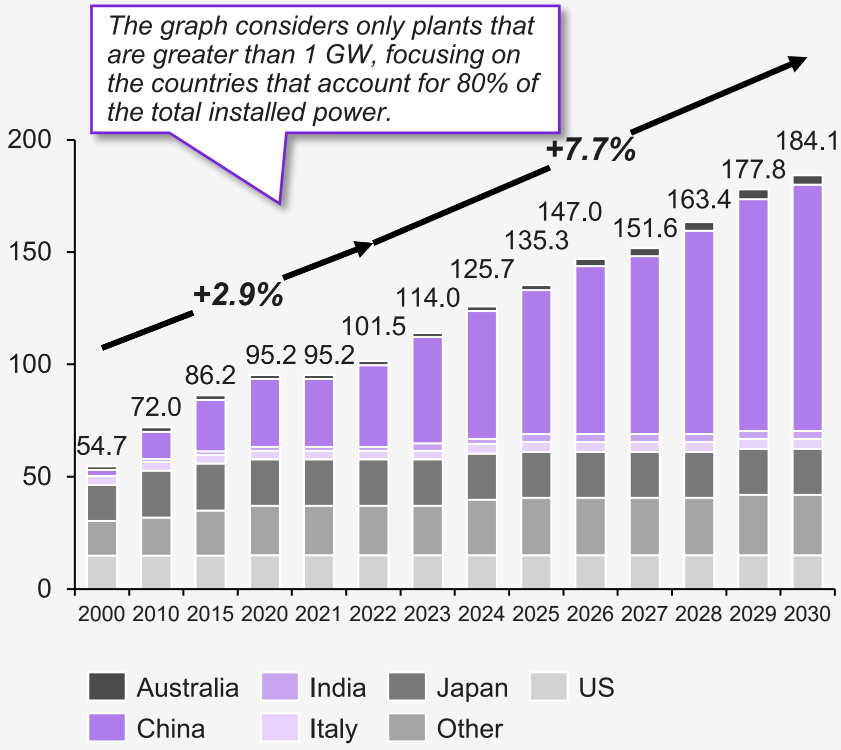
New geographies like Australia, Egypt, and India are gaining ground in large PHS projects

Large PHS (over 1 GW) installed and upcoming capacities by country[1]
GW, 2023



In the PHS market, Europe is the leader with a cumulative **capacity of 28 GW**, followed by **Asia Pacific** with **13.8 GW**. **Africa** holds **5.5 GW,** while **America** has the lowest capacity with **1.1 GW**.

Total installed storage capacity since 2000 by country
GW, 2000–2030



- **The growth, after 2022,** can be attributed to the **increasing adoption of variable renewables.**
- **From 2022 to 2030**, **China's** under-construction projects account for approximately **68 GW out of 80 GW** of all large PHS projects under construction, planned, or announced.

3.3 Pumped hydro storage

[1] Excluding China, Japan, and the United States
Sources: C.N. Papadakis et al., 2023, "A Review of Pumped-Hydro Storage Systems," Energies; Kearney Energy Transition Institute analysis

Flywheel and compressed air energy storage projects are at a standstill

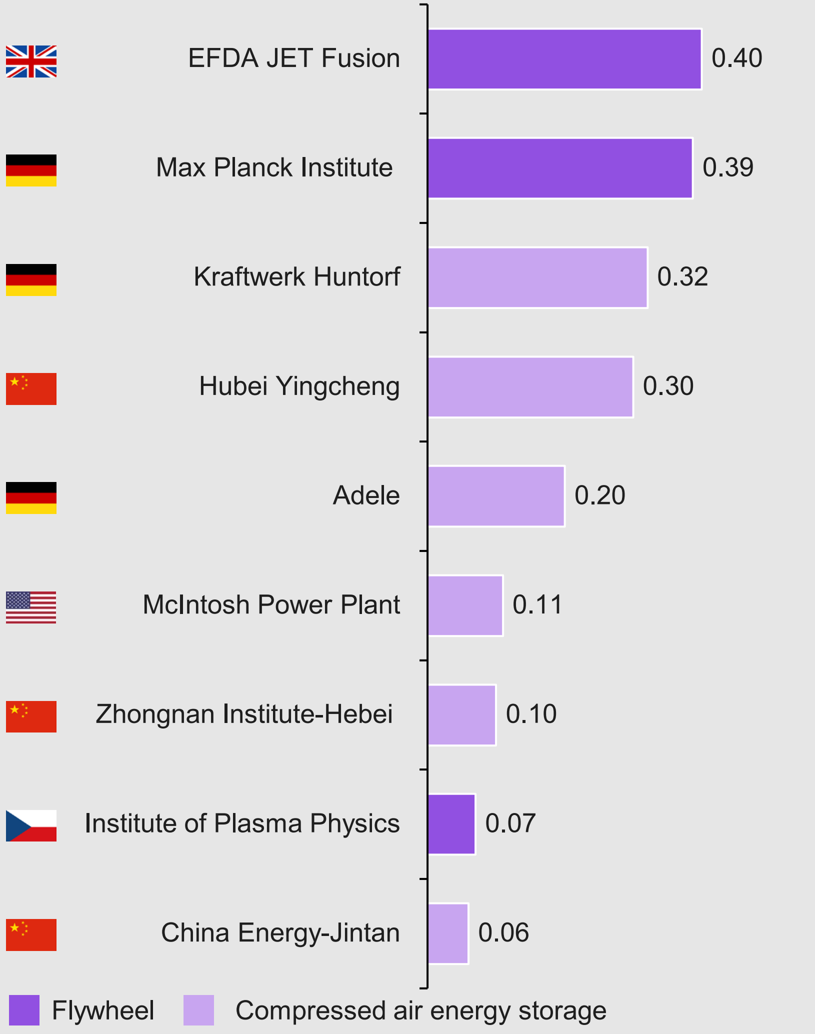
Despite being mature technologies, only nine flywheel and CAES projects have become operational in the last four decades.

In 2022, three CAES projects were commissioned, and six others are planned. No flywheel project is announced in the coming years.

3.4 Non-PHS storage

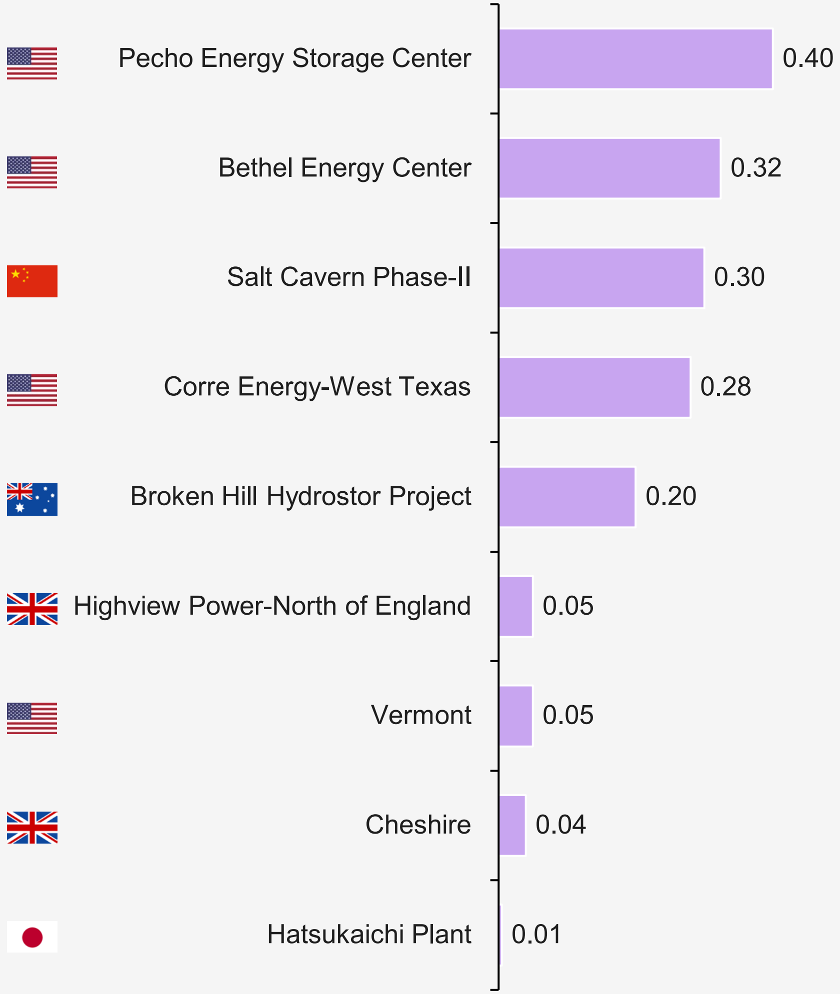
Largest flywheel and compressed air energy storage installations in operation worldwide by capacity

GW, 2023



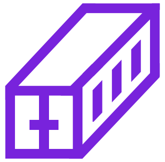
Pipeline of largest flywheel and compressed air energy storage projects worldwide by capacity

GW, 2023–2030



Sources: GlobalData, 2023; Kearney Energy Transition Institute analysis

Global non-pumped hydro storage (PHS) capacity currently stands at 93 GW, of which 84% is lithium-ion batteries

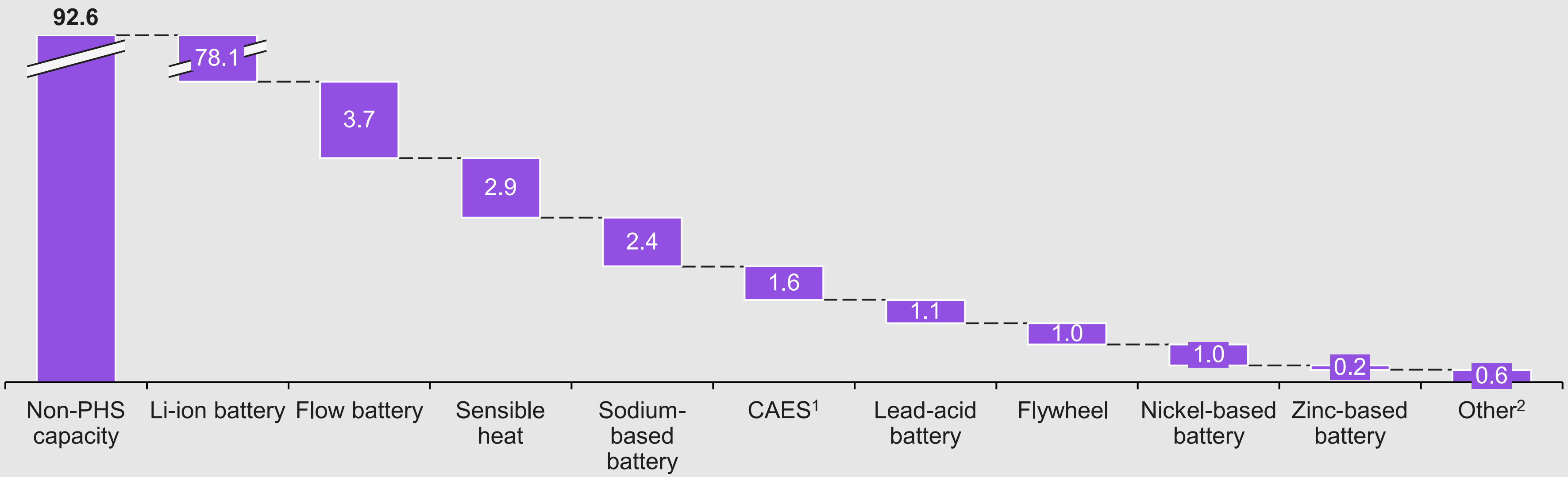


- Battery storage **installations represent 93%** of total non-PHS installed capacity today.
- **Batteries dominate storage additions, representing 97%** of non-PHS additions in 2023 (41 GW).

3.4 Non-PHS storage

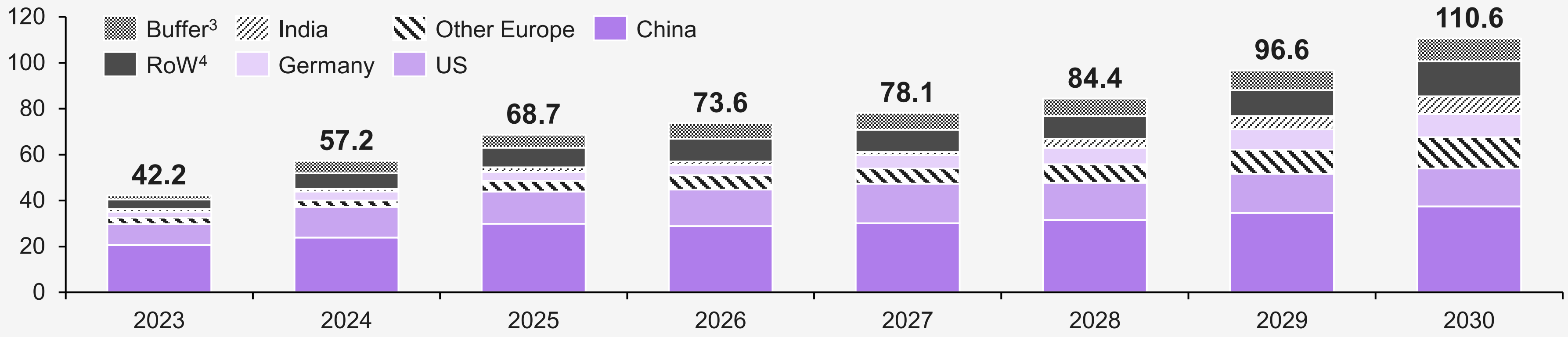
Non-PHS installed capacity by technology

GW, 2023



Expected non-PHS capacity additions by region

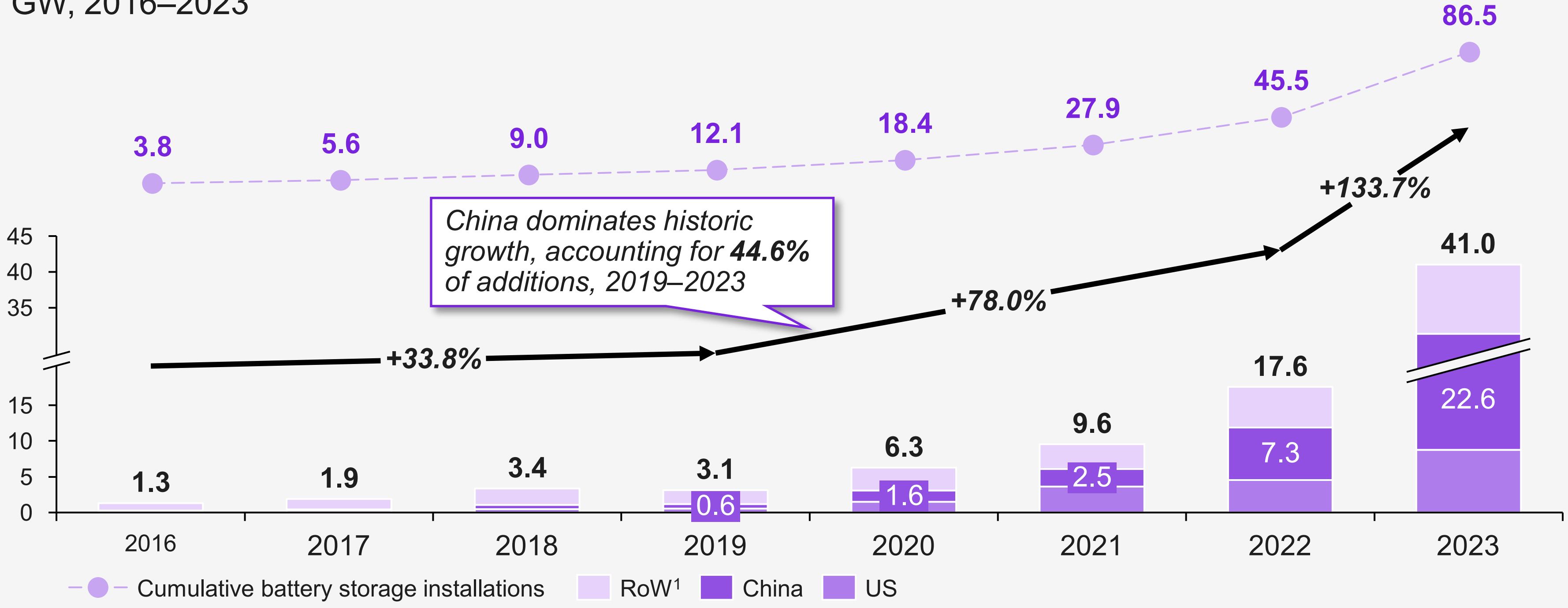
GW, 2023–2030



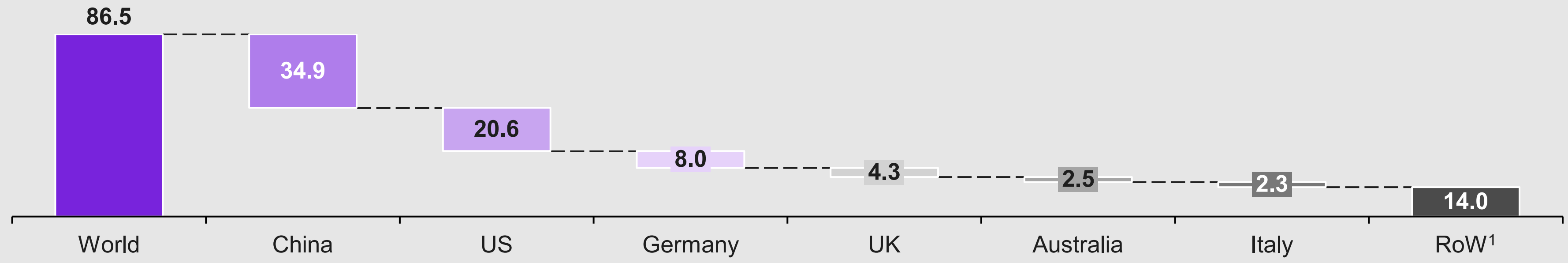
[1] Compressed air energy storage; [2] Includes heat thermal storage, latent heat, electrochemical capacitor, hydrogen storage, and unknown technologies; [3] Margin error is estimates; [4] Rest of world
Sources: GlobalData, 2023; DOE, 2023, Global energy storage database; BloombergNEF, 2023, 2H 2023 Energy Storage Market Outlook; US Department of Energy (DOE), 2023, Global energy storage database; IEA, 2024, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

Evolution of battery capacity annual additions and cumulative installations in key markets

Evolution of battery capacity annual additions and cumulative installations in key markets
GW, 2016–2023



Battery storage capacity installations by country
GW, 2023



- Around **65%** of battery additions are **front-of-the-meter**, with **behind-the-meter** storage comprising about **35%** in 2023.
- **China** and the **United States** battery storage installations represent **64%** of total installed capacity in 2023.

3.5 Battery storage

[1] Rest of world
Note: The data on operational battery storage capacity installations for 2023 in Germany, the UK, Australia, and Italy is sourced from BloombergNEF.
Sources: IEA, 2024, Batteries and Secure Energy Transitions; BloombergNEF, 2022, “Global Energy Storage Market to Grow 15-Fold by 2030”; BloombergNEF, 2024, “Global Energy Storage Market Record Biggest Jump Yet”; Kearney Energy Transition Institute analysis

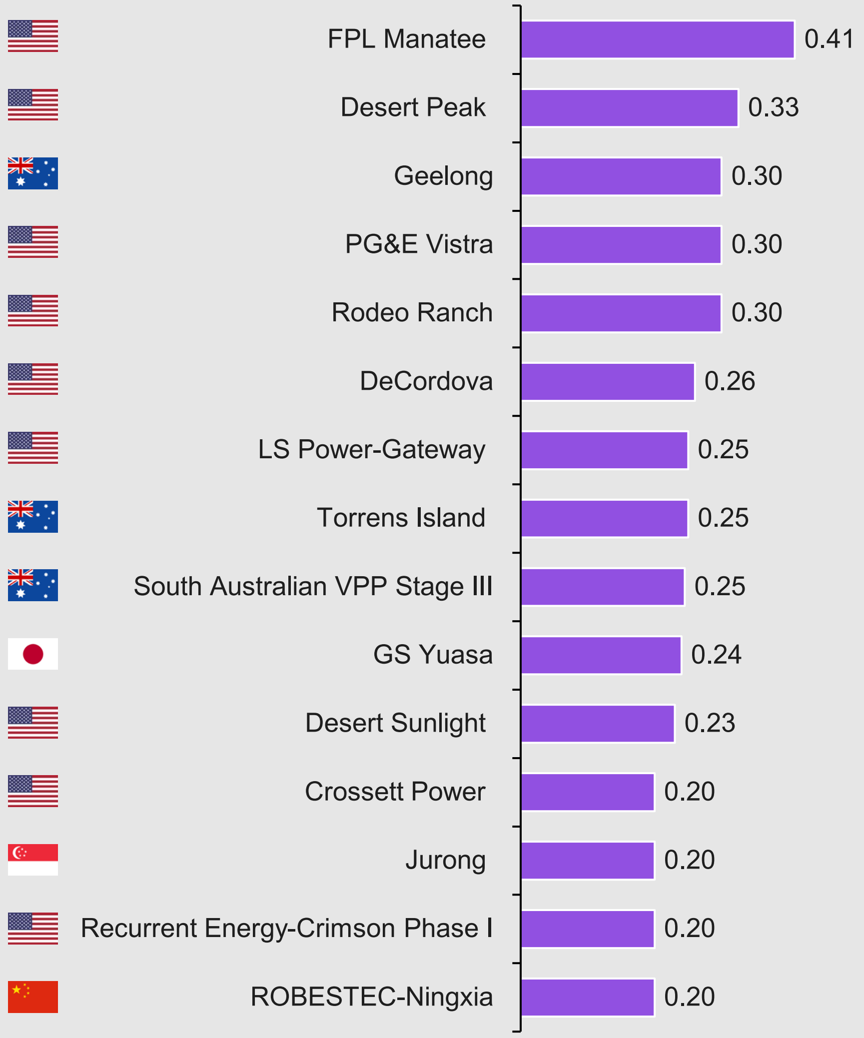
Large battery storage projects are in the pipeline for new markets

– Average capacity of the top 15 largest battery storage projects **in operation is 0.3 GW**.
– Average capacity of the top 15 largest battery storage projects expected to increase **to 1.7 GW for the 2030 pipeline.**

3.5 Battery storage

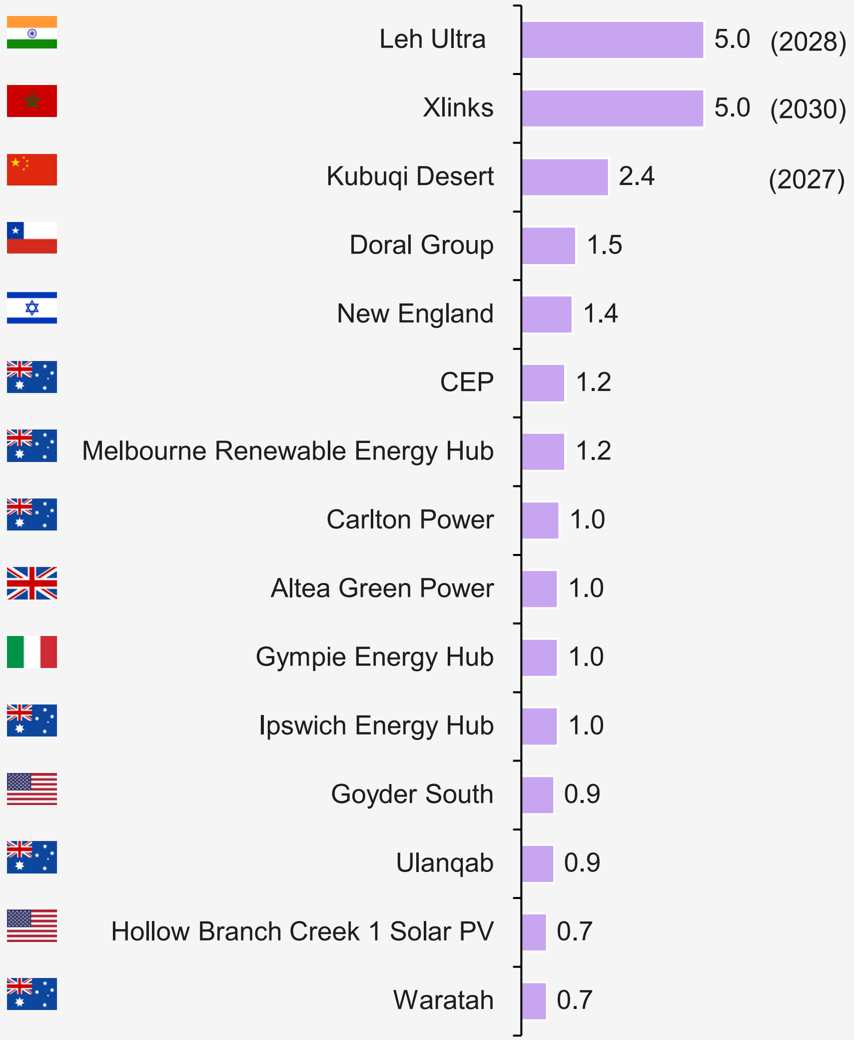
Largest battery storage installations in operation worldwide by capacity

GW, 2023



Pipeline of largest battery storage projects worldwide by capacity

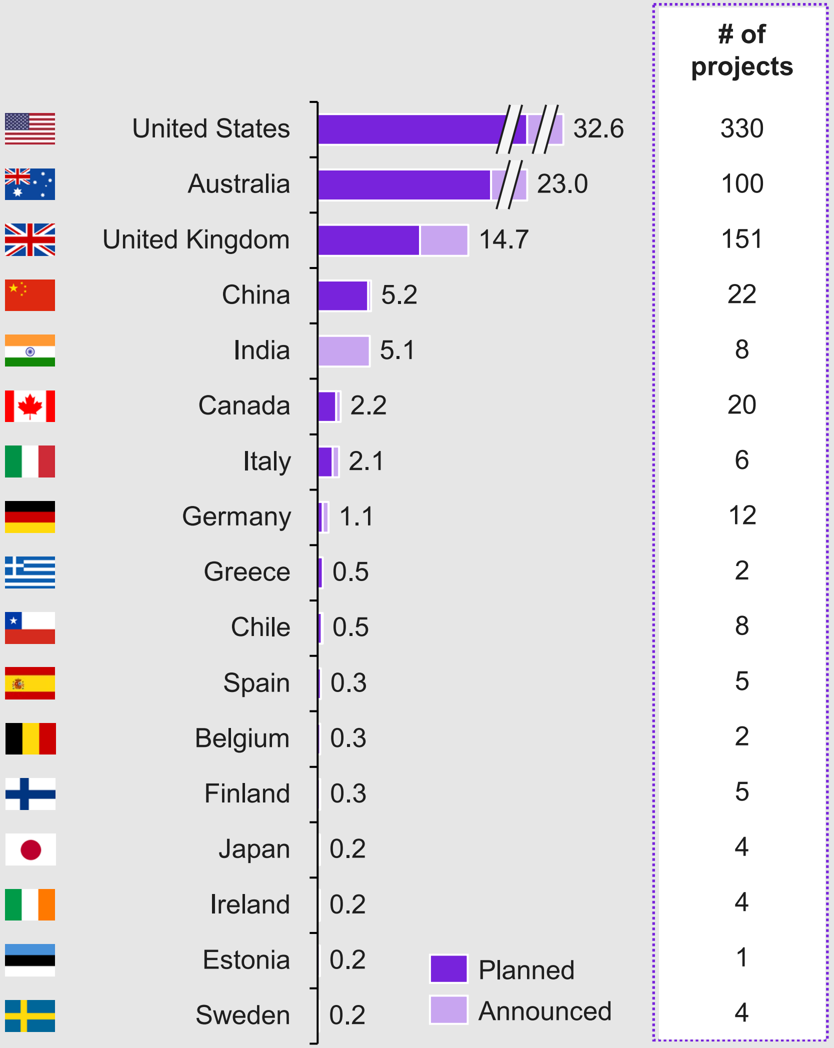
GW, 2023–2030, (Operation expected year)



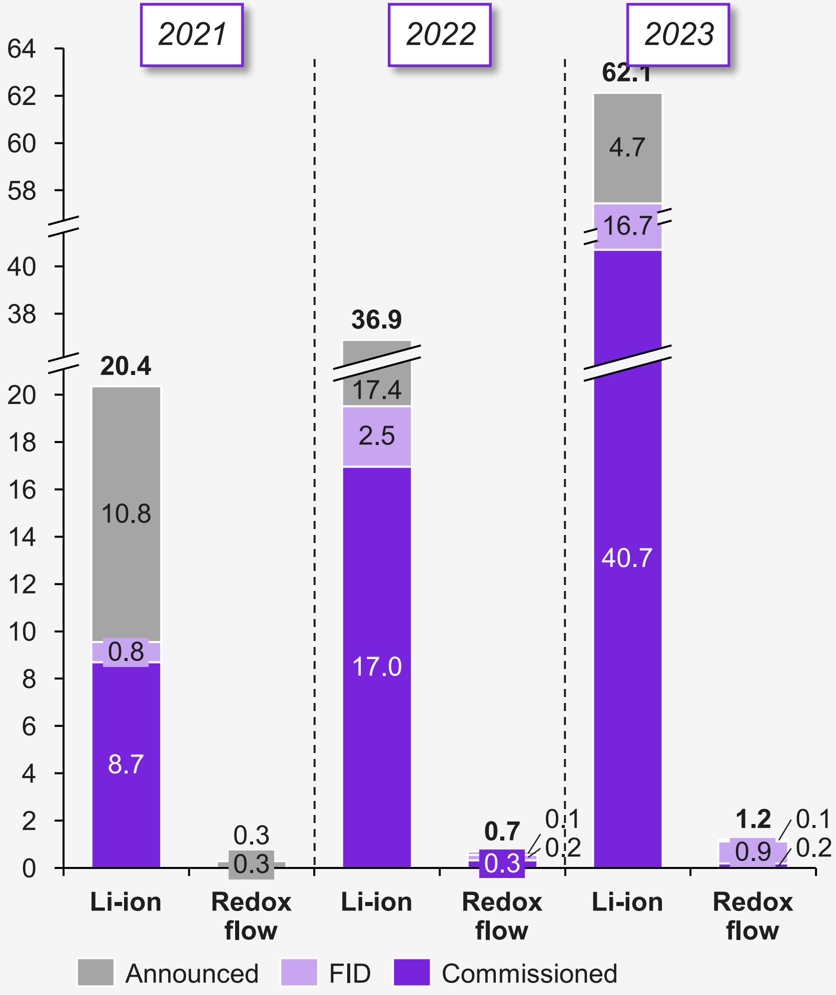
Sources: GlobalData, 2023; Energy Monitor, 2023, “Weekly data: Booming battery pipeline heralds era of renewables-dominated grids”; GlobalData, 2024, “Global Top 10 Upcoming Energy Storage Projects Market by 2030”; Kearney Energy Transition Institute analysis

Multiple markets are present in the pipeline of battery storage projects

Pipeline of battery storage projects worldwide by country
GW, 2023–2030



Announced, financial investment decisions and commissioned storage projects
GW, 2021–2023



- **88 GW** of announced and planned battery storage projects are found in **the pipeline** for selected markets.
- **Lithium-ion battery chemistry is predominant for storage**, with minimal shares for redox flow.

3.5 Battery storage

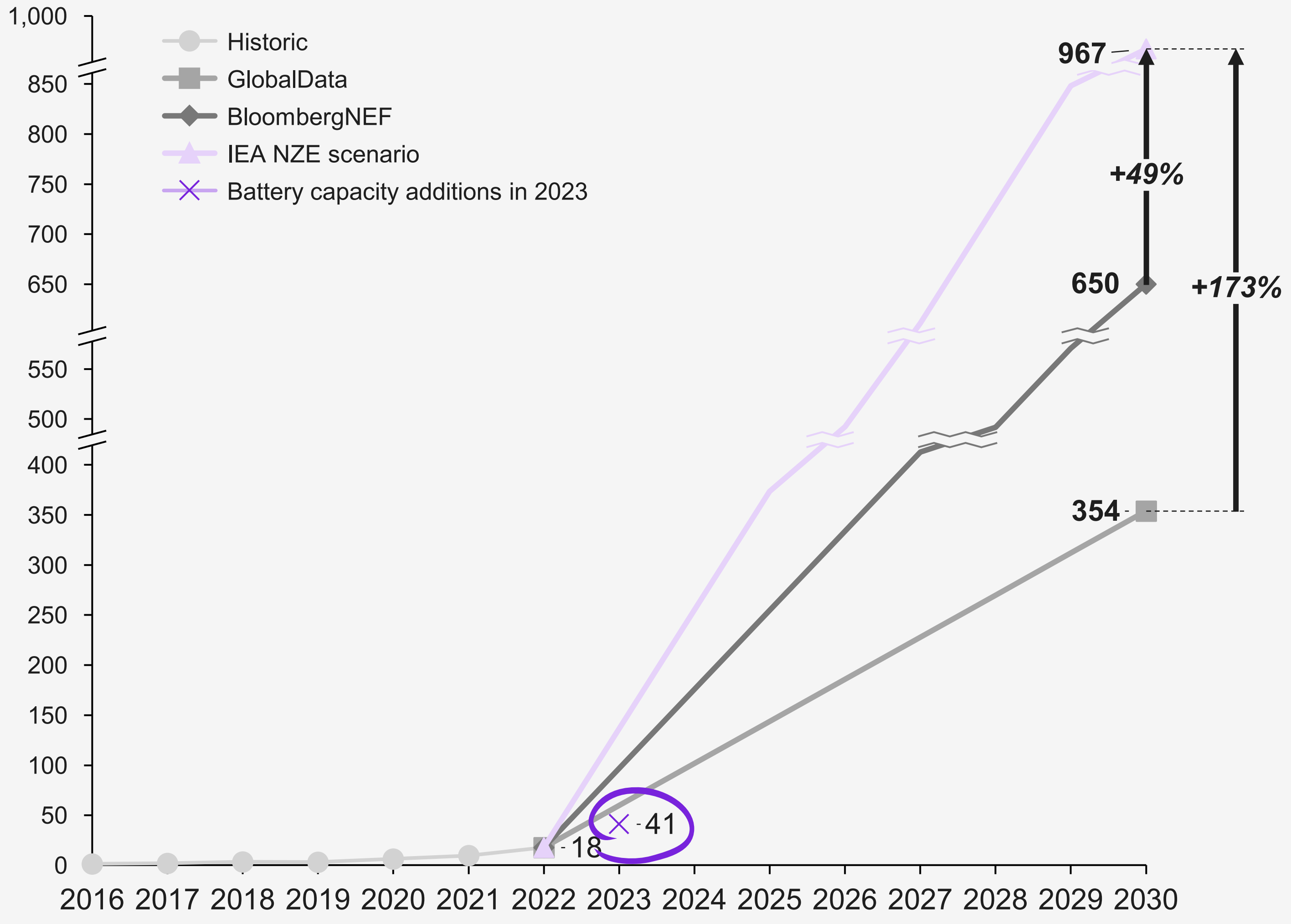
Sources: GlobalData, 2023; IEA, 2024, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

Despite the rapid increase in global battery capacity, the world falls short of the net zero emissions (NZE) scenario

Current battery storage deployment is between **1.5 and 3.5 times below** the projected grid-scale battery capacity needed to reach global climate ambitions.

3.5 Battery storage

Projected battery capacity additions relative to global climate ambitions
GW, 2016–2030



- **IEA's** projection denotes battery storage alone.
- **BloombergNEF's** projection encompasses all electricity storage technologies, except pumped hydro storage.
- **GlobalData's** projection consists of the forecasted grid-scale battery storage.

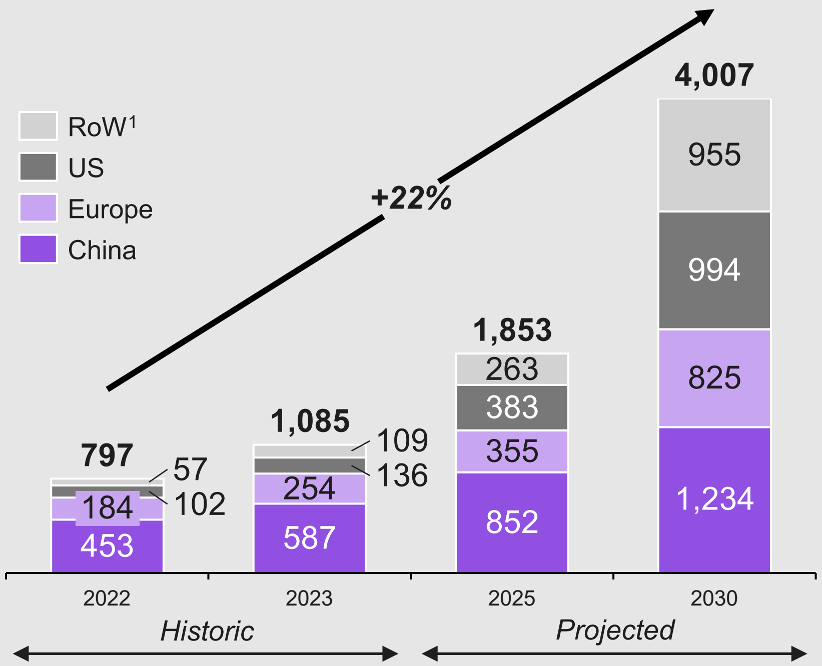
Note: BloombergNEF's projection for 2030 increased by 28% in Q4 2023 relative to Q1 2023 forecast.
Sources: BloombergNEF, 2023, 2H 2023 Energy Storage Market Outlook; IEA, 2024, Batteries and Secure Energy Transitions; IEA, 2023, World Energy Outlook 2023; Kearney Energy Transition Institute analysis

Battery storage growth is focused on lithium-ion batteries, driven by mobility applications

Lithium-ion demand is expected to soar over the next decade, increasing from **797 GWh in 2022** to approximately **4 TWh in 2030** at a **CAGR of 22%**, from 2022–2030.

3.5 Battery storage

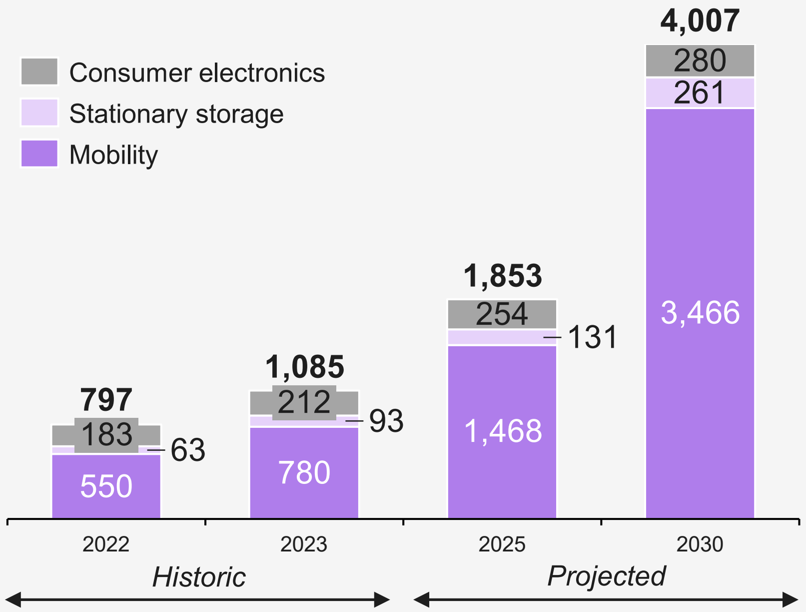
Annual lithium-ion battery demand by region
GWh, 2022–2030



– China offers a mature supply chain and is expected to maintain its high share of demand, accounting for 31% of the global total in 2030.

– Larger growth expected in Europe and the US, driven by regulatory incentives and supply chain localization.

Annual lithium-ion battery demand by application
GWh, 2022–2030



Mobility applications, such as electric vehicles (EVs), dominate future demand, driven by:

– Regulatory incentives for transport electrification, such as banning internal combustion engines (ICE)

– Increased consumer demand for clean technologies

– ICE phase-out targets announced by 13 out of 15 of the top original equipment manufacturers

[1] Rest of world

Note: The share per region is estimated based on the shares for the battery demand regarding mobility applications. Lithium-ion battery demand in mobility is taken from the Announced Pledges scenario of IEA.

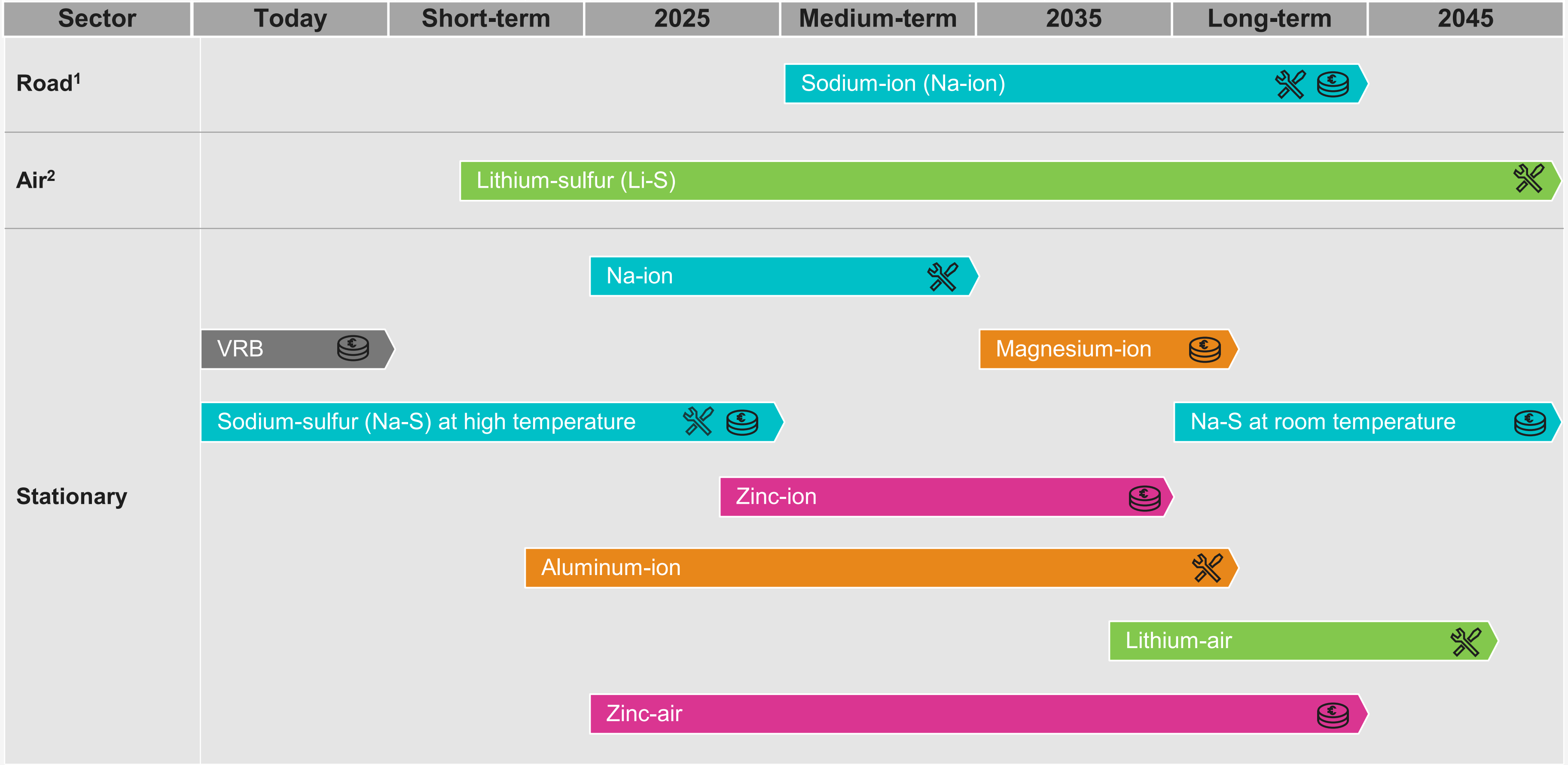
Sources: IEA, 2023, Global EV Outlook 2023; IEA, 2024, Global EV Outlook 2024; BloombergNEF, 2023, Electric Vehicle Outlook 2023; Kearney Energy Transition Institute analysis

Other types of batteries are gaining momentum both in mobility and stationary storage applications

Several alternatives to lithium-ion batteries exist, although their potential dominant role in applications remains to be confirmed.

Alternative batteries technology road map for dominant applications

2023–2045



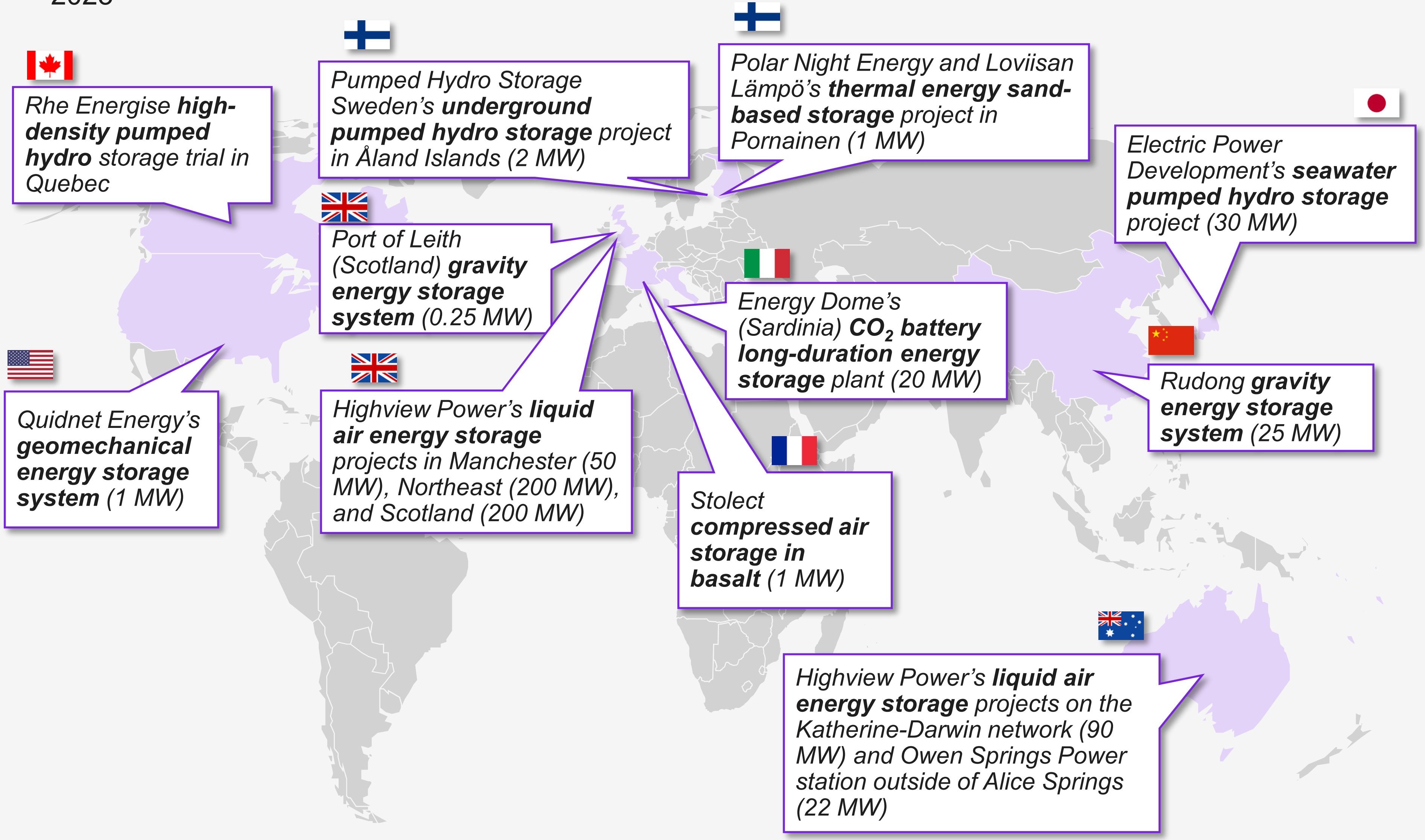
Technology advantage compared to lithium-ion batteries

Economic Technical

[1] Road includes 2- and 3-wheelers and light vehicles.
[2] Air comprises drones, electrical vertical take-off and landing aircrafts and high-altitude long-endurance aircrafts, and high-altitude platform station.
Notes: Other technologies that are expected to have a moderate role exist for these and additional applications. For more information, please refer to the source below.
Sources: Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+; Kearney Energy Transition Institute analysis

Unconventional electricity storage technologies are found at early demonstration phase

Emerging technologies electricity storage projects
2023



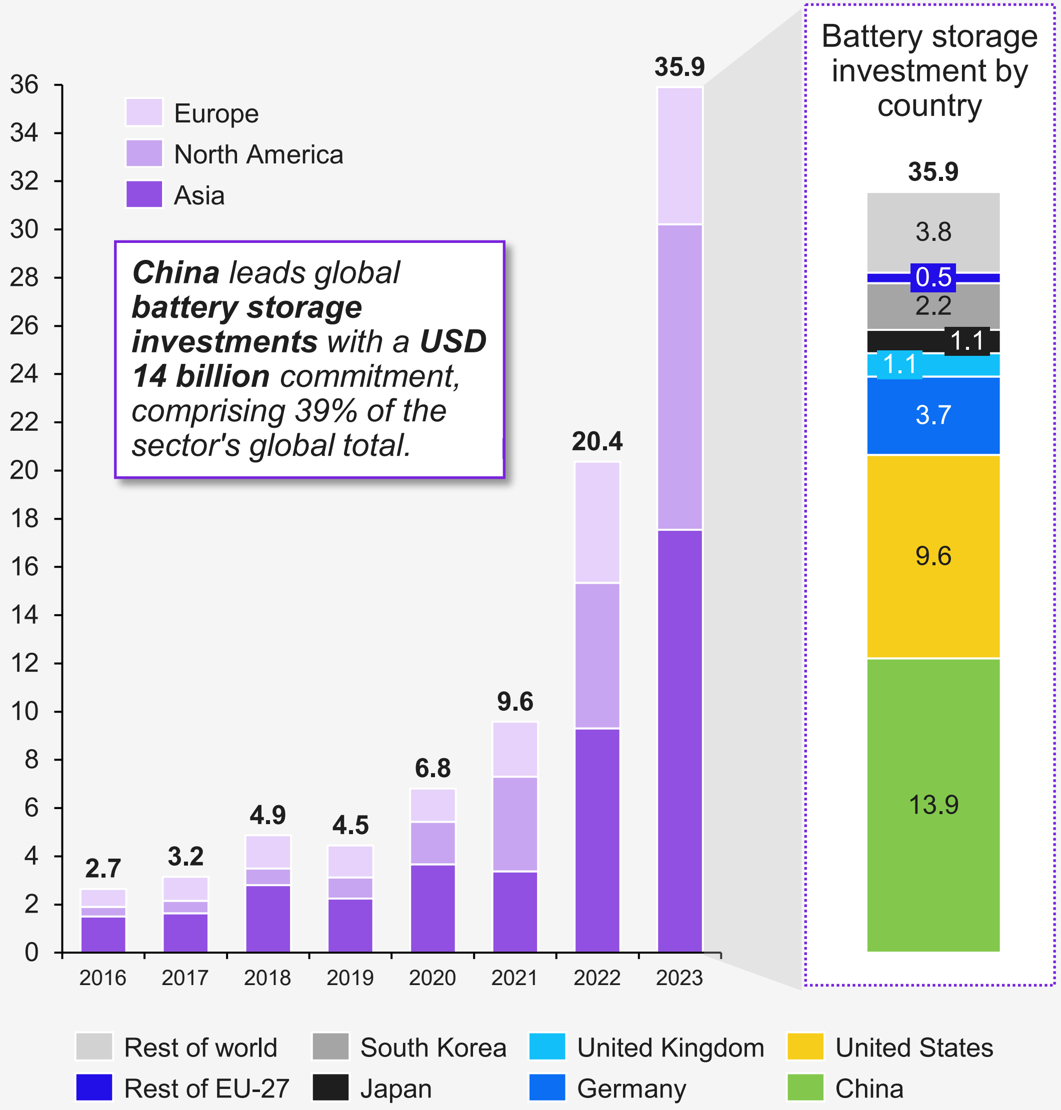
Sources: Power Technology, 2024, "Power plant profile: Renewable Underground Pumped Hydroelectric Energy Storage, Finland"; Energy Vault, 2023, "Rudong, China Gravity Energy Storage System"; Gravitricity, 2024, "Projects"; GlobeNewswire, 2022, "Quidnet Energy to Receive $10M in Federal Funding to Commercialize Clean Energy Technology"; Energy Dome, 2022, "Energy Dome successfully launches first CO2 Battery long-duration energy storage plant in the world"; Highview Power, 2024, "Projects"; Techniques de l'ingénieur, "Stoltect teste le stockage par batterie de Carnot", 2023; RheEnergise, web page, 2024; Kearney Energy Transition Institute analysis

Investment in battery storage is set for continued rapid growth, notably in utility-scale battery systems

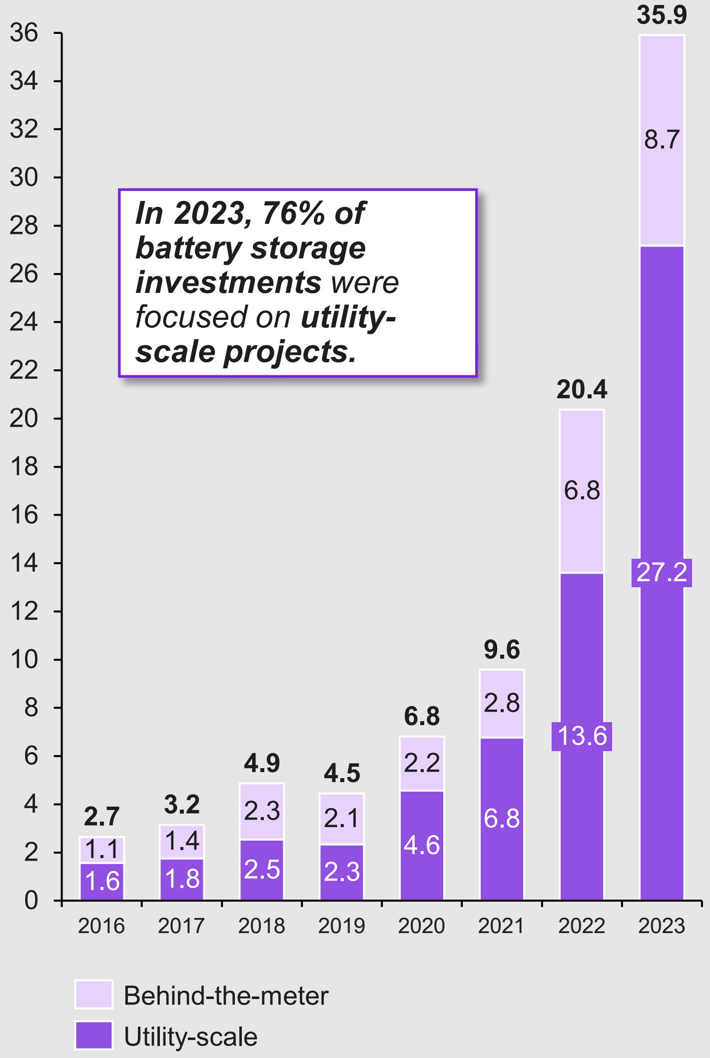
In 2023, 52 energy storage M&A deals totaled USD 4.6 billion, up from 49 deals worth USD 1.7 billion in 2022. **So far this year, Europe has had 18 transactions totaling USD 1.9 billion**, compared to 16 in the same period last year.

3.7 Investments in electricity storage

Battery storage investment by geography
billion USD, 2016–2023

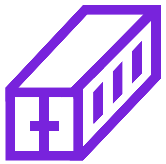


Battery storage investment by segment
billion USD, 2016–2023



Note: Values for M&A deals converted from EUR values with the exchange rate on the 31 December 2023.
Sources: IEA, 2023, World Energy Investment; BloombergNEF, 2024, Energy Transition Investment Trends 2024; Kearney Energy Transition Institute analysis

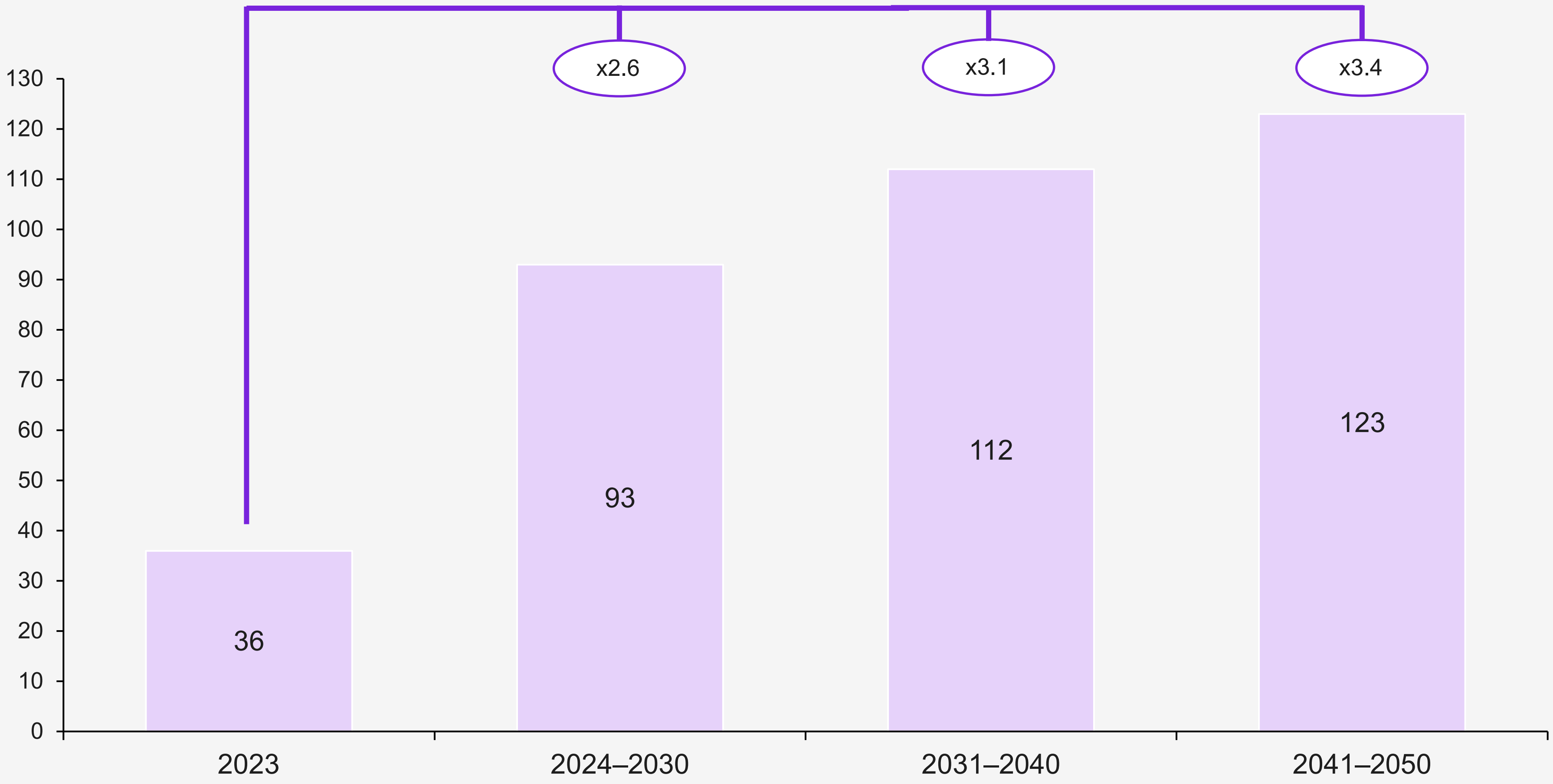
Reaching NZE scenario requires nearly three times today's investment levels[1]



To reach NZE scenario, a threefold increase of investment from 2023 levels is required. The investment further needs to rise by 10% to reach USD 123 billion per year in the 2040 decade.

3.7 Investments in electricity storage

Battery storage investment requirements for energy transition
billion USD/y, 2023–2050



[1] IEA's Net Zero Emissions Scenario
Note: The values shown in the graph consist of annual investments for the respective periods.
Sources: BloombergNEF, 2024, Energy Transition Investment Trends 2024; Kearney Energy Transition Institute analysis

4. Cost of electricity storage

Cost of electricity storage

The **investment cost** of an electricity storage solution is the **main driver** of total expenditure, representing **70–98%** of overall cost for the most common technologies compared to an average of 59% for traditional generation sources. Uncertainty regarding the potential reduction of storage investment cost is a **key barrier to uptake**, which must be addressed to stimulate market adoption by creating a profitable business case, especially while revenue streams remain uncertain.

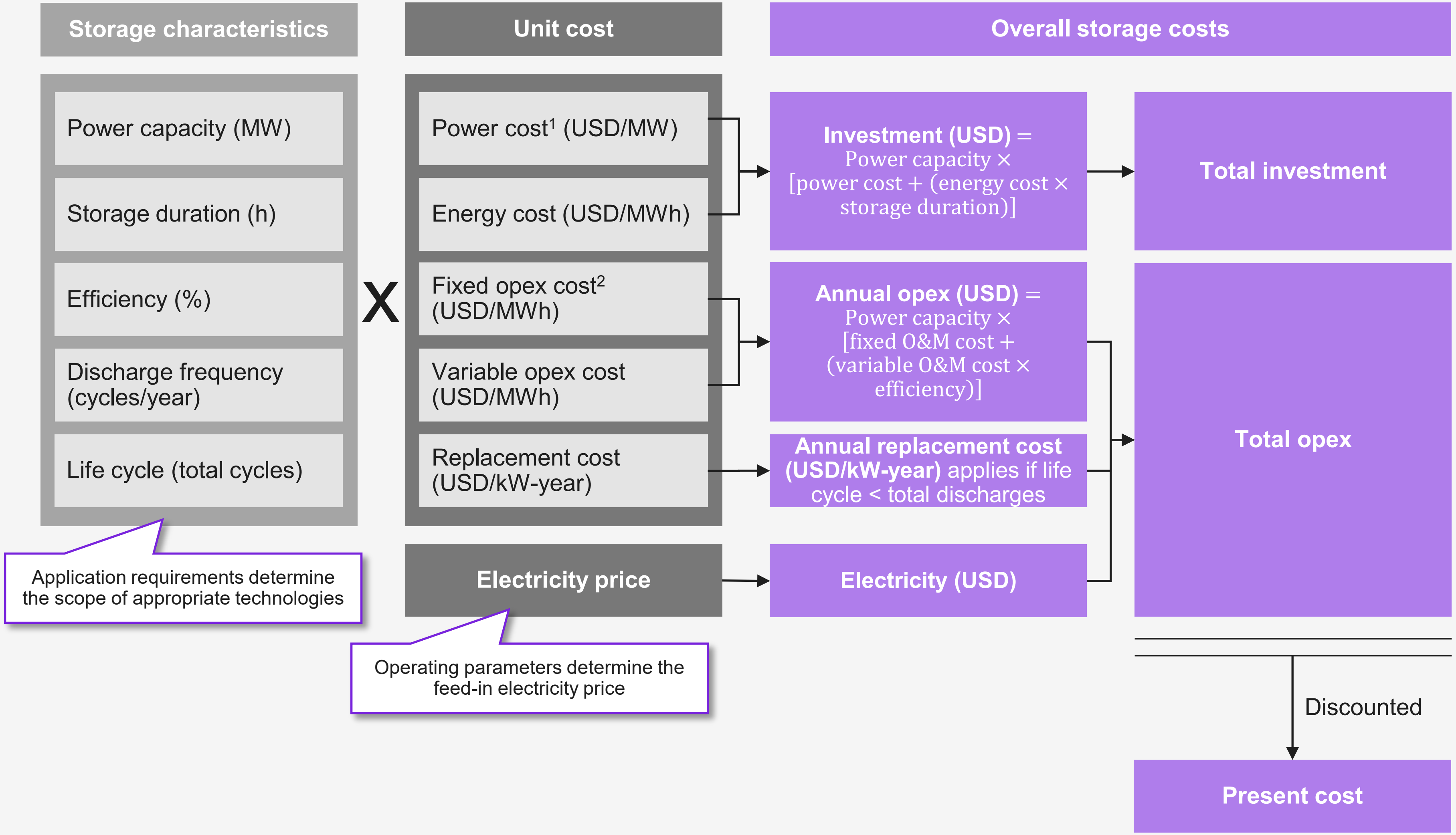
Experience curves describe the decrease in investment cost in line with increased installed capacity. Storage technologies experience rates fall in the range of **10–30%**, where more mature technologies—such as PHS and lead acid batteries—fall at the lower end. On the other hand, **Li-ion cells**—namely for electronics and EVs—**exhibit the highest experience rates (19–30%)**, which is expected to continue. Combining experience curves and market growth projections suggests an investment cost of **USD 75–870/kWh by 2040** compared to **USD 150–1,560/kWh in 2020** for the most common technologies, where Li-ion batteries for EV application exhibit the fastest decrease at a compound annual growth rate of **7.3%**, driven by more than 1 TWh of growth per year.

Lifetime cost offers a means to **compare storage technologies** for clearly defined applications, commonly quantified by the **levelized cost of storage (LCOS)**, which measures the discounted cost per unit of electricity discharged in USD/MWh. The competitiveness of a technology in terms of LCOS varies by application and the competitive landscape is expected to change over the following decades. Technologies offering suitability for a wider range of applications are likely to realize the greatest LCOS reduction by leveraging economies of scale and reaping the effects of learning by doing. For example, Li-ion batteries are increasingly common in energy arbitrage, black start, transmission and distribution upgrade deferral, and, chiefly, electric vehicles, and are expected to experience an accelerated decline in LCOS driven by falling investment costs by 2040. Other technologies, such as sodium-ion, might disrupt the dominance of Li-ion batteries as concerns regarding the volatility of lithium prices shift focus to sodium, a cheaper material.

4.0 Chapter summary

The cost structure of an electricity storage solution is influenced by multiple factors

Breakdown of electricity storage cost



[1] Power cost includes storage device cost, balance of system cost, and power conversion cost
[2] Operational expenditure (includes gas price for compressed air energy storage but excludes electricity price)
Sources: Kearney Energy Transition Institute analysis

4.1 Cost breakdown

The cost effectiveness of an electricity storage technology varies on a power and energy basis

Cost parameters for the most widely deployed **stationary** electricity storage technologies

Parameter	Unit	PHS	Li-ion	CAES	Flywheel	Lead acid	VRB[1]	Hydrogen	Supercapacitor
Investment cost	**Power** USD/kW	1,150–5,100	245–305	1,050–2,300	250–2,400	135–300	700	5,000	300
	Energy USD/kWh	50–350	40–700	30–40	3,000–11,500	120–700	295–1,200	30	10,000–70,000
Opex	USD/kW	5–45	5–55	10–20	5–10	5–15	5–15	30	1-30
	USD/MWh	0.5	0.3-0.4	0.5–2.5	0.5–30	0.3–0.5	0.5–2	0.4	1
Replacement cost	USD/kW	120	100	200	0	0	90	0	0
Replacement interval	Cycles	7,300	1,500	20,000	N/A	N/A	3,500	N/A	N/A
EOL[2] cost	USD/MWh	0.01-3.2	0.2-50	0.01-3.2	0.01-3.6	0.25-70	-(3-190)[3]	0.02-3.8	0.01-3.8

Charging cost is not included for comparison given **dependence on market-specific electricity prices** rather than technology

- Sealed batteries (lead acid and Li-ion) and SCs offer the lowest specific capex on a **power basis.**
- PHS, CAES, and hydrogen offer the lowest specific investment cost on an **energy basis.**
- **Sealed batteries are more likely to be cost effective for short discharge durations** (typically less than eight hours), while **PHS, CAES, and hydrogen are more attractive for longer durations** (greater than eight hours).

[1] Vanadium redox flow batteries; [2] End of life; [3] Resale value of vanadium contained in VRB realizes a negative EOL cost
Note: USD figures are 2020 values. End of life cost per KW is in the order of magnitude of 20 USD/KW for all technologies
Sources: Mongrid et al., 2020, An Evaluation of Energy Storage Cost and Performance Characteristics; Augustine and Blair, 2021, Storage Futures Study; Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

Investment cost generally represents between 70% and 98% of a storage technology's total cost

Example

Uncertainty regarding the potential investment cost reduction for storage is a **key barrier to uptake**, which must be addressed to stimulate market adoption, especially while revenue streams remain uncertain.

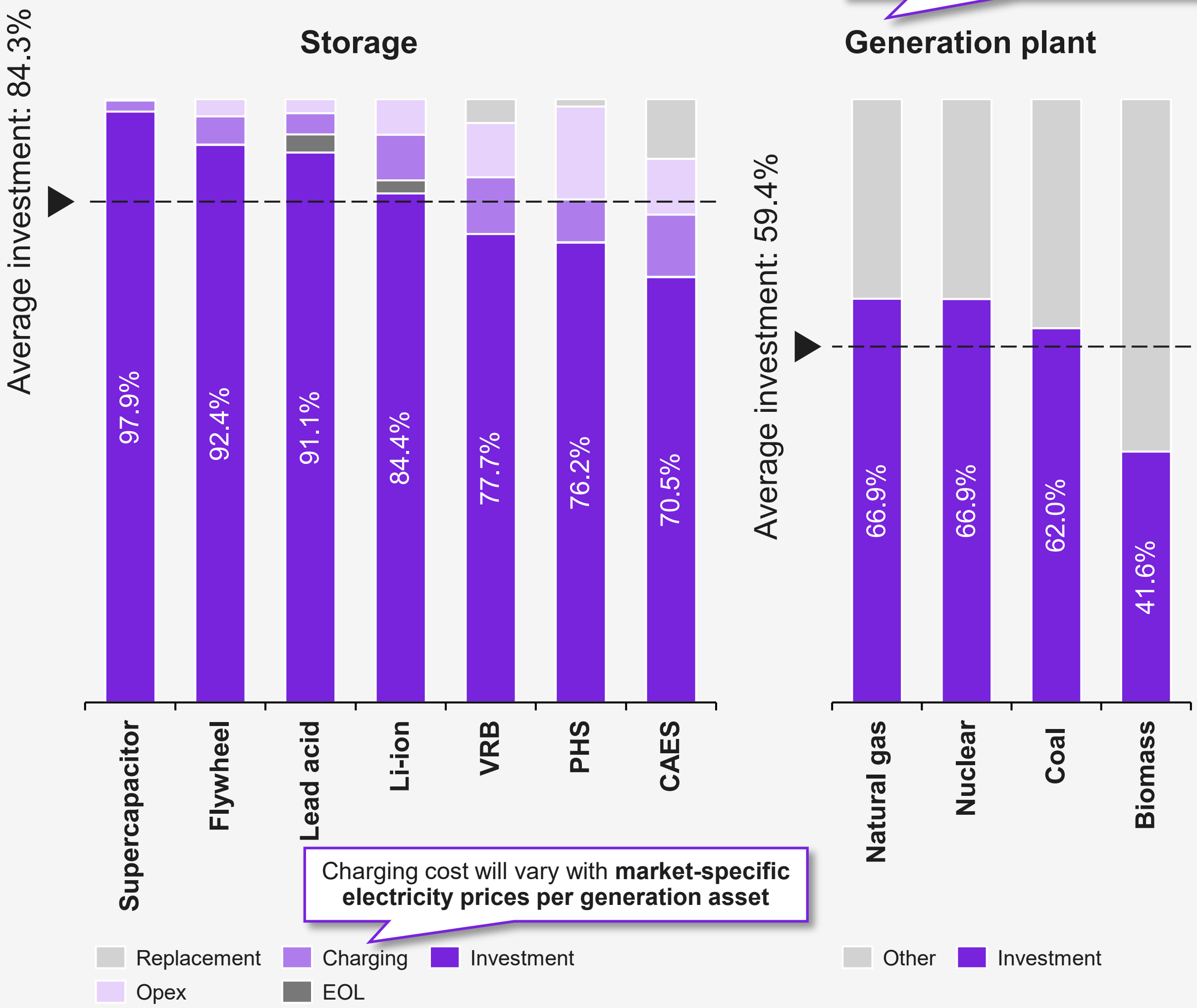
4.1 Cost breakdown

- Investment required by a new technology **determines whether it is successful in entering the mainstream market** or remains in research and development.
- Investment cost of storage remains **too elevated to compete** with traditional and established low-carbon generation technologies used for similar services, **averaging at 84.3% of cost compared to 59.4%**, respectively
- It is **essential to understand the potential investment reduction** for novel technologies to gauge future mass-market adoption.

Cost breakdown for select electricity storage technologies and power generation plants in the US[2]

USD/MWh basis

See bibliography and appendix for breakdown of other common applications



[1] Research and development; [2] Values consider the provision of frequency regulation to the grid and an electricity price of USD 50/MWh
Note: USD figures are 2023 values.
Sources: Energy Storage Ninja, 2023, Lifetime Storage; NREL, 2023, Electricity Annual Technology Baseline (ATB) Data; Kearney Energy Transition Institute analysis

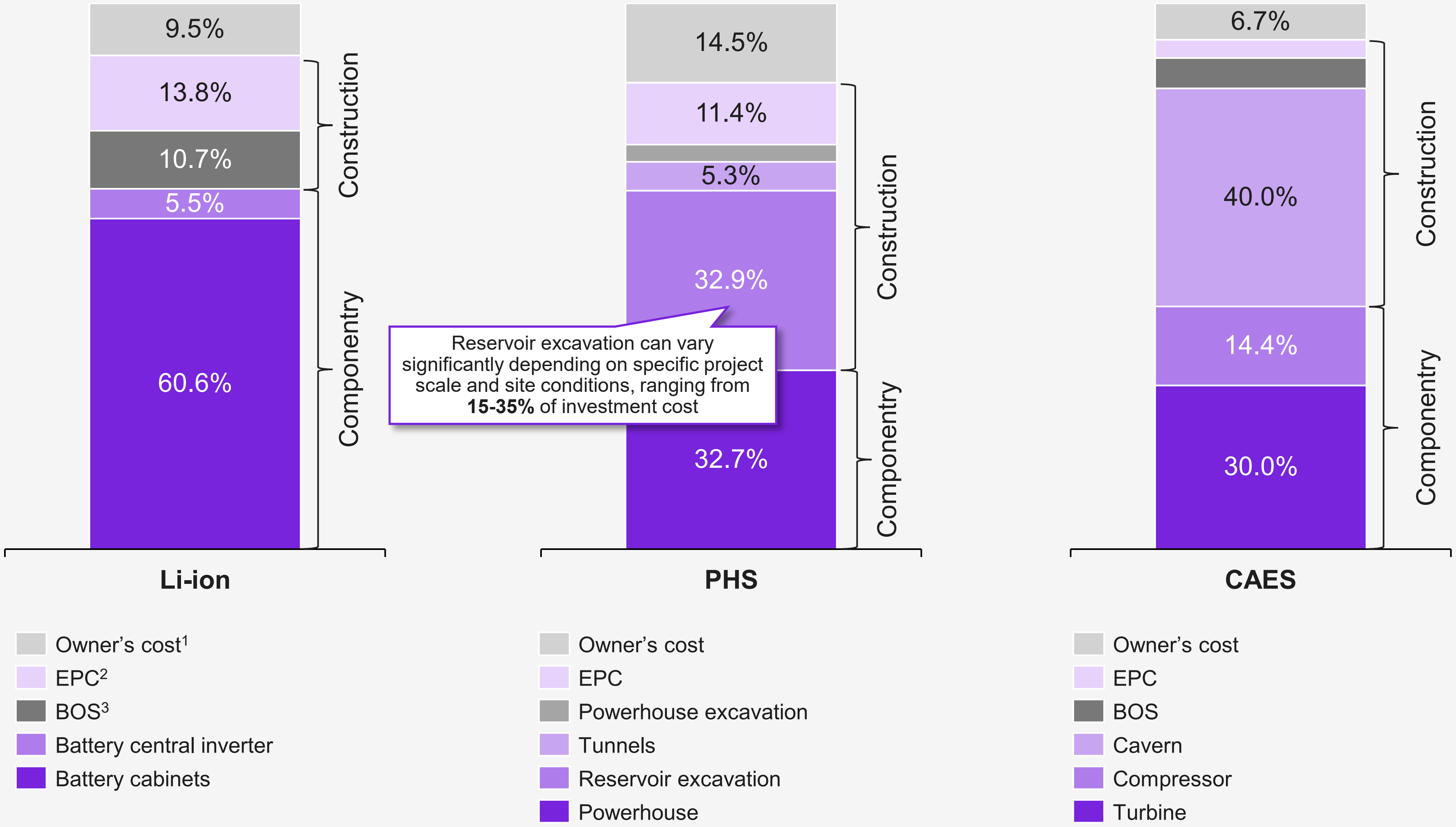
Kearney XX/ID

An opportunity exists to reduce Li-ion battery investment by substituting components for cheaper materials

Li-ion battery investment is driven by componentry, offering a clear route for cost reduction, whilst PHS and CAES face the challenge of identifying cheaper land (for reservoirs and caverns, respectively) and construction methods

4.1 Cost breakdown

Investment cost breakdown for select electricity storage technologies
USD/kW-year basis



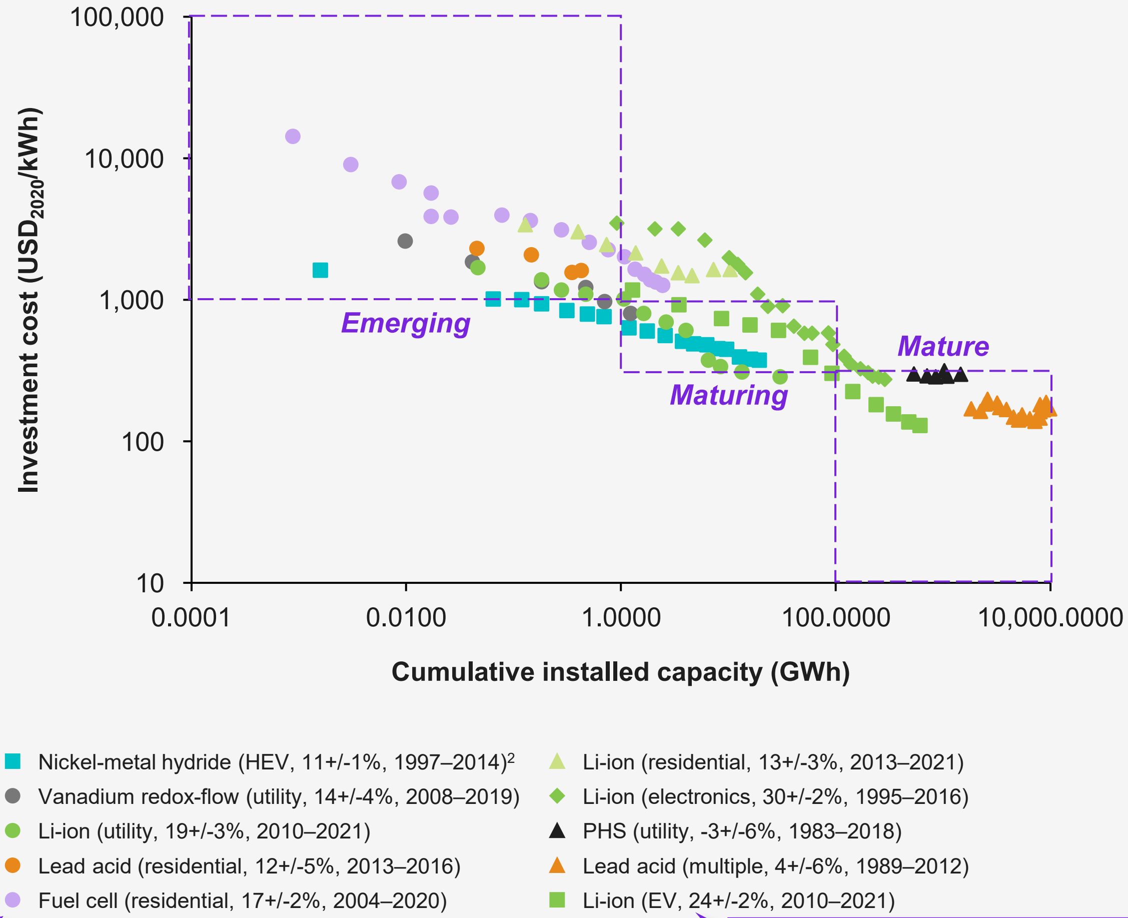
[1] Costs not covered by the EPC contract, such as land, financing, and insurance; [2] Engineering procurement and construction; [3] Balance of system
Note: USD figures are 2023 values.
Sources: Mongrid et al., 2020, An Evaluation of Energy Storage Cost and Performance Characteristics; NREL, 2024, A Component-Level Bottom-Up Cost Model for Pumped Storage Hydropower; Kearney Energy Transition Institute analysis

Experience curves describe the decrease in investment cost in line with increased installed capacity

- Historic technology cost reductions reveal **three maturity categories** based on investment cost and cumulative installed capacity: emerging (<1 GWh, > USD 1,000/kWh), maturing (1–100 GWh, > USD 300/kWh), and mature (>100 GWh, < USD 300/kWh).
- Experience rates for technologies considered fall in the range of **10–30%**, except PHS at -3%.
- **Negative experience rate for PHS** likely due to increasing site access difficulty, longer development times due to licensing requirements, and stricter environmental regulations.
- **Lead acid investment cost already in line with raw material cost** of lead with visible fluctuations commensurate to commodity price.
- Behavior of PHS and lead acid **exemplify the plateau in experience curve expected as technologies reach maturity**, at which point raw materials are the key influence on investment cost.
- **Li-ion cells, namely for electronics and electric vehicles, exhibit the highest experience rate**, reflected by the technology's dominance for such applications.

Historic investment cost evolution for select electricity storage technologies[1]

USD/kWh, GWh



Investment cost and installed capacity are differentiated by, e.g., utility, EV, HEV, residential, etc., given technology cost differs by application.

Technology (scope, experience rate+/-uncertainty, period)

[1] Storage technologies with insufficient price data are not included (such as flywheels, compressed air energy storage, and gravity storage) but still offer future promise.
[2] Hybrid electric vehicle
Note: USD figures are 2020 values.
Sources: Junginger et al., 2010, Technology Learning in the Energy Sector; Schmidt and Staffell, 2023, Monetizing Energy Storage ; Kearney Energy Transition Institute analysis

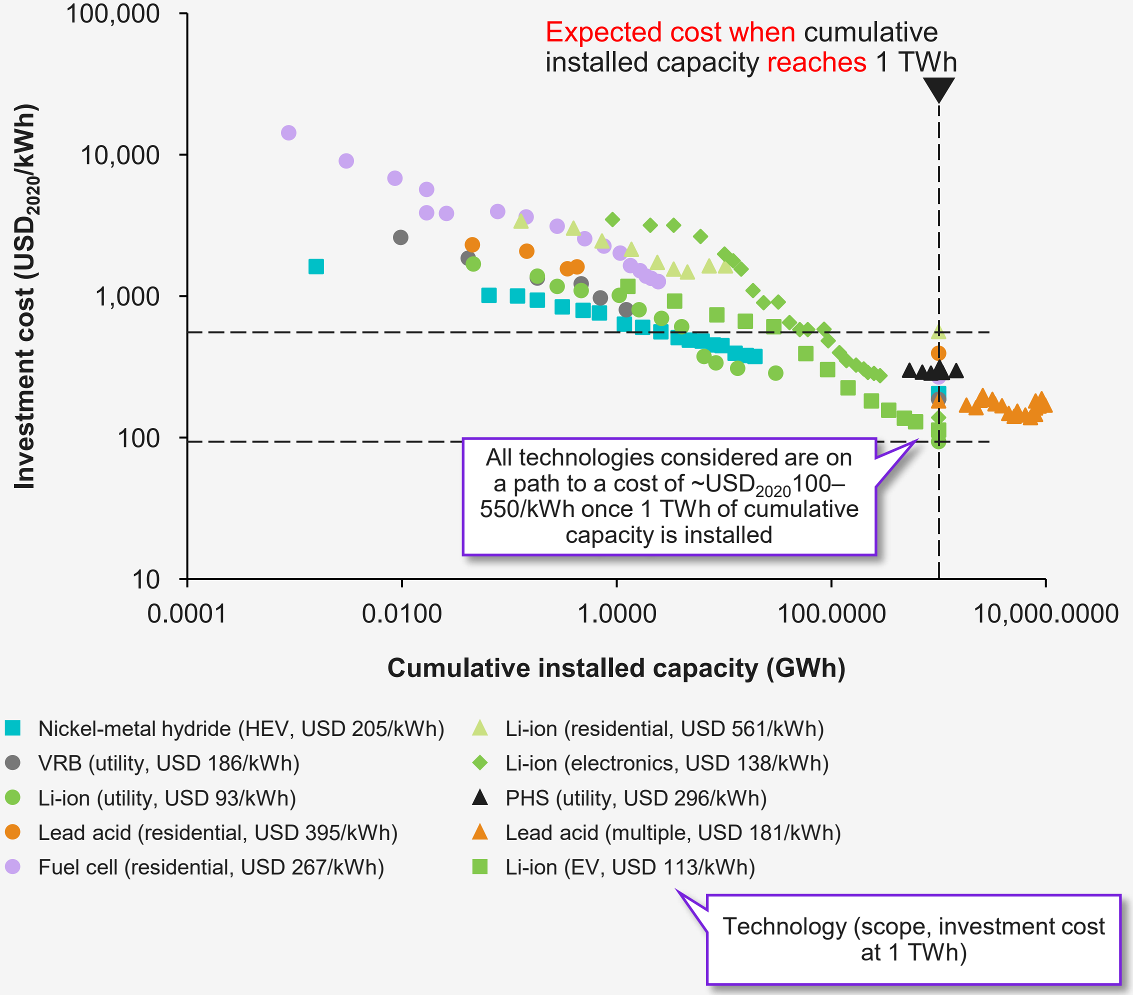
Extrapolating experience curves offers insight into potential future investment cost of a technology

- Projecting a common cost trajectory for all technologies to 1 TWh cumulative installed capacity suggests that **all commercially successful storage methods can achieve an investment cost of ~100–550 USD/kWh.**
- The technology to deploy 1 TWh first is most likely to achieve the cost range and establish a competitive advantage; **modular technologies used in several applications (such as Li-ion batteries) are at an advantage.**
- Uncertainty exists in projected values, stemming from experience rates and **unpredictable events** (commodity price shifts, knowledge spill-overs, policy intervention, technology breakthroughs, etc.).
- A lower cost boundary is set by Li-ion batteries for utility use rather than cells or packs, despite the more complex componentry required, which suggests a greater expense.
- At 1 TWh, Li-ion batteries for utility-scale applications offer a lower investment cost (USD 93.54/kWh) than electronics and EVs (USD 138.35/kWh and USD 113.11/kWh, respectively); however, by the time utility Li-ion reaches 1 TWh, electronics and EVs will have reached a far greater capacity.
- A **temporal lens is necessary when analyzing experience rates to paint a clear picture** of the competitive landscape of electricity storage technologies.

4.2 Cost evolution

Projected investment cost evolution for selected electricity storage technologies[1]

USD/kWh, GWh



[1] Storage technologies with insufficient price date are not included (such as compressed air energy storage, flywheels, gravity storage, and sodium-ion batteries) but still offer future promise.
Note: USD figures are 2020 values.
Sources: Junginger et al., 2010, Technology Learning in the Energy Sector; Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

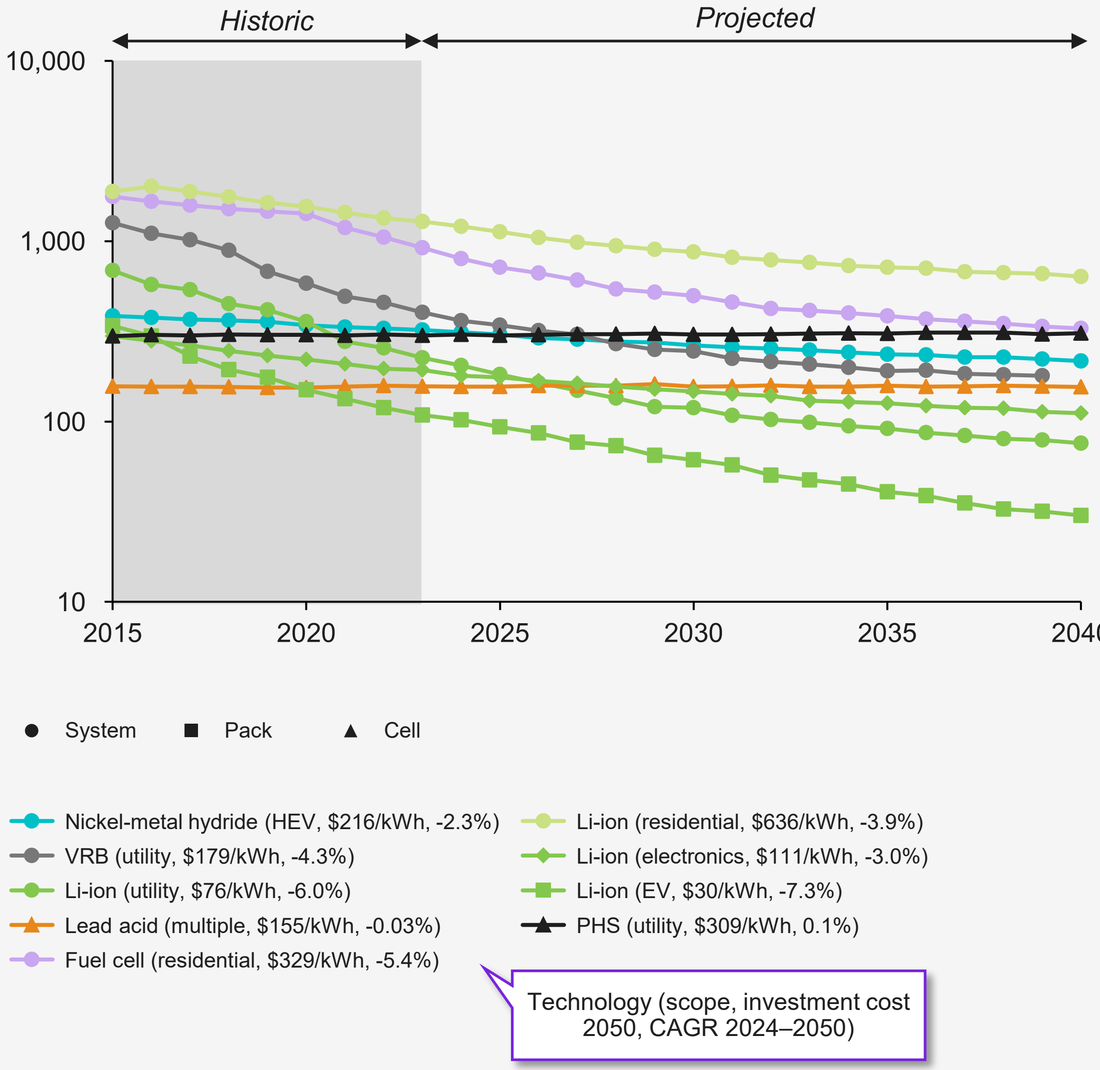
Market growth projections complement experience curves to estimate the investment cost of a storage technology as a function of time

- It is expected that an installed capacity of 1 TWh is feasible for most storage technologies within 5–20 years based on current market growth expectations.
- Projected growth yields a **stationary investment cost of USD 75/kWh** (utility-scale Li-ion**) to USD 870/kWh** (residential Li-ion) **by 2040.**
- Cost of Li-ion batteries for **EV application falls fastest at a CAGR of -7.3%** to USD 30/kWh by 2040, driven by more than 1 TWh of growth per year, dominating residential Li-ion (although it's likely to benefit from spill-over effects from EV pack cost reduction, which is not reflected in experience rate analysis).
- Li-ion batteries for consumer electronics cost more than those for EV use at USD 110/kWh, likely due to **difficulties associated with standardization** in the industry, while those for EVs (and stationary systems) benefit from greater standardization and economies of scale.
- **Limited sodium-ion battery data is available** to triangulate projections, but initial estimates **speculate cost competitiveness with Li-ion batteries by 2030** and further reductions by 2040 under specific market and policy conditions.

4.2 Cost evolution

Projected temporal investment cost of selected electricity storage technologies

USD/kWh, 2015–2040



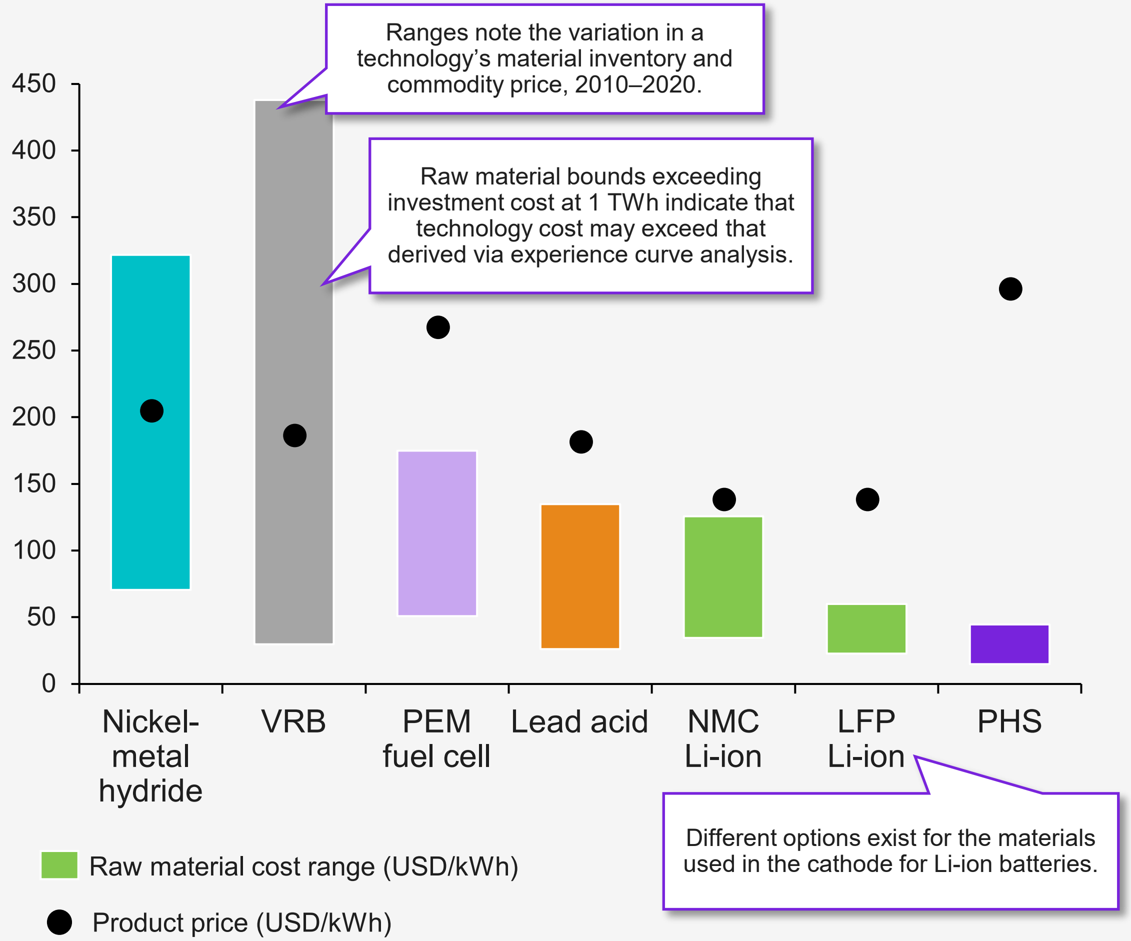
Note: USD figures are 2023 values.
Sources: Everett, 2003, Diffusion of Innovations; Lilley, 2021, Sodium-ion batteries: Inexpensive and Sustainable Energy Storage; Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

Raw material costs fluctuate with market commodity prices

- Raw material **floor cost is notably lower than investment cost derived via experience rate analysis** across technologies at a cumulative installed capacity of 1 TWh, strengthening the feasibility of the ~USD 100–550/kWh range.
- Raw material cost of nickel-metal hydride storage is relatively high given high amounts of expensive nickel required, the price of which **fluctuates in the commodity market**, rising to an upper bound of USD 250/kWh, **exceeding the investment cost** at 1 TWh of capacity.
- Fluctuations in the commodity market also influence the price of a VRB, rising to an upper bound of USD 408/kWh, similarly **exceeding the investment cost** at 1 TWh of capacity.
- Observations of raw material volatility for nickel-metal hydride and VRBs indicates that **investment cost may exceed that estimated via experience curve analysis temporarily.**
- Other technology costs are affected by commodity prices for active materials such as lead, lithium, and platinum.

Raw material cost range for selected electricity storage technologies relative to investment cost for a cumulative installed capacity of 1 TWh[1]

USD/kWh



[1] Storage technologies with insufficient price date are not included (such as flywheels, compressed air energy storage, and gravity storage) but still offer future promise.
[2] Nickel manganese cobalt; [3] Lithium iron phosphate; [4] Consumer electronics example
Note: USD figures are 2020 values.
Sources: Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

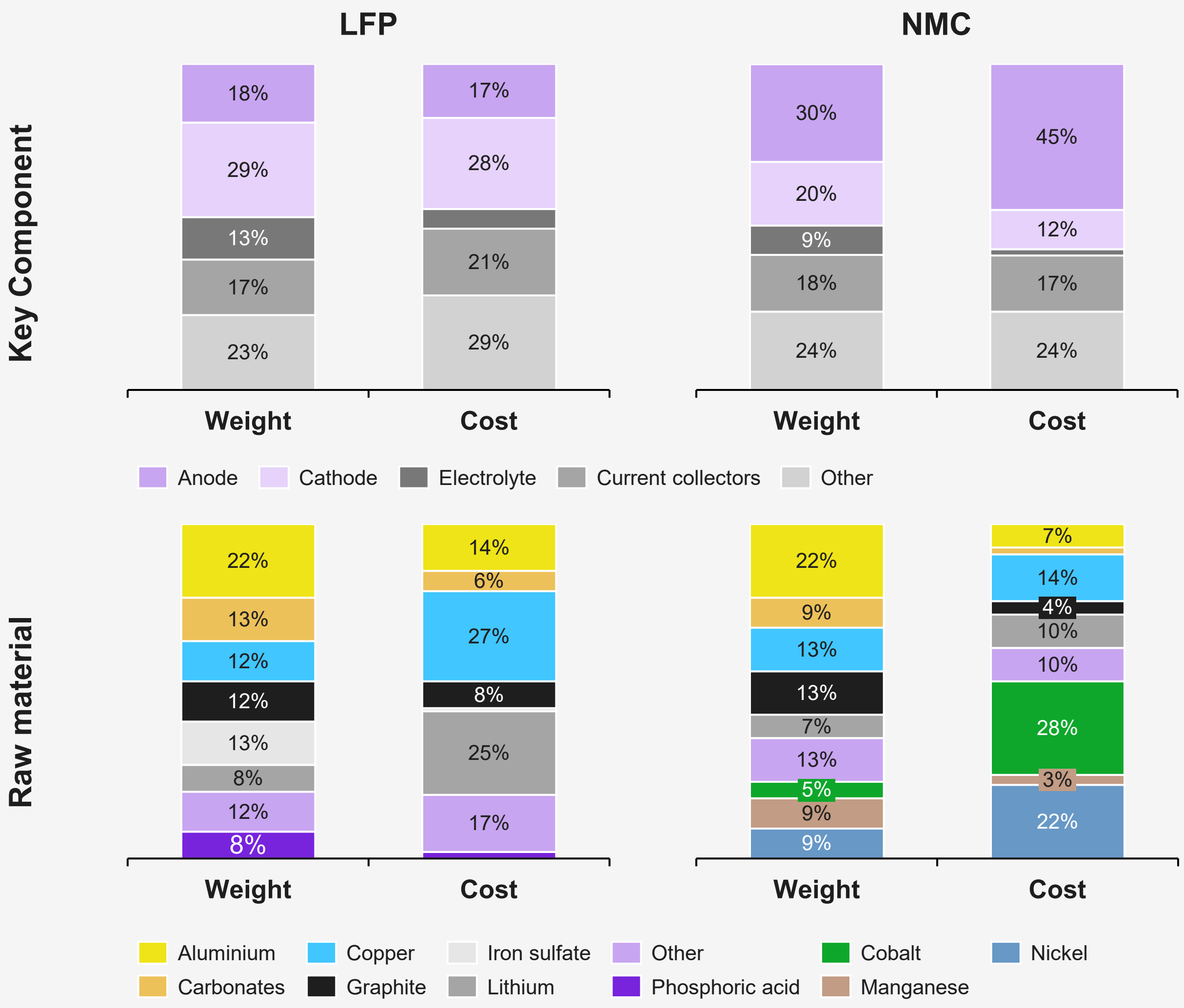
4.2 Cost evolution

It is important to understand the componentry of a storage technology to gauge the impact of fluctuations in the commodity market

- LFP and NMC are the **most common chemistries for an Li-ion battery cathode.**
- Aluminum accounts for 22% of weight in both compositions, given its use as the conductor and cell pack housing, followed by 12–13% graphite for the anode, and 12–13% copper for the current collector.
- Individual active materials for the cathode and lithium each constitute **less than 10%** of the raw material weight, yet lithium represents a **quarter of the LFP cost** and nickel and cobalt account for **more than 20% each of NMC cost.**
- Individual materials contribute to the raw material cost of NMC to a lesser extent than those of LFP, suggesting the former is **more robust to fluctuations in raw material markets.**

Cost and weight breakdown of key components and raw materials for LFP and NMC Li-ion batteries[1,2]

USD/kWh and USD/kg basis



[1] Nickel manganese cobalt; [2] Lithium iron phosphate
Note: USD figures are 2020 values.
Sources: Schmidt and Staffell, 2023, Monetizing Energy Storage; TSE, 2023, Lithium-ion batteries: breakdown of materials?; Kearney Energy Transition Institute analysis

4.2 Cost evolution

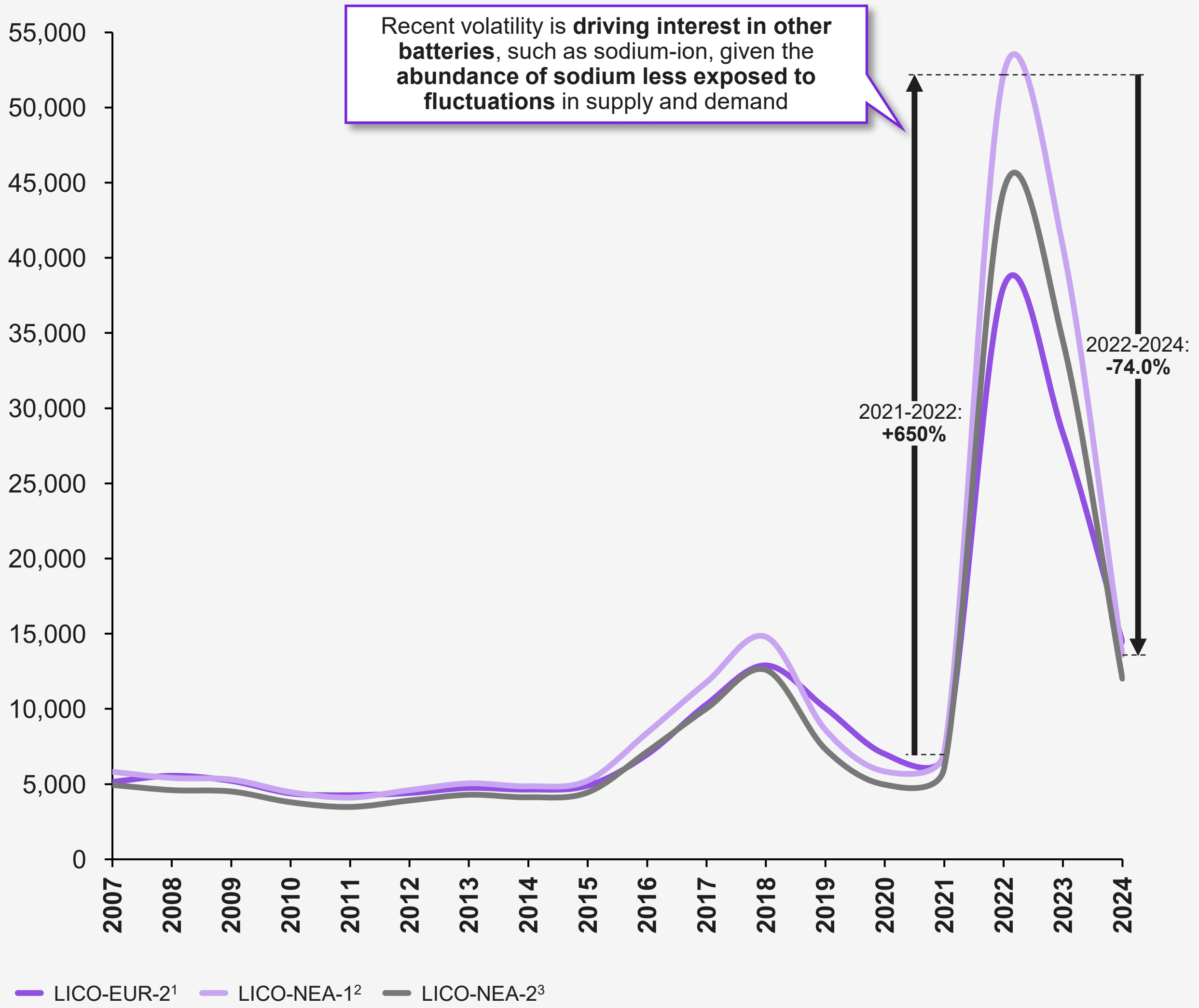
Historic lithium prices have been stable, but recent market dynamics raise concerns of volatility and repercussions on the cost of Li-ion batteries

Li-ion batteries will benefit from cost reduction due to economies of scale and learning-by-doing, but **dominance as an energy storage technology may be curtailed by fluctuations in raw material cost**

4.2 Cost evolution

Lithium carbonate commodity price

USD/metric tonne, 2007-2024



[1] Lithium carbonate, import transaction price, Belgium; [2] Lithium carbonate (battery grade), import spot price, China; [3] Lithium carbonate (industrial grade), domestic spot price, China.

Sources: Ferré, 2024, Crashing lithium prices turn the industry from 'euphoria' to 'despair': What's next?; Intratec, 2024, Lithium Carbonate Prices; SMM, 2024, Understanding the Volatile Changes in Lithium Prices; Kearney Energy Transition Institute analysis

Drivers of price volatility

- **Supply and demand fluctuations:** Rapid growth of EV and renewable energy storage demand raise prices; however, any slowdown in EV demand, such as the recent dip in the Chinese market, can cause price drop.
- **Geopolitical impact:** Geopolitical tensions and trade policies impact the supply chain, such as changes in export policies from major lithium-producing countries, such as Australia, Chile, and China, which shape supply.
- **Market speculation:** Speculative trading and market sentiment based on investors' expectations of future supply and demand.
- **Technology and production changes:** Advances in extraction methods and new mining projects increase supply and reduce prices.
- **Broader economic influences:** Rising inflation and interest rates, and currency fluctuations.

LCOE[1] is commonly used to compare the lifetime cost of electricity generation technologies, but no universally applied metric exists for storage

A **lack of standardization for storage** creates difficulty for manufacturers to verify cost competitiveness, investors to make informed financial decisions, and end users to select a technology.

4.3 Lifetime cost

Lifetime cost of storage

Lifetime cost offers a means to **compare storage technologies for clearly defined applications**, accounting for all technical and economic parameters influencing the cost of electricity provided.

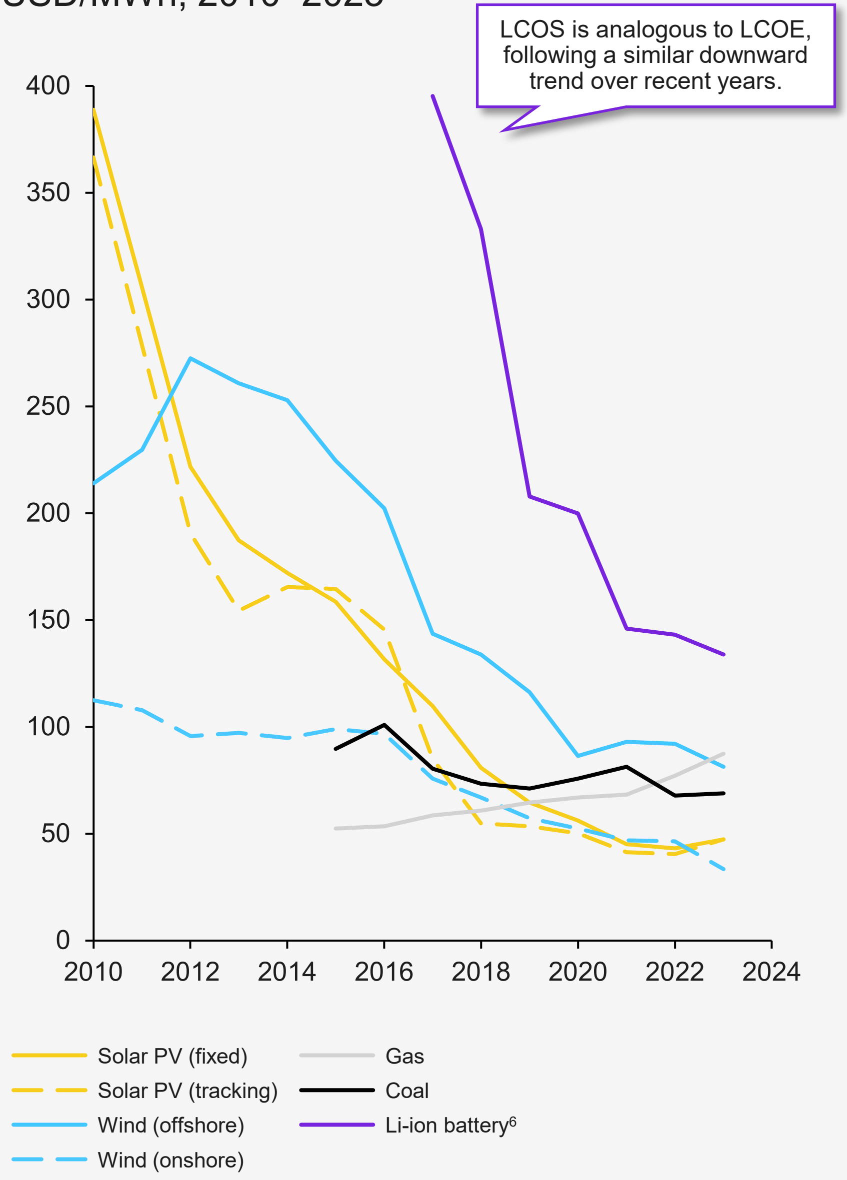
Two methods exist for calculating the lifetime cost of storage, representing the minimum revenue required for the project to achieve a NPV of zero:[2]

- **LCOS** quantifies the discounted cost per unit of electricity discharged in USD/MWh for a given storage technology and application, used for end uses that prioritize the delivery of electrical energy.[3]
- **ACC** quantifies the discounted cost per unit of electricity storage capacity provided for a given year in USD/kw-year, used for applications that prioritize the provision of power.[4]

The concept of LCOS and ACC is analogous to LCOE for generation technologies; therefore, **it is possible to directly compare the lifetime costs of storage and generation.**

Global LCOE and LCOS benchmarks[5]

USD/MWh, 2010–2023

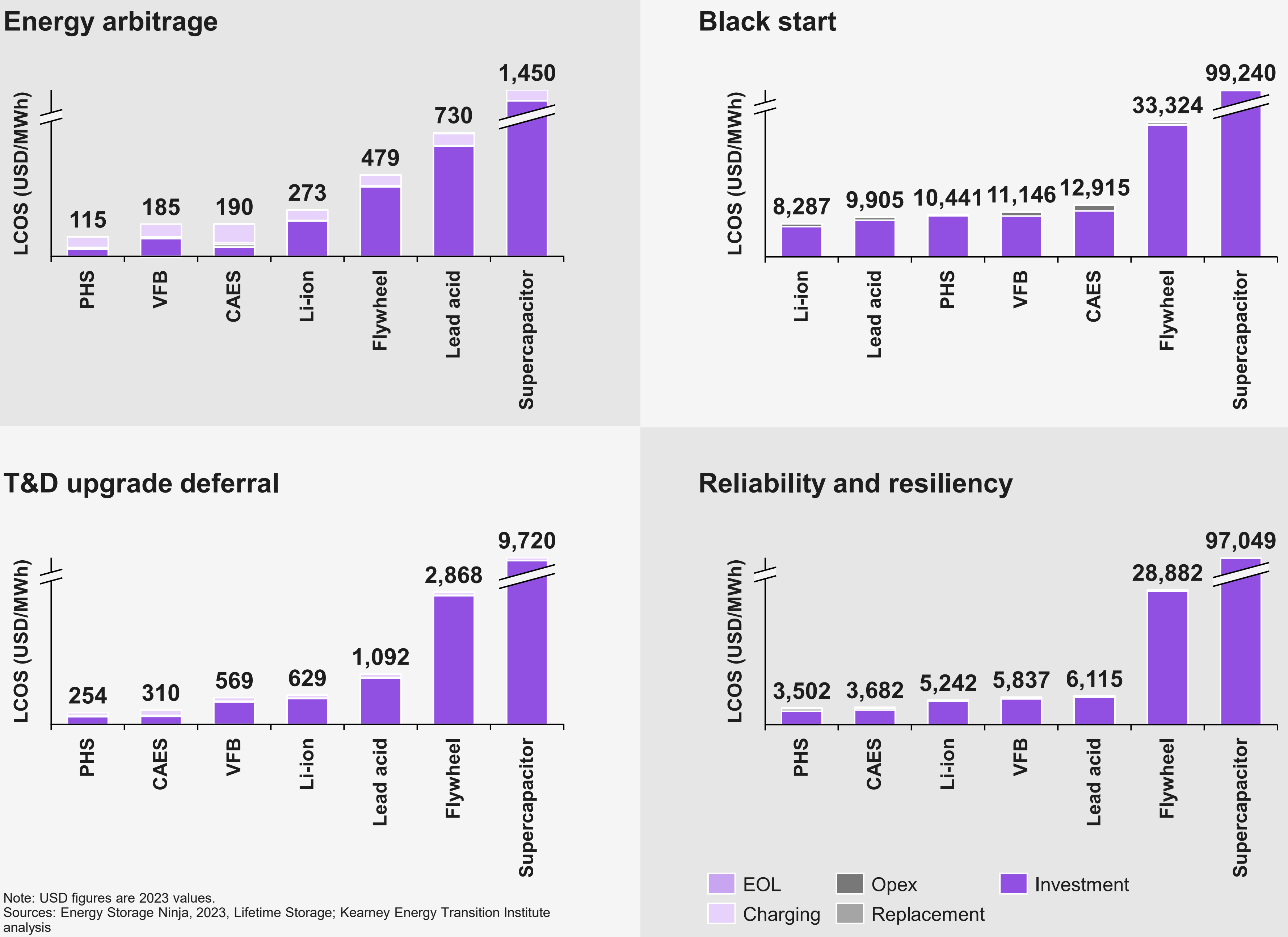


[1] Levelized cost of electricity; [2] Net present value; [3] Levelized cost of storage; [4] Annualized capacity cost; [5] Global capacity-weighted averages using latest country estimates. Wind (offshore) includes offshore transmission costs. Coal- and gas-fired power account for carbon pricing mechanisms where applicable. LCOE values do not include subsidies or tax credits; [6] Storage duration of four hours
Note: USD figures are 2022 values.
Sources: BloombergNEF, 2023, 2H 2023 LCOE Update; Mayr and Beushausen, 2016, Navigating the maze of energy storage costs; Pawel, 2014, The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy; Kearney Energy Transition Institute analysis

Competitiveness of storage technologies in terms of LCOS varies by application, driven by investment cost

Established technologies, such as **PHS, Li-ion, and CAES fall to the lower end of the LCOS range** across applications.

4.3 Lifetime cost



Note: USD figures are 2023 values.
Sources: Energy Storage Ninja, 2023, Lifetime Storage; Kearney Energy Transition Institute analysis

Co-location of electricity storage solutions and renewable generation assets is increasingly common to gain incremental revenue and cost efficiencies

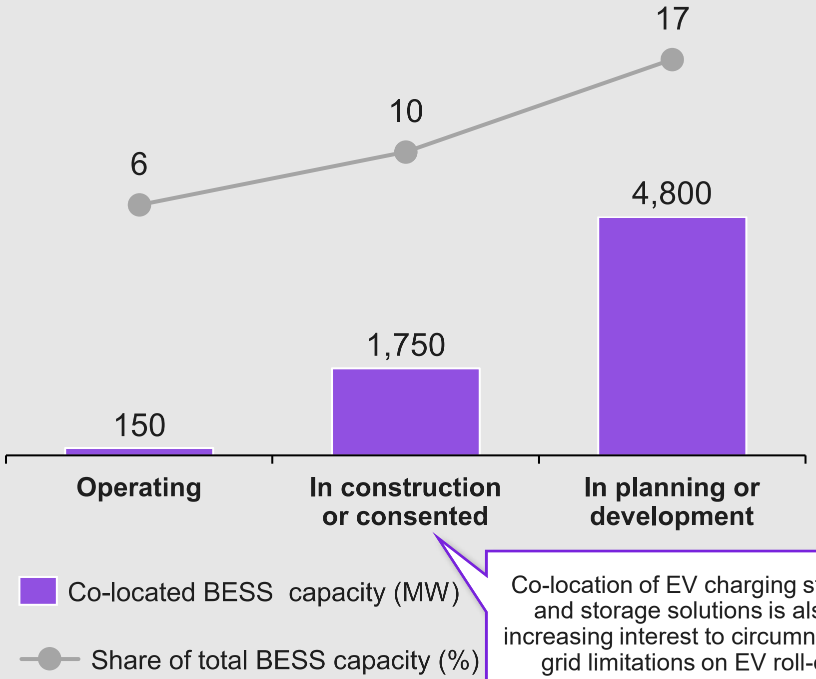
Example

Co-location refers to an electricity storage located on the **same site as generation, demand, or both, with a shared grid connection** – commonly solar PV and a battery energy storage system

4.3 Lifetime cost

Pipeline of co-located renewable generation and BESS[1] projects in the UK

MW, 2023



Co-location of EV charging stations and storage solutions is also of increasing interest to circumnavigate grid limitations on EV roll-out[2]

- An increasing share of pre-operational projects are expected to co-locate with renewable generation assets
- Currently, **seven co-located projects are operational** in the UK, constituting ~6% of total BESS capacity (~150 MW)
- Pipeline in planning or development represents a **32-fold increase** in current capacity

[1] Battery energy storage system; [2] For example, Zenobe partnered with Stagecoach to support the uptake of nine electric buses by co-locating grid-scale batteries with the charge point to avoid a roughly GBP 2.5 million upgrade to the on-site electricity supply
Sources: Gresham House, Collocation: a smart solution for the UK energy transition, 2023; HM Government, 2022, Taking charge: the electric vehicle infrastructure strategy; Kearney Energy Transition Institute analysis

Benefits of co-located renewable generation and BESS

Increase utilization of grid connections

- Delays in granting grid access creates a bottleneck for storage development (the UK currently quotes connection dates for 2037)
- Storage and renewable assets utilize a small portion of a grid connection (~10-15%)
- Co-location increases the utilization of increasingly rare grid connections

Expand revenue opportunities

- With the appropriate technology and operation, co-location offers new revenue opportunities, reducing long-term income risk
- E.g., a direct current coupled storage asset can charge from solar energy otherwise curtailed at the inverter to later sell on the wholesale market

Manage project risk

- Both assets face long-term price cannibalization risk
- Combining technologies, and associated business models, diversifies revenue streams to reduce risk

Share costs

- Reduce capex and opex relative to standalone systems by sharing resources
- Exacerbated by increasing connection costs that can make or break a business case

Storing electricity using battery storage can significantly increase the cost of electricity: example of a flexible power solution combining solar PV and a Li-ion battery

– LCOE considers the **direct costs of generating electricity** over the lifetime of a power facility, accounting for overnight capex, opex, fuel input costs, and capacity factor.

– LCOE does **not reflect the differing propositions of available technologies**, failing to account for the value or indirect costs required for comparison of electricity generation methods that operate differently, such as variable renewable sources and dispatchable technologies.

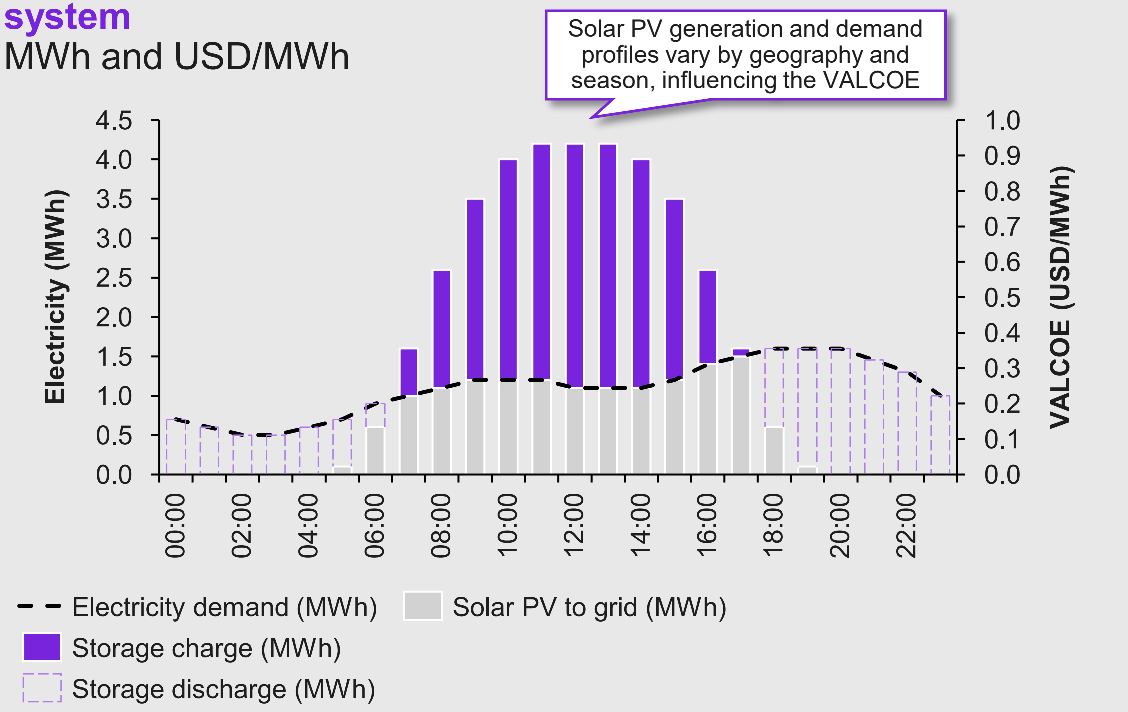
– VALCOE builds on LCOE by accounting for **three elements of value – energy, capacity, and flexibility** – to more accurately compare generation systems.

– VALCOE is a **more comprehensive metric of competitiveness** for electricity generation technologies, thus offering an estimate of the **full system cost of a technology.**

– In terms of co-locating storage and renewable energy facilities, VALCOE represents the **cost required for a non-dispatchable technology – such as solar PV – to deliver the services offered by traditional dispatchable means – such as gas turbines** – combining LCOE and LCOS.

Example of a US hybrid off-grid solar PV and Li-ion battery system

MWh and USD/MWh



– To match the electricity demand profile, the solar PV facility is complemented by a Li-ion battery to **store excess electricity generated during the day** (07:00–16:00) and **discharge when production falls short of demand** (00:00–06:00 and 18:00–23:00).

– The generation facility incurs costs for producing and storing electricity, reflected by LCOE (USD 41 /MWh) and LCOS (USD 273 /MWh), respectively.[2]

Without storage, the VALCOE is equal to the LCOE; with storage, and under specific conditions (irradiance, demand), the VALCOE accounts for the LCOS, **increasing to more than five times the cost of a standalone generation facility** (USD 314 /MWh).

Example

4.3 Lifetime cost

[1] Value-adjusted levelized cost of electricity; [2] LCOS for a Li-ion battery used for energy arbitrage (value will vary by application and location)
Note: USD figures are 2023 values.
Sources: IEA, 2020, Projected Costs of Generating Electricity; NREL, 2023, Electricity Annual Technology Baseline (ATB) Data; Schmidt et al., 2019, Projecting the Future Levelized Cost of Electricity Storage Technologies; Kearney Energy Transition Institute analysis

5. Battery value chain, from mining to recycling

Battery value chain, from mining to recycling

5.0 Chapter summary

The battery storage value chain is highly fragmented and encompasses a large network of specialized companies. The battery supply chain comprises four main stages: mining, raw material processing, cell component and battery module production, and application and recycling.

Mineral demand for stationary battery storage is expected to surge by over 30 times from 2020 to 2040, a trend driven by a similar increase in EV batteries demand over the same period. **Supply constraints** on raw materials **could threaten the deployment targets for electricity storage technologies in the coming years**. To limit risk exposure, **EV and battery cell manufacturers** are fortifying their position in the battery value chain by **securing raw materials supply**. Additionally, to achieve net zero emissions (NZE) requires spending **20% of yearly clean-tech supply chain investment on battery metals until 2030.**

Battery and component manufacturing future projects, primarily from China (76%), are set to increase fivefold for EV batteries production, which is currently 910 GWh. This increase should meet 80% of the demand projected in the IEA's NZE scenario. Global **lithium-ion battery manufacturing capacity** reached **2.8 TWh in 2023**, while the **demand** for EV and stationary storage **batteries** totaled approximately **950 GWh, presenting an oversupply in cells,** expected to remain in the near future.

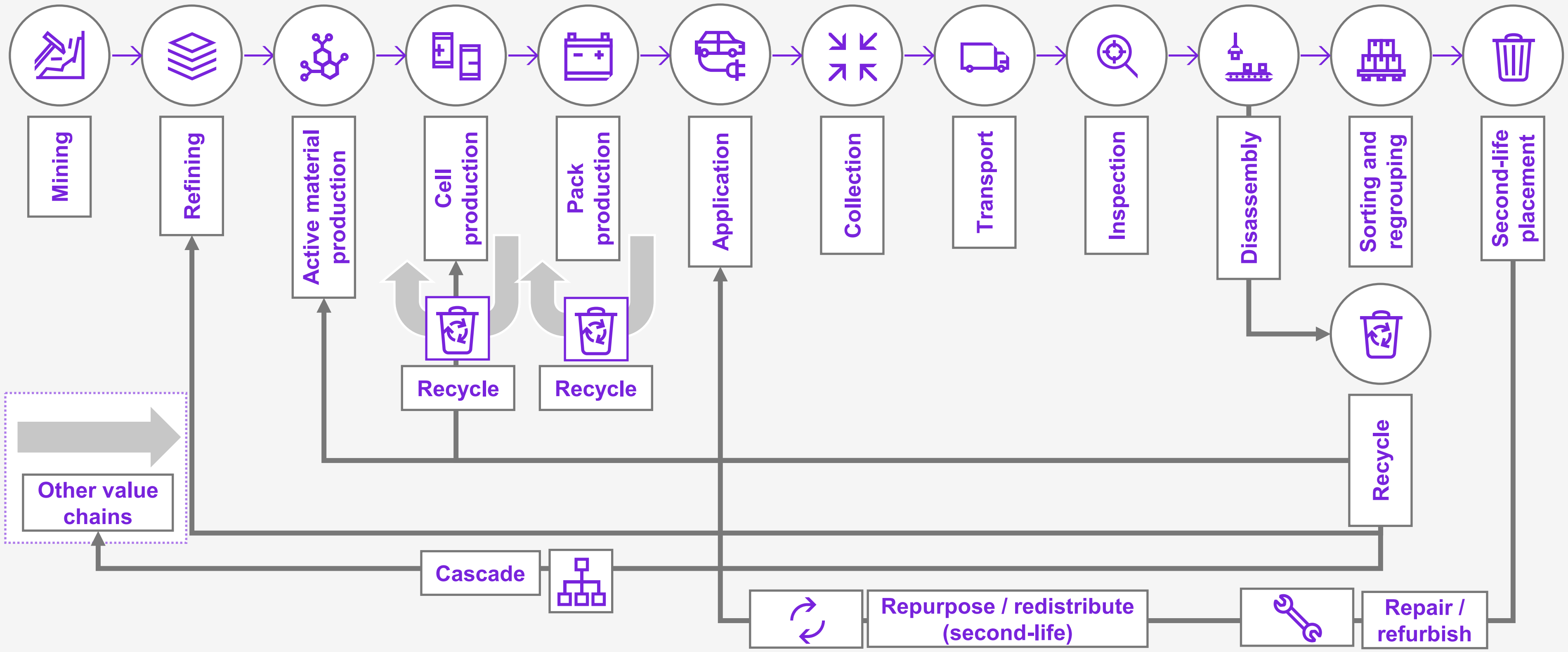
By 2030 around 9 TWh of gigafactory capacity is in the pipeline, with China leading the way with 68% of the capacity, followed by North America and Europe with 15% each. China plans 291 gigafactories, while Europe, North America, and other regions aim for approximately 37 each. Over 100 projects were announced by battery makers in 2022 and Q1 2023, contributing approximately 2 TWh out of the 9 TWh of battery capacity to the 2030 output. **Sustained investment, totaling at least USD 188 billion, is required in battery cell and component plants by the decade's end to keep pace with demand.**

Battery reuse and recycling sectors are developing across the globe. **The volume of spent EV and storage batteries reaching the end of their first life is projected to sharply rise after 2030, hitting 1.3 TWh by 2040**. The recycling to obtain **secondary materials could reduce** the **primary mineral supply** requirement by up to **12%**. Currently, **China (188 kt/y) leads the global battery recycling** capacity, while in Europe, local companies maintain their position. **With new plant announcements and expansions, recycling capacities in Europe are anticipated to reach 400 kt/y by 2025.**

The battery storage sector is highly fragmented, and the various steps of the chain are facing different challenges

Illustrative

Battery storage value chain steps



Challenges

Mining	Raw material processing	Cell component and battery module production	Application and recycling
– Availability and costs of critical mineral – ESG issues – Slow mining site setup	– Long lead times – Geographic distribution – Geopolitics	– Shortage of processing equipment – High investment costs – Market concentration	– Difficulty and safety concerns of recycling – Lack of guidance on repurposing – Competition for lithium and battery chemistries

Sources: Global Battery Alliance, World Economic Forum, 2019, A Vision for a Sustainable Battery Value Chain in 2030: Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation; International Council on Clean Transportation, 2023, Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches; RCS Global, 2016, The battery revolution: balancing progress with supply chain risks; Kearney Energy Transition Institute analysis.

The battery storage sector is highly fragmented and consists of a large network of specialized companies at each stage

Non-exhaustive

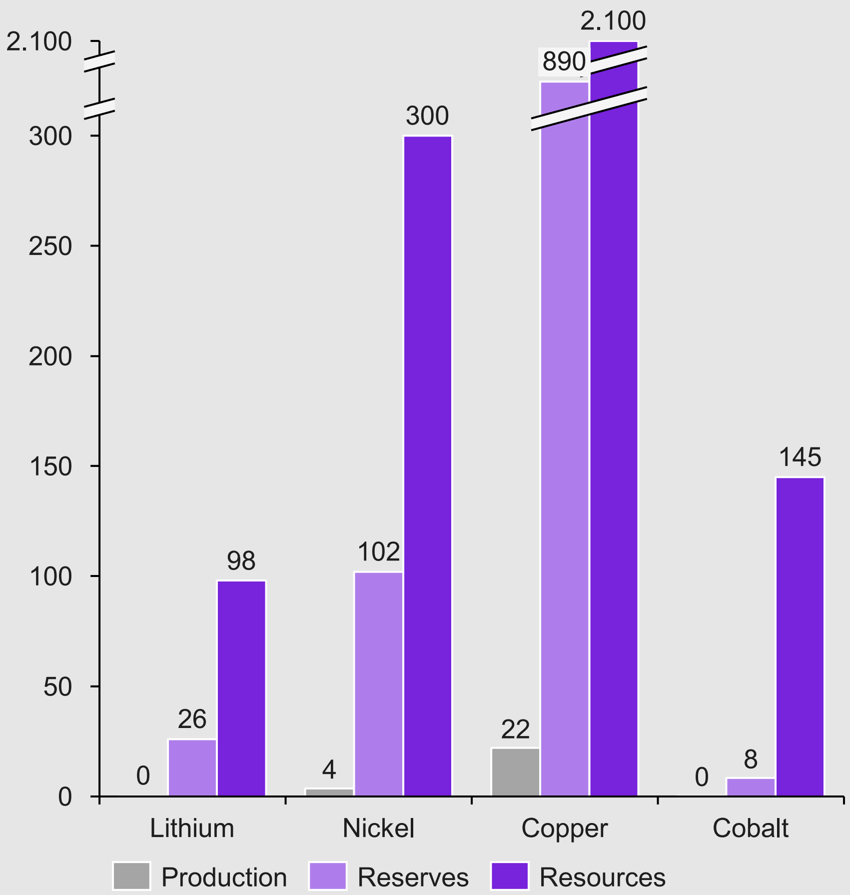
Mining	Raw materials processing	Cell component and battery module production	Second-life placement	Recycling	
Adionics	3M	Basquevolt	BeePlanet	Accurec	Retriev
Aepnus	Amprius Technologies	BlueSolutions	betteries	Akkuser Oy	Saft Ab
Albemarle	BASF	BMW	Connected energy	American Manganese	SNAM
Anglo American	ENEVATE	BYD	Enel	BAK Battery	SMCC Recycling
Barrick Gold Corporation	Group14	CALB	Evyon	Batrec	Sumitomo
CMOC Group Limited	Leverton Lithium	CATL	Mercedes Benz Energy GmbH	Belmond Trading	Toxco
Cornish Lithium Plc.	Lyten	ENVISION	Moment energy	Brunp	Umicore
Ganfeng Lithium	Mitsubishi Motors	General Motors	Nissan	Dowa	
Glencore	Nemaska	Gotion	Nunam	GEM recycling	
Impossible Metals	Nexeon	LG Chem	Octave	Glencore	
Lithios	Orocobre Limited	Mercedes-Benz	ReJoule	Inmetco	
Lithium Americas	Posco	Northvolt	Relectrify	JX Nippon Mining and Metals	
Livent	Solvay S.A.	Panasonic	Renault	Kaiho Sangyo	
Loke	Sumitomo Corporation	Renault	SAMSAR	Li-Cycle Corp	
Mangrove Lithium	Targray	Samsung	STABL	Neometals	
Rio Tinto	Umicore	SK innovation	Voltfang	OnTo Technology	
SQM	Volexion	Stellantis	Zenobē	Recupyl	
Tianqi Lithium	Vulcan	Tesla		Redux	
		Volkswagen			

Sources: Kearney Energy Transition Institute analysis based on desktop research

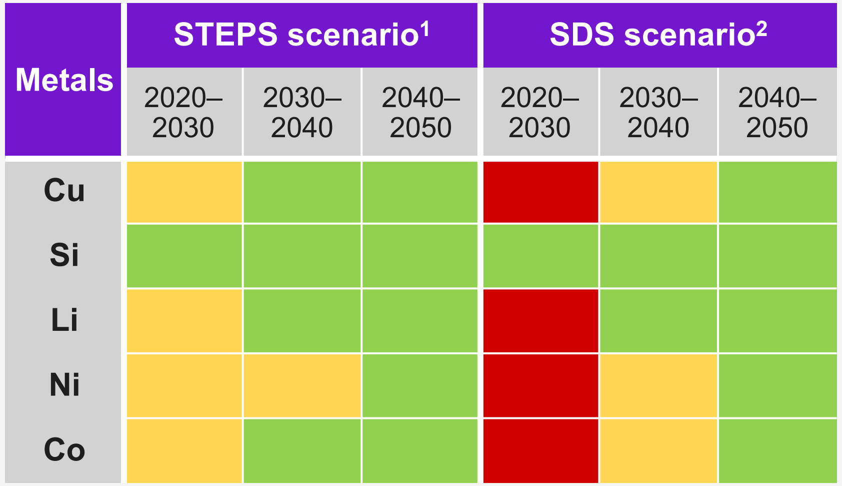
To reach the sustainable development scenario goals, supply shortfalls are foreseen on raw materials until the end of the 2020 decade

Resources, reserves, and production for selected mineral resources

Million metric tonnes, 2023



Risks on global raw material supply by decade



Not enough projects announced to meet demand

Base case supply insufficient, project pipeline sufficient; innovation and investments needed

No issues expected, supply potential sufficient

Supply constraints are anticipated to peak toward the end of the 2020 decade. This strain could persist until around 2040 for metals like copper, nickel, and cobalt.

Beyond 2030, uncertainties arise due to factors such as technological advancements in products like electric vehicle batteries, material substitution prospects, and **shifts in societal consumption patterns**, which could potentially lower metal requirements and soften future supply risks.

[1] IEA's Stated Policies Scenario; [2] IEA's Sustainable Development Scenario

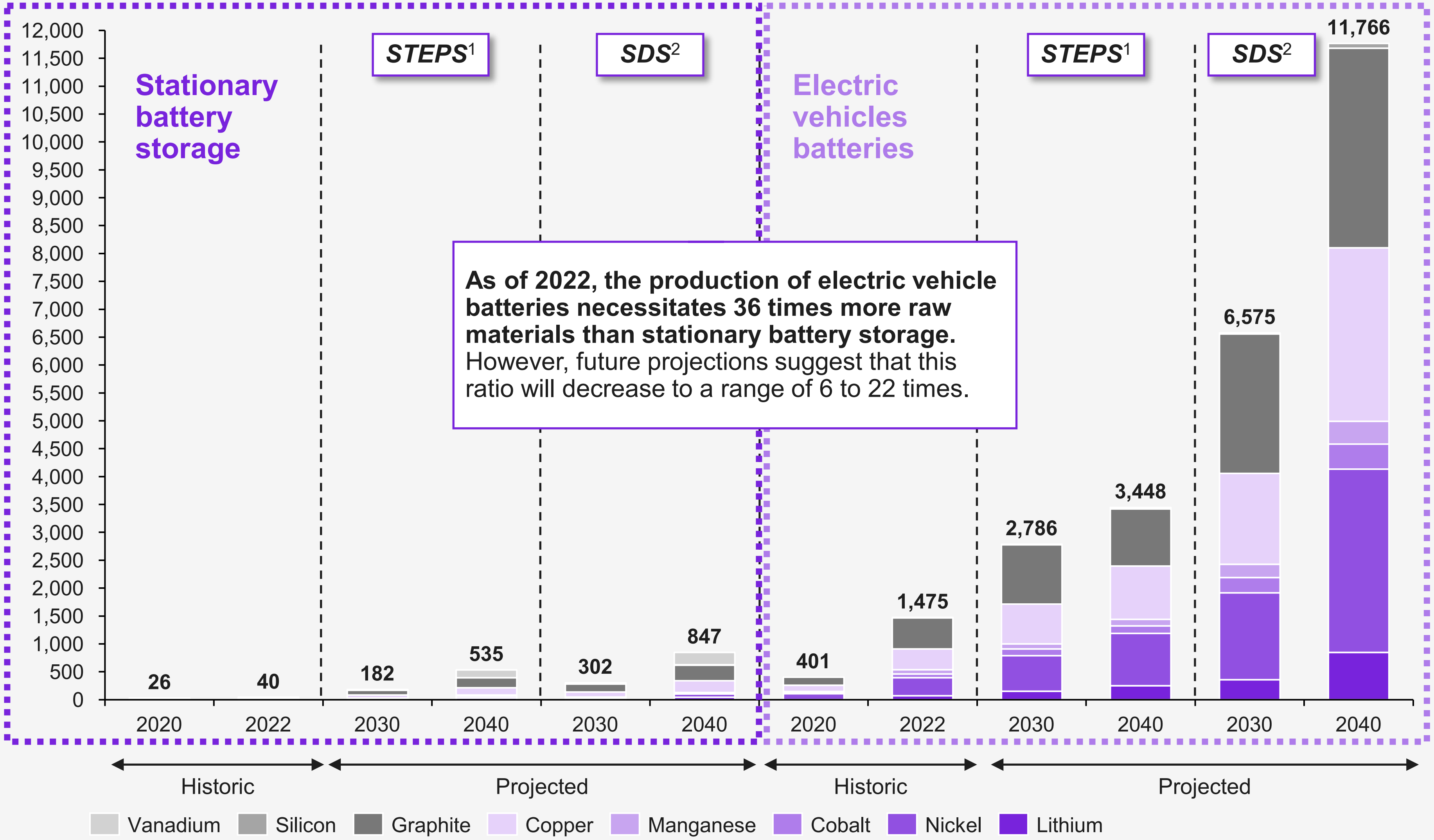
Sources: IEA, 2023, Critical Minerals Market Review; IEA, 2022, The Role of Critical Minerals in Clean Energy Transitions; KU Leuven, 2022, Metals for Clean Energy: Pathways to solving Europe's raw materials challenge; USGS (United States Geological Survey), 2023, Mineral Commodity Summaries 2023; Kearney Energy Transition Institute analysis

Raw material demand for battery applications is mainly driven by electric vehicle growth

The mineral demand for stationary battery storage in the SDS surges by more than 30-fold from 2020 to 2040. Similarly, the mineral demand for EV batteries experiences almost a 30-fold increase over the same period of time.

5.2 Supply of raw materials

Raw material use for stationary battery storage and electric vehicle batteries
kt, 2020–2040

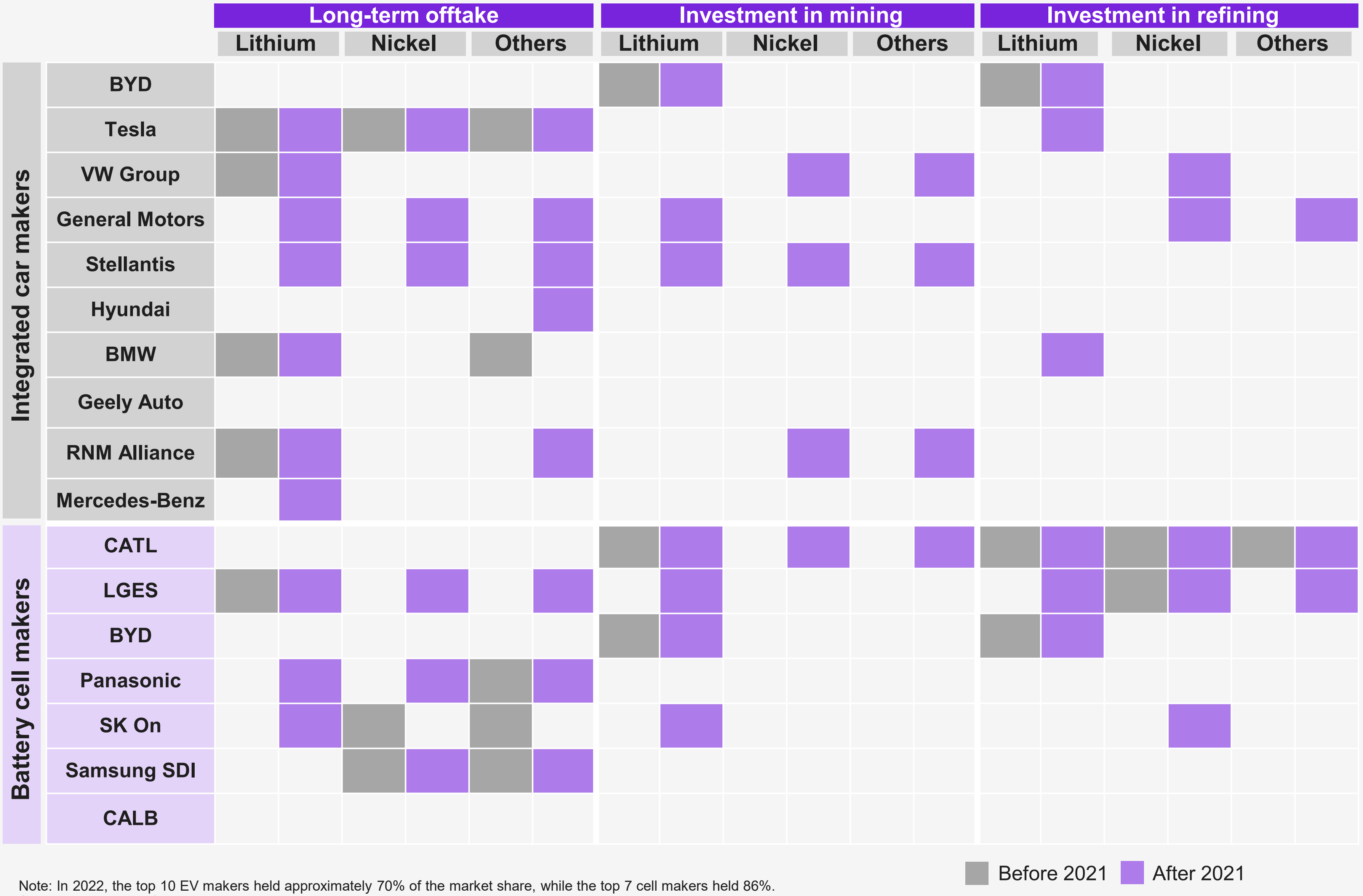


[1] IEA's Stated Policies Scenario; [2] IEA's Sustainable Development Scenario
Note: The raw material use reflects to the stationary battery storage additions and the new sales of electric vehicles.
Sources: IEA, 2023, Critical Minerals Market Review; IEA, 2022, The Role of Critical Minerals in Clean Energy Transitions; Kearney Energy Transition Institute analysis

EV and battery cell makers are securing their raw material supply by positioning themselves in the upstream activities

5.2 Supply of raw materials

Top car and battery cell makers getting involved in the raw material activities
Before and after 2021



Note: In 2022, the top 10 EV makers held approximately 70% of the market share, while the top 7 cell makers held 86%.
Sources: IEA, 2023, Critical Minerals Market Review; Kearney Energy Transition Institute analysis

Oil and gas companies are entering the storage sector through strategic investments and partnerships around lithium activities

5.2 Supply of raw materials

Oil and gas industry investment and partnerships in lithium activities
2023

Oil majors	Activities	Region
Equinor	Investment in Lithium de France, junior miner (USD 55 million raised in 2023); agreement with Standard Lithium Ltd to acquire a 45% share in two lithium project companies in Southwest Arkansas and East Texas	
Exxon Mobil	Announced project to exploit lithium in Arkansas	
Imperial	Investment in E3 Lithium, junior miner, with projects in Leduc oil fields	
Gazprom	Partnering with Irkutsk Oil Company to exploit lithium in Kovykta gas field	
Oxy	Joint venture with All-American Lithium to extract lithium from geothermal and brines	
YPF	Partnering with Catamarca Minera y Energética to prospect for lithium in the Fiambala salt flats	
Oil field services	**Activities**	
SLB	– Investment in EnergySource Minerals – Partnering with technology provider Gradiant for sustainable lithium compound production	
Others	**Activities**	
Berkshire Hathaway Energy	Lithium and geothermal project in the Salton Sea, California	
Koch	– Investment in lithium extraction processes – Investment in Standard Lithium (USD 100 million) and Compass Minerals' Utah project, (USD 252 million)	

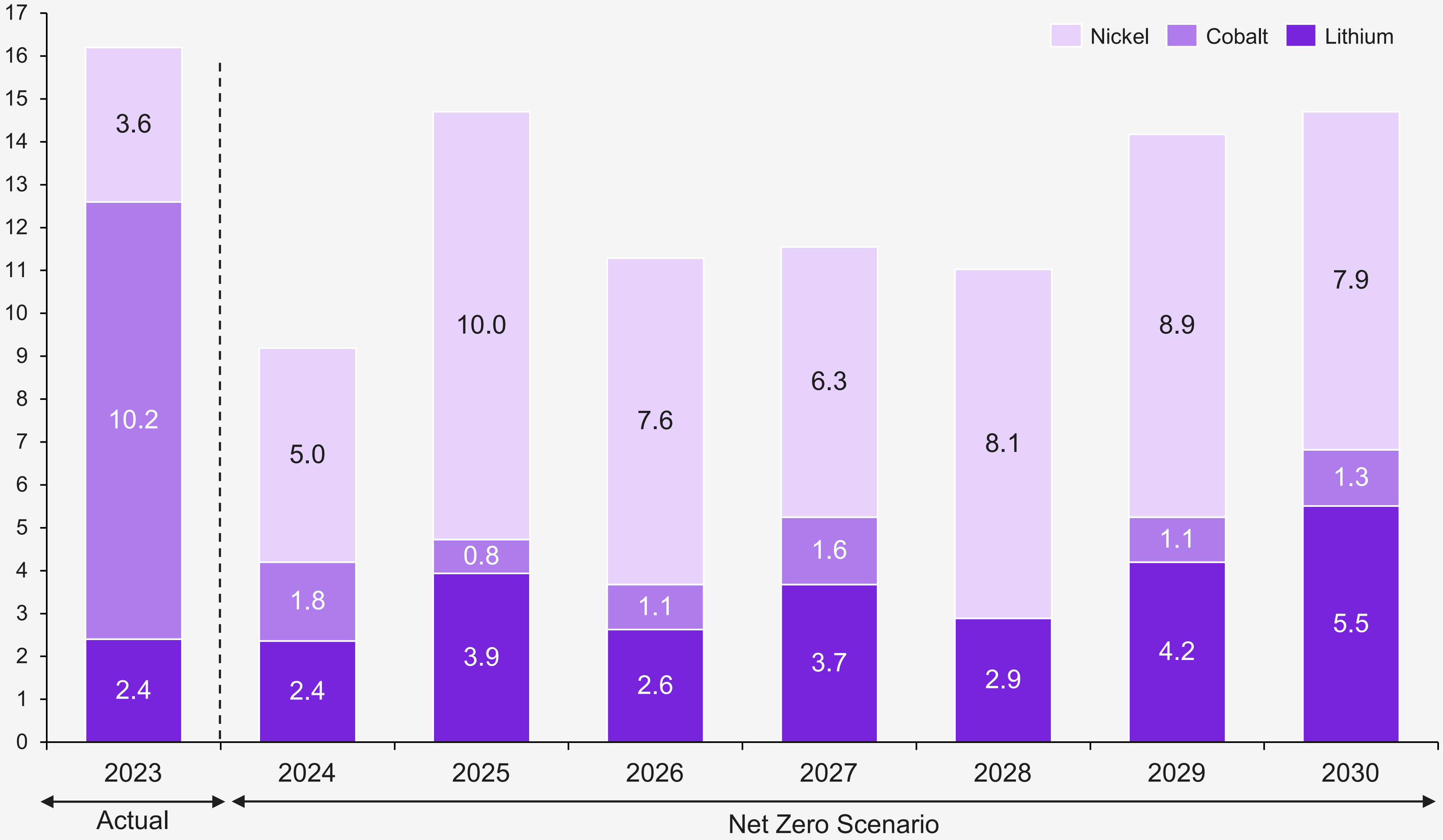
Sources: IEA, 2023, The Oil and Gas Industry in Net Zero Transitions; Equinor, 2024, "Equinor enters partnership with Standard Lithium"; Kearney Energy Transition Institute analysis

Spending on metals for batteries between 2024 and 2030 to achieve NZE goals represents about 20% of global supply chain clean-tech investment[1]

Investment fluctuations are expected on the account of delays, cathode chemistries evolution and metals markets developments.

5.2 Supply of raw materials

Current and required investments for battery metals supply chain
billion USD, 2023–2030



[1] Net Zero Emissions scenario from BloombergNEF
Note: Battery metals include mines and refineries.
Sources: BloombergNEF, 2024, Energy Transition Investment Trends; Kearney Energy Transition Institute analysis

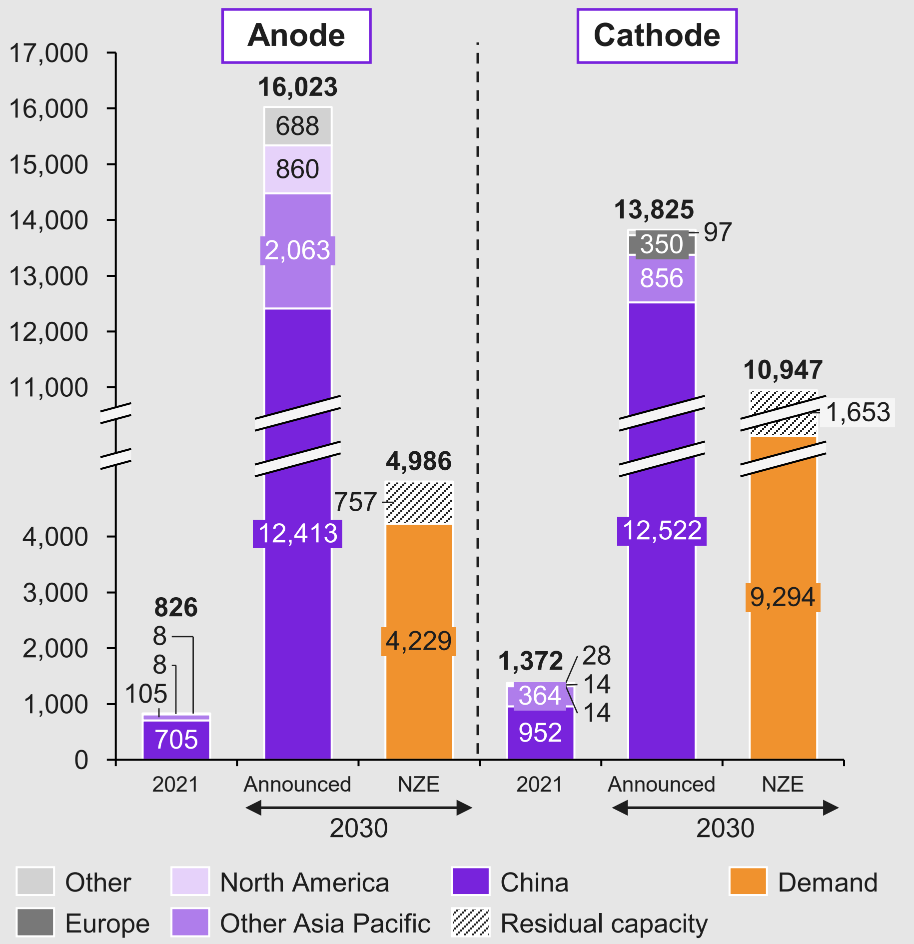
Global announced component manufacture is surpassing the NZE projected manufacturing capacity, mostly led by China

Currently announced projects are expected to **fivefold EV battery production by 2030**, meeting 80% of projected demand in 2030 in the NZE scenario.[1]

5.3 Cell components and battery module manufacturing

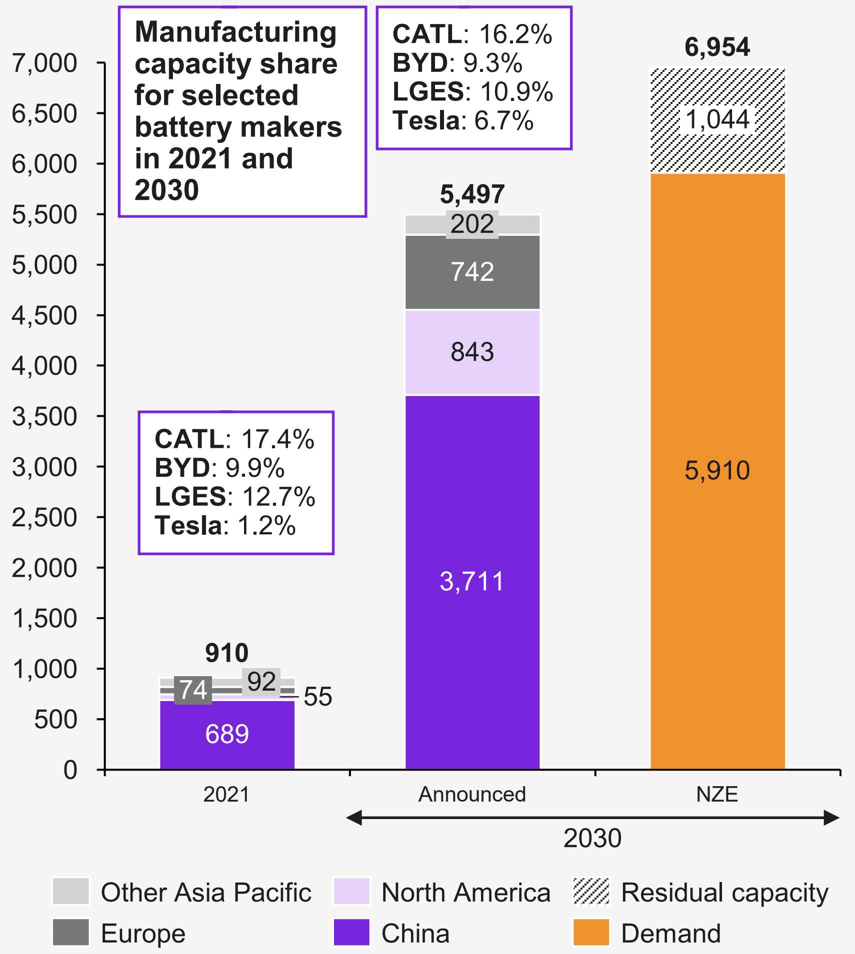
Component manufacturing[2] capacity by country / region according to announced projects and the NZE scenario

kt, 2021–2030



Battery manufacturing[3] capacity by country / region according to announced projects and the NZE scenario

GWh, 2021–2030



[1] IEA's Net Zero Emissions scenario

[2,3] Processors and refiners purify the raw materials, then use them to create cathode and anode active battery materials (midstream) and battery manufacturers assemble the battery cells into modules (downstream).

Note: Announced capacity includes existing capacity. The manufacturing capacity needed to meet projected demand in the NZE Scenario (NZE demand) is estimated assuming a utilization rate of 85%. NZE residual capacity, thus, represents the manufacturing capacity that would remain unused, on average, which provides some flexibility to accommodate demand fluctuations. Batteries for EV and grid storage applications are included in demand, with the latter accounting for 9% of the total in the NZE Scenario in 2030. Announced projects include battery factories from tier 1 and tier 2 battery makers, as per the Benchmark Mineral Intelligence classification.

Sources: IEA, 2023, Energy Technology Perspectives; Kearney Energy Transition Institute analysis

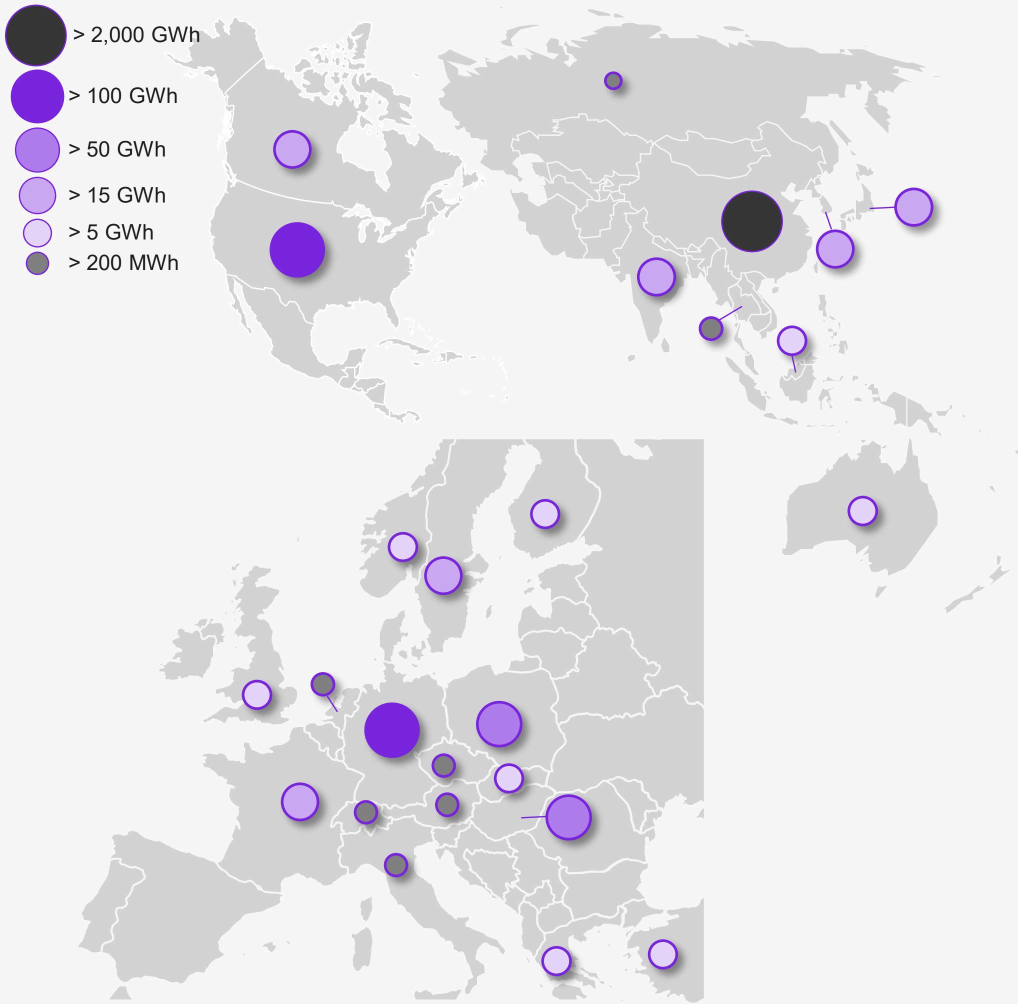
Current lithium-ion manufacturing battery capacity is spread globally, although China concentrates more than 70% of this capacity

In 2023, the global lithium-ion battery manufacturing capacity reached 2.8 TWh, while the demand for EV and stationary storage batteries totaled approximately 950 GWh. It is expected that this cell oversupply will continue in the near future.

5.3 Cell components and battery module manufacturing

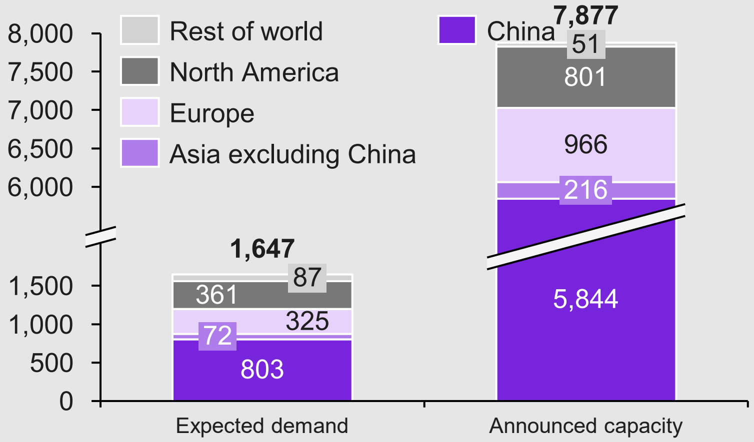
Lithium-ion battery manufacturing capacity by country

GWh, 2023



Lithium-ion battery manufacturing capacity by region

GWh, 2025



Many announced capacity plans won't materialize due to various reasons:

- delays or cancellations as challenges on scaling emerge
- supply chain limitations
- complexity of EV batteries, which are not yet a commodity product, and present varying formats and chemistries, including automaker preferences
- declining plant utilization rates

However, **despite accounting for substantial de-rating, the market is still projected to face significant oversupply**, creating several implications.

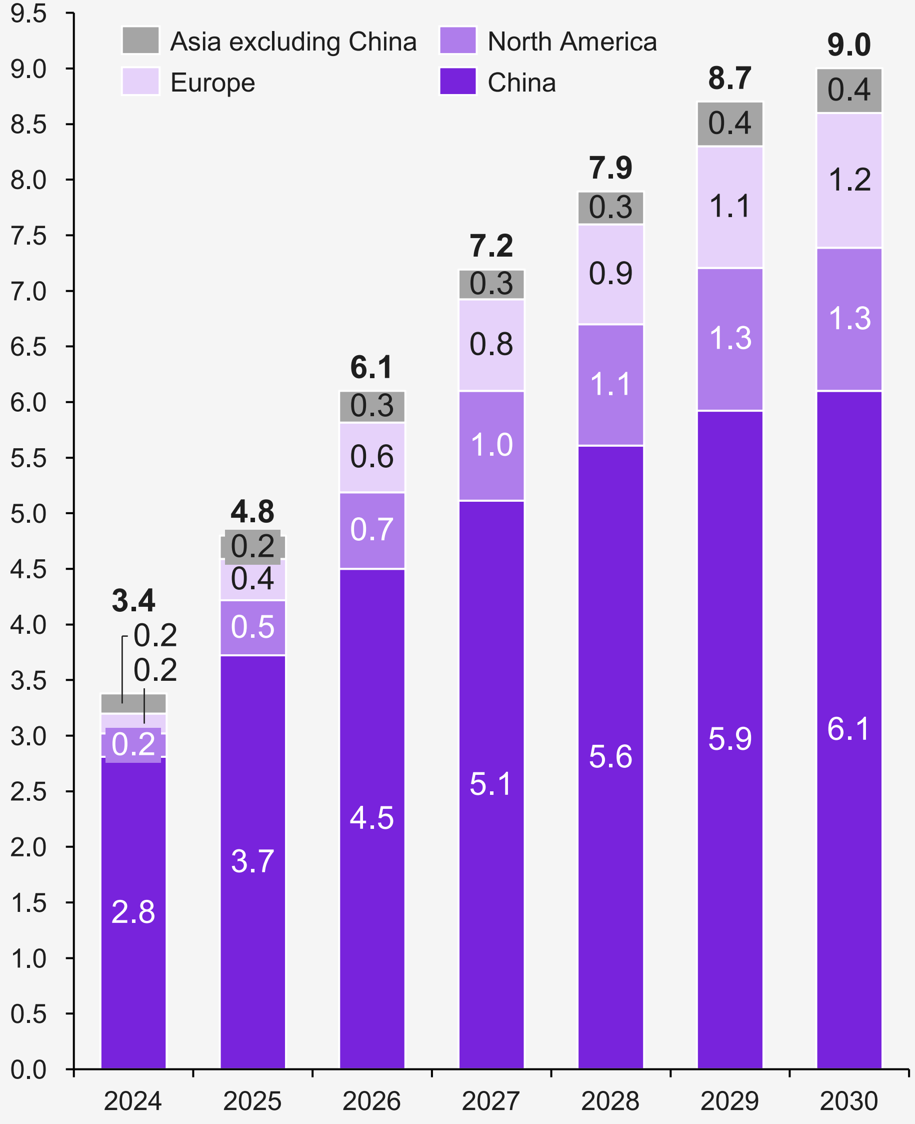
Sources: S&P Global Market Intelligence, 2023, “Lithium-ion battery capacity to grow steadily to 2030”; BloombergNEF, 2024, “China Already Makes as Many Batteries as the Entire World Wants”; Kearney Energy Transition Institute analysis

China control over the battery manufacturing supply chain is set to reduce toward 2030, as other regions increase their manufacturing capacities

China holds 68% of the 2030 pipeline, with a pipeline of 291 gigafactories. Europe, North America, and the rest of the world aim for around 37 gigafactories each.

5.3 Cell components and battery module manufacturing

Lithium-ion battery gigafactories pipeline by region
TWh, 2024–2030



Sources: Benchmark Minerals Intelligence, 2023, Gigafactory assessment; Kearney Energy Transition Institute analysis

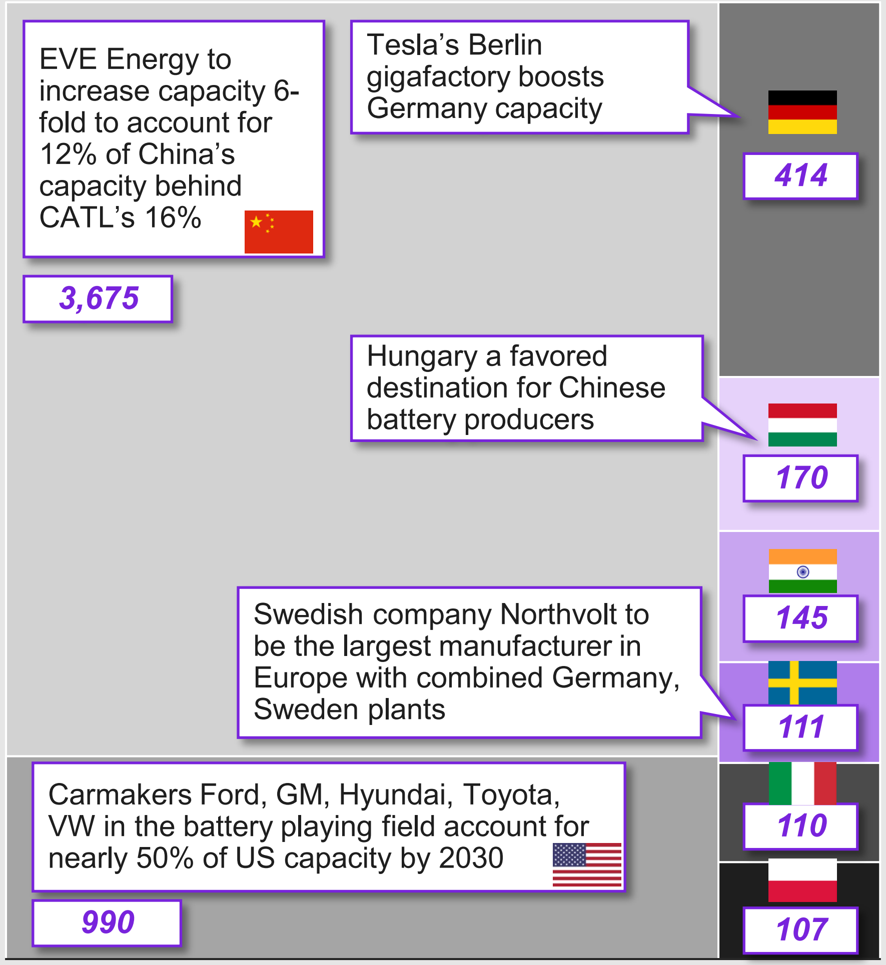
- The majority of **China's** provinces are home to battery production, with its top five battery-producing provinces boasting over 150 gigafactories.
- **North America** developments are largely concentrated in the US. The Inflation Reduction Act in 2022 has boosted battery cell developments in the region and by mid-2023 it had overtaken Europe with the second largest manufacturing capacity pipeline outside of China.
- **Europe** has a similar share of capacity in the pipeline to North America. Central Europe has emerged as a key gigafactory hub, with Poland, Hungary, and Germany set to be key battery-producing countries.
- **Gigafactories elsewhere** will only contribute to a small fraction of capacity by 2030. However, South Korean and Japanese battery producers are actively developing capacities in other regions, particularly North America.

At least a third of the global battery manufacturing pipeline for 2030 is dedicated to EV batteries, with Chinese manufacturers leading the way

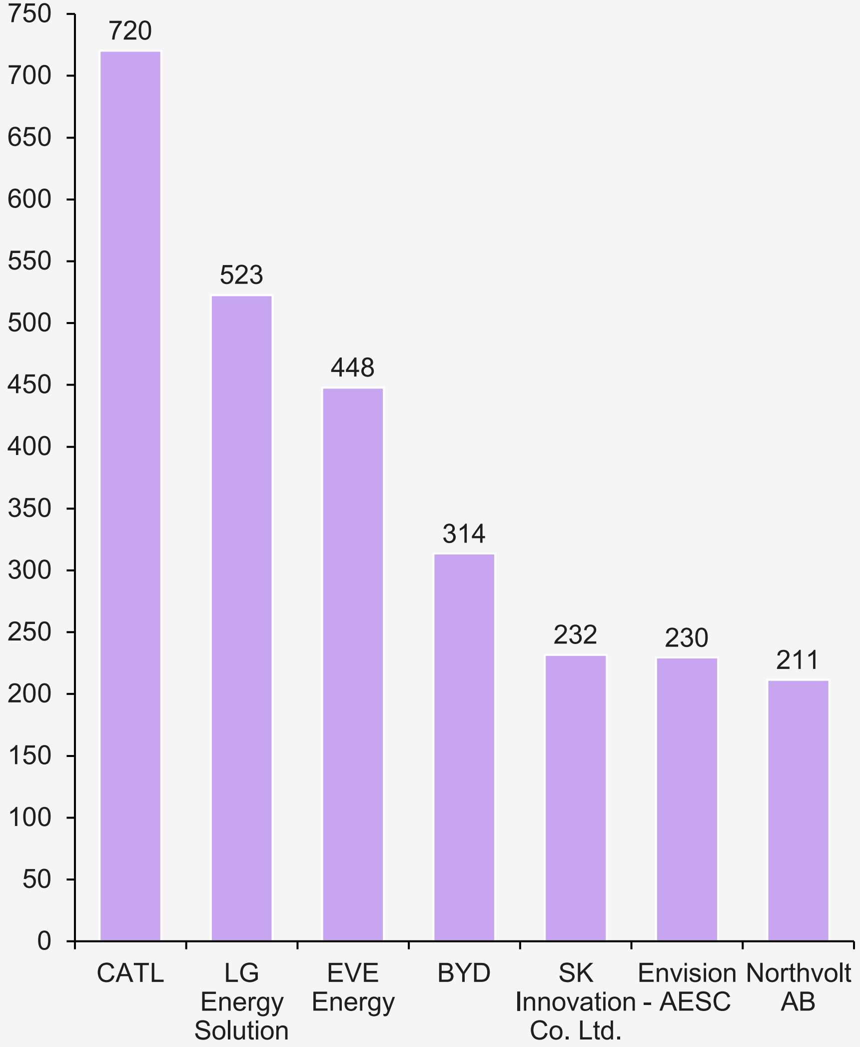
Over 100 projects were announced in 2022 and Q1 2023, contributing approximately 2 TWh of the 9 TWh of battery capacity to the 2030 output.

5.3 Cell components and battery module manufacturing

Top EV battery-manufacturing countries
GWh, 2030



Expected production from leading battery manufacturers
GWh, 2030



Sources: S&P Global Market Intelligence, 2023, Lithium-ion battery capacity to grow steadily to 2030; Kearney Energy Transition Institute analysis

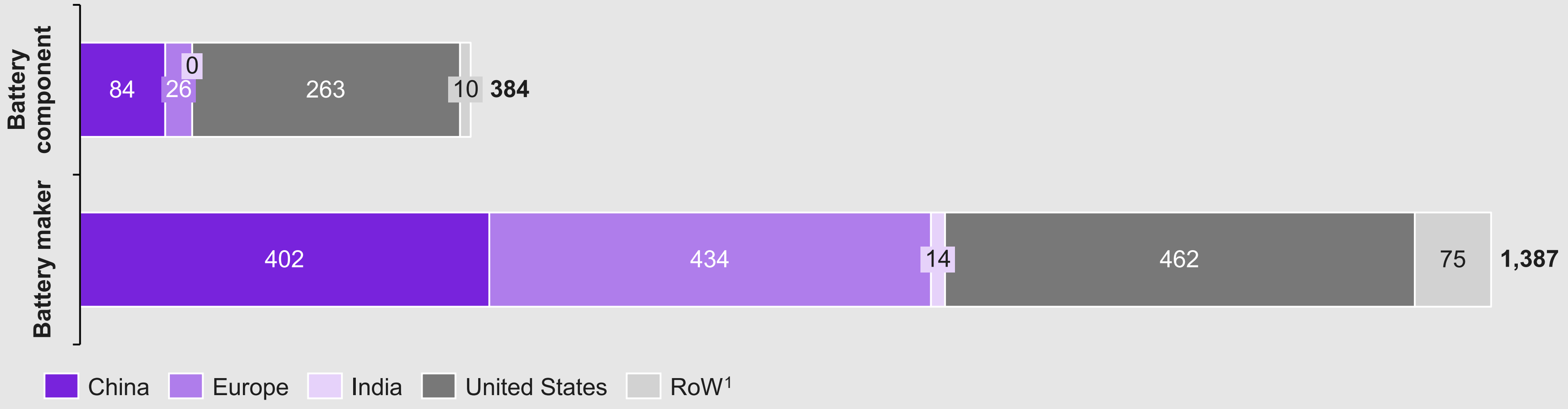
Investments need to be sustained across all areas of the battery supply chain in the second half of the decade to keep up with demand

Sustained investment will be required in the second half of the decade to keep up with battery demand. **At least USD 188 billion needs to be invested in battery cell and component plants by the end of the decade.**

5.3 Cell components and battery module manufacturing

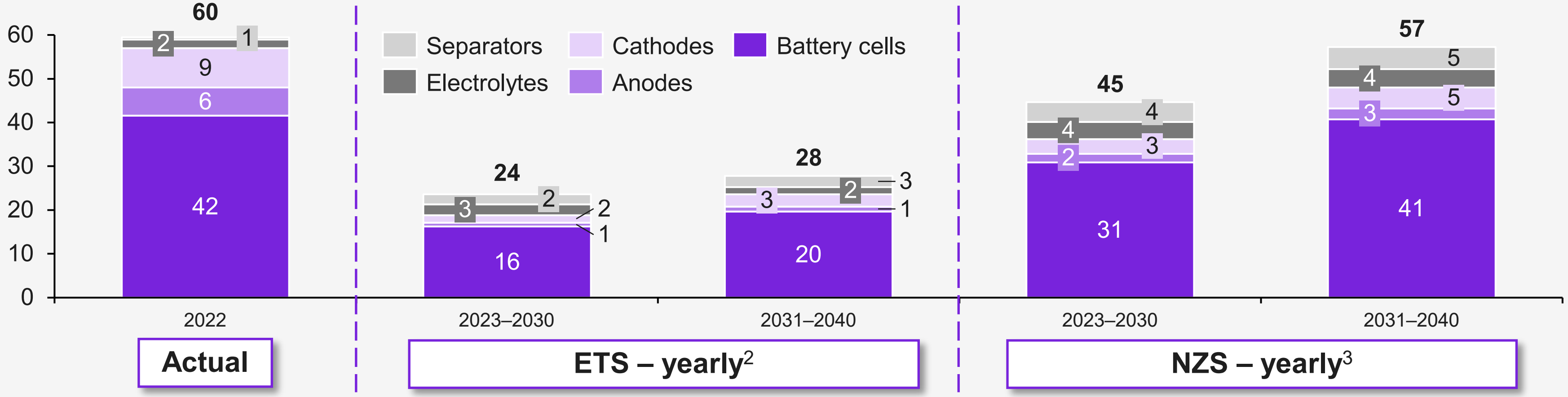
Share of total cumulative venture capital investment in electric mobility technology areas by country or region

million USD, 2018–2022



Annual battery factory investment by scenario

billion USD, 2022–2040



[1] Rest of world; [2] BloombergNEF's Economic Transition Scenario; [3] BloombergNEF's Net Zero Scenario

Note: The first figure includes both early- and growth-stage deals. The country or region is determined based on company headquarters and not the origin of investors. "Europe" includes European Union countries, Norway, Switzerland and the United Kingdom. In the second figure, battery factory requirements include investment needed to meet EV demand as well as stationary energy storage.

Sources: IEA, 2023, Global EV Outlook 2023: Catching up with climate ambitions; BloombergNEF, 2023, Electric Vehicle Outlook; Kearney Energy Transition Institute analysis

Several battery reuse initiatives have been implemented across the globe

Example

Examples of electric vehicle battery reuse projects
2022

Application	Project lead(s)	Region	Description
Street lighting	Nissan		Nissan aims to repurpose end-of-life Nissan Leaf batteries for streetlight power in "The Light Reborn" project, employing solar panels for charging.
Electric vehicle charging stations	Jaguar Land Rover and Pramac		Jaguar and Pramac created a solar-powered, off-grid portable battery charging station, configurable as a Type 2 22-kW AC charger for EVs.
	Volkswagen and Electrify America		Volkswagen intends to utilize batteries from used electric vehicles for energy storage at Electrify America charging stations.
Maritime and airport industrial site	The Seine Alliance and Renault		The Seine Alliance has partnered with Renault to deploy electric boats powered by 15-kW second-life electric vehicle batteries.
	Neoline Développement		The Neoline project consists of the development of an electric sail cargo fleet that uses second-life electric vehicle batteries for propulsion.
	Carwatt and Renault		In 2014, Carwatt collaborated with Renault to convert airport ground-support vehicles from combustion engines to electric, using second-life EV batteries.
Industrial site	RWE and Audi		Audi and RWE introduced an energy storage system utilizing 60 second-life Audi e-tron batteries, offering approximately 4.5 MWh of stored electricity to support industrial site operations.
	Renault and Connected Energy		In 2018, Renault and Connected Energy launched the "SmartHubs" pilot in the UK, using 360 kWh energy storage made from old EV batteries to reduce electricity costs by maximizing renewable energy usage at various sites.
	Zenobe and Aertssen		Zenobē partnered with Aertssen to maximize its on-site renewables using a 1.4 MW second-life battery (upcycled from an electric bus) leading to 69 MW of additional solar power being used per year.
Utility-scale grid storage	Renault		Renault's 2018 Advanced Battery Storage project across Europe combines new and used EV batteries to provide up to 50 MWh of energy storage, balancing renewable energy supply.
	Enel and Nissan		Enel, in collaboration with Nissan, constructed a 4-MW energy storage facility in Melilla, Spain, known as the Second Life project. It utilizes 78 Nissan Leaf batteries (48 used and 30 new) to enhance grid reliability by storing renewable energy.

Sources: International Council on Clean Transportation, 2023, Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches; Kearney Energy Transition Institute analysis

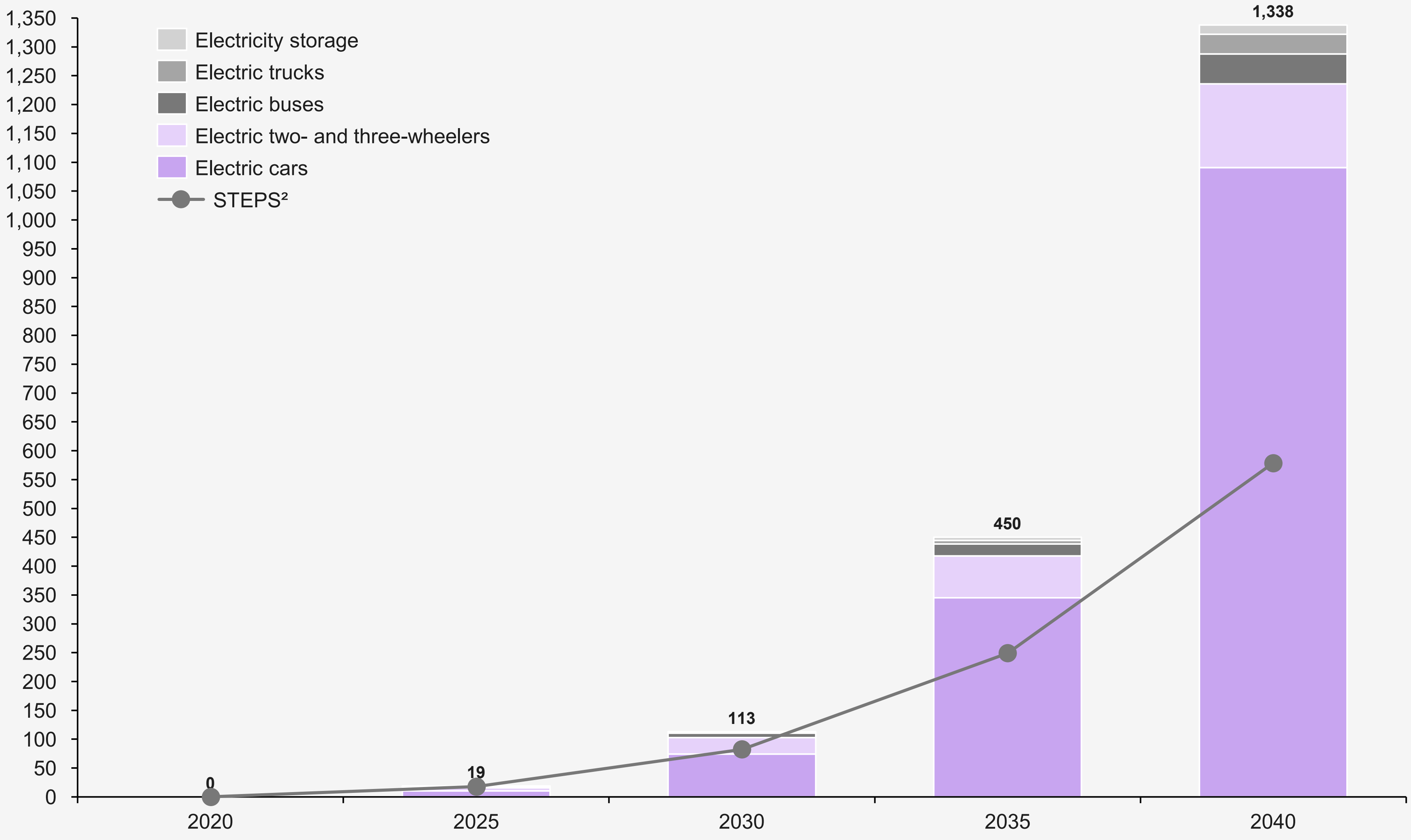
The projected surge in spent EV battery volumes suggests immense scope for recycling

The amount of spent EV[3] and storage[4] batteries reaching the end of their first life is expected to surge after 2030, reaching 1.3 TWh by 2040 in the IEA's sustainable development scenario.

5.5 Recycling

Amount of spent lithium-ion batteries for EVs and storage by application in the SDS[1]

GWh, 2020–2040



[1] IEA's Sustainable Development Scenario; [2] IEA's Stated Policies Scenario ; [3] EV considering an average 200,000 km lifetime mileage ; [3] ~1,500-2,000 cycles
Sources: IEA, 2022, The Role of Critical Minerals in Clean Energy Transitions; Kearney Energy Transition Institute analysis

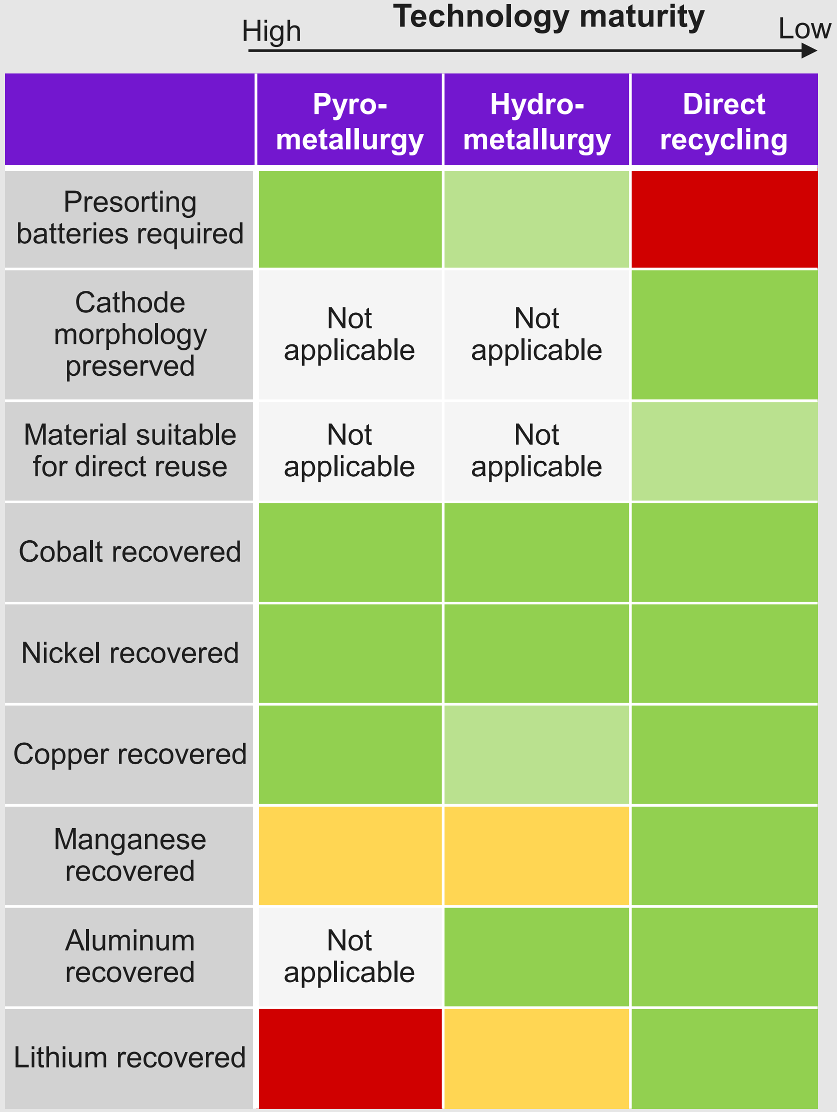
By 2040 recycling and reuse of EV and storage batteries could reduce the primary supply requirement for minerals by up to 12%

Illustrative

– **Primary supply:** Supply of metals deriving from mining and extracting resources.
– **Secondary supply:** Supply of metals derived from recycling resources.

5.5 Recycling

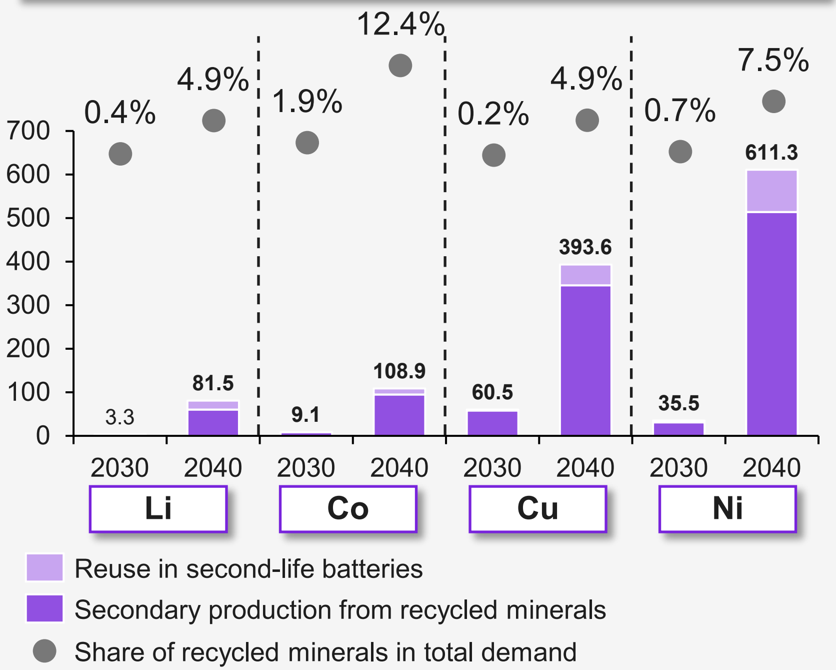
Comparison of various recycling methods[1]



Global contribution of recycling and reuse of batteries to reduce primary supply needs for selected minerals in SDS[2]

kt/y, 2030–2040

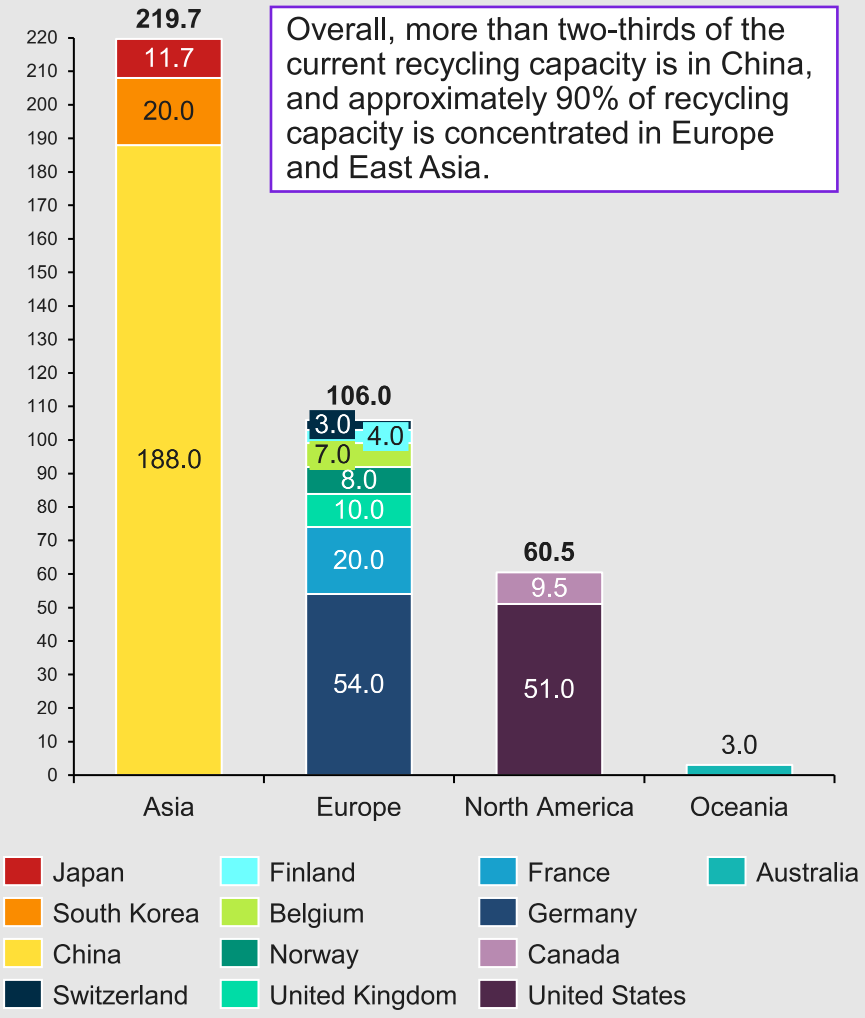
EU battery directive (2023) has mandated minimum levels of recycled content in industrial batteries, EV batteries, and automotive batteries containing Co, Pb, Li, or Ni in active materials. The mandatory minimum levels would be set for 2030 and 2035 (i.e., 12% cobalt, 85% lead, 4% lithium, and 4% nickel as of 1 January 2030, increasing to 20% cobalt, 10% lithium, and 12% nickel from 1 January 2035, the share for lead being unchanged). Another EU regulation includes **minimum recycling efficiency rates** and **targets for recovery of materials**.



[1] The comparison of the various recycling processes is presented in the Appendix; [2] IEA's Sustainable Development Scenario
Sources: IEA, 2022, The Role of Critical Minerals in Clean Energy Transitions; KU Leuven, 2022, Metals for Clean Energy: Pathways to solving Europe's raw materials challenge; G. Harper et al., 2019, "Recycling lithium-ion batteries from electric vehicles," Nature; EU directive Kearney Energy Transition Institute analysis

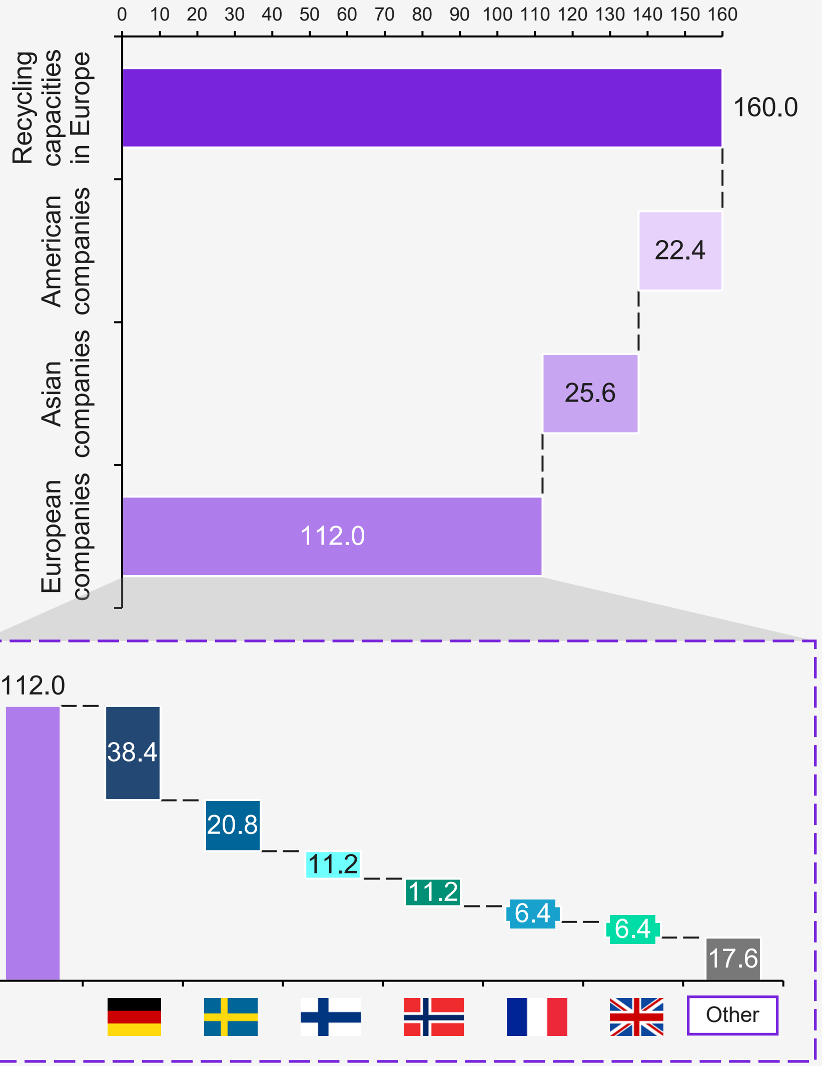
China is leading battery recycling capacity, while in Europe the European companies are holding their position against foreign competition

Existing and planned lithium-ion battery recycling capacity
kt/y, 2021



Overall, more than two-thirds of the current recycling capacity is in China, and approximately 90% of recycling capacity is concentrated in Europe and East Asia.

Operating lithium-ion battery recycling companies in Europe[1]
kt/y, 2023



[1] The origin of li-ion recycling plant operating companies is based on the location of their headquarters.
Sources: Z. J. Baum et al., 2022, "Lithium-Ion Battery Recycling – Overview of Techniques and Trends," ACS Energy Letters; Fraunhofer, 2023, Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players; Kearney Energy Transition Institute analysis

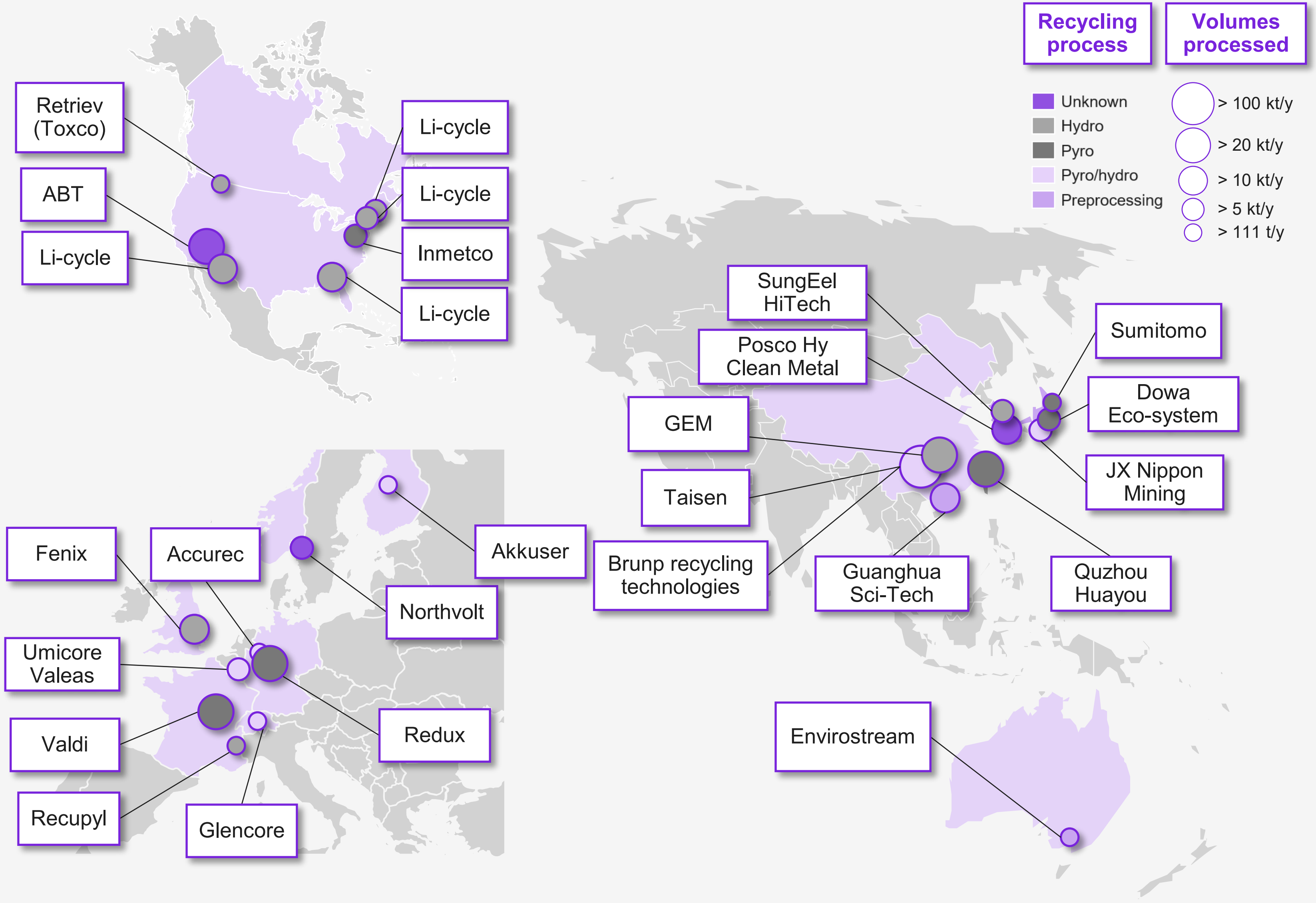
5.5 Recycling

A variety of companies are involved in lithium-ion batteries recycling

Non-exhaustive

5.5 Recycling

Companies and volumes processed recycling lithium-ion batteries
kt/y, by recycling technique, 2021

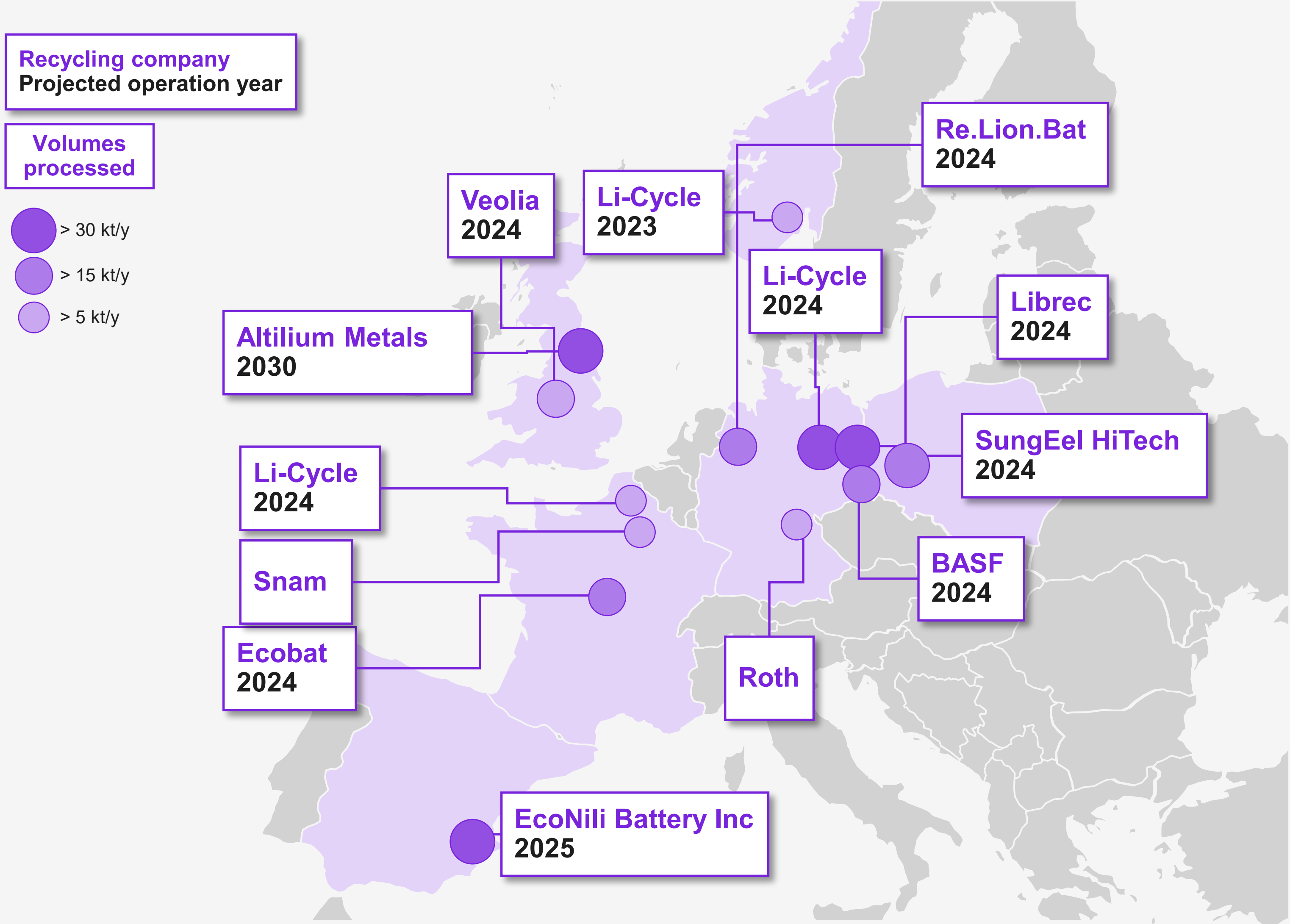


Sources: Z. J. Baum et al., 2022, “Lithium-Ion Battery Recycling – Overview of Techniques and Trends,” ACS Energy Letters; Kearney Energy Transition Institute analysis

With the announced new plants and expansions alone, recycling capacities in Europe are expected to reach 400,000 t/y in 2025

Non-exhaustive

Pipeline of recycling sites for lithium-ion batteries in Europe
kt/y, 2023–2025



Sources: Fraunhofer, 2023, "Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players"; Kearney Energy Transition Institute analysis

5.5 Recycling

6. Business models for electricity storage

Business models for power grid electricity storage services

The **profitability of an electricity storage system relies on an effective business model**, which differ by technology, application, and the method by which it increases profitability for the investor; for example, storage increases the utilization of the distribution network to defer investment in the grid, but also offers arbitrage opportunities by exploiting the volatility of electricity prices in the wholesale market. Despite the range of storage applications, **electricity markets rarely remunerate all services provided**, and thus the complete value of storage is not reflected in potential revenue streams. A disconnect exists between the value delivered to the power grid and the revenue generated, which is often insufficient to cover elevated costs, driven by technology investment.

A storage system can **maximize revenue potential by "stacking" income streams** of several applications, participating in multiple monetization mechanisms simultaneously. Leveraging multiple revenue sources increases storage utilization, optimizes activity to exploit the highest revenue potential at a given time, and reduces reliance on a single revenue stream, thus maximizing income to drive profitability.

International markets vary in terms of the revenue potential of storage applications, driven by differences in electricity market structure, ownership, regulation, and the services in which storage can participate. For example, system electric supply capacity revenue ranges from USD 194/kWh in the US to USD 2.55/kWh in the UK. No single market or application stands out to maximize value, hence developing an internationally applicable business model is near impossible.

The ancillary services market—namely frequency regulation—has traditionally offered the greatest revenue potential, but the market is shallow and is expected to quickly saturate. Energy arbitrage is less lucrative but offers a **larger and more durable market for storage solutions**.

Electric vehicles can enable active participation in the electricity system through various business models like **demand-side response, behind-the-meter support, and market trading**. **Vehicle-to-X and stationary battery storage offer the highest value potential per kWh during the EV battery life cycle**, encompassing applications such as second use in EVs, mobile energy storage, and recycling.

6.0 Chapter summary

A storage system offers a range of services, each of which increases the profitability of the asset

Non-exhaustive

6.1 Business model classification

Value proposition	Application											
	Power quality			Power reliability				Increased utilization			Arbitrage	
	Frequency regulation	Frequency response	Voltage support	System electric supply capacity	Black start	Ramping reserves	Reliability and resilience	Transmission congestion relief	Transmission upgrade deferral	Distribution upgrade deferral	Energy arbitrage	Time-of-use bill management
Avoid operational cost	■	■				■						
Defer investment cost			■	■	■		■	■	■	■		
Generate revenue											■	■

■ Potential revenue stream for application

□ Not a potential revenue stream for application

Sources: Baumgarte et al., 2020, Business Models and Profitability of Energy Storage; Hossain et al., 2020, A Comprehensive Review on Energy Storage Systems; Kearney Energy Transition Institute analysis

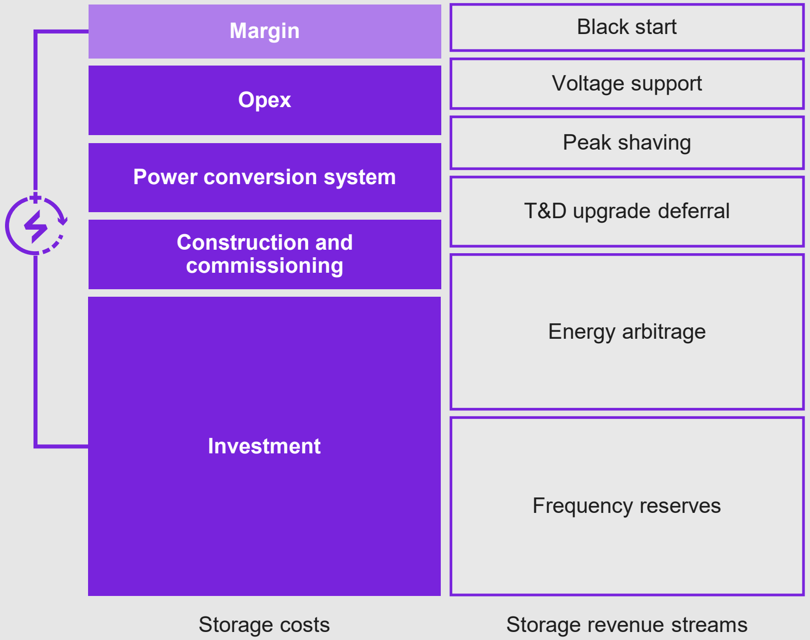
At current costs, storage projects must “stack” revenues to create a profitable business case

Illustrative

A strong business case is key to **stimulating uptake** of electricity storage, offering promising revenue and profit margin to realize a competitive rate of return.

6.2 Revenue stacking

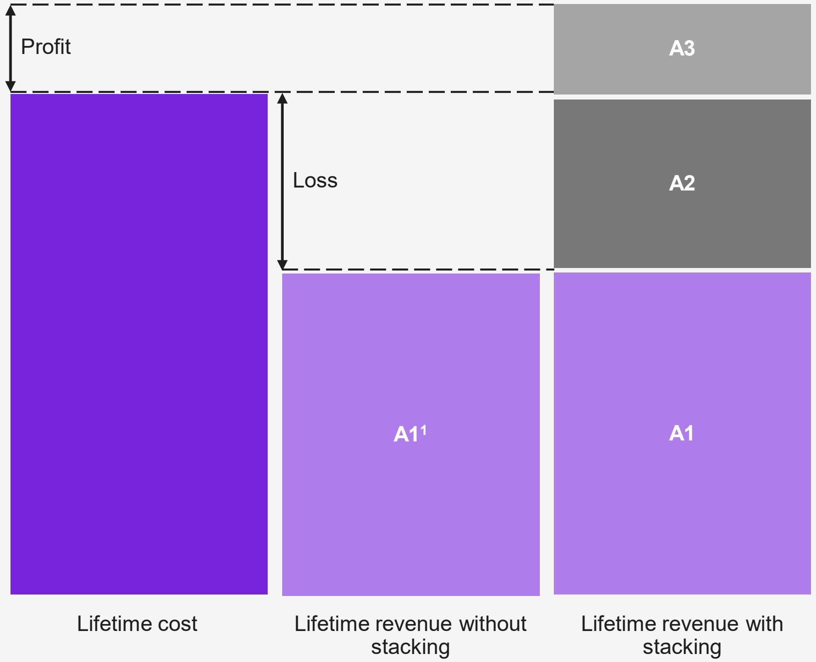
Electricity markets rarely renumerate the full range of services provided by storage solutions



- Value generated by each service **varies dynamically** over a technology’s lifetime as markets and prices evolve.
- A **disconnect exists** between the value delivered by storage to the power system and the revenue streams generated, which is often insufficient to cover the high technology costs.

[1] A1 corresponds to application 1, A2 to application 2, etc.; [2] Assuming that the increase in revenue is greater than any increase in operational cost incurred due to stacking activities.
Sources: E3 Analytics, 2023, Scaling-up Energy Storage: Technology and Policy; Kearney Energy Transition Institute analysis

Storage systems can maximize value potential by stacking the revenues of several applications



- Stacking allows storage solutions to **participate in multiple monetization mechanisms simultaneously.**
- Leveraging multiple revenue sources increases storage utilization, optimizes activity to exploit the highest revenue potential at a given time, and reduces reliance on a single revenue stream, **thus maximizing revenue to drive profitability[2].**

Revenue stacking across three key markets has driven storage expansion to date

Illustrative; non-exhaustive

The markets available for revenue stacking will **vary by geography depending on the local policy and infrastructure** that facilitate or hinder multiple revenue streams

6.2 Revenue stacking

Key selected markets for electricity storage participation and revenue stacking

Balancing market

Used to **correct imbalances between generation and consumption** in an electricity system

- Operator provides a detailed specification of the storage asset, namely discharge time and power.
- Operator places a daily bid into the day-ahead market auction.
- Successful operators buy and sell power with other participants intraday for feasible (and often more profitable) asset dispatch.
- Operator submits the planned asset dispatch on a minute-by-minute basis for the transmission service operator to follow in real time to balance supply and demand.

Capacity market[1]

Used to ensure **sufficient capacity** for future operations of an electricity system

- Operators bid for additional capacity required by the grid to satisfy projected peaks in electricity demand.
- Successful operators receive a premium for capacity provided and are penalized if they fail to meet capacity obligations.
- Premium paid motivates investment in capacity given energy providers often forgo large revenues in the wholesale market due to administrative actions and price caps during times of peak demand.

Wholesale market

Used for **energy arbitrage**, storing electricity when demand is low and selling when demand is high

- Operator charges storage asset when electricity price on the wholesale market is low during periods of low demand.
- Operator discharges storage asset when electricity price on the wholesale market is high during periods of high demand.

Stacking archetypes

Parallel stacking
Separates total power capacity into the **individual components** required for different applications served **simultaneously.**

Sequential stacking
Equal power capacity is provided to different applications served at **different times.**

Reverse sequential stacking
Equal power capacity is provided to different applications served at **different times**, where at least one application operates in the opposite direction.

Overlapped stacking
Equal power capacity is provided to different applications served **simultaneously.**

[1] Balancing and capacity markets are broadly referred to as ancillary services.
Sources: Energy Systems and Energy Storage Lab, 2015, Capacity markets and energy storage; FLEXPOWER, 2024, On which Energy Markets do Battery Energy Storage Systems (BESS) participate?; KYOS, 2021, What is the Balancing Mechanism?; Kearney Energy Transition Institute analysis

However, the opportunity to revenue stack varies by country given regulatory limitations on market participation

Barriers to storage participation in multiple markets **impede future deployment whilst costs remain high** and projects cannot demonstrate viable business case

6.2 Revenue stacking

Comparison of markets for electricity storage participation by country

Country	Balancing	Capacity	Wholesale
Australia	Legally eligible to participate	Eligible to participate in some jurisdictions for selected services	Legally eligible to participate
Canada	Eligible to participate in some jurisdictions for selected services	Eligible to participate in some jurisdictions for selected services	Eligible to participate in some jurisdictions for selected services
China	Eligible to participate in some jurisdictions for selected services	Not eligible to participate	Eligible to participate in some jurisdictions for selected services
Germany	Legally eligible to participate	Legally eligible to participate	Legally eligible to participate
India	Eligible to participate in some jurisdictions for selected services	Legally eligible to participate	Legally eligible to participate
Italy	Eligible to participate in some jurisdictions for selected services	Legally eligible to participate	Legally eligible to participate
Japan	Legally eligible to participate	Legally eligible to participate	Legally eligible to participate
Korea	Not eligible to participate	Legally eligible to participate	Not eligible to participate
UK	Legally eligible to participate	Legally eligible to participate	Legally eligible to participate
US	Legally eligible to participate	Eligible to participate in some jurisdictions for selected services	Legally eligible to participate

Legally eligible to participate | Eligible to participate in some jurisdictions for selected services | Not eligible to participate

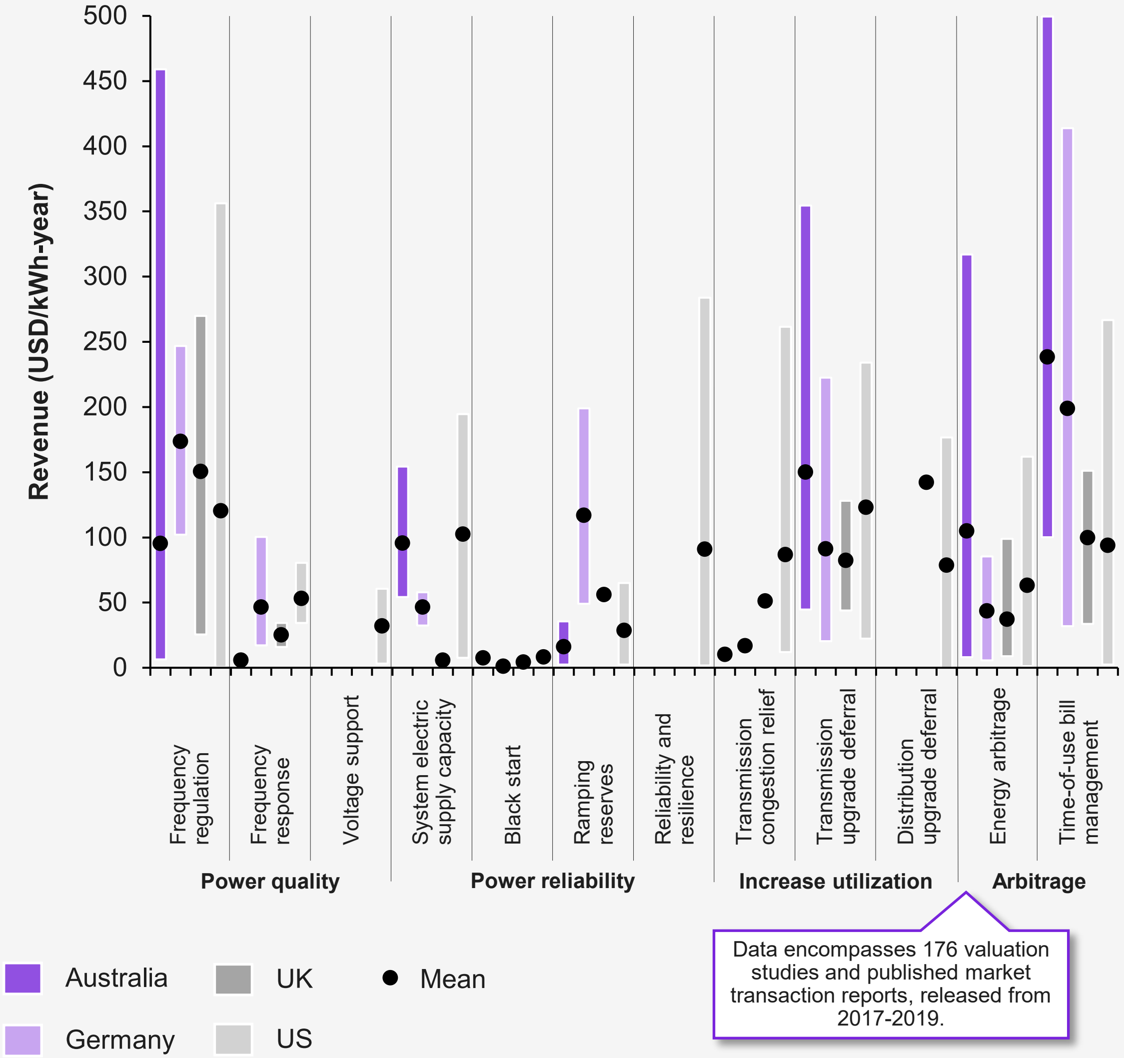
Sources: IEA, 2023, Batteries and Secure Energy Transitions; Kearney Energy Transition Institute analysis

No single storage market or application stands out to maximize value, hence developing an internationally applicable business model is near impossible

- **No standard electricity market exists**; international markets vary in terms of structure, ownership, regulation, and the **applications in which storage can participate**, thus driving a revenue disparity.
- **Time-of-use bill management and frequency regulation** offer the greatest revenue potential in all markets (>USD 90/kWh-year), the former of which is critical in Australia and Germany for high residential electricity prices.
- **Transmission upgrade deferral** offers similarly and consistently high potential (>USD 80/kWh-year) across markets, driven by major investment costs associated with transmission infrastructure, as well as the non-monetary complexities (planning, licensing, construction, etc.).
- **Black start** offers the least attractive potential (<USD 10/kWh-year) across markets given a minimal cost due to a limited number of cycles and duration, and it's already covered by existing power stations.
- **Congestion relief** is of greatest value in the US and UK given greater difficulties associated with grid congestion and limited interconnection compared to Australia and Germany, respectively.

The **value of a given application within a market has changed** due to capacity increases and market design iterations. A successful business model de-risks investment in storage by **embedding flexibility in its design**, maximizing the technology's ability to revenue stack such that it remains profitable under evolving market conditions.

Revenue potential of key electricity storage applications in selected markets



Note: USD figures are 2023 values.
Sources: Balducci et al., 2018, Assigning value to energy storage systems at multiple points in an electrical grid; Housden, 2019, An Evaluation of Energy Storage Profitability in the United Kingdom, Germany, Australia, and the United States; Kearney Energy Transition Institute analysis

The deployment of storage is limited by high costs relative to the revenue case

Action is required to address both the **cost and revenue** of storage to create a **profitable proposition** for investors.

6.4 Challenges for electricity storage profitability

Two key factors impede the profitability of storage

Elevated upfront investment cost

- Investment remains the **most significant cost** associated with storage, representing an average **85.2% of annualized expense.**[1]
- **Cost has fallen in recent years** for various technologies via experience rates as capacity grows, but the **impact on the business case is limited given increasing revenue uncertainty.**

Limited potential for revenue stacking

- Revenue stacking is the key approach to recoup the investment cost of storage and generate profit by **expanding the potential market**, offering investors confidence to support development.
- Revenue stacking remains **immature or impossible in several international markets**, compounded by concern that ancillary service markets are saturating, thus increasing demand for multiple revenue streams.

[1] Considering supercapacitors, flywheels, sodium sulfur batteries, lead acid batteries, Li-ion batteries, VRB, PHS, and CAES

Sources: Enel, 2023, Unlocking the full value stack for battery storage; MIT Science Policy Review, 2022, Battery deployment in the U.S. faces non-technical barriers; Moment Energy, 2022, How Can We Reduce the Cost of Energy Storage?; Baumgarte et al., 2020, Business Models and Profitability of Energy Storage; Scottish Power, 2023, Review of Scottish Power Energy Networks' uptake of flexibility services; Kearney Energy Transition Institute analysis

Consensus exists on the need for reduced costs and enhanced revenue stacking

…some challenges still prevent the mass adoption of energy storage. **One of them is cost** – today, energy storage is too expensive to be economically viable without government subsidies or other incentives
Moment Energy

…**costs**, particularly for more nascent storage technologies, are generally still **prohibitively high**
MIT Science Policy Review

Battery storage can provide significant bill savings and new revenue…if you can **optimize your energy use by value stacking**
Enel

Another area for policy reform is the **stacking of business models**, which is still banned in many jurisdictions…
Nature Energy

…the **highest importance barrier** (to mitigating revenue risk) is that it is **not always possible to stack revenues** across different flexibility markets
Scottish Power

In major countries, ancillary services market is shallow and will quickly saturate; energy arbitrage is less lucrative but offers a larger and more durable market

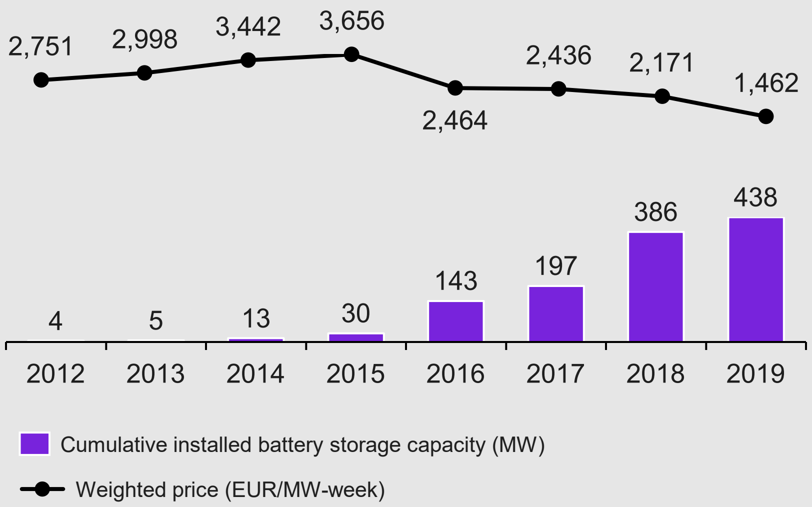
Example

A market is deemed shallow for a specific application when it can be **readily saturated by a relatively small amount of storage**, reducing prices to lifetime cost levels and limiting revenue potential.

6.5 Market value

Mean weekly prices for frequency response in Germany relative to cumulative installed battery capacity

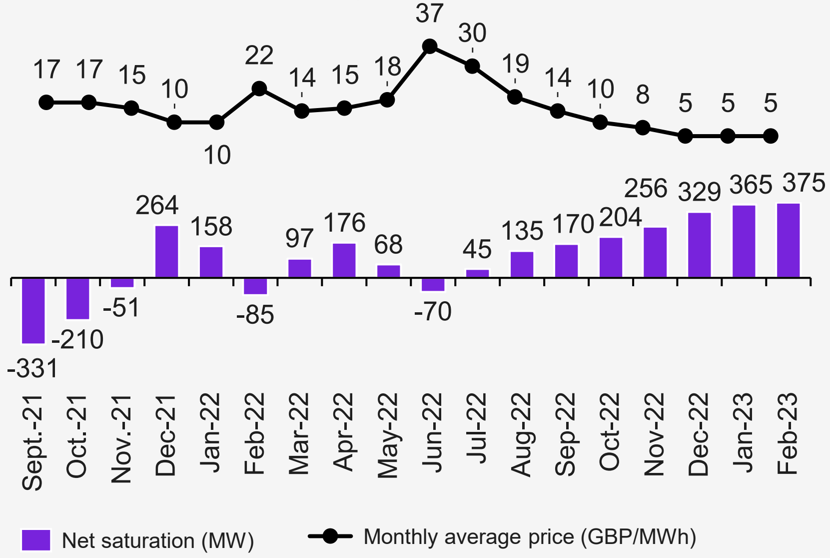
MW and EUR/MW-week, 2012–2019



- Germany's frequency response market is shallow, offering **~600 MW** for a peak demand of **~80 GW.**
- Cumulative battery storage capacity prequalified for participation in the country's ancillary services market increased from **0 MW to ~450 MW between 2012 and 2019** at a CAGR of 96%.
- Batteries offer a **lower price** than incumbent technologies for ancillary services, reflected by a decrease in the weighted price for weekly actions at a CAGR of -8.6% from **~2,750 EUR/MW-week pre-2015 to ~1,500 EUR/MW-week in 2019.**

Monthly average price for dynamic containment in the UK relative to net saturation

GBP/MWh and MW, 2021-2023



- Dynamic containment is a frequency response service to maintain UK transmission within safe frequency ranges following a system fault.
- Monthly price fell by **86% from a high of 37 GBP/MWh in June 2022 to 5 GBP/MWh in December 2022** due to increased saturation, thus revenue fell from **GBP 15.9 million** in the second half of 2022 to **GBP 6 million** in the first half of 2023.
- Dynamic containment and the wider ancillary service market will **continue to saturate** as installed battery capacity increases from 2.2 GW in 2022 to more than 6 GW predicted by the end of 2024.

Note: EUR figures are 2019 values; GBP figures are 2022 values.

Sources: Figgener et al., 2021, The development of stationary battery storage systems in Germany; Gresham House, 2023, Powering the renewable energy transition; Modo Energy, 2023, Dynamic Containment Low: what's setting post-saturation prices?; Regelleistung Online, 2020, Battery Storage Systems to Dominate the PRL Market; Kearney Energy Transition Institute analysis

However, the profitability of a storage technology for energy arbitrage varies by market, and its volatility creates complexity

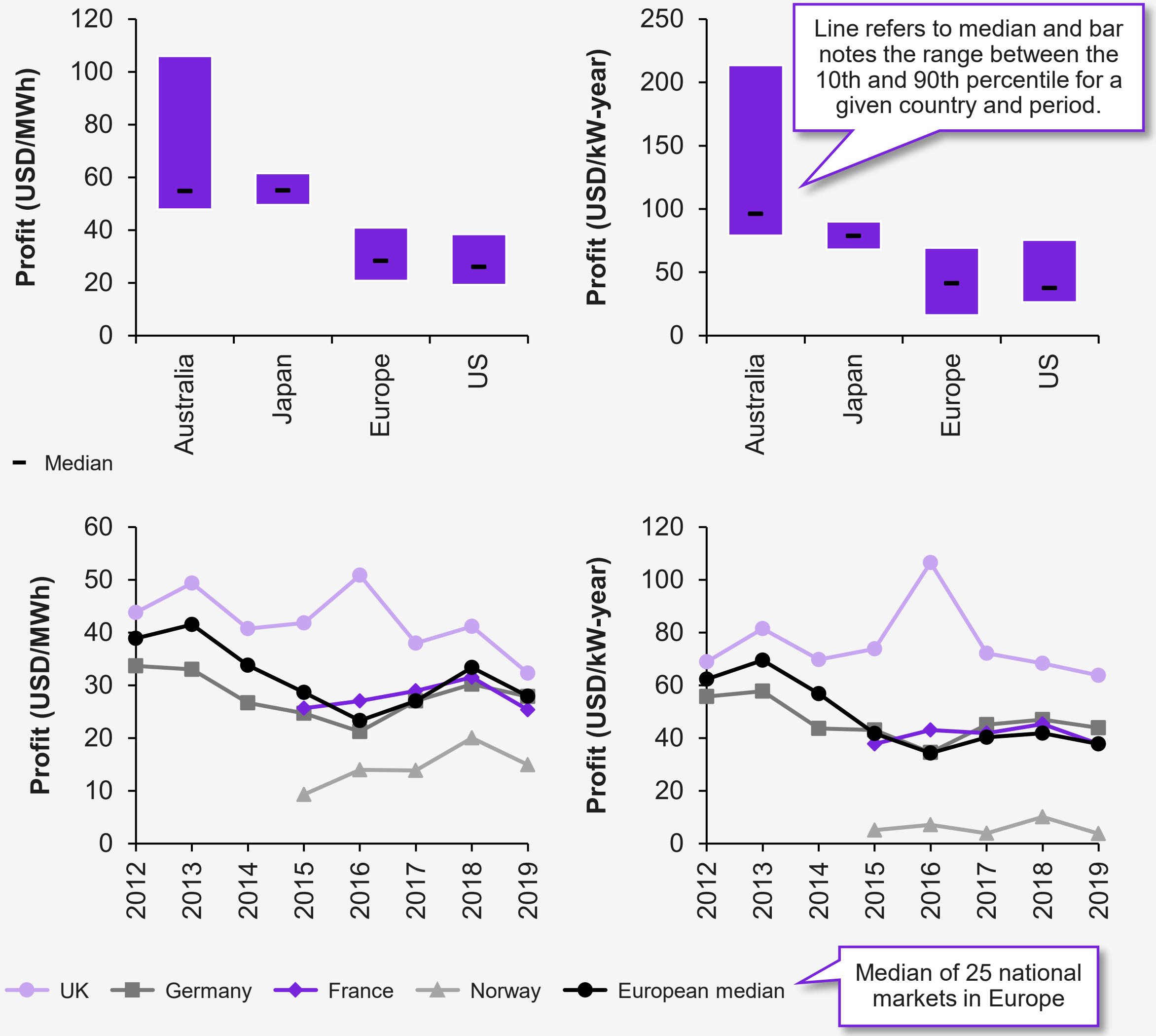
- Arbitrage profitability presented is pre-fixed costs, reflecting **revenue generated by selling discharged electricity less the cost of electricity purchased for charging.**
- The example highlights **Australia as the most attractive opportunity**, driven by large spikes in electricity price due to a low penetration of renewable energy and a limited presence of flexible technologies.
- **Profits in Europe and the US are ~50% of Japanese profit** due to higher availabilities of flexible technologies (including PHS), capacity margins, and extents of interconnection between markets.
- Arbitrage value **varies locally**, such as within Europe, where a Li-ion BESS can turn a profit 18 times greater than that in Norway on a power basis.[1]
- As an island nation with limited interconnection and PHS capacity given its geography, the **UK is one of the most lucrative arbitrage markets in Europe**, while Norway is dominated by flexible PHS, reflected by electricity prices that change gradually in line with the shallow value of water stored.
- Profitability fluctuates year-on-year within markets, varying by **+/- 25%** in most major markets, **creating uncertainty regarding the timeline for return on investment of a storage project.**

Example

6.5 Market value

Profitability of energy arbitrage in selected markets using a Li-ion battery[1]

USD/MWh discharged and USD/kW-year installed, 2012–2019



[1] Storage duration of four hours and round-trip efficiency of 86%
Note: USD figures are 2023 values.
Sources: Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

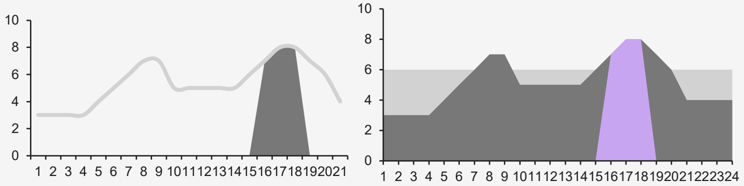
EVs provide the opportunity to meaningfully participate in the electricity system, with several business models being explored

6.5 Market value

Revenue opportunities of electric vehicle battery applications

Demand-side response

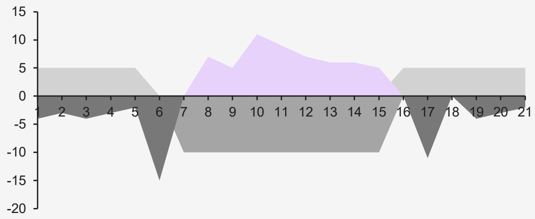
Demand-side response market trading



Scaling demand up/down in response to grid needs; e.g., charging/discharging EVs at certain times of the day

Behind-the-meter support

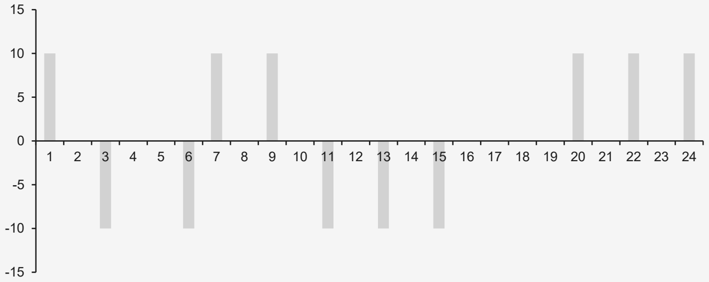
Local energy intermittency offset with renewables and storage



Optimizing energy demand/usage on site, e.g., discharging from EV at night to offset solar PV limitations

Flex market trading

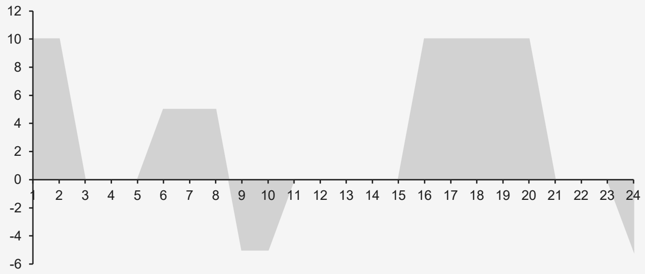
Capacity provision for ancillary services/grid balancing



Trading availability of assets to either consumer/discharge electricity at different periods, e.g., activating EV trucks at certain periods when electricity supply > demand

Wholesale market trading

Trading and arbitrage with storage opportunities



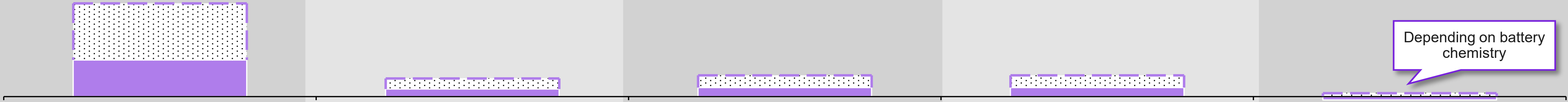
Trading demand and supply of electricity in traditional markets, including arbitrage opportunities, e.g., charge EV at low-cost periods and discharge at high -cost periods

Sources: Kearney; Kearney Energy Transition Institute analysis

V2X and stationary battery storage host the largest value potential per kWh in the EV battery lifecycle

Value pool potential per kWh for selected EV battery uses

EV use phase		*Post-EV use phase*		*End-of-life phase*
Vehicle-to-X	**Second use in EV**	**Stationary battery storage**	**Mobile energy storage**	**Recycling**



~ $40–80 per kWh	**~ $25–35 per kWh**	**~ 30–40 per kWh**	**~ $30–40 per kWh**	**~ -$11–12 per kWh**

Potential revenue for EV battery owner

Value pool potential per kWh reflects difference between revenue and operating + maintenance costs excluding e.g., battery acquisition costs and hardware costs

Vehicle-to-X

- **16-year lifetime value** of a 1 kWh EV battery in **an off-grid V2X application used for price arbitrage** through peak shaving
- Additional value stacking opportunities from, e.g., firm frequency response not considered

Second use in EV

- Value of a 1 kWh **EV battery when sold** post-first EV use phase at 80% capacity **for a 2nd use in EV**

Stationary battery storage

- **8-year lifetime value** of a 1 kWh EV battery post-EV use phase at 70% capacity in **an off-grid stationary battery storage application used for price arbitrage** through peak shaving
- Additional value stacking opportunities from, e.g., back-up power not considered

Mobile energy storage

- Value of a 1 kWh **EV battery when sold** post-EV use phase at 70% capacity **for a mobile battery storage** application

Recycling

- Value of **recycling** lithium, cobalt, nickel, manganese, copper, and aluminum from a **1 kWh EV battery of different chemistries**[1]

[1] Recycling of NMC 811, NMC523, NMC622, NCA+, LFP batteries under the hydrometallurgical recycling process

Sources: BNEF; Barclays; ICCT; S&P Global; London Metal Exchange; Ever Batt Model (Argonne National Library); Kearney; Kearney Energy Transition Institute analysis

7. Policy and regulation for electricity storage

Policy and regulation for electricity storage

Various policies can be set up to support the development of electricity storage technologies. Setting explicit targets for the share or total quantity of electricity storage provides clear market signals and helps coordinate stakeholder expectations. **Financial incentives**, such as grants, tax reductions, or accelerated asset depreciation, are essential to reduce the financial burden on investors and encourage rapid adoption. Additionally, **supporting the development of technology-specific road maps** can guide investment toward specific storage technologies. Policy intervention aims at overcoming various barriers to adoption of electricity storage technologies, such as ineffective market mechanisms, mismatches between current infrastructure and new technologies, and regulatory uncertainties that undermine investor confidence.

Several countries are advancing the deployment of stationary electricity storage technologies with specific national policies. **China plans to install over 30 GW** of electricity storage by 2025, excluding pumped hydropower storage. Similarly, **India** targets developing battery storage with capacities ranging from **51 to 84 GW by 2031–2032. Australia** aims to boost its electricity storage capacity from just under **2 GW in 2022 to 15 GW by 2030 and 61 GW by 2050**.

Investment in grid-scale battery storage has surged in **advanced economies and China, reaching over USD 20 billion in 2022 and accounting for more than 65% of total electricity storage investment.** This upward trend is likely to continue, with forecasts suggesting that investment could top **USD 35 billion in 2023**, fueled by a strong pipeline of projects and new governmental targets. Additionally, the **United States has enhanced the attractiveness of grid-scale storage projects with the Inflation Reduction Act**, which includes a specific investment tax credit for stand-alone storage projects. Meanwhile, **Chile** expects new grid-scale systems to enter operation by 2026, **driven by USD 2 billion in funding.**

Continuing the global momentum, in March 2023, the European Commission released a series of recommendations on electricity storage. These recommendations detail policy actions intended to facilitate greater deployment of electricity storage within the European Union.

By the end of 2023, 74 countries had targets to promote electric vehicles (EVs), with 18 countries introducing new policies to support EV adoption. While **most policies focus on passenger cars**, many governments also support electric buses, bikes, and commercial vehicles, demonstrating a broad commitment to sustainable transport.

Various policies can be set up to support the development of electricity storage technologies

Policies can either promote technology push, which develop a technology to the point of readiness for mass adoption, or demand pull, which create strong business cases by targeting market demand and promoting commercialization.

7.1 Policies overview

Policy options for electricity storage

1 Strategic plans and regulations

Define storage deployment targets, ensuring regulations support market design and assets integration, alongside framework legislation.

2 Finance

Provide money to developers to carry out an approved project and tax breaks or accelerate the depreciation of assets to reduce the cost for investors (e.g., grants, taxation, payments and transfers).

3 Technology

Support technology road maps of electricity storage technologies (e.g., technology road map and domestic manufacturing incentive).

Policy intervention aims at overcoming various barriers to adoption of electricity storage technologies

Policy intervention goals	Barriers to adoption
Sustained growth in the grid-scale energy storage market **Diversification of segments and use cases** that make up the storage market **Open standards** that allow diverse storage technologies **to "plug and play" in any system** **Complementary public and private investment** in research, development, demonstration, and early deployment of emerging storage technologies **Fair competition** among energy storage technology vendors	**Financial barriers: Weak profitability and business case of storage within the energy system.** Lack of strong market mechanisms and pricing to support the investment required. **Loss of competitiveness from the adoption of capital-intensive strategies: Initial costs required** can make electricity storage technologies less attractive compared to other options that might require less upfront investment. **Industrial characteristics: The discrepancy between current electricity system designs and the needs of new storage technologies,** as existing infrastructures and market setups do not align with the operational and business models required for energy storage. **Technical barriers:** The existing connection processes were designed for large, baseload generators and do not adequately account for smaller, more dynamic sources like **storage technologies, delaying the integration of the latter into the grid.** **Regulatory uncertainty:** The lack of clear regulations governing the use and integration of energy storage technologies **undermines investor confidence and further increases investor risks.**

Sources: DNV, 2023, Closing the energy storage gap: Overcoming barriers in models, methods, and markets; MIT Energy Initiative, 2018, Energy Storage for the Grid: Policy Options for Sustaining Innovation; Nuñez-Jimenez et al., 2019, Balancing technology-push and demand-pull policies for fostering innovations and accelerating their diffusion; Kearney Energy Transition Institute analysis

Global governments recognize and support electricity storage via capacity targets to demonstrate their commitment toward long-term goals

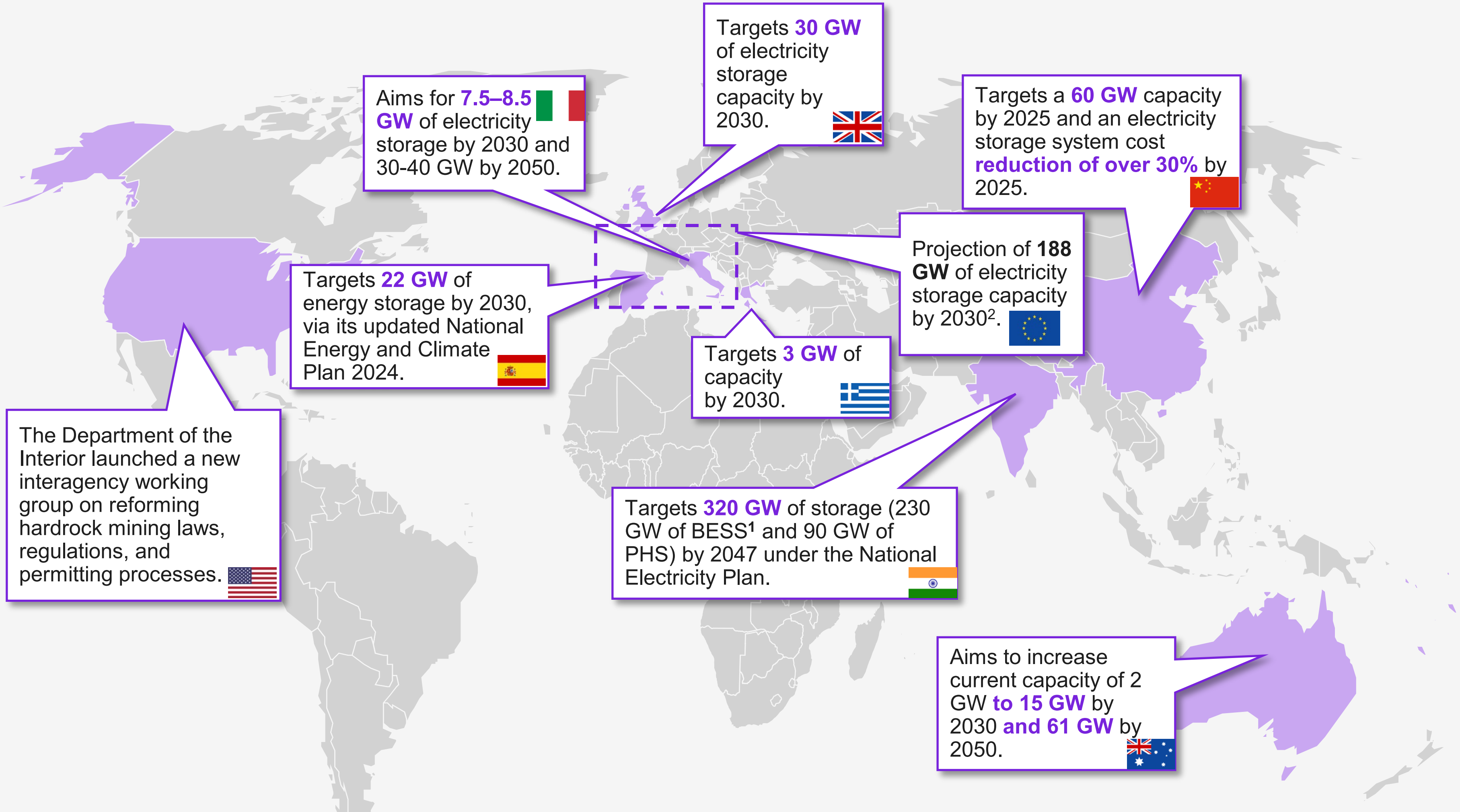
Non-exhaustive

1. Strategic plans and regulations
2. Finance
3. Technology

7.2 Stationary storage policies worldwide

Strategic plans-related policies in electricity storage

In force, 2023



[1] Battery energy storage system
[2] As per ENTSOE TYNDP 2024's National Trends+ scenario which is the aggregation of national approaches that reaches EU targets

Sources: IEA, 2023, Policies database; Bashir, S., 2024, Australia needs renewables, transmission and lots of storage to quit fossil fuels; Colthorpe, A., 2023, India requires 74 GW/411 GWh of energy storage by 2032; Couture et al., 2023, Italy Analysis of the Battery Storage Market; Leonti and Kline, 2023, Impacts of the Inflation Reduction Act on US battery developers; Tourino, J., 2023, Spain launches €280 million grants for standalone energy storage, thermal and PHES; Murray, C., 2023, Chile government seeks multi-gigawatts of large-scale storage for 2026-2028; Murray, C., 2023, Gigawatts of energy storage projects approved in Greece ahead of auction; UK GOV, 2023, Energy Security Bill factsheet: Defining electricity storage; Zhang, X., 2023, China's Booming Energy Storage: A Policy-Driven and Highly Concentrated Market; ENTSOE TYNDP 2024, Kearney Energy Transition Institute analysis

Finance-related policies are key to transforming electricity storage markets

Non-exhaustive

1 Strategic plans and regulations

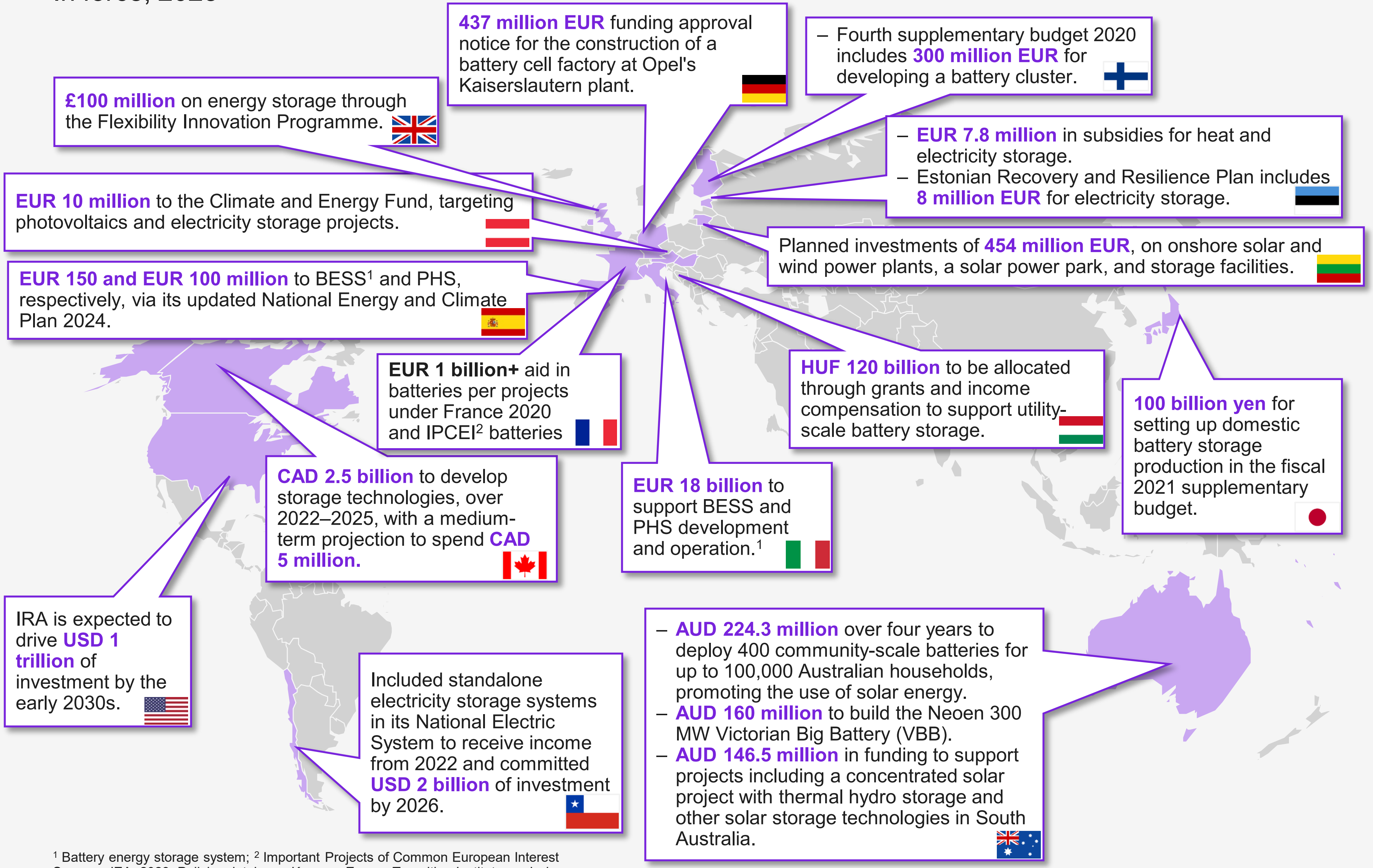
2 Finance

3 Technology

7.2 Stationary storage policies worldwide

Finance-related policies in electricity storage

In force, 2023



[1] Battery energy storage system; [2] Important Projects of Common European Interest
Sources: IEA, 2023, Policies database; Kearney Energy Transition Institute analysis

Current technology policy worldwide supports the deployment of storage at grid scale

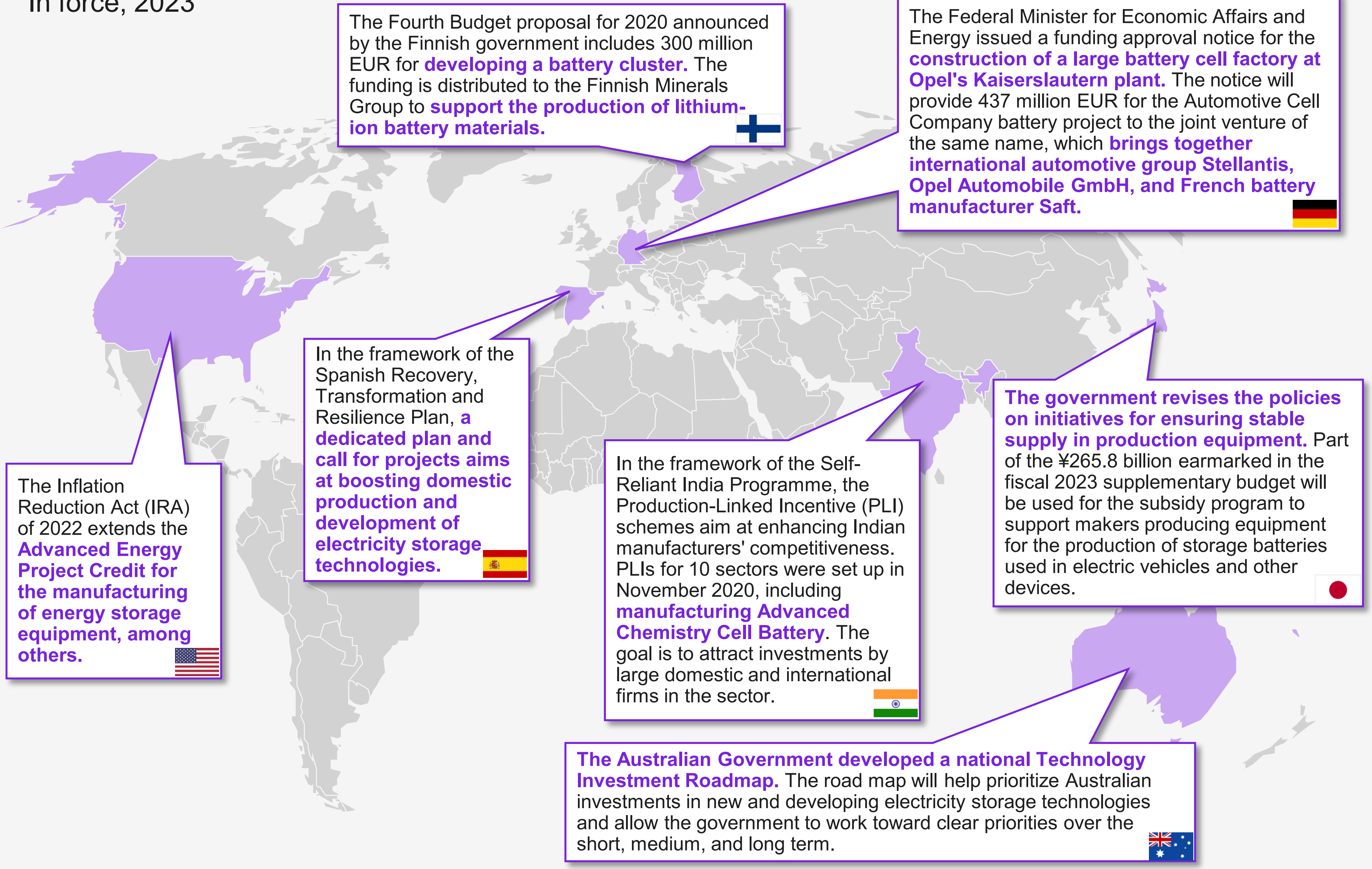
Non-exhaustive

1. Strategic plans and regulations
2. Finance
3. **Technology**

7.2 Stationary storage policies worldwide

Technology-related policies in electricity storage

In force, 2023



Sources: IEA, 2023, Policies database; The Japan News, 2023, Govt to subsidize battery production equipment – Manufacturers to be encouraged to form alliances; Kearney Energy Transition Institute analysis

The Inflation Reduction Act (IRA) sets the stage for US energy storage to thrive

Illustrative; non-exhaustive

The IRA is expected to drive **USD 1 trillion investment** in electricity storage by the early 2030s, encouraged by the mid-term certainty cemented by the government.

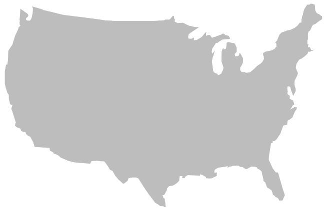
7.3 Stationary storage policies regional focus

Tax credit for national battery development

	Selected details
Expanded investment tax credits (ITC)	**The IRA introduces a 30% ITC for standalone energy storage, potentially increasing to 70% with added incentives for using US-**manufactured equipment and for projects in energy communities or decommissioned fossil fuel sites. The act extends these benefits through 2032, providing financial stability and broader project scope, including interconnection costs.
Support for domestic manufacturing and supply chain	**The IRA incentivizes domestic production of clean energy technologies and components,** aiming to reduce reliance on foreign manufacturing and stabilize supply chains affected by global disruptions. This effort is bolstered by additional tax credits and the strategic use of tariffs to encourage local production.
Accessibility and simplification of investment	**A new "direct pay" option allows tax-exempt entities like municipal utilities to receive direct federal payments,** enhancing their ability to invest in energy storage. Furthermore, the IRA simplifies the investment process by making tax credits transferable, reducing the need for complex tax equity arrangements and lowering transaction costs.
Labor and community benefits	**Projects must adhere to labor standards, including paying prevailing wages and meeting apprenticeship requirements**, to qualify for full tax credits. Additional incentives support projects in low-income and tribal communities, promoting environmental justice and community benefits.
Enhanced grid resilience and national decarbonization goals	By promoting the deployment of energy storage, the IRA supports **enhanced grid flexibility and resilience**, critical for integrating renewable energy and achieving the federal goal of a carbon-neutral power sector by 2035.

Sources: Utility Dive, 2022, The Inflation Reduction Act will turbocharge energy storage; Utility Dive, 2022, IRA sets the stage for US energy storage to thrive; Kearney Energy Transition Institute analysis

The Inflation Reduction Act (IRA) brings several challenges in the US battery market



Illustrative; non-exhaustive

The IRA will have significant impacts on US battery developers

Challenges

The IRA's ITC boosts standalone storage. This shift creates competitive pressures and requires **careful balancing** of merchant risks and contracted offtakes **to maintain profitability and attract investors.**

Developers of US storage projects in 2024 will have to push ahead with their developments despite tight constraints on the availability of batteries and other components. **In the short term, this means that the IRA will actually boost battery makers in other markets**, which are ready to supply technology to the US.

The significant backlog in grid interconnection queues, especially for projects with battery components, poses a major challenge. Anticipated reforms from the Federal Energy Regulatory Commission aim to address these issues.

The IRA-induced expansion in battery projects is exacerbating labor shortages in the renewable sector, emphasizing the critical need for more workforce training and expansion despite new apprenticeship and job creation initiatives.

Continued uncertainty in key areas of the IRA, including tax credit transferability, definitions of "energy communities," and credit applicability for hybrid projects, complicates investment decisions and project planning.

7.3 Stationary storage policies regional focus

Sources: Energy Institute, 2023, Impacts of the Inflation Reduction Act on US battery developers; Kearney Energy Transition Institute analysis

A number of EU regulations facilitate the development of electricity storage

Illustrative; non-exhaustive

The EU frameworks already provide the conditions needed to exploit the value of electricity storage technologies. However, there is remaining potential to be unlocked to provide benefits to consumers and to ensure a transition to the future energy system in the EU.

7.3 Stationary storage policies regional focus

A cross-cutting approach has been used to develop the EU and national regulatory framework and policies for electricity storage

	Description
REPowerEU Plan	This plan emphasizes the importance of **electricity storage for enhancing the flexibility and security** of the energy system.
EU Strategy for Energy System Integration and Hydrogen Strategy	**These strategies outline the vision for a decarbonized European energy system, highlighting the role of electricity storage in system integration and sector coupling.** They focus on creating a more interconnected energy system where electricity storage plays a crucial role in balancing and supporting the grid.
Fit-for-55 Package	– **Revision of the Energy Taxation Directive:** Includes provisions to end the double taxation of electricity storage, recognizing its value in climate change mitigation. – **Revision of the Renewable Energy Directive (RED):** Proposes increasing the renewable energy target and includes measures to facilitate electricity storage deployment, particularly thermal energy storage, to enhance grid flexibility. – **Revision of the Energy Efficiency Directive:** Encourages the use of electricity storage and demand-response systems to increase energy efficiency. – **Revision of the Energy Performance of Buildings Directive:** Supports the integration of electricity control, storage, and smart recharging infrastructure in buildings, facilitating the use of electric vehicles.
Proposals for Directive and Regulation on Internal Markets for Gases and Hydrogen	**These legislative proposals aim to promote energy carriers that offer storage and flexibility options**, such as hydrogen and renewable methane, enhancing the role of electricity storage in the renewable energy sector.
EU Action Plan on the Digitalization of Energy	**Focuses on accelerating the deployment of electricity storage technologies through enhanced interoperability, coordination, and data exchanges.** It also promotes investments in digital electricity infrastructure, crucial for optimizing energy storage and grid integration.
Governance Regulation and NECPs[1]	**Requires member states to include specific objectives, policies, and measures related to energy storage in their NECPs.** The plans should address how electricity storage can enhance flexibility, ensure fair market participation, boost energy security, and support the rapid deployment of renewable energy sources.

[1] National energy and climate plans

Sources: European Commission, 2023, Energy Storage – Underpinning a decarbonized and secure EU energy system; Kearney Energy Transition Institute analysis

The necessary uptake of electricity storage in the EU can be further increased

Illustrative; non-exhaustive

Timely implementation of EU legislation

Ensure the timely implementation of EU electricity market legislation at national levels to accommodate the unique dual role (consumer-generator) of electricity storage systems.

Regulatory framework for dual roles

Develop specific regulatory frameworks acknowledging the dual functionality of electricity storage systems, involving new categories or definitions within existing electricity market regulations.

Tailored financial support

Introduce tailored support and financing models, such as behind-the-meter storage solutions, e.g. electricity storage in the electricity consumer's home.

Revenue stacking and financial incentives

Promote revenue stacking by defining and monetizing possible services provided by electricity storage systems, e.g. flexibility services in distribution networks.

Network planning and charges

Integrate storage into network planning, operation, and tariff strategies. Explore opportunities that provide pricing signals to optimize electricity storage use.

Streamline permit processes

Simplify permit-granting procedures for utility-scale energy storage projects, streamlining bureaucratic processes to accelerate deployment.

Supply chain resilience for critical materials

Monitor and secure the supply chains for critical raw materials essential for electricity storage technologies.

Standardization and market integration

Revise market design for demand-side flexibility. Develop EU-wide standards for new market products, e.g. EV batteries into the grid, and storage technologies.

Sources: European Commission, 2023, Energy Storage – Underpinning a decarbonized and secure EU energy system; Kearney Energy Transition Institute analysis

Australia and Chile are advancing electricity storage through strategic investments

Illustrative; non-exhaustive

Australia and Chile's strategies set important goals for the future of electricity storage

Country	Description	Commentary
	**Capacity Investment Scheme 2023** – Commits the government to underwriting 9 GW storage capacity by 2030. **Integrated System Plan 2022** – Aims to increase installed capacity of electricity storage from 2 GW in 2022 to 15 GW and 61 GW by 2030 and 2050, respectively. **Large Scale Battery Storage Funding 2022** – Funding for grid-scale battery energy storage projects equipped with advanced inverters to provide essential services to the grid currently provided by thermal power plants. – Total of AUD 176 million conditional funding released to eight projects with a cumulative capacity of 2 GW in late 2022. **Powering Australia 2022** – Total budget of AUD 224 million from 2022–2026 for 400 community-scale batteries for up to 100,000 households, aiming to promote the use of solar energy by addressing intermittency concerns.	Heavily focused on funding rather than stimulating demand by establishing cost competitiveness in the market. Despite government's commitment to underwriting 9 GW of capacity by 2030, the targeted 15 GW remains a big ask.
	**Grid-Scale Energy Storage System Investment 2023** – Targets grid-scale systems scheduled for operation by 2026. – Offers USD 2 billion in funding. **National Electric System Energy Storage 2022** – Legislation to allow standalone storage systems to generate revenue by dispatching energy to the country's grid. – Aims to create a stronger business case for the development of storage technologies. **Strategy for a Just Energy Transition 2021** – High bar triggered an increase in demand for energy storage.	Initial steps taken to create a more favorable business case for energy storage besides funding by including storage in the national energy market. As of 2022, Chile is the wealthiest country in the world in terms of lithium reserves, placing it in a strong position to develop batteries quickly at a low cost.

Sources: Energy Storage, 2024, Australia needs renewables, transmission and lots of storage to quit fossil fuels; Energy Storage, 2022, Chile passes major energy storage bill; Energy Storage, 2023, Chile government seeks multi-gigawatts of large-scale storage for 2026-2028; Tamarindo, 2023, Chile: A 'showcase' for storage and the energy transition; Ministerio de Energía, 2021, Estrategia de Transición Justa en el sector Energía; Kearney Energy Transition Institute analysis

China and India are developing various strategies to scale up electricity storage

Illustrative; non-exhaustive

China and India road maps boost electricity storage expansion

Country	Description	Commentary
	**New Energy Storage Development Implementation Plan 2022** – Aims to reduce the cost of “new-type electricity storage systems” by over 30% by 2025. – New-type electricity storage encompasses a range of technologies (such as batteries, compressed air energy storage, flywheel systems) excluding PHS. – Secondary purpose to develop independent and controllable core technology and equipment for new-type electricity storage systems by 2030. **Guidance on Accelerating the Development of New Type Energy Storage 2021** – Plan to install more than 30 GW of electricity storage (excluding PHS) by 2025. – Represents an increase of more than 300% relative to 2021. – Plans announced by individual provinces collectively target 60 GW, surpassing the national target.	Utilization of electricity storage remains low given strict planning requirements for construction and insufficient grid scheduling mechanisms, creating high operating expenses for storage facilities.
	**National Electricity Plan 2023** – Fourth iteration offers a framework for long-term electricity sector development. – Targets electricity storage of 74 GW by 2032 to facilitate the integration of renewable energy. – Expected storage requirement of 320 GW by 2047 in line with renewable ambitions, although not explicitly set as a target.	India’s policy regarding electricity storage remains in the early stages of maturity, setting ambitious targets but lacking detail on the intervention offered by government.

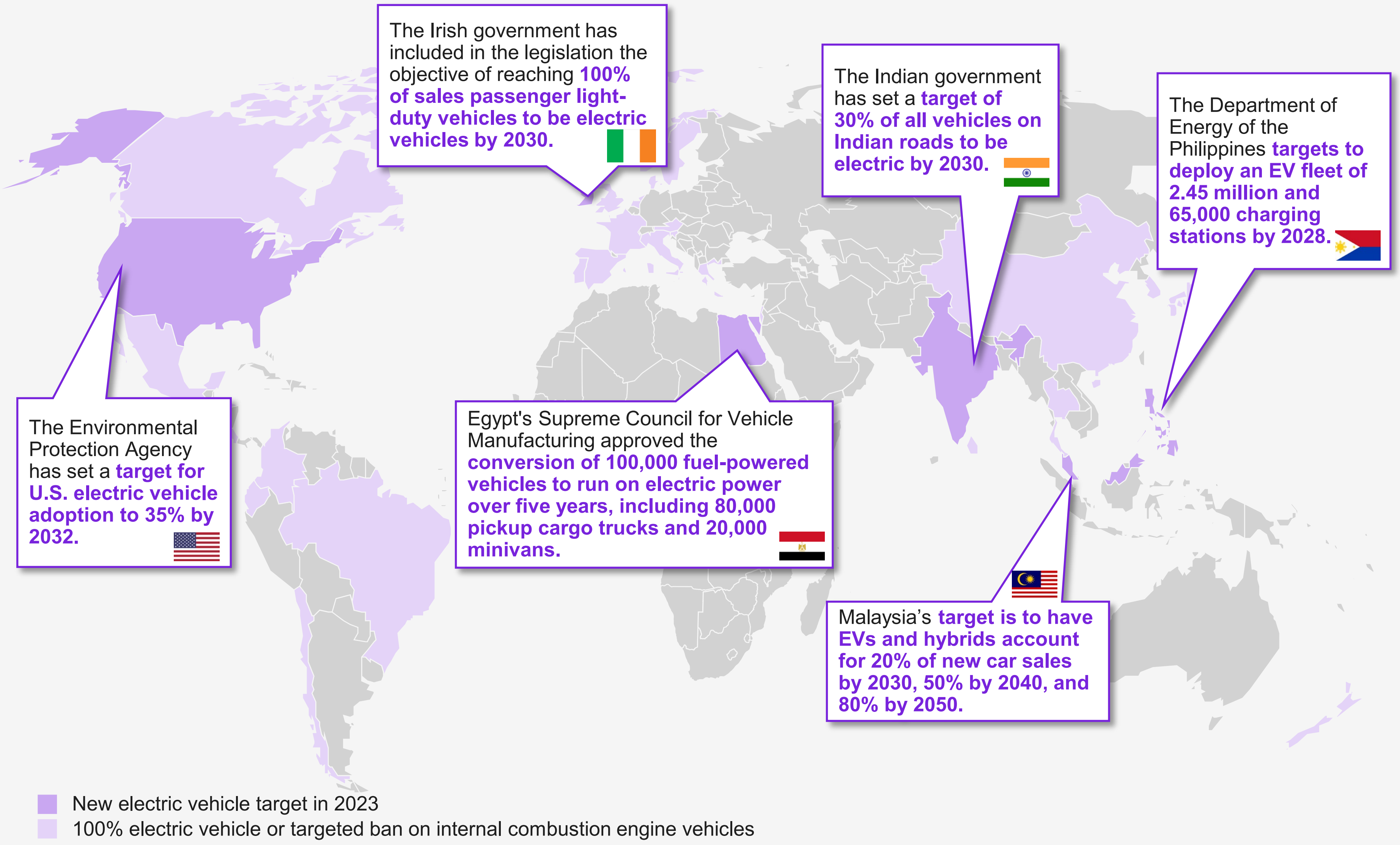
Sources: Apco, 2023, China’s Booming Energy Storage: A Policy-Driven and Highly Concentrated Market; Energy Storage, 2023, India requires 74GW / 411GWh of energy storage by 2032, according to National Electricity Plan; Kearney Energy Transition Institute analysis

Targets promoting electric vehicles continued to lead in road transport, with a total of 74 countries with such targets by the end of 2023

Non-exhaustive

Although most policies focus on passenger cars, many national, state, and local governments also support the adoption of electric buses, bikes, and commercial vehicles.

Targets for electric vehicle or ban on internal combustion engine vehicles
In force, 2023



Sources: IEA, 2023, Policies database; REN21, 2024, Global Status Report, Demand module; Kearney Energy Transition Institute analysis

8. Environmental and social impact of electricity storage

Environmental and social impact

The environmental impact of electricity storage is difficult to assess. It is necessary to consider direct and localized impacts, which vary according to the technology used, as well as the impact of the generation source, electricity displaced upon discharging, and the increase in generation needed to balance storage energy losses. Moreover, it is difficult to estimate the various impacts of end-of-life scenarios.

Integrating variable renewable sources with electricity storage technologies can occasionally result in a greater environmental footprint compared to conventional generation sources. A renewable grid mix can reduce the greenhouse gas footprint for storage by 80%. Additionally, recycling can significantly reduce the environmental impact of batteries, typically by around 25%.

Pumped hydro storage, compressed-air energy storage, and flywheel energy storage plants are generally less energy-intensive than electrochemical storage (batteries), typically by a factor ranging between 10 and 23. This difference is primarily due to the shorter cycling life of batteries, but it also varies depending on the materials used. Unlike pumped hydro storage and compressed-air energy storage, batteries often rely heavily on specific metals that require mining and processing.

Land footprint varies among technologies. **PHS has a high land footprint due to its poor energy density, while conventional electrochemical batteries offer a lower land use**, thanks to their **high modularity**, allowing them to be built vertically. **CAES is the technology with largest land footprint** due to the multitude of components required for its operation. **Among batteries, VRBs have the largest land footprint**. The water footprint of batteries fluctuates considerably depending on the geographic location of each stage in the value chain**. Raw material extraction accounts for 70–83% of the water consumption necessary for a Li-ion battery. Conventional CAES (diabatic) necessitates significant volumes of water to cool down the compressed air before storage.**

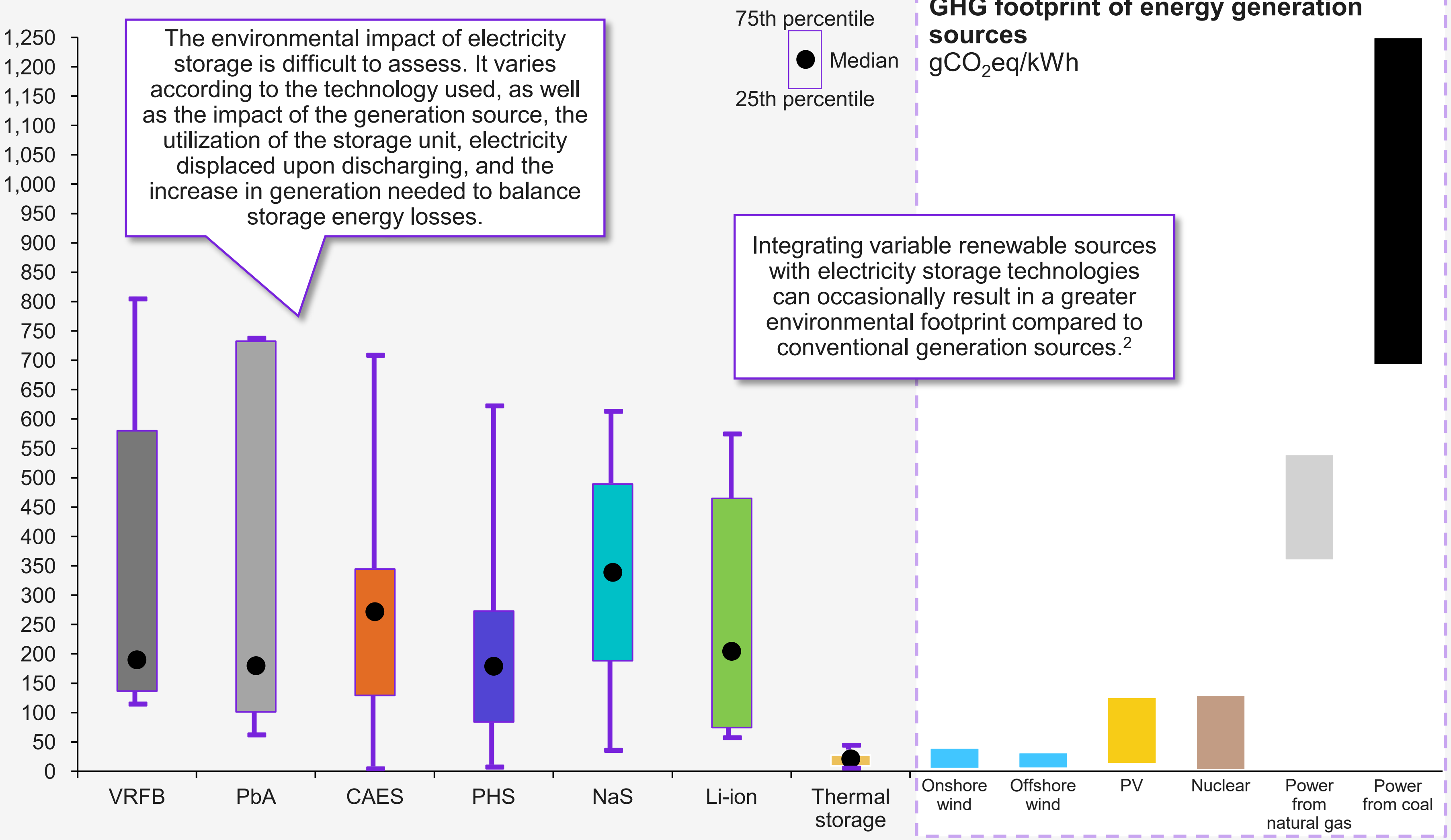
Each of the technologies have other impacts including biodiversity loss, water scarcity, raw materials mining, and chemicals. **The social impact of electricity storage remains significantly underreported.**

Closed loop PHS has the lowest GHG footprint among storage technologies[1]

Non-exhaustive

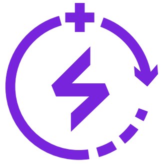
- A renewable electricity grid mix can result in an 80% reduction in the GHG footprint calculation for electricity storage technologies.
- Recycling can significantly reduce the GHG footprint, typically by around 25% for batteries.

8.1 GHG footprint of electricity storage technologies



[1] Greenhouse gases emissions.
[2] Greenhouse gases emissions ranges of the energy generation sources are also plotted on the same scale as a reference to help visualize the expected increases when integrated with storage solutions.
Note: The LCA analysis of the various electricity storage technologies does not include end-of-life scenarios. The functional unit of the studies that are shown in the graph is 1kWh.
Sources: NREL, 2023, Life Cycle Assessment of Closed-Loop Pumped Storage Hydropower in the United States; M.M. Rahman et al., 2020, "Assessment of energy storage technologies: A review," Energy Conversion and Management; J.A. Llamas-Orozco et al., 2023, "Estimating the environmental impacts of global lithium-ion battery supply chain: A temporal, geographical, and technological perspective", PNAS Nexus; Kearney Energy Transition Institute Solar PV FactBook and analysis

PHS, CAES, and FES plants are less energy intensive than electrochemical storage technologies

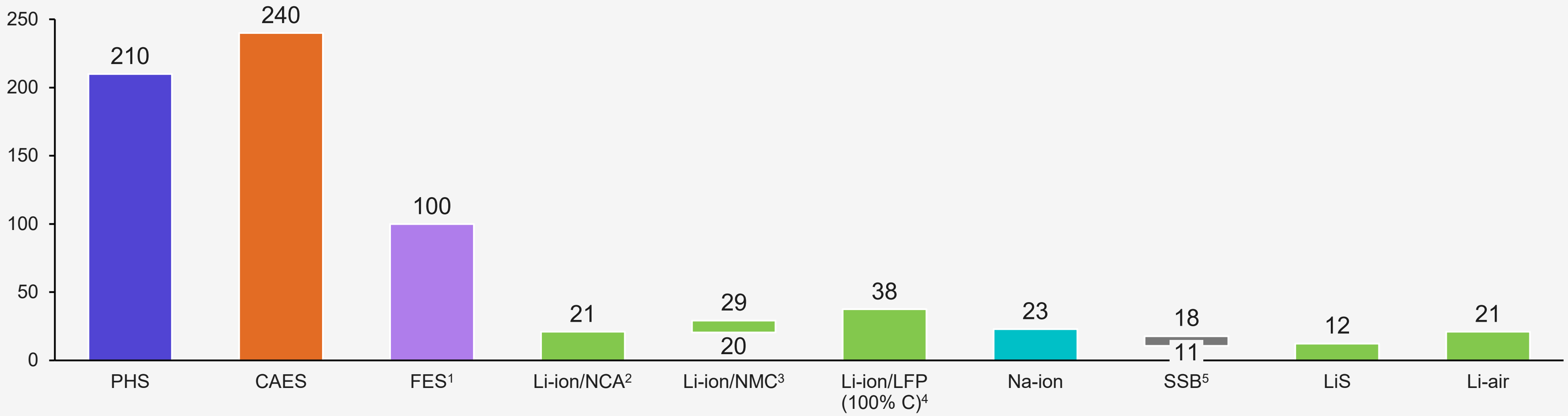


Energy intensity refers to the quantity of energy required per unit output or activity, meaning that using less energy to produce a product reduces its energy intensity.

8.2 Energy intensity of electricity storage

Energy intensity of electrical storage technologies (ratio of electrical energy stored and its embodied primary energy)

MJ/MJ



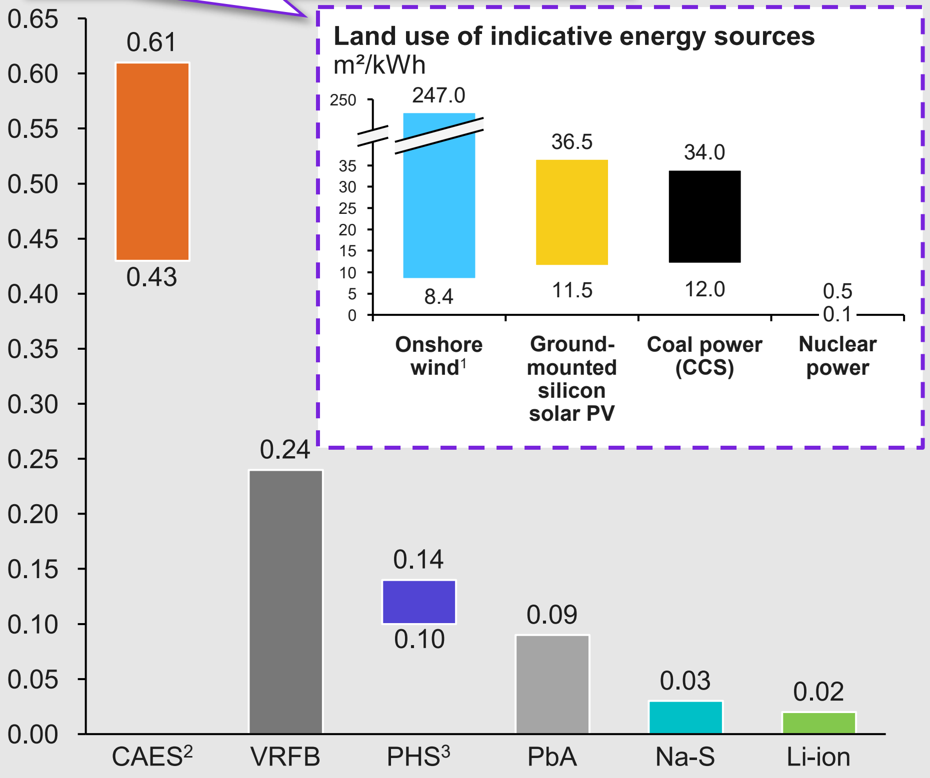
– **Pumped hydro storage, compressed-air energy storage, and flywheel energy storage plants are on average less energy intensive than electrochemical storage** (batteries) by a factor ranging between 10 and 23.
– **This is mainly resulting from the short cycling life of batteries**, but also depends on the material of which they are made. Unlike PHS and CAES, batteries tend to rely heavily on certain metals that need to be mined and transformed.
– **Cell production of novel batteries technologies requires less energy (11–23 kWh_{prod} per kWh_{cell}) than conventional Li-ion cell production (21–38 kWh_{prod} per kWh_{cell}).**
– **Technology advancements** promise a two-thirds reduction in energy consumption per produced battery cell energy by 2040 and **could save up to 85,400 GWh per year by 2040. Additionally, enhancing battery energy density could unlock savings of 10,800 GWh per year by 2040.**

[1] Flywheel energy storage; [2] Nickel-cobalt-aluminum;[3] Nickel-manganese-cobalt; [4] Lithium-iron-phosphate; [5] Solid-state
Note: The ratio between stored electrical energy and the embodied primary energy throughout the lifetime of batteries heavily hinges on their underlying chemistry. This fundamental aspect underscores the variance observed among different battery types, such as nickel-manganese-cobalt and solid-state batteries, each exhibiting its own distinct range.
Sources: F. Degen et al., 2023, "Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells", Nature Energy; K.R. Pullen, 2019, "The Status and Future of Flywheel Energy Storage", Future Energy; C. J. Barnhart, 2013, "On the importance of reducing the energetic and material demands of electrical energy storage", Energy & Environmental Science; Kearney Energy Transition Institute analysis

Batteries require less land than other technologies to store the same quantity of electricity

Land footprint by technology
m²/kWh

Electricity storage technologies require much less space than most energy generation sources, such as onshore wind and ground-mounted silicon solar PV.



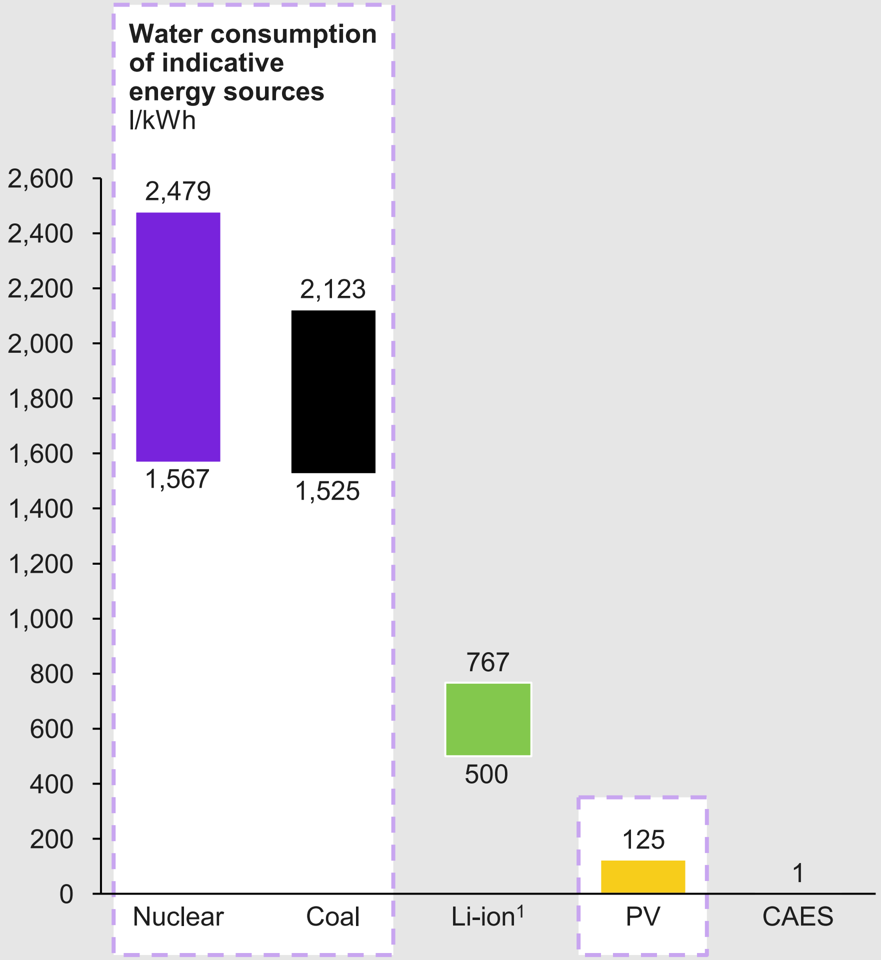
- **CAES systems have a large footprint because they require several components such as a compressor, turbine, heat exchanger, storage medium, etc**. The adiabatic CAES's land footprint is higher than conventional ones because it has significant storage requirements for thermal fluids.
- **VRB's land footprint is the largest among batteries as it requires different equipment to operate,** that is, storage tanks, heat exchangers, pumps, and stacks.
- **PHS has a high land footprint because of its poor energy density** (1 m^3 of water over a height of 100 m gives 0.27 kWh of potential energy).
- **Conventional electrochemical batteries** (Li-ion, Na-S, and PbA) **present a lower land use since they are highly modular,** so they can be divided into racks and cabinets and built vertically.

[1] The comparison takes into account the space required for a plant: a wind farm's land footprint can consider the space between turbines, which remains available for other activities such as agriculture or forestry.
[2] The range for compressed air energy storage encompasses both conventional and adiabatic types, with conventional systems typically requiring a smaller land footprint.
[3] The lower limit corresponds to the value calculated from the direct use of land storage capacity, while the upper limit represents the area of vegetation removal and storage capacity.

Sources: SEIA; Ritchie, 2022, "How does the land use of different electricity sources compare?"; J. Mou et al., 2023, "Feasibility Analysis of Compressed Air Energy Storage in Salt Caverns in the Yunying Area," Energies; A. Blakers et al., 2021, "A review of pumped-hydro energy storage," Progress in Energy; C.N. Papadakis et al., 2023, "A Review of Pumped-Hydro Storage Systems," Energies; J.D. Hunt et al., 2020, "Global resource potential of seasonal pumped hydropower storage for energy and water storage", Nature Communications; M. Stocks et al., 2021, "Global Atlas of Closed-Loop Pumped-Hydro Energy Storage," Joule; Utility Dive, 2022, "7 misperceptions about the viability of utility-scale battery storage"; P.A. Fokaides et al., 2022, Environmental Assessment of Renewable Energy Conversion Technologies, Elsevier; Kearney Energy Transition Institute analysis

Pumped hydro storage, CAES, and Li-ion batteries are associated with significant water consumption

Water footprint by technology
l/kWh



- While operating, energy plants usually need **water to cool**, so that they **do not get damaged and can continue generating electricity.**
- Devices also need to **be cleaned and maintained**, requiring more water.
- Air-cooling is usually enough for solar PV panels to be cooled, and panels need to be cleaned regularly.
- The water footprint of batteries varies significantly based on the geographic location of each stage of the value chain. **The extraction of raw materials corresponds to 70–83% of the water consumption needed for a li-ion battery.**
- Conventional CAES (diabatic) requires high volumes of water to cool down the compressed air before storing it.

[1] The depicted water consumption is associated with a nickel-manganese-cobalt 811 battery.
Sources: REN21, 2023, Renewable Energy and Sustainability Report; J.C. Kelly et al., 2020, "Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries," Mitigation and Adaptation Strategies for Global Change; UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources; IEA, 2016, World Energy Outlook, "Water-Energy Nexus"; Kearney Energy Transition Institute analysis

Pumped hydro storage and batteries present additional environmental impacts

Non-exhaustive

8.4 Other environmental impacts of electricity storage

Environmental risks categorization for various electricity storage technologies

Pumped hydro storage

Biodiversity

Hydropower dams affect freshwater ecosystems and biodiversity primarily by altering sediment flow and hydromorphology, resulting in habitat loss and reduced wildlife connectivity. Water quality may also suffer due to changes in sediment and nutrient dynamics.

Water scarcity

The declining storage capacity of lakes worldwide poses a significant challenge for PHS systems due to water scarcity.[1] A 53% decrease in these bodies was recorded between 1992 and 2020.

Water consumption

Water footprint estimates for PHS vary widely based on methodology. **In Europe, hydropower water footprint estimates range from 1.8 to 33 l/kWh.**

Most water loss in PHS occurs through evapotranspiration from large dam reservoirs, influenced by factors like climate, weather, and reservoir size. **Evapotranspiration losses from US reservoirs average around 17 l/kWh.**

Batteries

Raw materials

- **Copper and cobalt operations produce significant amounts of flotation waste** on a per ton basis.
- **Mining operations in Brazil, Indonesia, and Papua New Guinea have most risk to impact rich biodiverse countries.** The nickel industry is particularly pressuring biodiversity in these geographies. Copper mining has substantial impact, due to its low mining recovery rate.
- **Copper production has a significant impact on eutrophication and acidification potential**, amplified by the large annual volumes currently produced. Nickel production contributes to a large extent to acidification potential via the sulphur that is released in the smelting process.

Battery manufacturing and usage

Some metals and non-metals involved in battery manufacturing can threaten human health via different forms of exposure such as inhalation, skin or eye contact, ingestion, etc.

Disposal and recycling of battery

In different battery recycling stages, metals, non-metals, electrolytes, hard rubbers (or ebonite), and plastics are contributing to the creation of solid waste, wastewater, particulates emissions, and toxic gases.

[1] PHS is pumped hydropower storage.
Sources: REN21, 2023, Renewable Energy and Sustainability Report; KU Leuven, 2022, Metals for Clean Energy: Pathways to solving Europe's raw materials challenge; A.R. Dehghani-Sanij et al., 2019, "Study of energy storage systems and environmental challenges of batteries," Renewable and Sustainable Energy Reviews; Kearney Energy Transition Institute analysis

Pumped hydro storage systems' implementation is dependent on various social drivers and barriers

Social aspects related to PHS systems include public opposition, rural development, and proximity and cross-functional characteristics.

8.5 Social impact of electricity storage

Drivers				
Rural development			Proximity and cross-functional characteristics	
Job opportunities (Medium weight)	Business opportunities (Medium weight)	Quality of life for rural population (Low weight)	Nearby demand center (High weight)	Irrigation and drinking water (Low weight)
Creation of numerous job opportunities, especially for locals, during construction and operation.	Business opportunities include **uplifting tourism, fishing or fish farming, and property rentals** in the proximity of the project sites.	The location for PHS is often in remote areas that lack basic facilities such as roads and infrastructure, schools, and hospitals. **Therefore, the development of PHS reciprocally improves roads and other infrastructure and recreational facilities**, and the sharing of revenues and the payment of local taxes are positive economic indicators for rural development.	A configuration of PHS plants and the construction of integrated grid systems in close proximity would significantly **reduce power transmission losses, in the range of 8–15%.**	**Water for irrigation and drinking, especially from the run of river-type PHS plants**, as a possible driver for the construction of a pumped hydro project in far-off locations.

Barriers						
Public opposition						
Acceptance (inundation public) (High weight)	Forced displacements (High weight)	Affect fisheries business (High weight)	Awareness (Medium weight)	NIMBY (Medium weight)	Lengthy construction time (Medium weight)	Scattered houses (Low weight)

- **Local environmental groups perceive PHS as a "perpetual money machine" rather than a renewable energy solution, hindering its acceptance.**
- Public opposition to PHS construction can arise due to concerns over **stagnant water causing bad smells, disease from mosquitoes, and the risk of bursting during earthquakes.** Hydro projects in rural areas may face opposition due to prolonged construction timelines, disrupting communities and forcing relocation, as observed in cases such as Nepal.

High weight | Medium weight | Low weight

Note: The estimation of the weight is based on the number of studies on the respective factor.
Sources: S. Ali et al., 2021, "Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review," Cleaner Engineering and Technology; Kearney Energy Transition Institute analysis

Various social risks are associated to lithium-ion and vanadium redox flow batteries

Social risk indicators for li-ion and vanadium redox-flow battery

	Indicator	Li-ion	VRB
Workers	**Working hours:** weekly hours of work per employee	Low weight	Low weight
Workers	**Social benefits, legal issues:** social security expenditures, violation of employment laws and regulations	Medium weight	High weight
Workers	**Health and safety:** Workers affected by natural disasters, presence of sufficient safety measures, DALYs due to indoor and outdoor air/water pollution, accident rates at workplace (fatal and non-fatal)	Low weight	Medium weight
Workers	**Freedom of association and collective bargaining:** trade union density, right of association, collective bargaining and strike	High weight	High weight
Workers	**Forced labor:** Trafficking persons, goods produced by forced labor, frequency of forced labor	Medium weight	High weight
Workers	**Fair salary**	High weight	High weight
Workers	**Discrimination:** Women and men in the sectoral labor force, gender wage gap	Low weight	Low weight
Workers	**Child labor:** Children in employment (male and female)	Medium weight	Medium weight
Society	**Health and safety:** Life expectancy at birth, health expenditure, youth illiteracy rate	Low weight	Medium weight
Society	**Contribution to economic development:** Public expenditure on education, illiteracy rate, contribution of the sector to economic development	Medium weight	Medium weight
Local community	**Safe and healthy living conditions:** sanitation coverage, pollution level of the country, drinking water coverage	Medium weight	High weight
Local community	**Respect of indigenous rights**	Low weight	Medium weight
Local community	**Migration:** Net migration rate, migration flows, international migrant workers in the sector and migrant stock	Low weight	Low weight
Local community	**Local employment:** Unemployment rate	Low weight	Low weight
Local community	**Access to material resources:** level of industrial water use, GHG footprints, extraction of resources, certified environmental management systems	Medium weight	High weight

High weight

Medium weight

Low weight

Note: The depicted social risk indicators correspond to a nickel-manganese-cobalt battery. The weight corresponds to medium-risk hours, which specify the observed risks related to producing USD 1 of output.
Sources: M. Koese et al., 2023, "A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage," Journal of Industrial Ecology; Kearney Energy Transition Institute analysis

8.5 Social impact of electricity storage

9. Glossary, bibliography, and appendix

Glossary (1/3)

Energy and capacity services: Shift energy supply and demand over time to where it is most needed. Also found in the literature as generation support services or bulk storage services.	
Capacity firming	Use of electricity storage to render variable renewables output more constant during a given period of time. Electricity storage is used to store variable electricity production (wind or solar) during hours of peak production regardless of demand. This electricity is then discharged to supplement generation when the variable electricity unexpectedly reduces its output. Also found in the literature as load leveling or grid firming.
Energy arbitrage	Arbitrage is the practice of taking advantage of an electricity price difference in the wholesale electricity market. It is the use of storage to buy energy at low price and sell it at high price. Also found in the literature as energy time-shift.
Renewables curtailment minimization	Use of electricity storage to absorb variable renewables (wind or solar) that cannot be injected into the electricity grid due to lack of demand, either delivering it to the electricity grid when needed or converting it into another energy vector (gas, fuel, or heat) to be delivered to the relevant grid.
System electric supply capacity	System electric supply capacity is the use of electricity storage in place of combustion turbine (CT) to provide the system with peak generation capacity. Also found in the literature as peaking capacity.
Transmission and distribution services: Reduce or delay the need for transmission / distribution network upgrades.	
Distribution loss reduction	The objective is to use energy storage to perform some capacity/voltage support in order to reduce the impacts of the loss of a major grid component. Also found in the literature as contingency grid support.
Distribution upgrade deferral	The objective is to use electricity storage to defer or avoid distribution infrastructure upgrades and solve distribution congestion issues by installing energy storage systems instead of new lines. Moreover, the goal is to use electricity storage as a distribution grid component in order to decrease the "traditional" grid size during the grid planning process by basing its design on a medium power value and not a peak power value.
Distribution voltage support	Use electricity storage to maintain the voltage profile within admissible contractual/regulatory limits.

Sources: IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief; IRENA, 2020, Electricity Storage Valuation Framework: Assessing system value and ensuring project viability; NREL, 2019, An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind; Kearney Energy Transition Institute analysis

Glossary (2/3)

Transmission congestion relief	The objective is to use electricity storage to solve transmission congestion issues steering either the supply or demand and postponing/avoiding the necessity to increase lines in grid segments nearing capacity.
Transmission upgrade deferral	The objective is to use electricity storage to defer transmission infrastructure upgrades by installing electricity storage systems instead of new lines.
Ancillary services: Fast and accurate shifts in supply and demand under normal and emergency operations	
Black-start capacity	Capacity that can be started without either external power or a reference grid frequency, and then provide power to start other generators, primarily used to restart a grid post-blackout.
Contingency reserves	Reserves used to address power plant or transmission line failures by increasing output from generators. These include spinning reserves, which respond quickly and are then supplemented or replaced with slower-responding (and less costly) non-spinning/replacement reserves.
Frequency containment reserves (contingency reserves – spinning)	Active power reserves available to contain system frequency after the occurrence of an imbalance. Also found in the literature as primary reserves.
Frequency restoration reserves (contingency reserves – non-spinning)	Active power reserves available to restore system frequency to the nominal frequency and, for a synchronous area consisting of more than one load-frequency control area, to restore power balance to the scheduled value. A distinction is made between automatic FRRs and manual FRRs. Also found in the literature as secondary reserves.
Replacement reserves (contingency reserves – replacement)	Active power reserve available to restore or support the required level of FRRs to be prepared for additional system imbalances, including generation reserves. Also found in the literature as tertiary reserves.
Frequency-responsive reserves	Services that act to slow and arrest the change in frequency via rapid and automatic responses that increase or decrease output from generators providing these services. Traditionally provided by synchronous generators, these services include inertial response and primary frequency response (PFR). An emerging product is “fast frequency response,” which can be provided by multiple generator types and demand response and may replace some fraction of traditional inertia / PFR.

Sources: IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief; IRENA, 2020, Electricity Storage Valuation Framework: Assessing system value and ensuring project viability; NREL, 2019, An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind; Kearney Energy Transition Institute analysis

Glossary (3/3)

Ramping reserves	Fast ramping resources that can respond to large net load variations in a short time. This product properly remunerates the fast-ramping capability of generators and incentivizes flexibility.
Regulating reserves	Rapid response by generators used to help restore system frequency. These reserves may be deployed after an event and are also used to address normal random short-term fluctuations in load that can create imbalances in supply and demand.
Primary frequency regulation	The automatic local regulation provided by generating unit speed regulators. This level of regulation sustains frequency levels, preventing large deviations from the scheduled value.
Secondary frequency regulation	The automatic regional regulation provided by automatic generation control (AGC), which sends signals from the control center to certain generators to reestablish the nominal frequency value and restore the primary reserve capacity.
Tertiary frequency regulation	The manual regional regulation provided by generating units and controlled by the system operator.
Voltage support	Used to maintain voltage within tolerance levels and provided by local resources.
Customer-level services: Ensure affordable, continuous, and reliable supply for end customers	
End-user peak shaving	Use of energy storage to level out peaks in electricity use by residential or industrial and commercial power consumers, with the aim of minimizing the cost of a customer's invoice that varies according to their highest power demand. Also found in the literature as demand charge reduction.
Power quality	The objective is to use electricity storage to provide a high level of power quality above and beyond what the system offers (e.g., critical load) to some customers.
Reliability and resilience	Use of electricity storage device to substitute the network in case of interruption. Also found in the literature as continuity of energy supply.
Time-of-use bill management	Use of electricity storage by customers subject to variable or "time-of-use" electricity pricing to reduce the overall costs for electric service. For instance, customers may store electricity from the grid when prices are low and discharge the storage for self-consumption when prices are high, thus reducing their overall energy costs.

Sources: IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief; IRENA, 2020, Electricity Storage Valuation Framework: Assessing system value and ensuring project viability; NREL, 2019, An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind; Kearney Energy Transition Institute analysis

Acronyms (1/2)

AC	Alternate current
ACC	Annualized capacity cost
Al-ion	Aluminum-ion
AUD	Australian dollar
BASE	Beta alumina solid electrolyte
BESS	Battery energy storage system
CAD	Canadian dollars
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CSP	Concentrating solar power
BOS	Balance of system
CSP	Concentrating solar power
DC	Direct current
ELDC	Electrochemical double layer capacitor
EOL	End-of-life
EPC	Engineering procurement and construction
ETS	Economic Transition Scenario
EU	European Union
EUR	Euro
EV	Electric vehicle
FES	Flywheel energy storage
GBP	Great British pound
GES	Gravity energy storage
GHG	Greenhouse gases
GW	Gigawatt
GWh	Gigawatt hour
HEV	Hybrid electric vehicle
HT	High temperature
HUF	Hungarian forints
Hz	Hertz
ICE	Internal combustion engine
IEA	International Energy Agency
IRA	Inflation Reduction Act
IRENA	Internable Renewable Energy Agency
kt	kilo tonnes
kW	Kilowatt
kWh	Kilowatt hour
LAES	Liquid air energy storage
LCA	Life cycle assessment
LCOE	Levelized cost of electricity
LCOS	Levelized cost of storage
LFP	Lithium iron phosphate

Acronyms (2/2)

Li-air (ion)	Lithium-air or Lithium-ion
Mg-ion	Magnesium-ion
MW	Megawatt
MWh	Megawatt hour
Na-ion	Sodium-ion
NaNiCl2	Sodium nickel chloride battery (ZEBRA)
NaS	Sodium-sulfur
NCA	Lithium nickel cobalt aluminum battery
NECPs	National energy and climate plans
Ni-Cd	Nickel-cadmium
Ni-MH	Nickel metal hydride battery
NMC	Nickel manganese cobalt
NREL	National Renewable Energy Laboratory (US government funded)
NZE	Net zero emissions
NZS	Net zero scenario
OEM	Original equipment manufacturer
P2X	Power to X
PbA	Lead-acid battery
PHS	Pumped hydro storage
PSB	Polysulphide bromine flow battery
PV	Photovoltaic
R&D	Research and development
SC	Supercapacitor (specifically ELDC)
SDS	Sustainable development scenario
SMES	Superconducting magnetic energy storage
SSB	Solid-state battery
STEPS	Stated policies scenario
T&D	Transmission and distribution
TES	Thermal energy storage
TWh	Terawatt hour
TRL	Technology readiness level (from IEA)
UK	United Kingdom
US	United States
USD	United States dollar
VALCOE	Value-adjusted levelized cost of electricity
VLA	Vented lead-acid (VLA) battery
VRLA	Valve-regulated lead-acid battery
VRB	Vanadium redox (flow) battery
ZEBRA	Sodium nickel chloride battery
Zn-air (ion)	Zinc-air or Zinc-ion
Zn Br	Zinc bromine flow battery

9.1 Acronyms

Bibliography (1/10)

Ali et al., 2021, Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review

American Chemical Society, 2020, How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts?

Apco, 2023, China's Booming Energy Storage: A Policy-Driven and Highly Concentrated Market

Augustine and Blair, 2021, Storage Futures Study

Balducci et al., 2018, Assigning value to energy storage systems at multiple points in an electrical grid

Barnhart, 2013, On the importance of reducing the energetic and material demands of electrical energy storage

Bashir, S., 2024, Australia needs renewables, transmission and lots of storage to quit fossil fuels

Baum et al., 2022, Lithium-Ion Battery Recycling – Overview of Techniques and Trends

Baumgarte et al., 2020, Business Models and Profitability of Energy Storage

Behabtu et al., 2020, A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration

Benchmark Mineral Intelligence, 2023, Gigafactory assessment

Benjamin R. Bollinger, 2021, Malta Pumped Heat Energy Storage

Betz et al., 2018, Theoretical versus Practical Energy: A Plea for More Transparency in the Energy Calculation of Different Rechargeable Battery Systems

Blakers et al., 2021, A review of pumped-hydro energy storage

BloombergNEF, 2022, 2H 2022 Energy Storage Market Outlook

BloombergNEF, 2023, 2H 2023 Energy Storage Market Outlook

Bibliography (2/10)

BloombergNEF, 2023, Electric Vehicle Outlook 2023

BloombergNEF, 2024, China Already Makes as Many Batteries as the Entire World Wants

BloombergNEF, 2024, Energy Transition Investment Trends 2024

CICenergiGUNE, 2023, The battery industry´s new strategy: Cross value chain integration

Colthorpe, A., 2023, India requires 74 GW/411 GWh of energy storage by 2032

Couture et al., 2023, Italy Analysis of the Battery Storage Market

Degen et al., 2023, Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells

Dehghani-Sanij et al., 2019, Study of energy storage systems and environmental challenges of batteries

DNV, 2023, Closing the energy storage gap: Overcoming barriers in models, methods, and markets

DOE, 2023, Global energy storage database

E3 Analytics, 2023, Scaling-up Energy Storage: Technology and Policy

Ecole Polytechnique, 2020, Electrical Grid

ENEL, 2023, Unlocking the full value stack for battery storage

Energy Dome, 2022, Energy Dome successfully launches first CO2 Battery long-duration energy storage plant in the world

Energy Institute, 2023, Impacts of the Inflation Reduction Act on US battery developers

Energy Monitor, 2023, Weekly data: Booming battery pipeline heralds era of renewables-dominated grids

Bibliography (3/10)

Energy Storage Ninja, 2023, Lifetime Storage

Energy Storage, 2022, Chile passes major energy storage bill

Energy Storage, 2023, Chile government seeks multi-gigawatts of large-scale storage for 2026-2028

Energy Storage, 2023, India requires 74GW / 411GWh of energy storage by 2032, according to National Electricity Plan

Energy Storage, 2024, Australia needs renewables, transmission and lots of storage to quit fossil fuels

Energy Systems and Energy Storage Lab, 2015, Capacity markets and energy storage

Energy Vault, 2023, Rudong, China Gravity Energy Storage System

Engineering Toolbox, Data for Gibbs free energy of formation

ENTEC - Energy Transition Expertise Centre, 2023, Study on Energy Storage

European Commission, 2023, Energy Storage – Underpinning a decarbonized and secure EU energy system

Everett, 2003, Diffusion of Innovations

Ferré, 2024, Crashing lithium prices turn the industry from ‘euphoria’ to ‘despair’: What’s next?

Figgener et al., 2021, The development of stationary battery storage systems in Germany

FLEXPOWER, 2024, On which Energy Markets do Battery Energy Storage Systems (BESS) participate?

Fokaides et al., 2022, Environmental Assessment of Renewable Energy Conversion Technologies

Fraunhofer ISI, 2022, Solid State Battery Roadmap 2035+

Bibliography (4/10)

Fraunhofer ISI, 2023, Alternative Battery Technologies Roadmap 2030+

Fraunhofer ISI, 2023, Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players

Global Battery Alliance; World Economic Forum, 2019, A Vision for a Sustainable Battery Value Chain in 2030: Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation

GlobalData, 2023, Electricity storage database

GlobalData, 2024, Global Top 10 Upcoming Energy Storage Projects Market by 2030

GlobeNewswire, 2022, Quidnet Energy to Receive $10M in Federal Funding to Commercialize Clean Energy Technology

Gravitricity, 2024, Projects

Gresham House, 2023, Powering the renewable energy transition

Gresham House, Collocation: a smart solution for the UK energy transition, 2023

Harper et al., 2019, Recycling lithium-ion batteries from electric vehicles

Highview Power, 2024, Projects

HM Government, 2022, Taking charge: the electric vehicle infrastructure strategy

Hossain et al., 2020, A Comprehensive Review on Energy Storage Systems

Housden, 2019, An Evaluation of Energy Storage Profitability in the United Kingdom, Germany, Australia, and the United States

Hunt et al., 2020, Global resource potential of seasonal pumped hydropower storage for energy and water storage

IEA, 2016, World Energy Outlook, Water-Energy Nexus

Bibliography (5/10)

IEA, 2020, Assessing technology readiness: The ETP Clean Energy Technology Guide

IEA, 2020, Projected Costs of Generating Electricity

IEA, 2022, The Role of Critical Minerals in Clean Energy Transitions

IEA, 2023, Batteries and Secure Energy Transitions

IEA, 2023, Critical Minerals Market Review

IEA, 2023, Energy Technology Perspectives

IEA, 2023, Global EV Outlook 2023

IEA, 2023, Grid-scale Storage

IEA, 2023, Policies database

IEA, 2023, The Oil and Gas Industry in Net Zero Transitions

IEA, 2023, World Energy Investment

IEA, 2023, World Energy Outlook 2023

IHA, 2022, Hydropower Status Report: Sector trends and insights

IHA, 2023, Pumped storage tracking tool

International Council on Clean Transportation, 2023, Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches

Intratec, 2024, Lithium Carbonate Prices

Bibliography (6/10)

IRENA, 2017, Electricity storage and renewables: Costs and markets to 2030

IRENA, 2019, Innovative Ancillary Services: Innovation Landscape Brief

IRENA, 2020, Innovation Outlook: Thermal energy storage

IRENA, 2020, Electricity Storage Valuation Framework: Assessing system value and ensuring project viability

Junginger et al., 2010, Technology Learning in the Energy Sector

Juqu et al., 2022, Advances in paper-based battery research for biodegradable energy storage

Katsanevakis et al., 2016, Aggregated applications and benefits of energy storage systems with application-specific control methods: A review

Kebede et al., 2022, A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration

Kelly et al., 2020, Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries

Koese et al., 2023, A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage

KU Leuven, 2022, Metals for Clean Energy: Pathways to solving Europe’s raw materials challenge

KYOS, 2021, What is the Balancing Mechanism?

Leonti and Kline, 2023, Impacts of the Inflation Reduction Act on US battery developers

Li et al., 2022, Emerging rechargeable aqueous magnesium ion battery

Lilley, 2021, Sodium-ion batteries: Inexpensive and Sustainable Energy Storage

Llamas-Orozco et al., 2023, Estimating the environmental impacts of global lithium-ion battery supply chain: A temporal, geographical, and technological perspective

Bibliography (7/10)

Mayr and Beushausen, 2016, Navigating the maze of energy storage costs

Ministerio de Energía, 2021, Estrategia de Transición Justa en el sector Energía

MIT Energy Initiative, 2018, Energy Storage for the Grid: Policy Options for Sustaining Innovation

MIT Science Policy Review, 2022, Battery deployment in the U.S. faces non-technical barriers

Mitali et al., 2022, Energy storage systems: a review

Modo Energy, 2023, Dynamic Containment Low: what's setting post-saturation prices?

Moment Energy, 2022, How Can We Reduce the Cost of Energy Storage?;

Mongrid et al., 2020, An Evaluation of Energy Storage Cost and Performance Characteristics

Mou et al., 2023, Feasibility Analysis of Compressed Air Energy Storage in Salt Caverns in the Yunying Area

Murray, C., 2023, Chile government seeks multi-gigawatts of large-scale storage for 2026-2028

Murray, C., 2023, Gigawatts of energy storage projects approved in Greece ahead of auction

National Renewable Energy Laboratory (NREL)/USAID, 2021, Grid scale energy storage technologies primer

NREL, 2019, An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind

NREL, 2023, Electricity Annual Technology Baseline (ATB) Data

NREL, 2023, Life Cycle Assessment of Closed-Loop Pumped Storage Hydropower in the United States

NREL, 2024, A Component-Level Bottom-Up Cost Model for Pumped Storage Hydropower

Bibliography (8/10)

Nuñez-Jimenez et al., 2019, Balancing technology-push and demand-pull policies for fostering innovations and accelerating their diffusion

Papadakis et al., 2023, A Review of Pumped-Hydro Storage Systems

Pawel, 2014, The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy

Power Technology, 2024, Power plant profile: Renewable Underground Pumped Hydroelectric Energy Storage, Finland

Pullen, 2019, The Status and Future of Flywheel Energy Storage

Rahman et al., 2020, Assessment of energy storage technologies: A review

RCS Global, 2016, The battery revolution: balancing progress with supply chain risks

Regelleistung Online, 2020, Battery Storage Systems to Dominate the PRL Market

REN21, 2023, Renewable Energy and Sustainability Report

Ritchie, 2022, How does the land use of different electricity sources compare?

S&P Global Market Intelligence, 2023, Lithium-ion battery capacity to grow steadily to 2030

Sani et al., 2020, Energy storage system policies: Way forward and opportunities for emerging economies

Schmidt and Staffell, 2023, Monetizing Energy Storage

Schmidt et al., 2019, Projecting the Future Levelized Cost of Electricity Storage Technologies

Scottish Power, 2023, Review of Scottish Power Energy Networks' uptake of flexibility services

SMM, 2024, Understanding the Volatile Changes in Lithium Prices

Bibliography (9/10)

Solar Energy Industries Asoociation

Ssengonzi et al., 2022, An efficient method to estimate renewable energy capacity credit at increasing regional grid penetration levels

Stocks et al., 2021, Global Atlas of Closed-Loop Pumped-Hydro Energy Storage

SystemIQ, 2024, Catalysing the global opportunity for electrothermal energy storage

Tamarindo, 2023, Chile: A ‘showcase’ for storage and the energy transition

The Japan News, 2023, Govt to subsidize battery production equipment – Manufacturers to be encouraged to form alliances

Timera Energy, 2022, Beyond ancillaries

Tourino, J., 2023, Spain launches €280 million grants for standalone energy storage, thermal and PHES

TSE, 2023, Litium ion batteries: breakdown of materials?

UK GOV, 2023, Energy Security Bill factsheet: Defining electricity storage

UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources

USGS, 2023, Mineral Commodity Summaries 2023

Utility Dive, 2022, 7 misperceptions about the viability of utility-scale battery storage

Utility Dive, 2022, IRA sets the stage for US energy storage to thrive

Utility Dive, 2022, The Inflation Reduction Act will turbocharge energy storage

Wei et al., 2023, Progress in Energy Storage Technologies and Methods for Renewable Energy Systems Application

Bibliography (10/10)

Yosef et al., 2019, Battery Energy Storage Applications: Two Case Studies

Zhang, X., 2023, China’s Booming Energy Storage: A Policy-Driven and Highly Concentrated Market

Picture credits (1/3)

Slide 1	Every electricity storage technology you need to know about	Link
Slide 28	Ultracapacitor Cabinets	Link
Slide 28, 173	NGK NAS battery energy storage systems	Link
Slide 28, 184	Seneca Pumped Storage Generating Station	Link
Slide 28	Two-tank thermal storage system	Link
Slide 28	Chemical storage	Link
Slide 164	Charge and discharge processes of an EDLC	Link
Slide 165	Skeleton's supercapacitor	Link
Slide 166	Super magnetic energy storage (SMES) system design	Link
Slide 167	MVA/1 s SMES at Kameyama field test, in Japan	Link
Slide 168	Charging and discharging cycle of an electrochemical battery cell	Link
Slide 169	AES Energy Storage	Link
Slide 170	Lyten delivers first lithium-sulphur battery cells to customers	Link
Slide 171	Sunlight Group grows lead-acid production capacity to reach 9GWh	Link
Slide 172	CATL's first-generation sodium-ion battery	Link
Slide 174	An FZSoNick Na-NiCl2 battery system	Link

Picture credits (2/3)

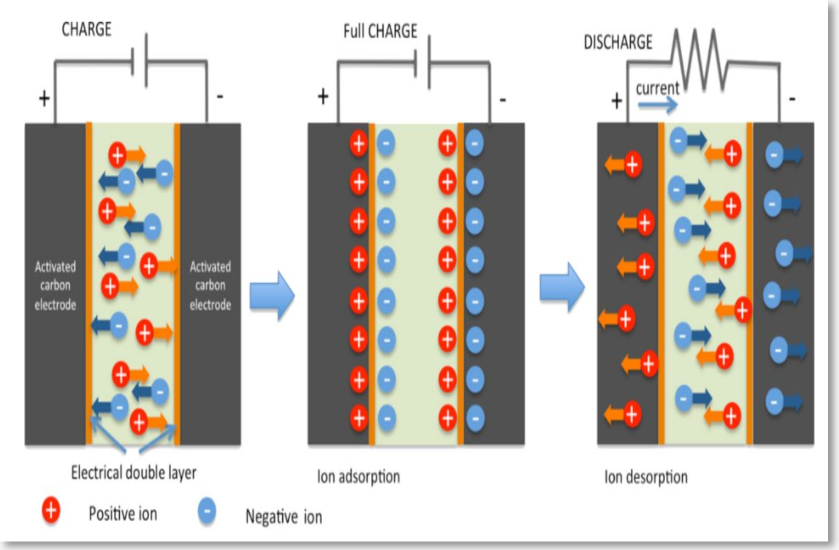
Slide 175	Ishihama Plant, Toyota Industries Corporation plant	Link
Slide 176	Lyten lithium-sulfur battery for electric vehicles	Link
Slide 177	A new zinc-air battery developed by NantEnergy costs much less than traditional lithium-ion batteries	Link
Slide 178	Solid-state batteries	Link
Slide 179	Design of a generic flow battery system	Link
Slide 180	One of the world's largest vanadium flow battery energy storage systems	Link
Slide 181	Redflow's project for California biofuel producer Anaergia	Link
Slide 182	All-Iron Flow Battery from Energy Storage Systems at Intersolar	Link
Slide 183	Closed-loop pumped storage plant arrangement	Link
Slide 184	Components of Flywheel Energy Storage System	Link
Slide 186	Beacon Power's flywheel energy storage plant in Stephentown, New York	Link
Slide 187	Illustration of Compressed Air Energy Storage System	Link
Slide 188	Large scale Compressed Air Energy Storage (CAES) site reliably running since the 1970s	Link
Slide 189	Geochemical Pumped Storage	Link
Slide 190	Geochemical Pumped Storage	Link
Slide 191	Energy storage is the fundamental element of the new energy system	Link

Picture credits (3/3)

Slide 192	Gravitricity generates electricity by dropping an iron weight down a shaft	Link
Slide 193	Carnot batteries	Link
Slide 194	View of a storage facility developed by Stolect	Link
Slide 195	Thermo-Electric Energy Storage	Link
Slide 196	The sand battery has been installed and is functioning well according to the power company	Link
Slide 197	Highview Power, Pilsworth Liquid Air Energy Storage (LAES) Plant	Link
Slide 198	Sardinia CO2 Battery demonstration	Link

Appendix of section 2 Electricity storage technologies

Supercapacitors polarize an electrolytic solution to store energy electrostatically



FactCard: Supercapacitor

1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

9.4 Appendix of section 2 Electricity storage technologies

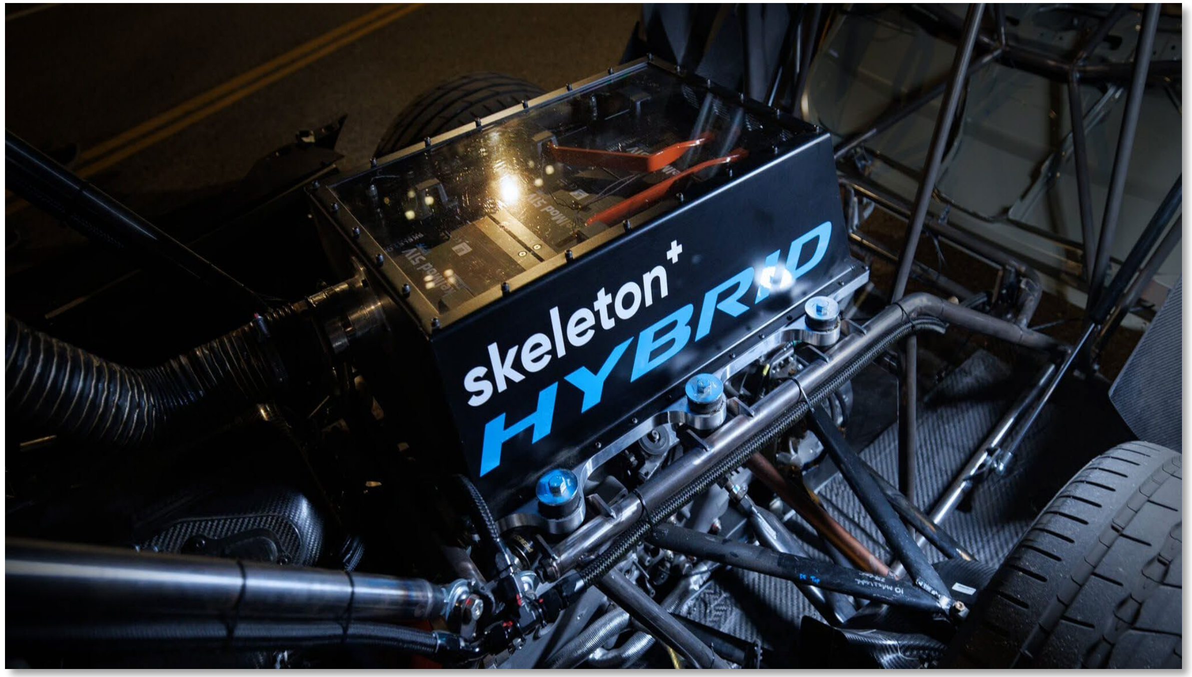
Pros	Cons
• High efficiency • Long lifetime • Scalable / flexible • High power capacity	• Low energy density • Requires power conditioning to deliver steady output power • Expensive per unit of energy capacity

Overview and working principle

- Supercapacitors are **also known as ultra capacitors or electrochemical double-layer capacitors**. Conventional capacitors consist of two conducting carbon-based electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Supercapacitors utilize an electrochemical double-layer of charge to store energy. As voltage is applied, charge accumulates on the electrode surfaces. Ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. However, the electrodes are engineered to prevent the recombination of the ions. Thus, a double-layer of charge is produced at each electrode.
- Capacitance, the ability of a body to store electrical charge, increases in proportion to the surface area of the electrodes and in inverse proportion to the distance between the electrodes. **To maximize their capacitance** (energy stored), **supercapacitors use high-surface-area electrodes** (up to 1,000 m2/g) made of special materials such as activated carbon, with distance of charge separation in the order of one ten-billionth of a meter.
- Supercapacitors are **high-power, low-energy devices that can react very quickly**. Due to the absence of a chemical reaction (unlike batteries), they can withstand a very high number of cycles. They are highly efficient but because the voltage varies linearly with the charge contained in the system, they require power electronics to ensure steady output.

Sources: Kearney Energy Transition Institute analysis

Supercapacitor: FactCard



Technology R&D / innovation focus areas

- Recently, supercapacitors have been used in start/stop systems for cars. Hence, they have potential applications in EVs as they can absorb power fast enough to be used for regenerative breaking.
- Specific capacitance can be increased by developing highly porous electrodes (such as graphene-like carbons or carbon nano tubes). Currently, the electrodes are made of activated carbons based on synthetic or wood precursors.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<1 kWh	◔
Power capacity	<300 kW	◔
Discharge duration	s–min	◔
Response time	ms	●
Efficiency	90–95%	●
Cycles	10^4–10^8	●
Lifetime	20+ years	◑
CAPEX: energy	10,000 to 20,000 €/kWh	●
CAPEX: power	100 to 300 €/kW	◔

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	○
Transmission support	◔
Distribution support	◔
Ancillary services	◔
Behind the meter/customer management	◔

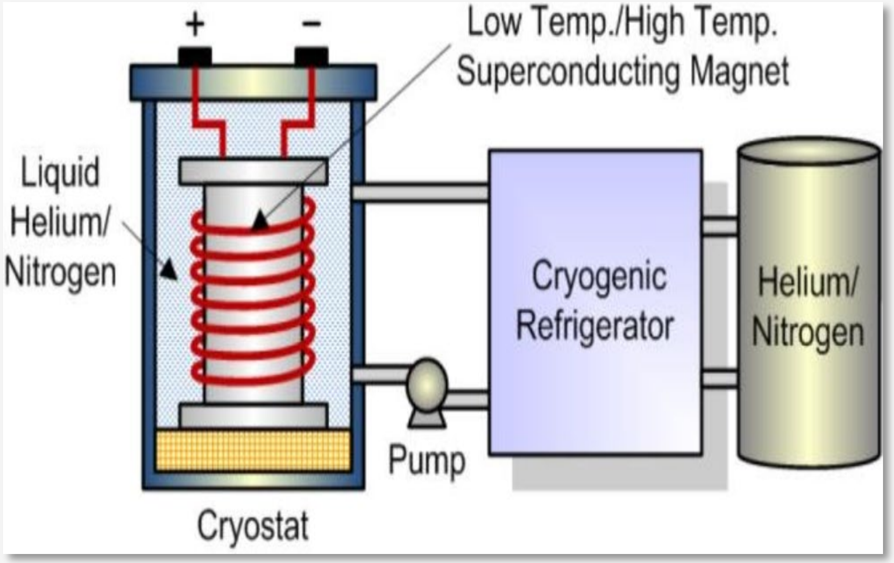
Sources: Kearney Energy Transition Institute analysis

Superconducting magnets store electricity in a magnetic field

FactCard: SMES

1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

9.4 Appendix of section 2 Electricity storage technologies



Pros	Cons
• High power density • Quick response and charging time • High efficiency • Low maintenance	• High cost • Low energy density • Need to be kept at cryogenic temperatures

Overview and working principle

- Superconducting magnetic energy storage (SMES) devices store electricity in a magnetic field generated by current flowing through a superconducting coil. The coil, made from a superconducting material, has no resistance when current is passed through it, reducing losses to almost zero. However, to maintain the superconducting state, a refrigeration system (e.g., using liquid nitrogen) is used.
- In addition to the coil and the refrigeration system, SMES require power electronics such as alternating current/direct current (AC/DC) converters to control the flow of the current into and out of the coil that charges and discharges the SMES. They also need a physical structure to mechanically support the coil, which is subjected to magnetic forces during operations, providing protection and additional equipment for system control.
- SMES react almost instantaneously and have a very high cycling life. They require limited maintenance and can achieve high efficiencies, with only between 2% and 3% losses resulting from AC/DC converters. However, due to the high energy requirements of refrigeration, the complexity of the system, and the high cost of superconductors, SMES are currently at an early demonstration phase and are only suitable for short-term storage.

Sources: Kearney Energy Transition Institute analysis

SMES: FactCard

Technology R&D / innovation focus areas

– High-temperature superconducting materials such as ceramics would lower the associated costs of cooling the SMES system. However, these materials typically display poorer operating characteristics relative to traditional superconducting materials. Improving performance, stability, and reliability of these high-temperature superconducting materials remains a key focus area.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<20 MWh	◑
Power capacity	<40 MW ()	◑
Discharge duration	ms–min	◔
Response time	ms	●
Efficiency	90–95%	●
Cycles	10^4	◑
Lifetime	20–30 years	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

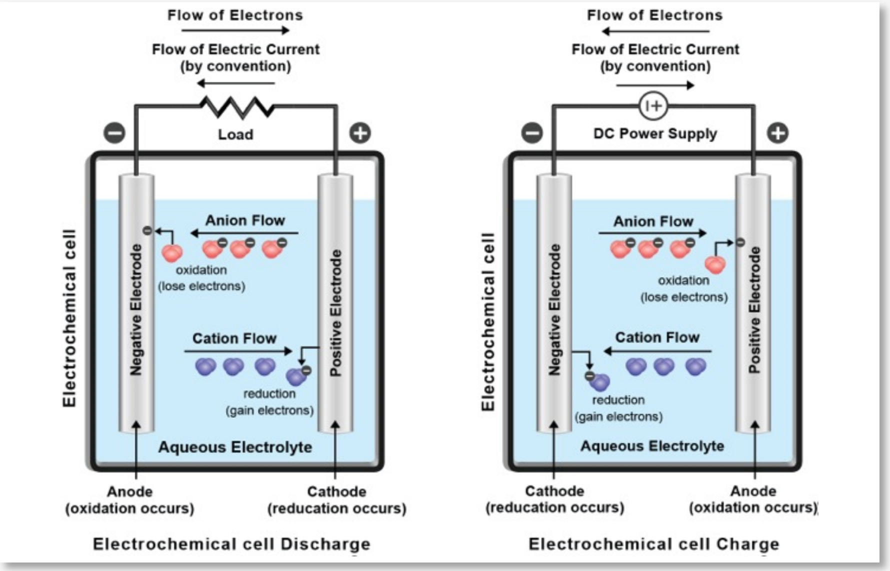
Generation support and bulk storage	○
Transmission support	○
Distribution support	○
Ancillary services	◔
Behind the meter/customer management	◔

Sources: Kearney Energy Transition Institute analysis

Rechargeable batteries, categorized according to their chemical composition, are based on electrochemical reactions in which electrons flow between two electrodes

FactCard: Batteries

9.4 Appendix of section 2 Electricity storage technologies



Pros	Cons
• High efficiency • Extensive experience in portable applications • Suitable for small- to medium-scale applications	• Limited life cycle • Environmental and safety hazards • Value chain concerns • Limited flexibility in power/energy sizing

Sources: Kearney Energy Transition Institute analysis

Overview and working principle

- Rechargeable batteries commonly used in mobile and portable applications are based on reversible electrochemical reactions: during discharge, the negative electrode is oxidized, producing electrons, while the positive electrode is reduced, consuming electrons. These electrons flow through an external circuit, creating an electrical current (and vice versa upon discharging), while ions (anions and cations) flow through an electrolyte. The reaction requires active components (i.e., ions, contained in the electrode material and electrolyte solution) that combine with electrons during reactions.

- The amount of energy that can be stored in a battery depends on the quantity of active components that can be stored in the electrolyte. The power rating is determined by the surface area of the electrodes and the resistance of the cell. However, this assumes there is enough electrolyte for the oxidation reaction to be possible, meaning that power and energy sizing is usually closely related.

- Batteries are generally highly efficient (60–95%) and relatively responsive. Their performance is highly dependent on their chemistry (i.e., the chemical composition of their electrodes and electrolyte). They are suited both to small- and large-scale applications, as they can be used on their own, in series, and in parallel. They face life cycle limitations, present environmental and safety hazards, and are currently costly.

Lithium ion (Li-ion): FactCard

Technology R&D / innovation focus areas

– Increasing energy density (by moving toward pure lithium for cathode and adding silicon to anode), higher power output, safety, decreasing costs, longer life, and reducing reliance on scarce minerals

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<1,000 MWh	●
Power capacity	<500 MW	◕
Discharge duration	min-h	◑
Response time	ms	●
Efficiency	85–89%	◕
Cycles	1,500–3,500	◔
Lifetime	10–20 years	◔
CAPEX: energy	40 to 700 €/kWh	◑
CAPEX: power	150 to 305 €/kW	◔

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●
Mobility	●

Sources: Kearney Energy Transition Institute analysis

Lithium sulphur (Li-S): FactCard

Technology R&D/innovation focus areas

- Li-S batteries offer high energy density with lower costs and lesser resource constraints and life cycle emissions (due to lower use of Ni, Co, Mn, and Cu) vs. Li-ion.
- High energy density makes them a good fit for mobility applications (especially air and marine). Use for stationary storage is also being explored.
- Low power density, low cycle life, flammability of the electrolyte, and reactivity of the metallic Li are some of the key challenges.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	NA	NA
Power capacity	NA	NA
Discharge duration	NA	NA
Response time	ms	●
Efficiency	85%	◕
Cycles	50–300	◔
Lifetime	NA	◔

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●
Mobility	●

Sources: Kearney Energy Transition Institute analysis

Lead acid: FactCard

Technology R&D / innovation focus areas

– Increase life cycle through hybrid systems (especially supercapacitors) and carbon-modified system designs

Key data

Low/slow — High/fast

Energy capacity	<10 MWh
Power capacity	<40 MW
Discharge duration	h
Response time	ms
Efficiency	75–85%
Cycles	250–2000
Lifetime	8–20 years
CAPEX: energy	100 to 200 €/kWh
CAPEX: power	100 to 500 €/kW

Applications

Limited coverage — Stronger coverage

Generation support and bulk storage
Transmission support
Distribution support
Ancillary services
Behind the meter/customer management

Note: This type of batteries have been used to electrify cars alternators
Sources: Kearney Energy Transition Institute analysis

Metal ion (Me-ion): FactCard

Technology R&D / innovation focus areas

– Li-ion batteries are the most prominent metal ion-based batteries but other metals (such as sodium, aluminum, zinc, and magnesium instead of lithium) are also being researched.

– Depending on their specific characteristics and performance, these batteries aim to provide an alternative to (not replacement for) Li-ion batteries. Ex: sodium-ion batteries (Na-ion) are, depending on their cell design, well-suited for stationary applications or light electric vehicles.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<1 MWh	◔
Power capacity	<250 kW	◔
Discharge duration	h	◑
Response time	ms	●
Efficiency	<92%	●
Cycles	100–1,000	◔
Lifetime	15 years	◔

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●
Mobility	●

Sources: Kearney Energy Transition Institute analysis

Sodium sulphur (NaS): FactCard

Technology R&D / innovation focus areas

– Replacing solid beta-alumina ceramic with liquid electrolyte to reduce the operating temperature and corrosion (which can lead to higher self-discharge rates)

9.4 Appendix of section 2 Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<300 MWh	◕
Power capacity	<100 MW	◕
Discharge duration	h	◑
Response time	ms	●
Efficiency	75–85%	◕
Cycles	4,000–7,300	◔
Lifetime	10–20 years	◔
CAPEX: energy	300 to 450 €/kWh	◑
CAPEX: power	2000 to 3000 €/kW	●

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●

Sources: Kearney Energy Transition Institute analysis

Sodium nickel chloride (ZEBRA): FactCard

Technology R&D / innovation focus areas

– Developing ZEBRA batteries that operate below 200°C and reduce or eliminate the use of costly nickel in the cathode, replacing nickel with iron

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	<10 MWh	◑
Power capacity	<5 MW	◑
Discharge duration	h	◑
Response time	ms	●
Efficiency	80–90%	◕
Cycles	2,500–4,500	◔
Lifetime	10–20 years	◔
CAPEX: energy	550 to 750 €/kWh	◑
CAPEX: power	150 to 1000 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●

Sources: Kearney Energy Transition Institute analysis

Nickel based (Ni-Cd/Ni-MH): FactCard

Technology R&D / innovation focus areas

– Ni-MH replaced Ni-Cd technology and now it is being replaced by Li-ion technology.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	Few MWh	◑
Power capacity	<40/<3 MW	◔
Discharge duration	h	◑
Response time	ms	●
Efficiency	60–70/50–80%	◕
Cycles	1,000–5,000/300–1,800	◔
Lifetime	10–25/5–15 years	◔
CAPEX: energy	400 to 700 €/kWh	◑
CAPEX: power	500 to 1500 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●

Sources: Kearney Energy Transition Institute analysis

Metal sulphur (Me-S): FactCard

Technology R&D / innovation focus areas

– Metal-sulfur (Me-S) batteries are being studied and developed because of the high availability, low price, and low weight of S as cathode active material.

– Metals under consideration: Li, Na, K, and multivalent Mg, Ca, and Al

– These batteries are primarily being designed for operations at room temperature hence are different from NaS/$NaNiCl_2$ batteries (which operate at high temperature, thus referred to as Na S - HT).

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	NA	NA
Power capacity	NA	NA
Discharge duration	NA	NA
Response time	ms	●
Efficiency	< 89%	◕
Cycles	>300	◔
Lifetime	NA	NA

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●

Sources: Kearney Energy Transition Institute analysis

Metal air (Me-air): FactCard

Technology R&D / innovation focus areas

– Primary metal-air (Me-air) batteries are already widely used (e.g., Zn-air batteries in hearing aids); the focus is on developing secondary Me-air batteries.

– Prominent materials under consideration: Li, Zn, Ca, Na, Al, Mg, Fe, and K

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	Few MWh	◑
Power capacity	Few MW	◑
Discharge duration	h	◑
Response time	ms	●
Efficiency	60–80%	◑
Cycles	< 550	◔
Lifetime	NA	NA
CAPEX: energy	160 USD/kWh	
CAPEX: power	1000 USD/kW	

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●

Sources: Kearney Energy Transition Institute analysis

Solid-state (SSB): FactCard

Technology R&D / innovation focus areas

- As the potential for further optimization of liquid electrolyte-based Li-ion batteries is diminishing, a new generation of solid-state batteries (SSB) based on solid electrolytes is being developed.
- Currently, three groups of solid electrolyte materials seem most promising, namely oxide electrolytes, sulfide electrolytes, and polymer electrolytes.
- Li and Si (as anodes) in combination with layered oxide and lithium iron phosphate (as cathodes) are some of the cell concepts under study.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	Few MWh	◑
Power capacity	Few MW	◑
Discharge duration	h	◑
Response time	ms	●
Efficiency	< 97%	●
Cycles	<4,000	◔
Lifetime	15 years	◔

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

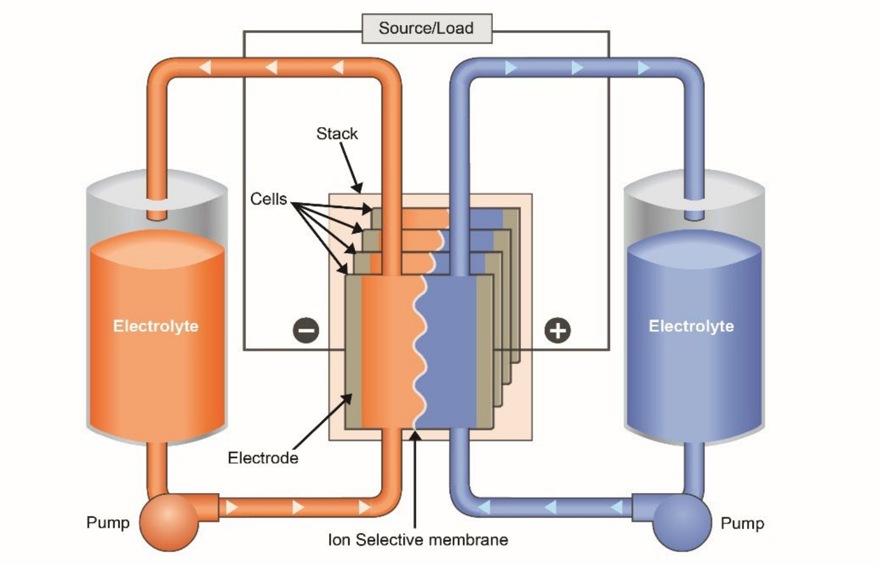
Generation support and bulk storage	◕
Transmission support	●
Distribution support	●
Ancillary services	●
Behind the meter/customer management	●
Mobility	●

Sources: Kearney Energy Transition Institute analysis

Unlike classic rechargeable batteries, flow batteries rely on two separately stored electrolytes to decouple their power and energy capacities

FactCard: Flow batteries

9.4 Appendix of section 2 Electricity storage technologies



Pros	Cons
• Independent energy and power sizing • Scalable for large applications • Longer lifetime in deep discharge	• More complex than classic batteries • Early stage of development

Overview and working principle

- The electrochemical process in flow batteries is comparable to that in classic batteries. Ions contained in the electrolytes move from the negative and positive electrodes, upon charging and discharging, through a selective polymer membrane. A cooling system is usually needed, as charging and discharging releases heat.
- Unlike classic batteries, flow batteries contain two electrolyte solutions in two separate tanks, circulated through two independent loops. The chemical composition of the electrolyte solution defines the sub-categories of batteries, the most important being vanadium redox (VRB) and zinc-bromine (Zn/Br).
- This more complex design allows the dissociation of power (defined by the number of cells in the stack and the size of electrodes) and energy (defined by the volume and concentration of the electrolytes).
- Operational temperature is usually between 20°C and 40°C, but higher temperatures are possible, provided plate coolers are used to avoid over-heating the plates. Flow batteries are usually between 65% and 80% efficient, allow approximately 10,000 to 20,000 cycles, and have a short response time.

Sources: Kearney Energy Transition Institute analysis

Vanadium redox flow (VRB): FactCard

Technology R&D / innovation focus areas

- Lowering the costs and increasing efficiency
- Developing newer battery chemistries with fewer raw materials and storage costs
- Additives and new developments in redox couple chemistry to increase the temperature range

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	10 kWh–800 MWh	◕
Power capacity	<200 MW	◕
Discharge duration	h	◕
Response time	ms–s	◕
Efficiency	68–80%	◑
Cycles	$>10^4$	◑
Lifetime	10–25 years	◑
CAPEX: energy	100 to 400 €/kWh	◔
CAPEX: power	500 to 700 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	◕
Distribution support	●
Ancillary services	●
Behind the meter/customer management	◑

Sources: Kearney Energy Transition Institute analysis

Zinc bromine redox flow: FactCard

Technology R&D / innovation focus areas

– Reduce complexity and balance-of-system costs of zinc-bromine flow batteries by eliminating the need for a membrane separator and separate electrolyte tanks

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	few kWh–100 MWh	◕
Power capacity	5–10 MW	◑
Discharge duration	h	◑
Response time	ms–s	◕
Efficiency	70–75%	◑
Cycles	2,000–3,000	◔
Lifetime	5–15 years	◔
CAPEX: energy	100 to 400 €/kWh	◔
CAPEX: power	500 to 1300 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	◕
Distribution support	●
Ancillary services	●
Behind the meter/customer management	◑

Sources: Kearney Energy Transition Institute analysis

Iron redox flow batteries: FactCard

Technology R&D / innovation focus areas

– Finding suitable redox systems and components to build stable batteries

9.4 Appendix of section 2
Electricity storage
technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	few MWh	◑
Power capacity	<3 MW	◑
Discharge duration	h	◕
Response time	ms–s	◕
Efficiency	70–75%	◑
Cycles	$1x10^4$–$2x10^4$	◑
Lifetime	15–25 years	◑
CAPEX: energy	100 to 400 €/kWh	◔
CAPEX: power	500 to 1300 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	◕
Distribution support	●
Ancillary services	●
Behind the meter/customer management	◑

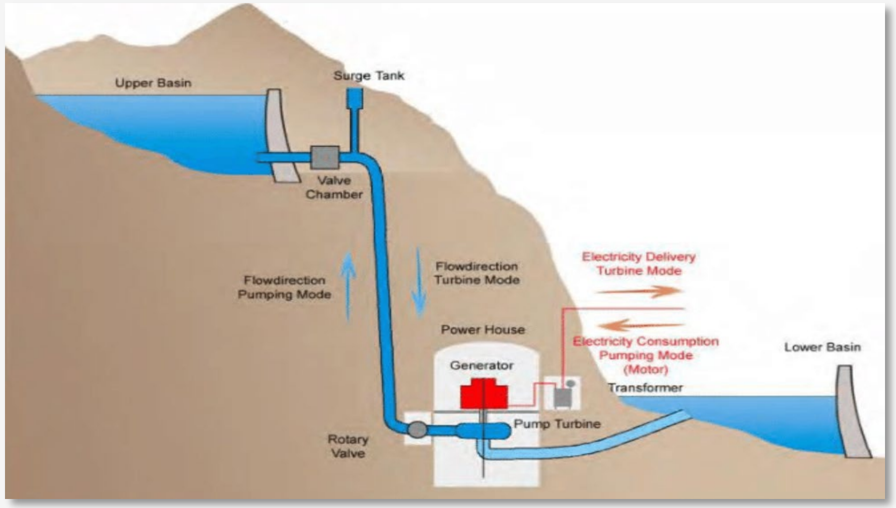
Sources: Kearney Energy Transition Institute analysis

Pumped hydro storage uses the gravitational potential energy of water by pumping / releasing water between two vertically separated reservoirs

FactCard: PHS

1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

9.4 Appendix of section 2 Electricity storage technologies



Note: Hydropower plants (HPP) utilize the potential energy of water being pulled by gravity through turbines to generate electrical energy. This is identical to the generating cycle of PHS, but there is no pumping capability present at an HPP. Hence, not all HPP are PHS but many HPP can be retrofitted into PHS where both an upper and lower reservoir are available.

Pros	Cons
• Most mature storage concept in respect to installed capacity and storage volume	• Lack of suitable sites • Not suited to distributed generation • Relatively low energy density results in indirect environmental impact

Sources: Kearney Energy Transition Institute analysis

Overview and working principle

- Pumped hydro storage (PHS) makes use of two vertically separated water reservoirs. It uses low-cost electricity to pump water from the lower to the higher elevated reservoir using either a pump and turbine or a reversible pump turbine. During periods of high demand, it acts like a conventional hydro power plant, releasing water to drive turbines and thereby generating electricity.
- Efficiency typically ranges between 70% and 85%. Losses mainly occur in the pumping and turbine stages, both of which are around 92% efficient, and to a lesser extent in the transformers, motors, generators, and shaft line.
- In general, pumped hydro storage plants can reach their full power load in a few minutes, with reaction time ranging in the seconds. In recent years, variable-speed pump turbines have been developed with the ability to generate power synchronously with the grid frequency, but pumping asynchronously, providing faster power adjustment.
- PHS requires high elevation differences between reservoirs or very large reservoirs to increase its relatively low energy density (1 cubic meter water released from a height of 100 meters gives 0.27 kWh of potential energy). This reduces the number of naturally suitable sites and can result in a large environmental footprint. Alternative solutions are being investigated to avoid these issues (e.g., artificial reservoirs underground or in the sea).

PHS: FactCard

Technology R&D / innovation focus areas

– Using asynchronous motor-generators to increase the operation range of PHS

– Underfloor PHS systems: the concept is equivalent to conventional PHS, but instead of surface reservoir/ponds the storages are arranged below ground; e.g., existing mines. Refer to geo-mechanical pumped storage (GPS) in the next slides.

– Studying the development of PHS adopting the sea as a lower reservoir

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	0.5–100 GWh	●
Power capacity	10 MW – 3 GW	●
Discharge duration	min–h	◑
Response time	s–min	◑
Efficiency	70–85%	◑
Cycles	$2X10^4$–$10X10^4$	◕
Lifetime	50–100 years	●
CAPEX: energy	40 to 150 €/kWh	◔
CAPEX: power	400 to 1,500 €/kW	◑

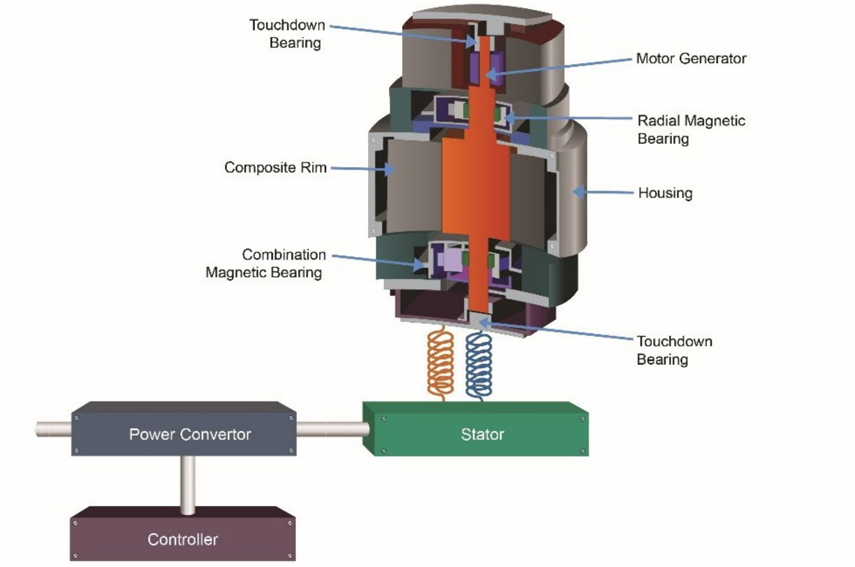
Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	●
Transmission support	◕
Distribution support	◑
Ancillary services	◕
Behind the meter/customer management	○

Sources: Kearney Energy Transition Institute analysis

Flywheels store electrical energy in the form of rotational energy via a flywheel rotating in a frictionless container



Overview and working principle

- Flywheels rely on the inertia of a mass rotating within a frictionless container. When charging, electricity is used to accelerate a rotor, called a flywheel, to very high speeds (30,000 to 50,000 rotations per minute). Energy can be stored for a long time, as only small losses are incurred through friction with the container. To reduce these losses further, the rotor is levitated with permanent magnets and an electromagnetic bearing. When energy needs to be extracted from the system, the inertial energy of the rotor is used to drive a generator, reducing the flywheel's rotational speed.
- The flywheel system is usually contained within a single cabinet made of a benign and inert material, presenting minimal environmental and safety risks. The main components of the system include a power convertor, a stator, bearings, and a rotor. Auxiliary components are the fuse boxes, contactors, and cooling fans. The system requires limited maintenance and has a longer lifespan than batteries (up to 20,000 cycles). However, the replacement of bearings is expected to be difficult and expensive.
- The larger the rotational diameter and rotational speed of the flywheel, the higher its energy rating. The centrifugal forces induce fatigue, so fatigue-resistant materials such as special alloys or reinforced plastics are used. Flywheels tend to be high-power, low-energy devices. However, high-energy flywheels are being designed (several kW distributed over hours), and high-power flywheels (1 MW over 10 to 15 seconds) are already commercial.

Pros	Cons
• High power density • Low detrimental environmental impact • High cycle life • Independent power and energy sizing	• Low energy density • Difficult / expensive replacement of bearings • High-energy failures must be contained

FactCard: Flywheel

Sources: Kearney Energy Transition Institute analysis

Flywheel: FactCard

Technology R&D / innovation focus areas

– Relatively mature technology hence it registers fewer R&D efforts compared to other storage technologies

– Outside the power sector, there is interest in flywheels for applications in the public transportation sector for capturing energy that is wasted during deacceleration.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	5 kWh–5 MWh	◑
Power capacity	1–20 MW	◑
Discharge duration	s–min	◑
Response time	s	◕
Efficiency	85–95%	●
Cycles	10^5–10^7	●
Lifetime	20+ years	◑

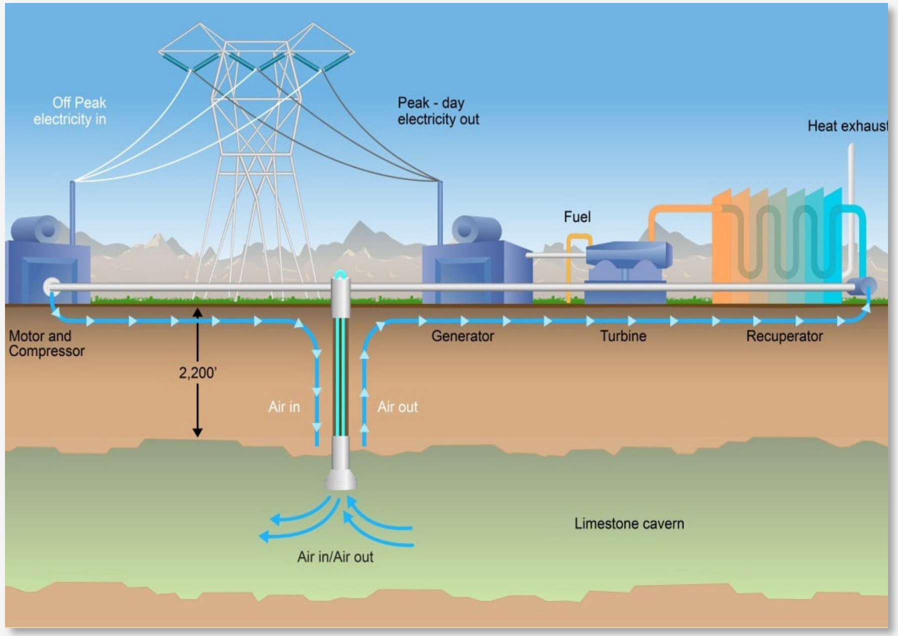
Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	○
Transmission support	◕
Distribution support	◔
Ancillary services	◔
Behind the meter/customer management	◔

Sources: Kearney Energy Transition Institute analysis

Compressed-air energy storage mechanically compresses air for storage and releases it during discharge to drive a turbine, producing electricity



Pros	Cons
• Large energy and power capacity • Competitive, with low costs per kWh • Adjustable to decentralized plants with artificial reservoirs	• Constraints on availability of suitable geological formations • Existing designs rely on gas burners • Lower efficiency

Sources: Kearney Energy Transition Institute analysis

Overview and working principle

- Compressed-air energy storage (CAES or diabatic CAES) uses electricity to compress air into a confined space (underground mines, salt caverns, or underground aquifers), where it is stored. When needed, the pressurized air is released to drive the compressor of a natural-gas turbine, thereby generating electricity.
- Much of the heat made during the compression phase is dissipated by intercoolers to comply with the technical requirements of the storage cavity. Therefore, a way must be found to re-heat the air prior to expansion in the turbine. Conventional diabatic systems use a natural-gas burner to heat the air upon expansion. Gas consumption can be reduced by recycling flue gas from power plants for air preheating. This solution decreases system efficiency, but is the simplest and the only one practiced today. Alternatives are being investigated, notably adiabatic systems that retain and store the heat emitted during compression and reintroduce it to the air upon expansion.
- In conventional designs, the cycle is achieved with electrically powered turbo compressors and turbo expanders with efficiencies of 45% to 55%, compared with more than 70% expected for adiabatic options. Ramp-up time is around 10 minutes and the system has a relatively long lifetime.
- Man-made salt caverns are the best option for storage but are not always geologically available. Alternative storage vessels are being investigated. Artificial pressure tanks have the advantage of being compatible with distributed applications. Using depleted gas fields is also worth considering, but the risk of the air reacting or mixing with residues of other gases must first be resolved.

CAES: FactCard

Technology R&D / innovation focus areas

- **Adiabatic CAES,** i.e., a form of CAES that does not require the use of natural gas to reheat the air during generation, is currently in the research and development phase. It is characterized by higher efficiency ~70%, 30+ years lifetime with <1,000 cycles.
- Upgrade a diabatic-CAES with a thermal energy storage (TES) device. In this application, the TES delivers only a part of the required heat which can make the deployment achievable within a moderate time frame.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	100 MWh–10 GWh	●
Power capacity	10–300 MW	◕
Discharge duration	h	◕
Response time	min	◔
Efficiency	42–54%	◑
Cycles	5,000–20,000	◑
Lifetime	25–40 years	◕
CAPEX: energy	30 to 40 €/kWh	◔
CAPEX: power	400 to 2,000 €/kW	◑

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

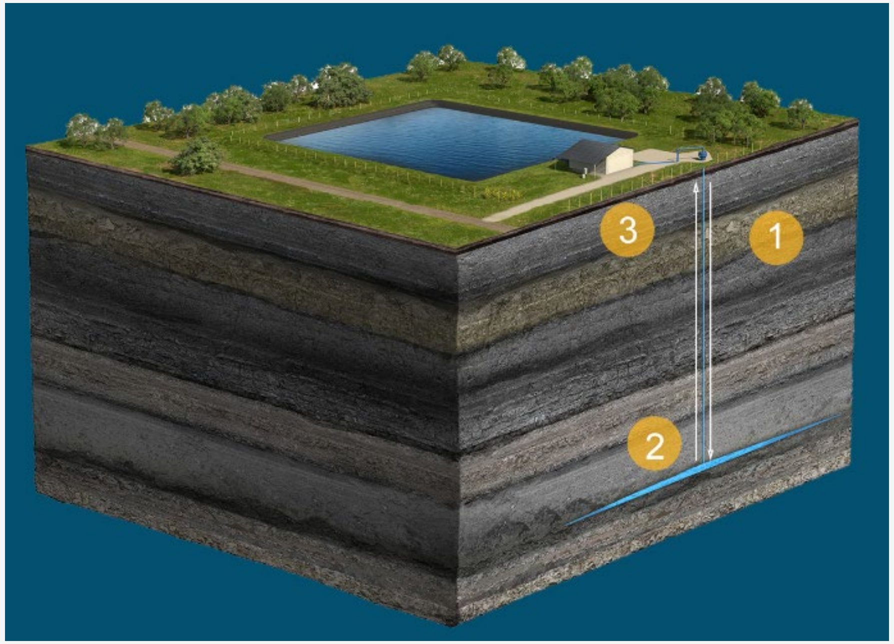
Generation support and bulk storage	●
Transmission support	◕
Distribution support	◔
Ancillary services	◕
Behind the meter/customer management	◑

Sources: Kearney Energy Transition Institute analysis

Geo-mechanical pump storage combines conventional drilling technology and mature hydropower technology

FactCard: GPS

9.4 Appendix of section 2 Electricity storage technologies



Pros	Cons
• No geographic constraints unlike conventional PHS • Lower costs • Faster deployment	• Lower energy and power capacity than conventional PHS

Overview and working principle

- Geo-mechanical pump storage (GPS) uses the same principles as aboveground PHS but with subsurface water reservoirs.
  1. When electricity is abundant, it is used to pump water from a pond down a well and into a body of rock.
  2. The well is closed, keeping the energy stored under pressure between rock layers for as long as needed.
  3. When electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity and return to the pond ready for the next cycle.
- These facilities can operate with closed-loop water systems, designed for conservation against evaporative loss. The energy-storing rock bodies are non-hydrocarbon bearing and found abundantly throughout the world, intersecting with major electricity transmission and distribution hubs.
- This approach avoids the substantial capital associated with construction on the sides and tops of mountains required to build traditional pumped hydro facilities.
- It utilizes mature components from well-established industries such as oil and gas and mining, which eliminates the need for new supply chains and is expected to enable rapid implementation and scaling to meet the substantial global energy storage need.
- Underground pumped-storage hydro power plants in closed-down underground hard coal mines are an active area of interest, especially in Europe.

Sources: Kearney Energy Transition Institute analysis

GPS: FactCard

Technology R&D / innovation focus areas

- Achieving mechanical efficiencies better than alternative reversible rotodynamic machines, targeting >95% mechanical efficiency (each way) in both the pumping and generation modes
- Target <$100/kw INGEN (Injector-Generator) manufacturing cost at scale long term

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	MWh	◑
Power capacity	0.5–10 MW	◑
Discharge duration	h	◕
Response time	s	◕
Efficiency	NA	NA
Cycles	NA	NA
Lifetime	NA	NA

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	●
Transmission support	◕
Distribution support	◑
Ancillary services	◕
Behind the meter/customer management	○

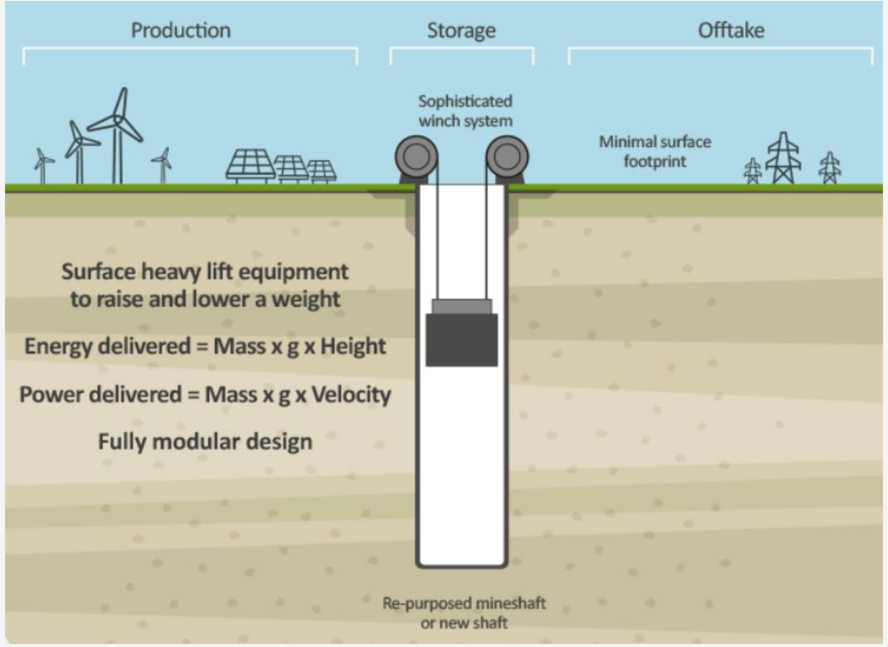
Sources: Kearney Energy Transition Institute analysis

Excess electricity is used to raise a mass (such as concrete blocks) to store gravitational potential energy which can be converted back to electrical energy later

FactCard: GES

1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

9.4 Appendix of section 2 Electricity storage technologies



Pros	Cons
• No geographic constraints unlike conventional PHS • High efficiency • Lower costs • Flexible and modular • Possible storage for other fluids (e. g. hydrogen)	• Nascent technology • Safety concerns • Challenges in scaling up

Sources: Kearney Energy Transition Institute analysis

Overview and working principle

- Gravity energy storage (GES), also known as hydraulic rock storage or gravity battery, is premised on storing gravitational energy of an object (usually concrete mass) resulting from a change in height (achieved through externally supplied electricity).
- There can be different designs of GES such as using renewable energy to pump water under a heavy piston and lift it. When power is needed, the piston weight is released, forcing the water through a hydroelectric generator. However, the operating principle remains consistent in all of them.
- **PHS** is the most common form of gravity energy storage and usually works at a large scale.
- **Gravitricity and EnergyVault** are proposing solutions which use an existing mineshaft to support 1,000s of tonnes of mass to store electricity which can operate on MWh/MW scale.
- **GravityLight** is an example of a small-scale gravity-powered light that operates by manually lifting a bag of rocks or sand up and then letting it fall by itself to generate energy. It is useful in off-grid areas and is commercially available in few countries.
- Gravity energy storage can use and extend the life of existing infrastructure (used mines, grid connections, etc.) utilizing embedded costs while saving Gravity Light decommissioning costs.

GES: FactCard

Technology R&D / innovation focus areas

– Addressing technical challenges such as torques exerted by the steel cables as they untwist while lifting the weight

– Integrating with existing assets such as Energy Vault's Rudong (China) project which is under construction directly adjacent to a wind farm and national grid

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	kWh–100 MWh	◕
Power capacity	kW–25 MW	◑
Discharge duration	h	◑
Response time	s	◕
Efficiency	80%	◕
Cycles	$5X10^4$	◑
Lifetime	35–50+ years	●

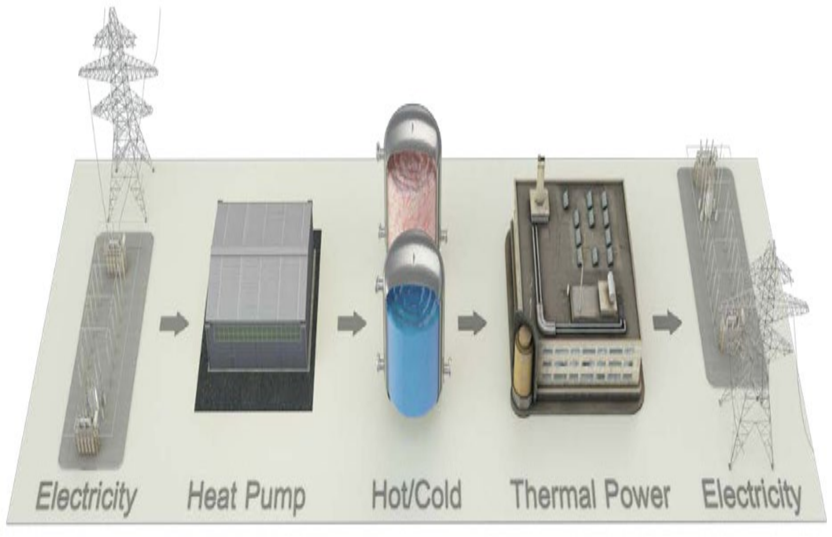
Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	●
Transmission support	◕
Distribution support	◑
Ancillary services	◕
Behind the meter/customer management	○

Sources: Kearney Energy Transition Institute analysis

Thermal energy storage systems consisting of heating storage technologies can be used to accumulate heat and deliver electricity over long durations



Overview and working principle

- Carnot batteries are medium- and long-duration electricity storage technologies based on the power to heat conversion, heat/cold storage, and heat use or electricity reconversion.
- Electrothermal energy storage systems are built upon well-established principles in thermodynamics:
  1. **Collection:** Energy is gathered from wind, solar, or fossil generators on the grid as electrical energy.
  2. **Conversion:** The electricity drives a heat pump, which converts electrical energy into thermal energy by creating a temperature difference.
  3. **Storage:** The heat is then stored in molten salt, while the cold is stored in a chilled liquid.
  4. **Re-conversion:** The temperature difference is converted back to electrical energy with a heat engine (usually Rankine or Brayton cycle).
  5. **Distribution:** Electricity is sent back to the grid when it is needed. Clean, co-generated steam is used for district heating or industrial use.
- Different variants of this technology exist depending on the material used for the conversion phase and the temperature limits of each material. The different types include concrete modules, sand, ceramic, rock beds, steel rods, molten salts, liquid CO_2, and air (LAES).
- All these technologies are at different levels of development, some are in research and development scales, while others are in demonstration stage with the first pilot and commercial plants operating.
- Also called pumped thermal electricity storage (PTES) or pumped heat storage (PHES).

Pros	Cons
• Generally suitable for long storage duration • Reduced land and environmental footprint • Abundant raw materials • Site flexibility • System integration and scalability	• Molten salts can be corrosive, and repair/maintenance is costly • LAES technologies may have higher costs and lower efficiencies • Liquid CO_2 presents safety concerns

Sources: Novotny, V. et al.; "Review of Carnot battery technology commercial development", 2022; NREL, Carnot batteries for electricity storage, 2019; Kearney Energy Transition Institute analysis

FactCard: Carnot batteries

1 Electrical storage
2 Electrochemical storage
3 Mechanical storage
4 Thermal storage
5 Chemical storage

Basalt battery: FactCard

Technology R&D/innovation focus areas

- High-temperature compressor technologies
- Modeling and control of the high temperature cycle
- Dynamic modeling and control of the entire system

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	MWh – GWh	●
Power capacity	10 MW – 1 GW	◕
Discharge duration	h–days	●
Response time	s–min	◑
Efficiency (power to power)	60–70%	◑
Cycles	~10,000	◔
Lifetime	>30 years	◕

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	◑
Distribution support	◔
Ancillary services	◔
Behind the meter/customer management	◔

Sources: Kearney Energy Transition Institute analysis

Molten salt (standalone): FactCard

Technology R&D / innovation focus areas

- Corrosion mitigation in a molten salt environment
- Stability of the components during fast discharge phases

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	1 GWh	●
Power capacity	50–200+ MW	◕
Discharge duration	h–weeks	●
Response time	s–min	◑
Efficiency (power to power)	55–90%	◑
Cycles	<10,000	◔
Lifetime	>30 years	◕

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	◕
Transmission support	◑
Distribution support	◔
Ancillary services	◔
Behind the meter/customer management	◔

Sources: Kearney Energy Transition Institute analysis

Sand battery: FactCard

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	1 GWh	●
Power capacity	< 100 MW	◕
Discharge duration	h–weeks	●
Response time	s–min	◑
Efficiency (power to power)	20–30%	◔
Cycles	<10,000	◔
Lifetime	>50 years	●

Technology R&D / innovation focus areas

– Polar Night will start a two-year program of development and commercialization of its electricity production, i.e., power-to-heat-to-power capabilities

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	NA
Transmission support	NA
Distribution support	NA
Ancillary services	NA
Behind the meter/customer management	NA

9.4 Appendix of section 2
Electricity storage technologies

Sources: Kearney Energy Transition Institute analysis

LAES: FactCard

Technology R&D / innovation focus areas

- Efficient storage and internal use of hot and cold energy streams within LAES process is key to performance. Several technological solutions for thermal recycle have been proposed which adopt different heat transfer fluids, storage media, and TES (thermal energy storage) configurations.
- Integrating LAES with external thermal sources can enhance its performance and make it a more versatile energy storage system.

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	10 MWh–7.8 GWh	●
Power capacity	5–650 MW	●
Discharge duration	h	◕
Response time	min	◔
Efficiency	45–70%	◑
Cycles	22,000–30,000	◑
Lifetime	40 years	◕
CAPEX: energy	60 to 600 €/kWh	◔
CAPEX: power	500 to 3,500 €/kW	◕

Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	●
Transmission support	◕
Distribution support	◕
Ancillary services	◕
Behind the meter/customer management	◑

Sources: Kearney Energy Transition Institute analysis

Liquid CO_2 storage: FactCard

Technology R&D / innovation focus areas

– Maintaining long life of heat exchangers to last (potentially) decades, i.e., plant's lifetime

9.4 Appendix of section 2
Electricity storage technologies

Key data

Low/slow ○ ◔ ◑ ◕ ● High/fast

Energy capacity	4–200 MWh	◕
Power capacity	2–25 MW	◑
Discharge duration	h	◕
Response time	s	◕
Efficiency	75%	◑
Cycles	NA	NA
Lifetime	30+ years	◕

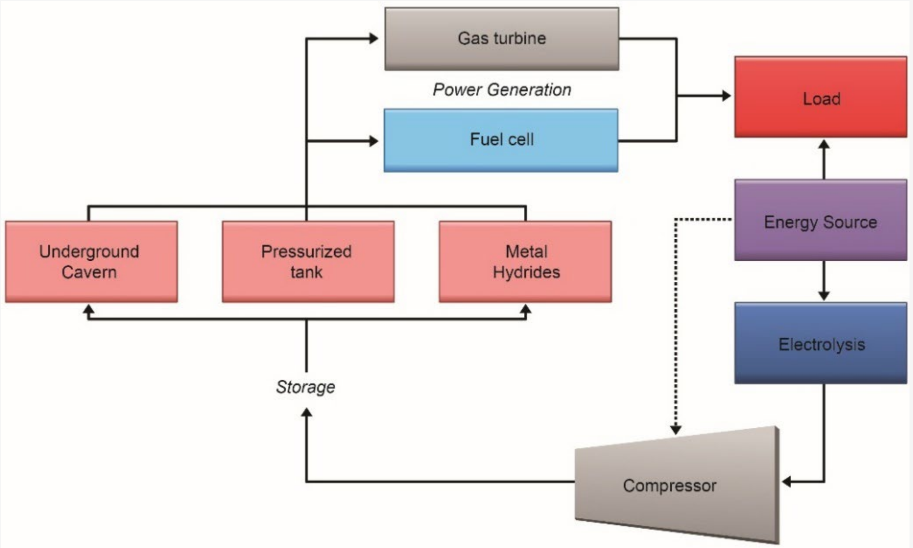
Applications

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

Generation support and bulk storage	●
Transmission support	◕
Distribution support	◕
Ancillary services	◕
Behind the meter/customer management	◑

Sources: Kearney Energy Transition Institute analysis

Chemical storage, typically hydrogen produced by water electrolysis using renewable energy, can offer inter-seasonal storage



Pros	Cons
• Scalable from distributed to long-term, large-scale storage • Low detrimental effect on environment	• Low round-trip efficiency • High capital cost • Safety concerns • Low energy density at ambient conditions

Overview and working principle

- Hydrogen energy storage technologies are based on the chemical conversion of electricity into hydrogen. Electrolysis is used to split water (H_2O) into its constituent elements, hydrogen (H_2) and oxygen (O_2). Due to its low atomic mass, it has an unrivalled specific energy. The electrolysis process can be reversed (i.e., hydrogen and oxygen generate electricity and water) to feed electricity back into the grid, using a fuel cell. Otherwise, hydrogen can be passed through heat engines in a similar way to natural gas, to produce electricity.
- Hydrogen can be stored in three main ways, each with different implications for the energy capacity of the system and its layout: as a gas in very large underground caverns within geological formations or in high-pressure tanks; as a liquid in cryogenic tanks; or as solid or liquid hydrides (e.g., ammonia, magnesium). Hydrogen-storage technologies can capitalize on the experience of the chemicals and petrochemicals industries, which have long used hydrogen as a feedstock. These technologies have minimal environmental impacts and are highly reliable and responsive. However, some losses are unavoidable during the conversion and reconversion process, and investments in conversion facilities are required.
- Power to X pathway: Conversion to hydrogen enables energy to be stored as gas and opens up the use of existing gas infrastructure. Further, it can also be used to derive synthetic fuels and liquids such as ammonia, methane, methanol, etc.
- However, the technology is still under development. The efficiency is low and infrastructure needs to be developed.

Sources: Kearney Energy Transition Institute analysis

FactCard: Chemical storage

Chemical storage: FactCard

Key data

	Hydrogen		Ammonia		Methane		Methanol/Gasoline	
Energy capacity	kWh–GWh	●	MWh–GWh	●	MWh–GWh	●	MWh–GWh	●
Power capacity	kW–GW	●	MW to GW	●	MW to GW	●	MW to GW	●
Discharge duration	h–weeks	●	weeks	●	weeks	●	weeks	●
Response time	s–min	◑	s	◕	s	◕	s	◕
Efficiency	20–40%	◔	NA	NA	NA	NA	NA	NA
Lifetime	5–30 years	◑	30 years	◑	30 years	◑	30 years	◑

Low/slow ○ ◔ ◑ ◕ ● High/fast

Applications

	Hydrogen	Ammonia	Methane	Methanol/Gasoline
Generation support and bulk storage	◕	NA	NA	NA
Transmission support	○	NA	NA	NA
Distribution support	◔	NA	NA	NA
Ancillary services	◕	NA	NA	NA
Behind the meter/customer management	◔	NA	NA	NA

Limited coverage ○ ◔ ◑ ◕ ● Stronger coverage

As the focus of the FactBook is electricity storage, chemical storage solutions can be found in a dedicated **FactBook: Hydrogen applications and business models**

9.4 Appendix of section 2 Electricity storage technologies

Summary of the technical performance of the different battery types

Battery	Energy capacity	Power capacity	Specific energy (Wh/kg)	Specific power (W/kg)	Energy density (Wh/L)	Power density (W/L)	Daily self discharge[2] (%)	Discharge duration	Efficiency	Cycles	Lifetime
Deployed chemistries											
Lithium ion	< 1 GWh	< 500 MW	75–207	80–370	150–500	50–5,000+	0.036–0.33	30 min–6 h	85–90%	1,500–3,500	10–20 years
Lead acid	< 10 MWh	< 40 MW	15–50	25–415	25–100	10–700	0.1–0.3	1–6 h	75–85%	250–2,000	8–20 years
Sodium sulphur HT[1]	100 kWh–300 MWh	Few kW–100 MW	100–240	150–230	150–280	150–300	0.05–20	< 7 h	75–85%	4,000–7,300	10–20 years
Sodium nickel-chloride	Few kWh–10 MWh	< 5 MW	100–120	150–200	100–190	54–500	11–15	< 4 h	80–90%	2,500–4,500	10–20 years
Vanadium flow	10 kWh–800 MWh	< 200 MW	10–35	80–166	10–70	0.5–34	0.2	10–12 h	60–80%	10,000+	10–25 years
Nickel–cadmium	Few MWh	< 40 MW	30–80	100–300	15–150	100–450	0.2–0.6	min–h	60–70%	1,000–5,000	10–25 years
Nickel–metal hydride	Few MWh	< 3 MW	30–90	177–220	83–320	7.8–580	5–20	min–h	50–80%	300–1,800	5–15 years
Emerging chemistries											
Sodium-ion	< 1 MWh	< 250 kW	140–160	100–300	200–300	NA	NA	< 5 h	< 92%	100–1,000	15 years
Lithium air	Few MWh	Few MW	< 500	NA	NA	NA	NA	h	60–80%	< 550	NA
Zinc air	Few MWh	Few MW	150–300	NA	100–200	NA	NA	h	55–65%	< 100	NA
Lithium sulphur	NA	NA	> 300	< 500	300–450	NA	NA	NA	< 89%	50–300	NA
Lithium polymer solid state	< 30 MWh	< 10 MW	255	NA	380	NA	10	1–3 h	< 97%	4,000	15 years
Zinc bromide flow	< 100 MWh	< 10 MW	20–50	90–110	20–60	2.58–6	0.24	< 10 h	70–75%	2,000–3,000	5–15 years

[1] HT: high temperature; [2] Percentage of energy lost per day
Sources: ENTEC - Energy Transition Expertise Centre, 2023, "Study on Energy Storage"; Kebede et. al, 2022, "A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration"; Behabtu et. al, 2020, "A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration"; Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Advanced-stage battery storage technologies[1]

	Lithium-ion batteries	Lead-acid batteries	Molten sodium-based batteries	Flow batteries
Definition and technology focus	– Typically, in this rechargeable electrochemical cell, the positive electrode is a lithium metal oxide and the negative electrode is graphite. The electrolyte is composed of a lithium salt (e.g., LiPF6) in a mixture of organic solvents – Dominant electrochemical grid energy storage technology due to high energy density, high power, high efficiency, and low self-discharge. However, resource shortage (especially cobalt), recycling, and enhancing safety remain key challenges.	– Basic components of a typical rechargeable lead-acid electrochemical battery system include a lead dioxide (PbO2) positive electrode, a spongy lead (Pb) negative electrode, an electrolyte solution made of higher concentration of aqueous sulfuric acid solution (H2SO4(aq)), and water. – Has low upfront capital costs but lower energy density and a relatively short life span compared to other battery technologies	– Electrochemical cells that use molten sodium anode and a ceramic sodium-ion conducting solid-state separator, most commonly β”-alumina (BASE [Beta Alumina Solid Electrolyte]) along with molten cathode. – While still relatively expensive, molten sodium battery chemistries are technologically mature enough for global deployment on the scale of hundreds of megawatt-hours (MWhs) while offering high energy density, low levels of self-discharge (which correspond to higher efficiencies), and relatively long cycle life.	– Rechargeable electrochemical cell stores and releases energy through the circulation of electrolyte solutions stored in external tanks. The electrolytes flow through the cell stack during charging and discharging processes. – Could potentially deliver high scalability, high storage capacity, and long cycle life.
Sub-technologies	– **Lithium nickel manganese cobalt (NMC)** uses mixed metal oxides of lithium, nickel, manganese, and cobalt with the general formula LiNixMnyCo1-x-yO2 as cathode. It outperforms other cathode materials in energy density and specific energy, performance, calendar, and cycle life and costs. Hence, it is the dominant chemistry in the market currently. – **Lithium nickel cobalt aluminum (NCA)** is composed of the cations of the chemical elements lithium, nickel, cobalt, and aluminum as cathode. The compounds of this class have a general formula LiNixCoyAlzO2 with x + y + z = 1. – **Lithium iron phosphate (LFP)** uses lithium iron phosphate (LiFePO4) as the cathode material alongside a graphite carbon electrode with a metallic backing as the anode. LFP is currently being improved by substituting iron with manganese to form LiFe1-xMnxPO4 (LMFP), which increases cell voltage.	– **Vented lead-acid (VLA)** is a flooded or ventilated electrolyte lead-acid battery, where the electrodes are submerged in excess of liquid electrolyte. – **Valve-regulated lead-acid (VRLA)** is sealed or regulated by a valve where the electrolyte is immobilized in an absorbent separator or in a gel.	– **Sodium sulphur (NaS)**: it oxidizes (discharges) and reduces (charges) sodium, relying on the reversible reduction (discharge) and oxidation (charge) of molten sulfur. This battery operates at a high temperature, hence it is referred to as NaS HT. – **Sodium-nickel chloride (Na-NiCl2, ZEBRA)**: like the NaS battery, it relies on the oxidation and reduction of sodium at the anode and uses a BASE separator, but instead depends on the oxidation and reduction of nickel metal at the cathode. Specifically, the cathode reaction is supported in a metal halide molten salt electrolyte.	– **Vanadium redox (VRB)** uses vanadium ions in different oxidation states (V2+/V3+ and V4+/V5+) as the electroactive species in both the anolyte and catholyte. – **Polysulphide bromine (PSB)** uses sodium disulfide, a solution pumped to the sodium tribromide anode (NaBr3). – **Iron-chromium redox**: the anode and cathode electrolytes contain iron and chromium ions in different oxidation states. – **Zinc-bromine (Zn Br)** uses zinc and bromine as the electroactive species. During discharge, zinc is oxidized at the anode, releasing electrons. The bromine at the cathode is reduced to bromide ions. During charging, these reactions are reversed. – **Organic redox,** early stage focusing on organic molecules as electroactive species in redox flow batteries. Organic redox flow batteries aim to utilize organic compounds in the electrolyte, providing a potentially cost-effective and more environmentally friendly option.

1. Except nickel-based batteries. Ni-Cd is widely banned in EU due to toxicity concerns and its replacement, Ni-MH, is now being phased out of storage applications by Lithium-ion.
Sources: Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Early-stage battery storage technologies

	Metal ion batteries[1]	Metal sulphur batteries[2]	Metal air batteries	Solid-state batteries
Definition and technology focus	– Employs a metal cathode, a non-selective, electrically insulating porous polymer separator, a carbon or a titanate anode, and an organic or aqueous liquid electrolyte. – Lithium ion is the most mature representative, but more cost effective and sustainable alternatives are being researched.	– Electrochemical cell using metallic anode along with sulphur as a cathode active material. – This battery chemistry is in focus due to high availability, low price, and low weight of sulphur. Challenges include low electronic conductivity and short cycle life.	– Electrochemical cells that use a metal as the anode and oxygen from the air as the cathode. Could potentially deliver high energy density. – Challenging electrode degradation, electrolyte stability, and practical issues related to re-chargeability and cycle life need to be addressed for widespread commercial adoption.	– Use solid electrolytes instead of liquid electrolytes. – Potentially improve safety, deliver higher energy density, and longer cycle life. – Still in the early stages of development and face challenges such as manufacturing scalability, cost, and optimizing performance.
Sub-technologies	– **Sodium-ion (Na-ion)** uses cathode consisting of a sodium-based material, an anode (not necessarily a sodium-based material and usually carbon-based), and a liquid electrolyte consisting of sodium salts with small amounts of additives. – **Potassium-ion (K-ion)** has the same working principle as Li-ion and Na-ion with the cation being potassium. K-ion also relies on abundant materials for its leading cathode and anode materials. Unlike Na-ion, K-ion can use graphite anodes which means it can use the graphite anode supply chains developed for Li-ion. – **Magnesium-ion batteries** are similar to Li-ion and Na-ion with the difference that the anode is made of metallic Mg. Material research is ongoing for the cathode and the electrolyte. – **Zinc-ion batteries** utilize Zn as the anode, Zn-intercalating materials as the cathode, and a Zn-containing electrolyte. However, research is still being carried out into suitable material combinations. – **Aluminum-ion batteries** use Al foil and graphite as electrodes combination and an electrolyte of ionic liquids.	– **Lithium sulphur (LiS)** is mainly a liquid electrolyte-based system with thin Li-metal (< 30 µm) as anode and S as cathode. It features a discharge voltage between 2.4 and 2.0 V and is the most advanced Me-S battery type for room temperature (RT) operation. It can potentially offer high gravimetric energy. – **Sodium sulphur (NaS)** substitutes the resource-critical Li with Na. In general, the main setup and working principle of Li-S and Na-S batteries are comparable, with significant differences due to the higher reactivity of Na. This battery operates at room temperature instead of high temperatures; hence it is referred to as NaS RT (i.e., different from molten sodium batteries NaS HT). – **Multivalent metals (such as Mg, Ca, and Al) sulphur** uses metal ion as its charge carrier, metal as anode, and sulfur as cathode. They require non-standard electrolytes which are based on solvents and salts.	– **Iron-air**: uses iron as the anode and oxygen as the cathode. Iron undergoes oxidation at the anode during discharge, generating electrical energy. Iron-air batteries are being studied for their potential in grid-scale energy storage due to the abundance and low cost of iron. – **Sodium-air**: use sodium as the anode and oxygen as the cathode. Sodium-air batteries are being investigated as an alternative to lithium-based systems, with potential applications in large-scale energy storage. – **Lithium-air**: lithium serves as the anode and oxygen as the cathode. During discharge, lithium ions move from the anode to the cathode, reacting with oxygen to produce lithium oxide and electrical energy. Lithium-air batteries have the potential for even higher energy density than lithium-ion batteries, making them attractive for electric vehicles and portable electronics. – **Zinc-air**: zinc serves as the anode, and oxygen from the air reacts with the cathode. The zinc electrode undergoes oxidation, releasing electrons that flow through an external circuit, producing electrical power. – **Aluminum-air**: aluminum serves as the anode and oxygen as the cathode. During discharge, aluminum is oxidized at the anode, releasing electrons. Key challenges related to aluminum corrosion and electrolyte management.	– **Lithium-ion (Li-ion)**: replace the liquid electrolyte with a solid electrolyte, typically a ceramic material or a polymer. Solid-state Li-ion batteries have the potential to offer higher energy density and longer cycle life compared to traditional Li-ion batteries. – **Sodium-ion**: use a solid electrolyte but with sodium ions instead of lithium ions. Sodium is more abundant and less expensive than lithium, making it an attractive alternative for large-scale energy storage applications. – **Lithium-polymer**: combine the advantages of solid-state technology with the flexible form factor of lithium polymer batteries. They use solid electrolytes in a polymer matrix, providing flexibility and potentially enabling new form factors for devices. – **Lithium-sulphur**: use sulphur as the cathode material, and in solid-state configurations, they replace the liquid electrolyte with a solid electrolyte. Solid-state lithium-sulphur batteries have the potential to offer higher energy density and lower cost compared to traditional lithium-ion batteries. – **Magnesium:** use magnesium ions instead of lithium ions for charge transport.

[1] Except lithium-ion batteries (mature);[2] Except molten sodium sulphur batteries which operate at high temperature (NaS HT)
Sources: Fraunhofer ISI, 2023, "Alternative Battery Technologies Roadmap 2030+"; Fraunhofer ISI, 2022, "Solid State Battery Roadmap 2035+"; Kearney Energy Transition Institute analysis

Paper and paper-like substrates have been explored to design biodegradable battery systems

Currently, power output of paper batteries is low (i.e. μW–mW), making them unsuitable for energy storage applications.

However, the research is focused on optimizing electrode materials, electrolyte formulations, and device architectures.

9.4 Appendix of section 2 Electricity storage technologies

Overview

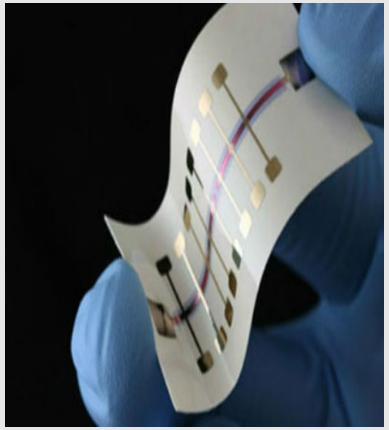
Cellulose paper's suitability as a substrate for energy storage devices is demonstrated by its good conductivity, porosity, and chemical stability. Further, paper can play various roles within the battery system, such as a current collector when coated with conductive material, substrate for electrode deposition, and electrolyte storage:

– Cell components such electrolytes and separators are integrated on the paper substrate to create fully functional paper-based batteries (with operating principle similar to a classic battery).

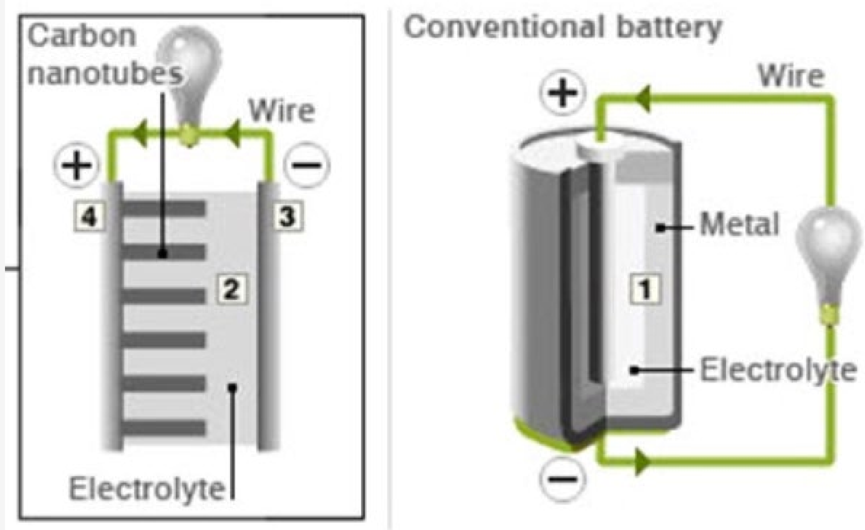
– The fabrication process for paper-based batteries involves the amalgamation of highly conductive materials such as metals, conductive polymers, and allotropes of carbon; graphite, fullerenes, graphene, carbon nanotubes, nanocrystals, and nanowires with an ordinary sheet of paper.

Applications

Different applications targeted by paper-based batteries include low-power electronics, medical sensors, and disposable devices: Fluidic batteries for on-chip fluorescence assay analysis on microfluidic paper-based analytical devices (μPADs), urine-activated paper battery for biosystems, photoelectrochemical paper devices combined into supercapacitors, microbial paper-based fuel cells for disposable diagnostic devices, etc.



Comparison with classic battery



Pros	Cons
• Biodegradable and recyclable • Safety as no leakage, overheating, toxicity, and corrosion concerns compared to classic batteries	• Performance and integration within a paper-based system is a challenge • Fabrication of paper substrates is either time-consuming or costly

Note: μW corresponds to microwatts and mW correspond to miliwatts.
Sources: Juqu et al., 2022, "Advances in paper-based battery research for biodegradable energy storage," Advanced Sensor and Energy Materials; Kearney Energy Transition Institute analysis

Calculation methodology of theoretical specific energy and energy density of for various types of batteries

9.4 Appendix of section 2 Electricity storage technologies

Calculation methodology of theoretical specific energy and energy density

Any chemical reaction in which charge transfer occurs can be used for electrochemical energy storage (A and B: reactants; C and D: products, α, β, γ, and δ: coefficients). In general, such a reaction can be written as:

$$\alpha A + \beta B \Rightarrow \gamma C + \delta D$$

Gibbs free energy of reaction under standard condition can be calculated by summing up Gibbs free energy of formation of the reactants and the products as shown in the following equation:

$$\Delta_r G = \gamma \Delta_f G_C + \delta \Delta_f G_D - (\alpha \Delta_f G_A + \beta \Delta_f G_B)$$

$\Delta_f G_C, \Delta_f G_D, \Delta_f G_A, \Delta_f G_B$ are the Gibbs free energy of reactants and products.

If Gibbs free energy of reaction is negative, the reaction occurs spontaneously under the standard condition. The maximum electrical work exerted from this reaction equals to Gibbs free energy of reaction when the reaction is reversible.

$$\Delta_r G = -nFE$$

Here n refers to the number of the charge transferred per mole of reactant, F is the Faraday constant (F = 96485 C/mol), and E is the thermodynamic equilibrium voltage or electromotive force (EMF). Specific energy could be expressed as the theoretical gravimetric energy density (TGED, Wh/kg). TGED of a battery can be calculated through the following formula:

$$TGED = \frac{\Delta_r G}{\sum_{i=A,B}^{2} \alpha_i M_i}$$

$\sum_{i=A,B}^{2} \alpha_i M_i$ is the sum of the molar mass of the reactants and $\Delta_r G$ is the Gibbs free energy of reaction, calculated from either one of the above-mentioned equations. Energy density could be expressed as the theoretical volumetric energy density (TVED, Wh/l). TVED of a battery can be calculated through the following formula:

$$TVED = \frac{\Delta_r G}{\sum_{i=A,B}^{2} \alpha_i V_i}$$

$\sum_{i=A,B}^{2} \alpha_i V_i$ is the sum of the molar volume of the reactants and $\Delta_r G$ is the Gibbs free energy of reaction, calculated from either one of the above-mentioned equations. The Gibbs free energy of formation of the reactants and the products, that is used, refers to 25°C.

Sources: Kearney Energy Transition Institute analysis

Appendix of section 4: Cost of electricity storage

Lifetime costs account for several cost components of a storage technology

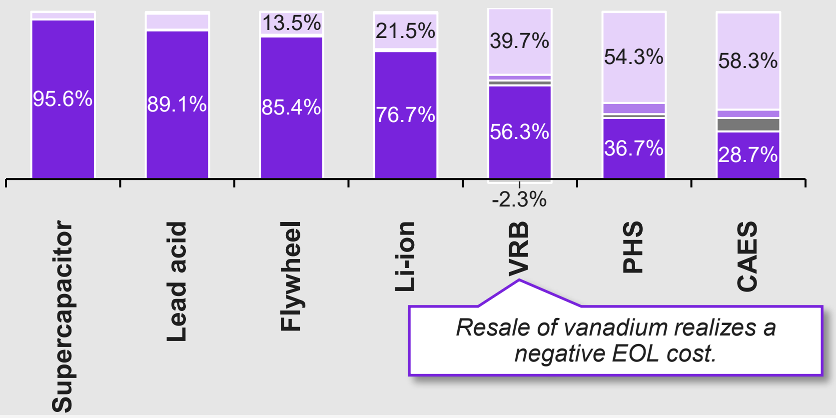
Cost parameters for the calculation of lifetime cost of a storage technology

Cost component	Description
Investment cost	– The total of the **sum of the specific investment costs for power components** (multiplied by power capacity) and the **sum of the specific investment cost for energy components** (multiplied by energy capacity) – Costs that cannot be readily allocated to power or energy, such as engineering and installation, are equally split across the two.
Opex	– Represented on an annual basis by taking the **sum of the fixed components** (multiplied by power capacity) **and the variable component** (multiplied by energy discharged per year) – Accounts for energy capacity degradation – Discounted on an annual basis to reflect future value
Replacement cost	– The total of the **sum of the specific replacement costs for power components** (multiplied by power capacity) and the **sum of the specific replacement cost for energy components** (multiplied by energy capacity) within the technology's lifetime – Discounted to reflect future value
EOL cost	– Determined by the **sum of the cost or value of power components** (multiplied by power capacity) and **energy components** (multiplied by degraded energy capacity) at the end of the technology's lifetime – Discounted to reflect future value
Charging cost	– Represented on an annual basis by taking the **product of nominal energy capacity, annual cycles, depth-of-discharge, and electricity price, divided by round-trip efficiency** – Accounts for energy capacity degradation (and the consequent reduction in charging capacity) – Discounted on an annual basis to reflect future value

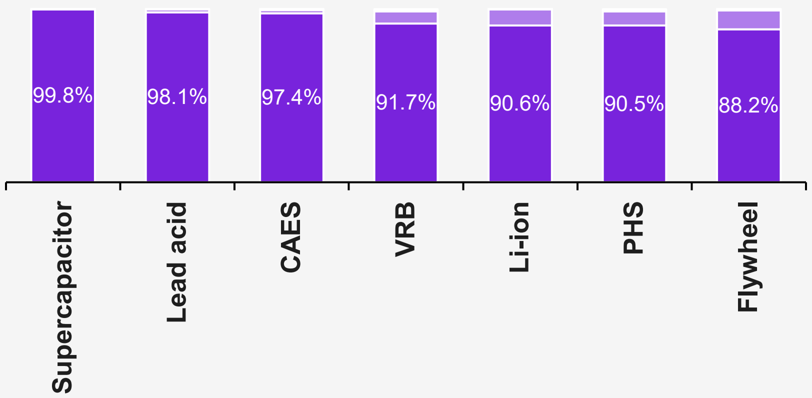
Sources: Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

Investment cost is the key driver of electricity storage cost, representing up to 99% of overall expenditure

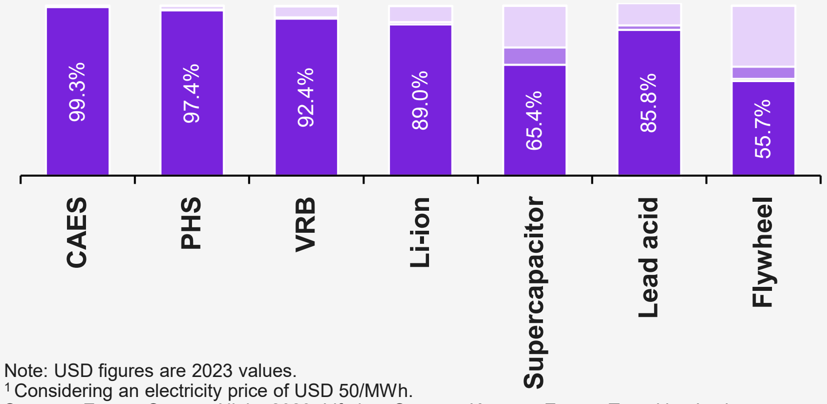
Cost breakdown for selected electricity storage technologies used for energy arbitrage
USD/kW-year basis



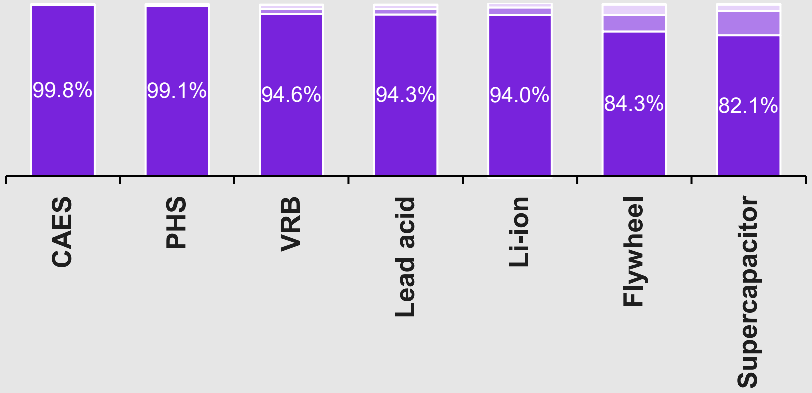
Cost breakdown for selected electricity storage technologies used for black start
USD/MWh basis



Cost breakdown for selected electricity storage technologies used for T&D upgrade deferral
USD/MWh basis



Cost breakdown for selected electricity storage technologies used for reliability and resilience
USD/MWh basis



Replacement
Opex
Charging[1]
EOL
Investment

Note: USD figures are 2023 values.
[1] Considering an electricity price of USD 50/MWh.
Sources: Energy Storage Ninja, 2023, Lifetime Storage; Kearney Energy Transition Institute analysis

9.5 Appendix of section 4
Cost of electricity storage

LCOS and ACC follow similar calculation methods, differentiated by the denominator of energy delivered and power capacity, respectively

LCOS quantifies the discounted cost **per unit of electricity discharged** for a specific technology and application by dividing its total lifetime cost by cumulative delivered electricity in $/MWh.

$$LCOS = \frac{\sum_n^N \frac{IC}{(1+r)^n} + \sum_n^N \frac{RC}{(1+r)^n} + \sum_n^N \frac{Opex}{(1+r)^n} + \sum_n^N \frac{CC}{(1+r)^n} + \frac{EOL}{(1+r)^{N+1}}}{\sum_n^N \frac{E_{Out}}{(1+r)^n}}$$

N = Final year; n = Initial year; IC = Investment cost ($); r = Discount rate; RC = Replacement cost ($/year); $OPEX$ = Operational expenditure ($/year); CC = Charging cost ($/year); EOL = End-of-life cost ($); E_{Out} = Electricity delivered (MWh/year)

ACC quantifies the discounted cost **per unit of electricity storage capacity** provided for a specific technology and application by dividing its total lifetime cost by cumulative power capacity in $/MW-year.

Calculations assume that the investment cost is paid in year zero and the system operates from year n to N

$$ACC = \frac{\sum_n^N \frac{IC}{(1+r)^n} + \sum_n^N \frac{RC}{(1+r)^n} + \sum_n^N \frac{Opex}{(1+r)^n} + \sum_n^N \frac{CC}{(1+r)^n} + \frac{EOL}{(1+r)^{N+1}}}{\sum_n^N \frac{CAP}{(1+r)^n}}$$

N = Final year; n = Initial year; IC = Investment cost (USD); r = Discount rate; RC = Replacement cost (USD); $Opex$ = Operational expenditure (USD); CC = Charging cost (USD); EOL = End-of-life cost (USD); CAP = Capacity provided (MW-year)

9.5 Appendix of section 4
Cost of electricity storage

Sources: Schmidt and Staffell, 2023, Monetizing Energy Storage; Kearney Energy Transition Institute analysis

Appendix of section 5: Battery value chain, from mining to recycling

Several options exist for the recycling of Li-ion batteries, which differ in terms of technology and cost

Illustrative

Comparison of different Li-ion recycling processes

Criteria	Pyrometallurgy	Hydrometallurgy	Direct recycling
Technology readiness			
Complexity			
Quality of recovered material			
Quantity of recovered material			
Waste generation			
Energy usage			
Capex			
Production cost			

Best — Worst

Sources: G. Harper et al., 2019, "Recycling lithium-ion batteries from electric vehicles," Nature; Kearney Energy Transition Institute analysis