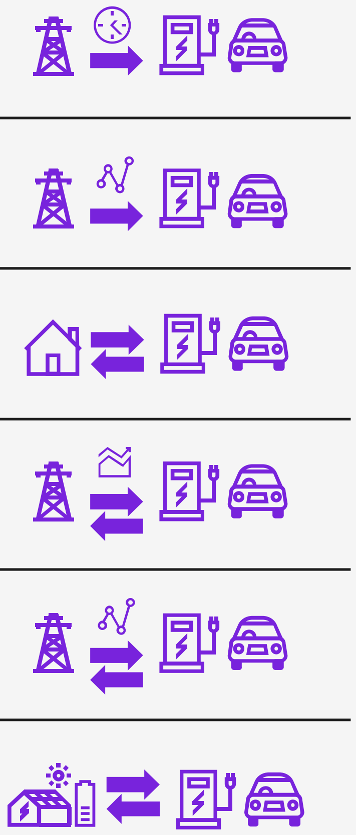
Smart EV charging offers power system flexibility, reduces grid reinforcement needs, and accommodates additional electricity demand

1.3 Electricity storage role and applications

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*

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

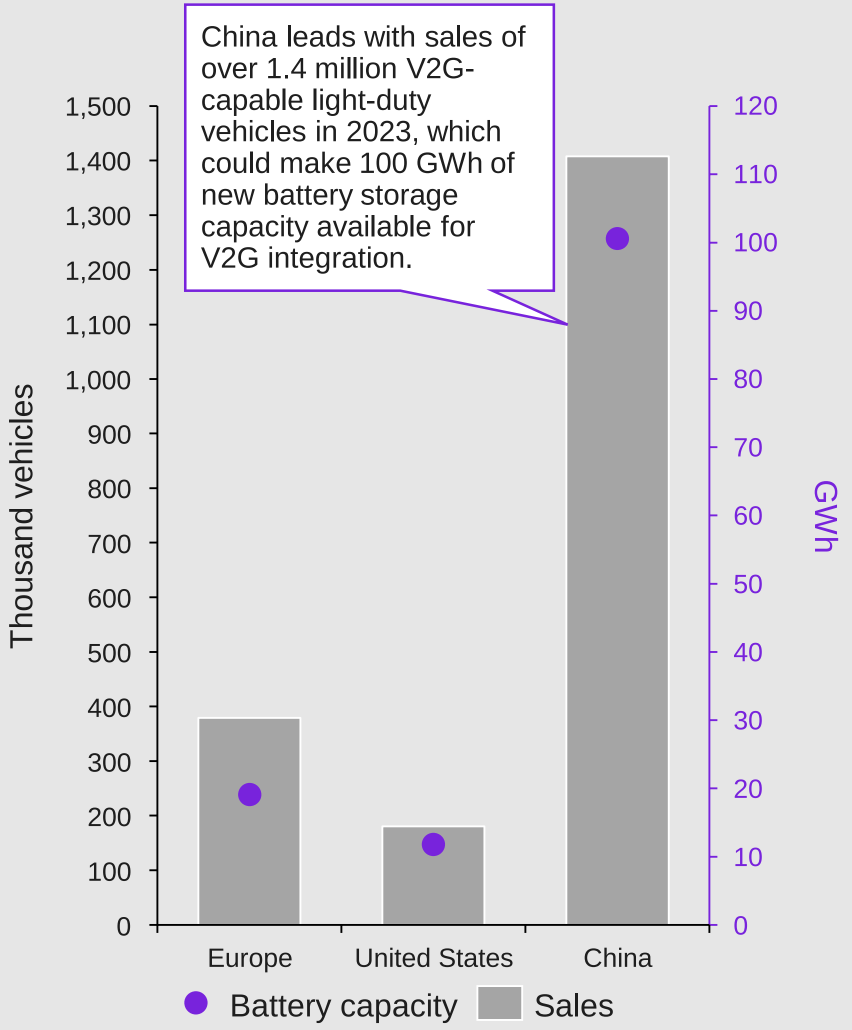
The relationship between EVs and electricity networks is evolving with vehicle-to-grid applications

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



China leads with sales of over 1.4 million V2G-capable light-duty vehicles in 2023, which could make 100 GWh of new battery storage capacity available for V2G integration.

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

Challenges for V2B and V2G deployment

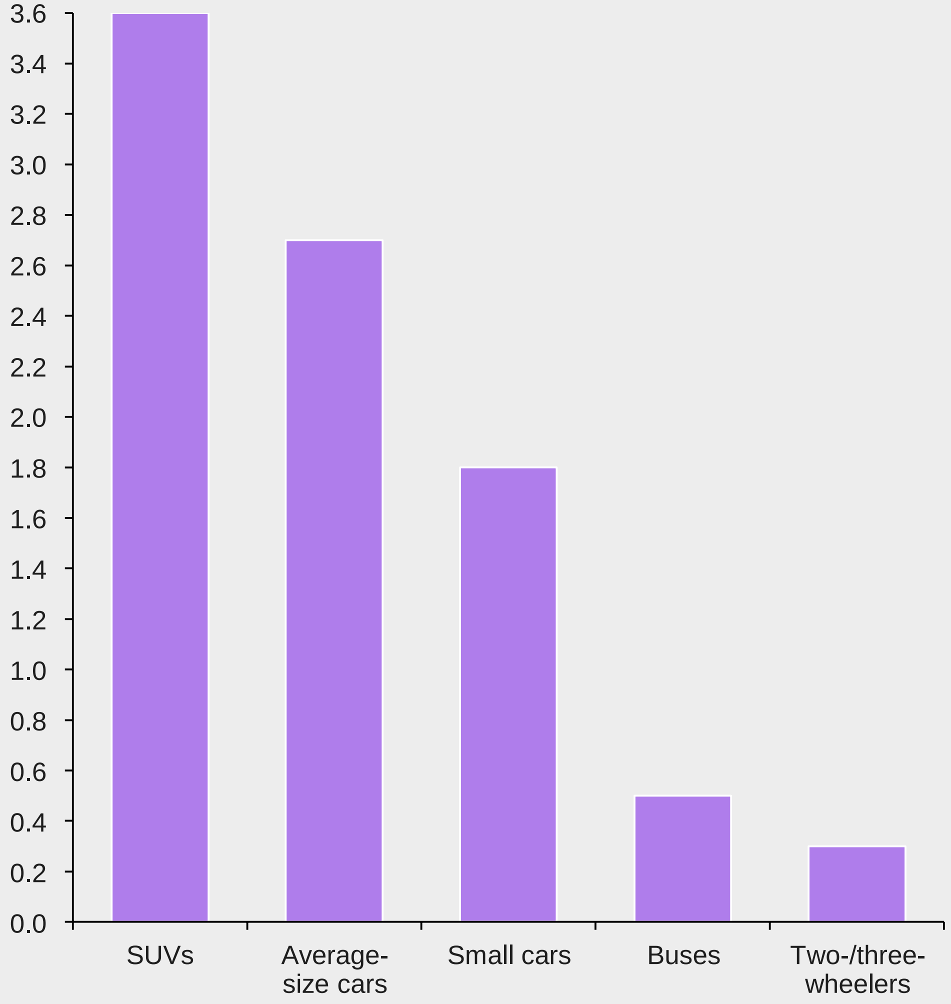
- **Electric vehicle (EV) batteries are typically designed for fewer cycles than storage batteries**, and additional cycling from V2G/V2B usage can accelerate battery degradation.
- V2G/V2B operations are usually not covered by EV battery warranties, **making these applications less attractive to consumers.**
- 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

1.3 Electricity storage role and applications

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).**

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

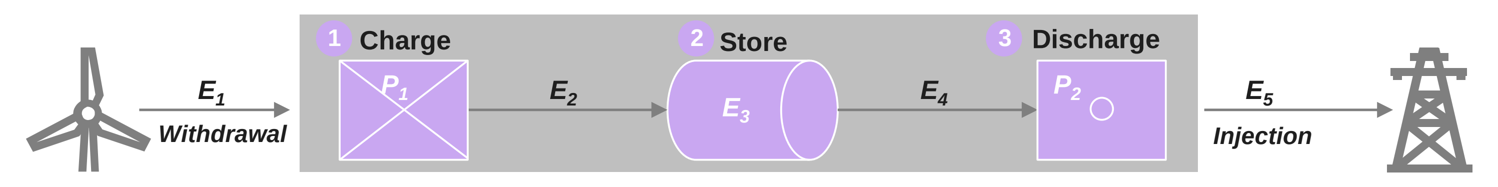
Illustrative

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.

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

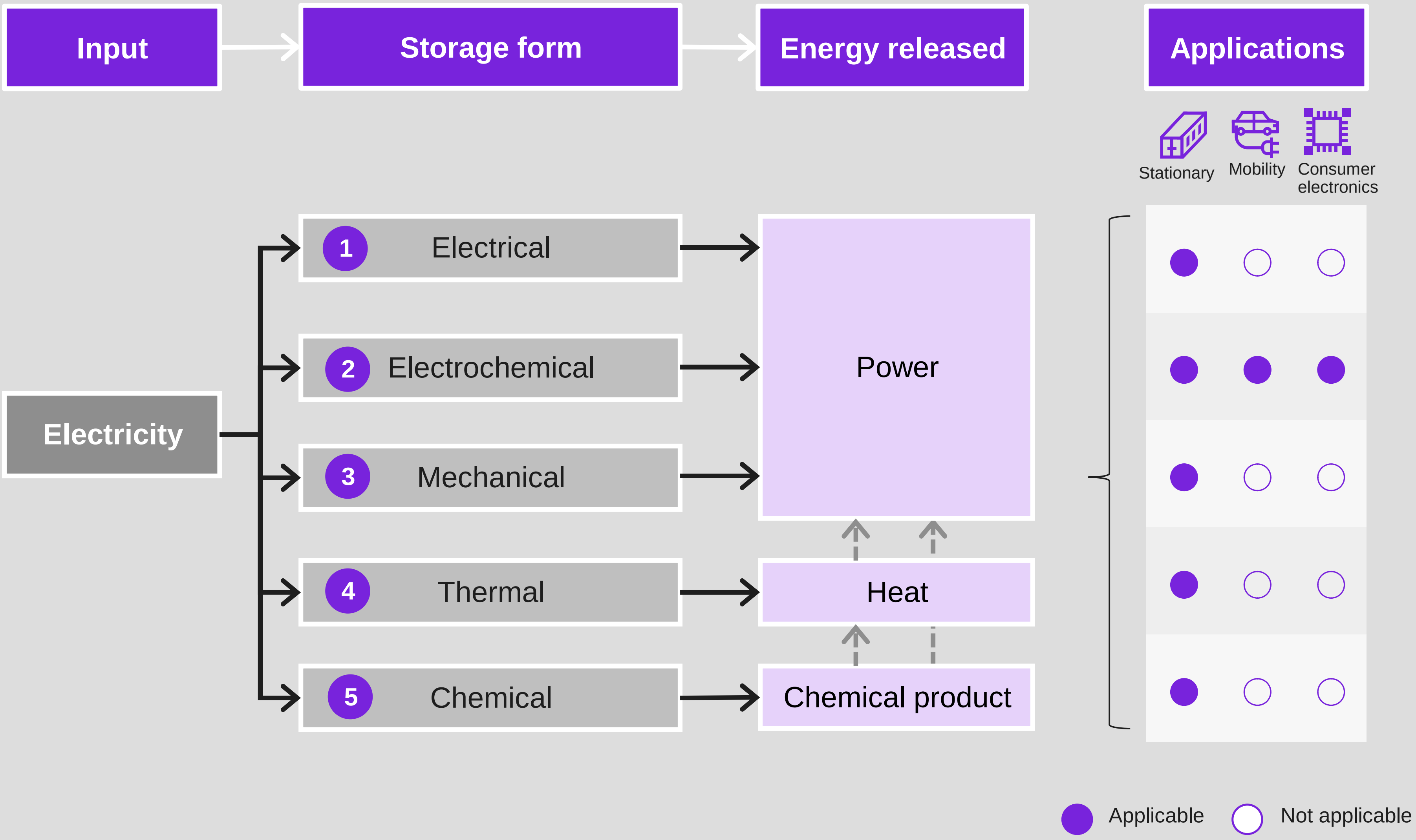
Scope definition:

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



Input	Storage form	Energy released	Stationary	Mobility	Consumer electronics
Electricity	1 Electrical	Power	●	○	○
	2 Electrochemical	Power	●	●	●
	3 Mechanical	Power	●	○	○
	4 Thermal	Heat	●	○	○
	5 Chemical	Chemical product	●	○	○

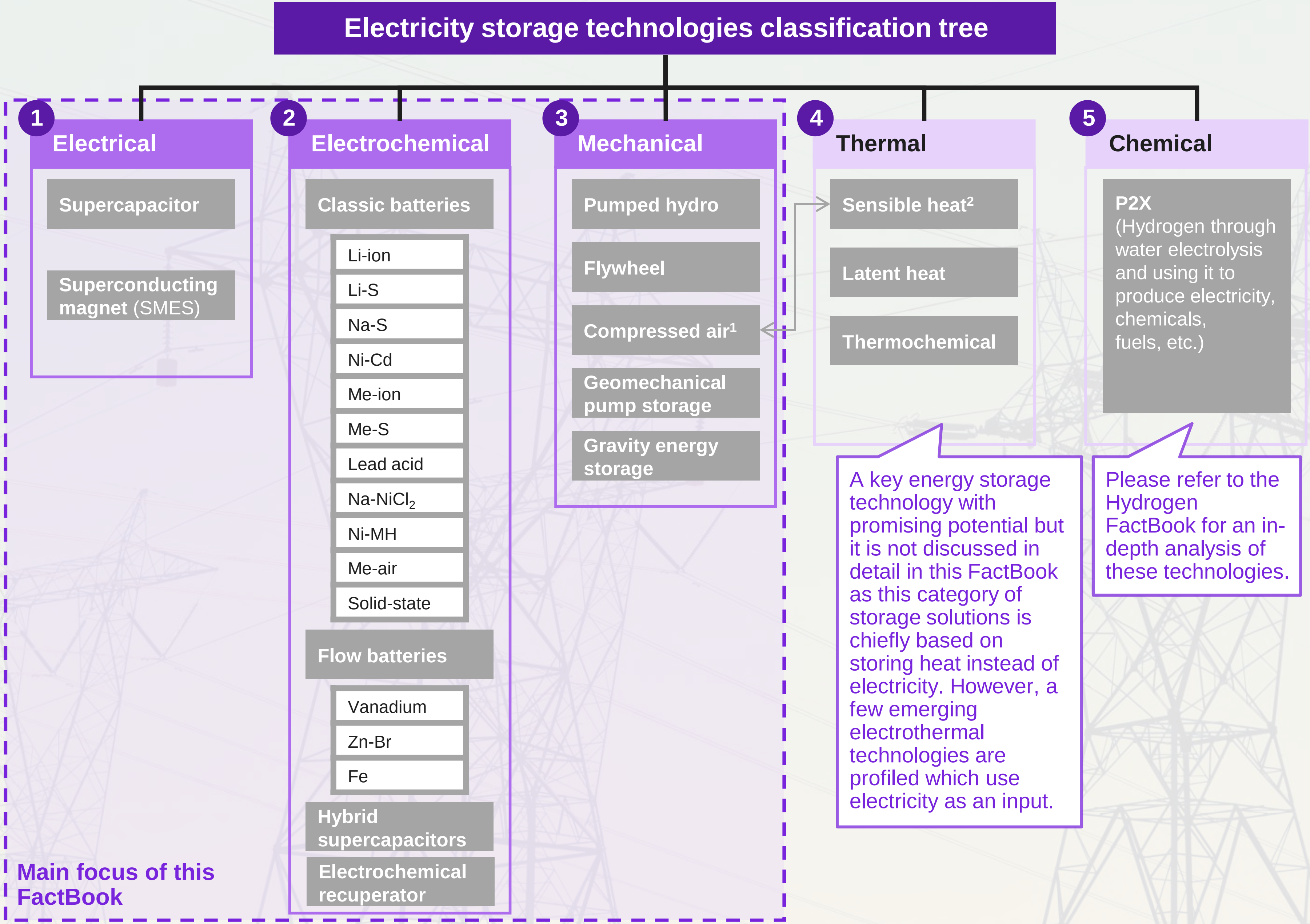
Applications

● Applicable ○ Not applicable

Source: Kearney Energy Transition Institute analysis

Overview of the various electricity storage technologies

Non-exhaustive



Electricity storage technologies classification tree

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

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

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.

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

Main focus of this FactBook

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