

Energy Storage Attributes and Applications

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Energy storage and energy storage attributes

(bidirectional) Energy storage refers to a technology capable of converting electricity into a storable form of energy and converting this stored energy back to electricity.

Technological properties

- Power and energy density
- Round-trip efficiency (ratio between energy output and energy input)
- Response time and power ramping rates (kW/sec)
- Ageing (two dimensions: cycle and calendar)
- Discharging/Charging power

Other important attributes

- Cost
- Scalability (how large a device can be)
- Environmental impact and life cycle

Power and energy density: Ragone Chart

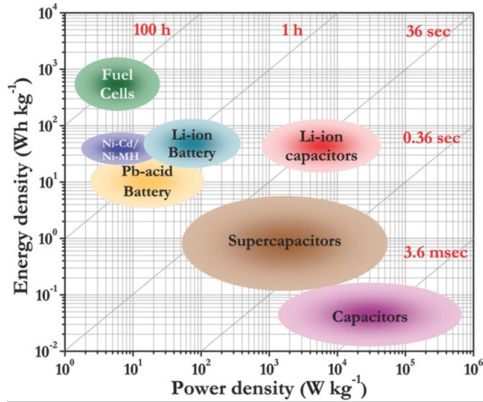


Figure: Ragone chart, Aravindan et al. (2014), Insertion-type electrodes for nonaqueous Li-ion capacitors. Chemical reviews.

Gasoline: 13 kWh/kg; Amprium lithium-ions energy cells: 0.45 kWh/kg.

Spatial power and energy density of generation sources

Hydropower spatial density is defined as the installed power generation capacity over the flooded surface area. Values are in the range $0.008 \text{ W/m}^2 \div 0.87 \text{ W/m}^2$ (Van Zalk et al. (2018), The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S.).

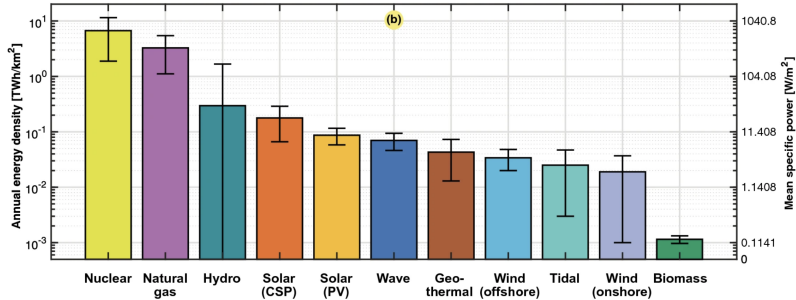


Figure: Average and standard deviation values of the annual energy and power density in log scale of various sources. Nøland et al (2022). Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep.

Cost projections of energy storage

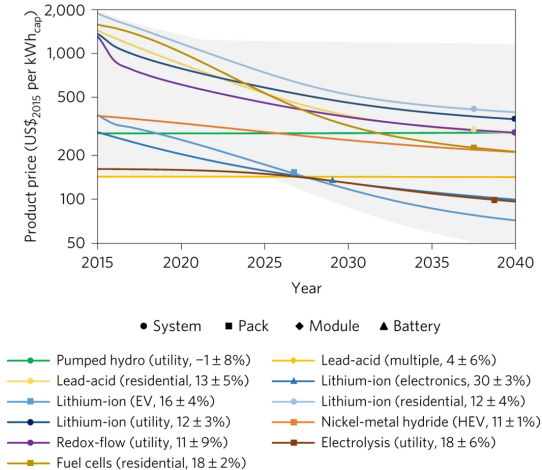
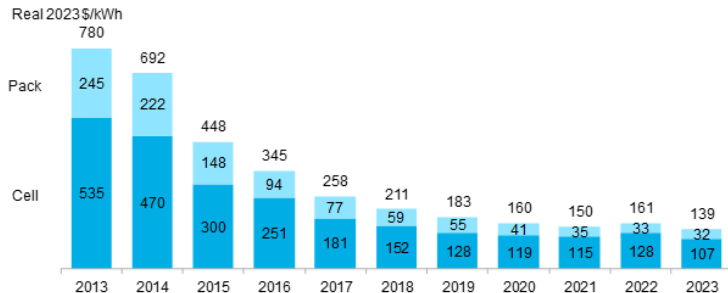


Figure: Cost projections of energy storage based on experience rates. Schmidt et al. (2017).
The future cost of electrical energy storage based on experience rates. Nature Energy.

Current costs of lithium-ion cells and modules

Figure 1: Volume-weighted average lithium-ion battery pack and cell price split, 2013-2023



Source: BloombergNEF. Historical prices have been updated to reflect real 2023 dollars. Weighted average survey value includes 303 data points from passenger cars, buses, commercial vehicles, and stationary storage.

Figure: Historical prices have been updated to reflect real 2023 US dollars. Weighted average survey value includes 303 data points from passenger cars, buses, commercial vehicles, and stationary storage. BloombergNEF (2023).

Round-trip efficiency

Monthly round-trip efficiency, by storage technology (Jan 2018–Dec 2019)

percent

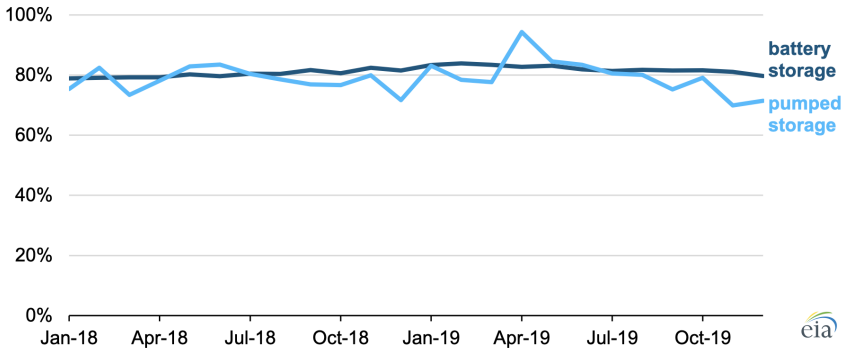


Figure: U.S. Energy Information Administration.

Round-trip efficiency (cont'd)

Some more evidence:

- Lithium-ion: 83%
- Pumped hydro 81%
- Vanadium redox flow: 75%
- Sodium sulfur: 75%
- Advanced lead-acid: 85%
- Flywheel: 81%.
- Compressed air: 50%
- Electrolysis + Fuel cell: 40%

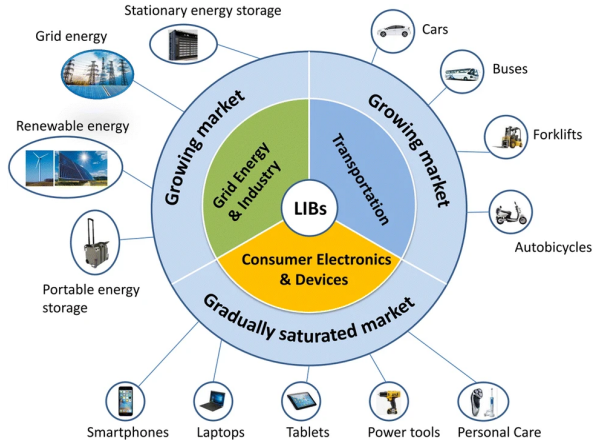
References: W.G. Manuel (2014) Energy Storage Study 2014, V. Viswanathan et al. (2013), National Assessment of Energy Storage for Grid, IEC (2011), Electrical Energy Storage: White Paper, IEC (2011), Electrical Energy Storage: White Paper, Headley et al. (2022) Chapter 11: Hydrogen Energy Storage.

Closing remarks

- Ramping rates. We will cover this aspect for some specific technologies we will review more deeply throughout the course. Example figures: Hydropower: 20% of the nameplate power per minute (water and mechanical time constant ...); batteries: 10 times the rated power per second.
- Ageing will be discussed for batteries. Example figures: Hydropower: calendar life is approx. 50 years; batteries: calendar life is approx. 20 years.
- Environmental and life cycle analysis (LCA) are huge topics (not tackled in this course). For example, there are environmental and social concerns associated with lithium-ion technologies due to the use of rare-earth material or extraction in third-world countries with poor labor conditions. Much of the complexity of LCA is that quantifying the benefit of energy storage in power system applications is difficult due to complex interactions in a power grid interconnected system. Emerging technologies, such as sodium-ions cells, offer new perspectives on these matters.
- This discussion covered the main and currently most promising energy storage technologies and is not exhaustive; there might be others (e.g., gravitational storage with cranes).

Energy storage applications

Applications of energy storage (batteries)



Y. Ding et al. (2019). Automotive Li-Ion Batteries: Current Status and Future Perspectives. *Electrochem. Energ. Rev.*

Power systems crash course: what is an electrical power system?

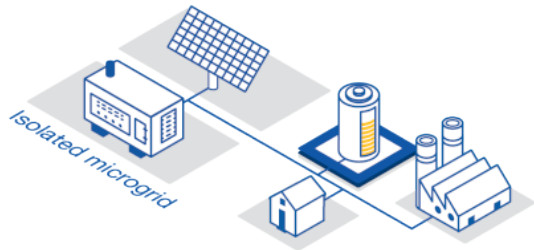
An electrical power system is a set of assets (power plants, lines, transformers, circuit breakers and protections, monitoring equipment) and operational procedures aimed at supplying electric power:

- reliably (continuously and possibly with no disruptions)
- resiliently (if there is a problem, it can be solved)
- in an economically convenient manner
- where it is needed

Electrical power systems are a mission-critical infrastructure on which many other services depend (e.g., hospitals, transportation, production processes).

Interconnected electrical power systems are the largest machine ever created by engineers. It stands as the top engineering achievement of the 20th century according to the US National Academy of Engineering.

Geographical extension of power systems



From microgrids (rural areas far from a public grid connection) ...



... to large interconnected grids (a portion of the European grid).

Structure of an interconnected power system



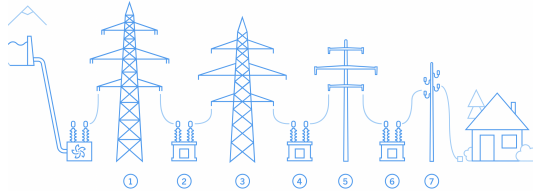
Power plants produce electricity by converting a local energy source

Transmission lines transport electricity over long distances (high or extra-high voltage, 380 kV and 220 kV in CH)

Distribution lines deliver electricity to end consumers (medium and low voltage, ≤ 36 kV and ≤ 1 kV, resp.)

Industrial, residential, and commercial consumers use electricity

Swissgrid grid levels



Transmission lines (lignes de transport)

- Level 1: The 380 kV or 220 kV electricity flows into the transmission grid from the power plants and from abroad → extra-high-voltage level
- Level 3: between 36 kV and 150 kV → high-voltage level

Distribution lines (lignes de distribution)

- Level 5: between 1 kV and 36 kV → medium-voltage level
- Level 7: below 1 kV → low-voltage level. Voltage at which the electricity reaches the customers.

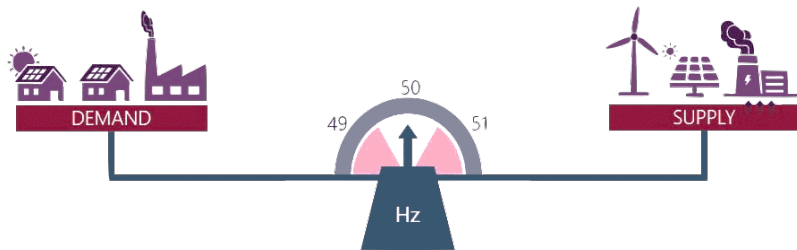
Levels 2, 4, 6 are transformers.

Operational requirements

Two main classes of operational requirements:

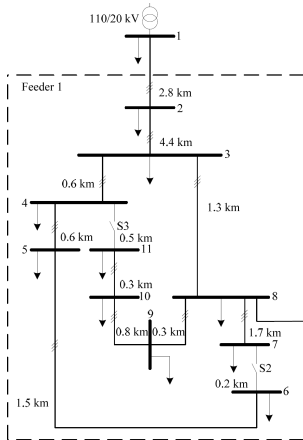
- Grid balancing
- Network performance

Operational requirements: Grid balancing



- Generated power must meet power demand at all times
- The “grid frequency” (i.e., rotational speeds of synchronized generators) is a proxy for imbalances between generation and demand in the grid
- Realized by keeping the grid frequency near the nominal value (e.g., 50 Hz)

Operational requirements: Network Performance



- Voltage levels must be within specified limits in all grid levels
- Current in the lines and transformers must be below the ratings

Vertical unbundling in power systems

Vertical unbundling refers to separating operative roles among different companies according to the grid's functional level. In Europe, the following division generally exist:

- Generation companies: responsible for generating electricity; Operation & Maintenance (O&M) of power plants - which sometimes might be subcontracted.
- Transmission System Operators (TSOs): O&M of transmission lines; responsible to keep the overall system stable and functional, and deliver power to the primary substations;
- Distribution System Operators (DSOs): O&M of distribution lines; responsible to deliver electricity to consumers in the medium- and low-voltage grid.

Vertical unbundling is not implemented everywhere. E.g., the notion of “utility” (a company that integrates all the functions above for a certain region) is more common.

As we shall see, entities above have different understanding and interpretations of the role of energy storage.

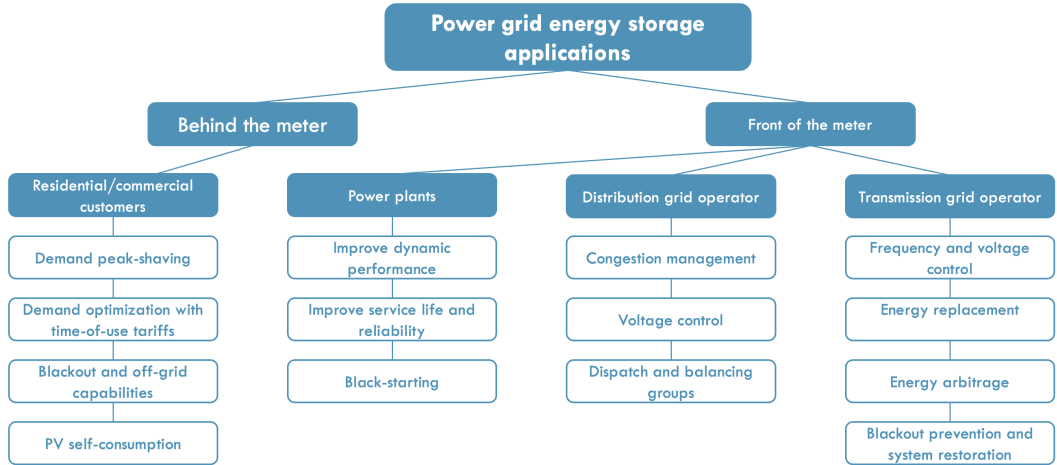
Vertical unbundling in power systems (cont'd)

Other entities worth of mention that are not related to vertical unbundling:

- Electricity markets operators and Electricity retailers (related to liberalization of electricity markets $\neq$ vertical unbundling)
- (trivial) Consumers, as it has always been, use electricity for their own purposes (e.g., residential uses, energy conversion and work in industry).

Energy storage applications in power systems

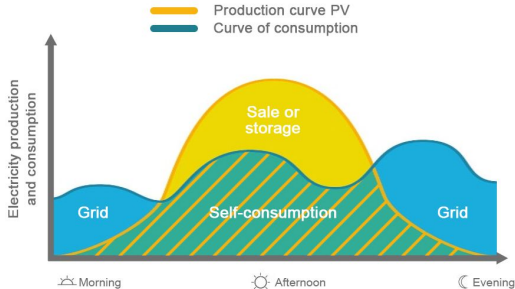
Taxonomy of energy storage applications in power systems



PV = Photovoltaic

Example of applications: PV self-consumption

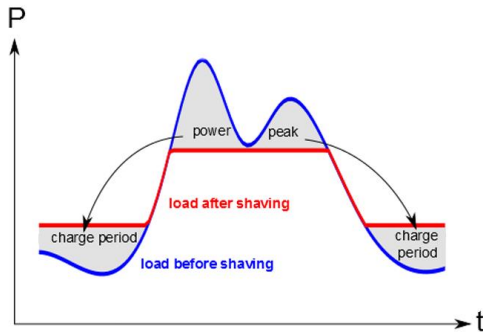
Consider a household with a roof-top PV system.



- Depending on contracts (e.g., net billing), exported PV generation might be remunerated with a smaller rate (\$/kWh) than the one used to charge consumption → it makes economic sense to consume own PV electricity.
- Some degree of PV self-consumption might arise naturally. PV self-consumption can be improved by shifting consumption to when PV electricity is available.
- PV self-consumption could be implemented by local bidirectional energy storage, or shifting demand (activate your water boiler, charging electric vehicles, etc).
- Simple and easy-to-implement notion that indirectly benefits grid operators too.

Example of applications: Behind-the-meter demand peak shaving

Electricity demand time series is typically characterized by peaks and valleys.

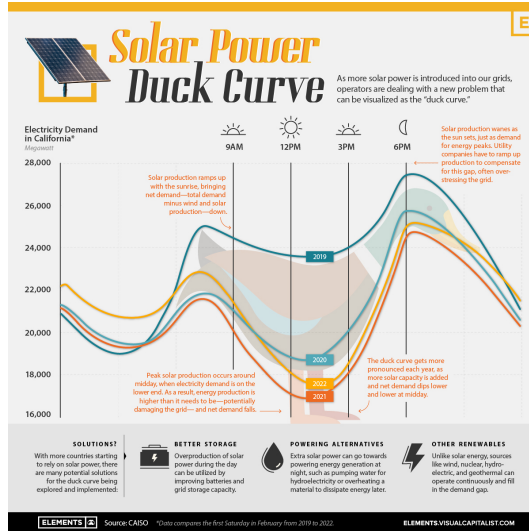


- Peak-shaving refers to trimming peaks of consumption
- Useful when one has contractual obligations on the maximum power that can be drawn from the grid connection
- Large consumers (¹) are subject to not only electricity tariffs but also to power tariffs (CHF/kW per month applied to the largest power recorded in one month, metered on a 15 min basis.)

¹Customers supplied with either high and medium voltage, or with low voltage and consumption ≥ 50 MWh/year (BKW).

Energy storage in California

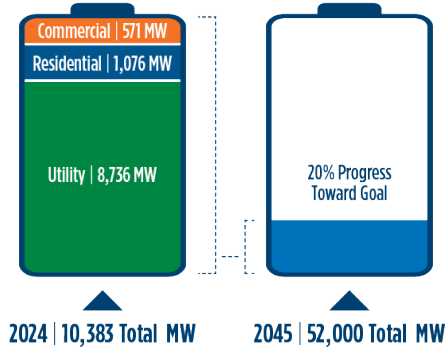
Example: energy storage in California, US – Duck curve



Example: energy storage in California, US

Energy Storage in California by Type

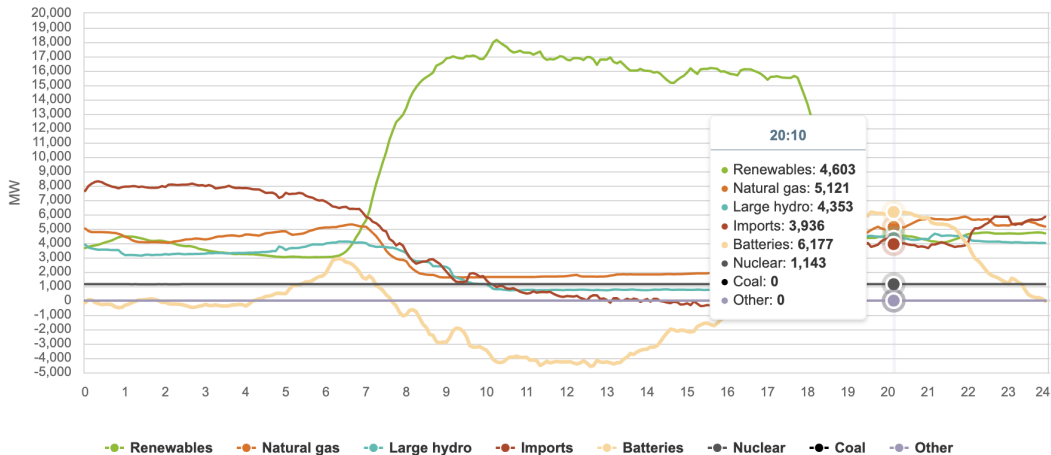
** As of April 15, 2024*



*Hydropower installed capacity in CH amounts to 17 GW.

Recent empirical evidence: energy storage in California, US

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Exercises

Self-assessment of understanding

- What does the Ragone chart show?
- Which technologies appear to be more suitable to offset seasonal variations of energy storage?
- Recall the definition of energy efficiency.
- What are the main applications of energy storage in power grids?

Exercise 2.1

Four friends (average weight: 75 kg) of yours went hiking. On their return, they missed the last bus from Simplon Pass (elevation: 2'000 meters) down to Brig (700 m). You decide to rescue them. You rent an Electric Vehicle (EV) in Brig, climb the pass, and drive them back (total distance: 40 km). The EV spec's are: average consumption 150 W/km (¹), mass 2'000 kg, battery capacity 80 kWh, battery charging/discharging efficiency 95%, electric motor efficiency: 85%. Neither space heating nor A/C is needed.

Estimates the following quantities (next slide). Introduce suitable elementary energetic considerations (and assumptions) when needed.

¹This value generally refers to the energy discharged from the battery (as recorded by the car) under standardized test cycles. Assume that this value is representative of the consumption on flat terrains at your cruise speed (neglect rolling friction and aerodynamic drag as a function of the speed) and that other energetic contributions that might appear in the problem appear as additional linear contributions. Assume braking action is entirely regenerative.

Exercise 2.1 (cont'd)

- 1 Estimate the EV state of charge at the end of the trip considering that you started it with a full charge.
- 2 Estimate the lowest SOC level you will hit.
- 3 Calculate the final consumption (kWh/km) for your trip.
- 4 Compare the final consumption (kWh/km) against the one of a diesel car with a fuel economy of 20 l/km and a mass of 1'600 kg. Diesel low-heating value: 43.4 MJ/kg. Diesel density: 0.85 kg/l. Engine efficiency (till the wheel) 35%.

Exercise 2.2

Given with the simple SOC model with efficiency

$$\text{SOC}(t+1) = \text{SOC}(0) + \frac{\Delta T}{\bar{E}} \sum_{\tau=0}^t \left(\eta [P(\tau)]^+ - \frac{1}{\eta} [P(\tau)]^- \right).$$

calculate the round-trip efficiency as a function of the (symmetric) charging/discharging efficiency η .