# Energy Storage Attributes and Applications

Prof. Dr. Fabrizio Sossan (HES-SO Valais-Wallis)
fabrizio.sossan@hevs.ch

EPFL EE-466

Slides compiled on: September 18, 2025

# 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
- 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

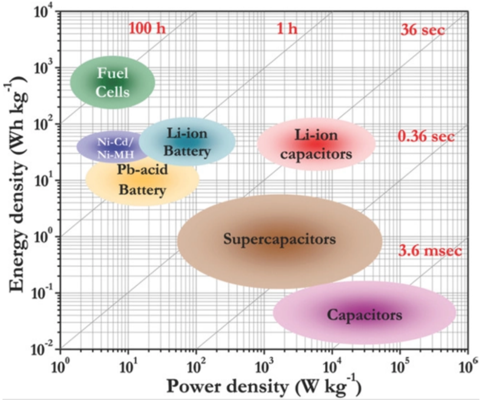


Figure: Ragone chart, Aravindan et al. (2014), Insertion-type electrodes for nonaqueous Li-ion capacitors. Chemical reviews.

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 W/m2 ÷ 0.87 W/m2 (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.).

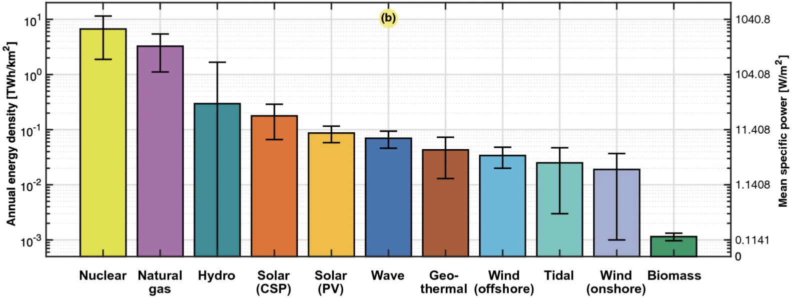


Figure: Average and standard deviation values of the annual energy and power density in log scale of various sources. Nøland et al (2022). Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep.

# Round-trip efficiency: empirical values

Two remarks to be discussed in the class: efficiency of the whole conversion stage, and limit and assumptions of the round-trip efficiency.
Empirical values for grid-connected system:

- 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.

# Round-trip efficiency: another sources

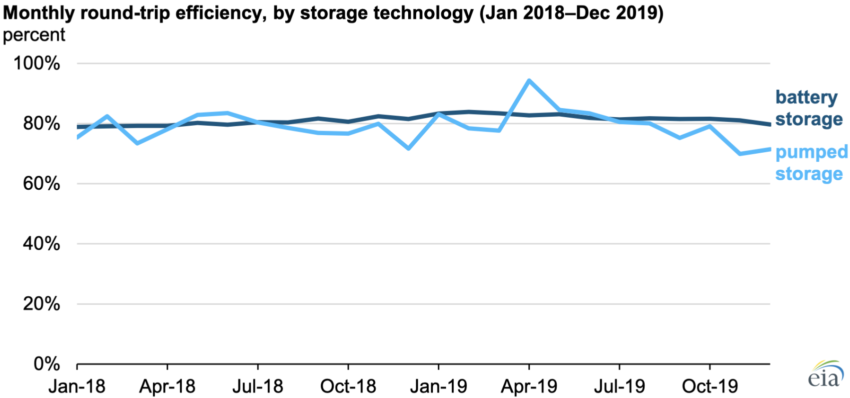


Figure: U.S. Energy Information Administration.

# Cost projections of energy storage

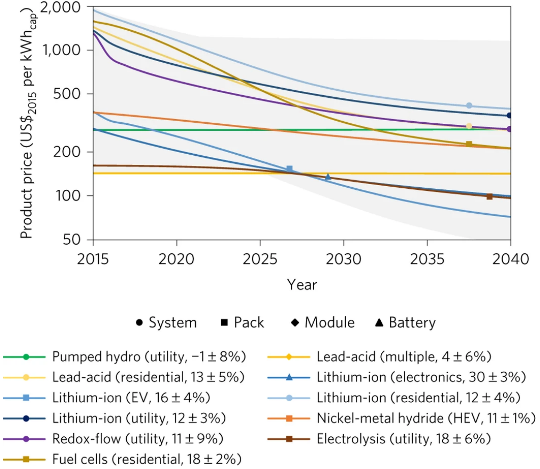
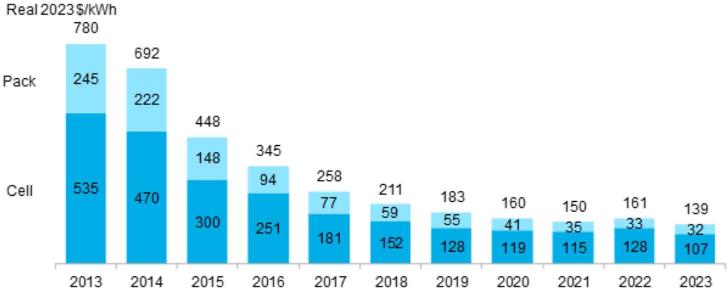


Figure: Cost projections of energy storage based on experience rates. Schmidt et al. (2017). The future cost of electrical energy storage based on experience rates. Nature Energy.

# 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).

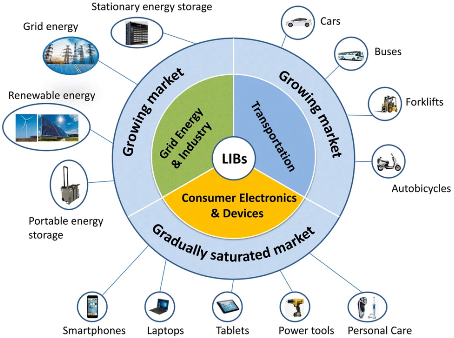
# Closing remarks

- 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).

# Introduction to power systems, and to energy storage applications

# Battery applications: a wide range

Kyburz



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

We will refer mostly to power grid applications, although the models are to some extent extendable to other applications.

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

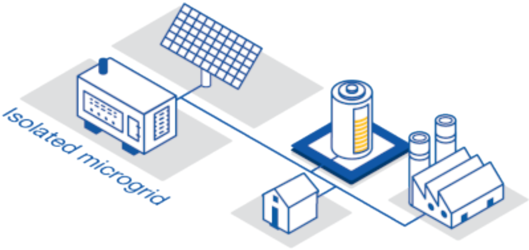
An electrical power system is a set of assets (power plants, lines, transformers, circuit breakers and protections, monitoring equipment) and operational procedures aimed at supplying electric power:

- reliably (continuosly 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

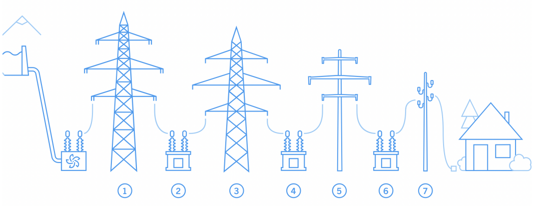
Transmission lines transport electricity over long distances (high or extra-high voltage, 380 kV and 220 kV in CH)

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

Industrial, residential, and commercial consumers use electricity

Not included in the figure: breakers and switches for grid reconfigurations, protections, monitoring, additional equipment for regulations (capacitor banks).

# Swissgrid grid levels



Transmission

- Level 1: 380 kV or 220 kV, extra high-voltage, overhead lines
- Level 3: between 36 kV and 150 kV, high-voltage, overhead lines

Distribution

- Level 5: between 1 kV and 36 kV → medium-voltage level, typically overhead lines.
- Level 7: 400 V ($< 1$ kV) → low-voltage level, typically buried cables (lines)

Levels 2, 4, 6 are power transformers.

# A (level-6) transformer, and line to cable transition (BKW, Simmental)

# Vertically unbundling

In the past (around $< 2000$), national power systems were operated by a single company.

Nowadays, different functional levels are managed by different companies (vertical unbundling):

- Generation companies own and operate power plants. (... examples?)
- Transmission system operators (TSOs) operate the high-voltage transmission grid and are generally responsible for the proper functioning of the entire system. (... examples?)
- Distribution system operators (DSOs) operate distribution grids. (... examples?)

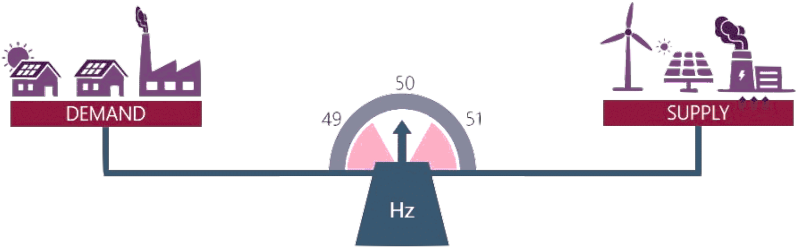
# Operational requirements

In short summary, two main classes of operational requirements:

- Grid balancing
- Ensuring grid performance (electrical quantities within bounds)

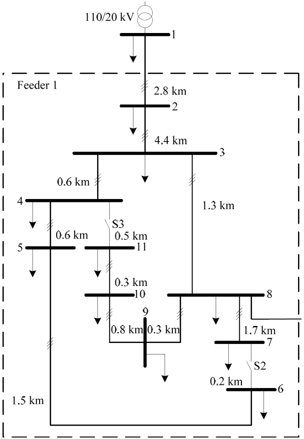
# Operational requirements: Grid balancing

Generated power must meet power demand at all times



- The "grid frequency" (i.e., rotational speeds of synchronized generators) is the proxy to imbalances between generation and demand in the grid
- Power plants measure the grid frequency and adjust production to keep the balance (primary frequency control)

# Operational requirements: Grid Performance



- Currents in lines and transformers must remain below their rated limits.
- Voltage levels must remain within specified limits at all levels of the grid (primarily a power-quality concern that may also include metrics such as harmonic distortion).

# 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.

Consumers (residential, commercial, industrial) use electricity for their own purposes – as it has always been.

Vertical unbundling might take different forms according to the country.

# Vertical unbundling $\neq$ Open electricity markets (but an enabling factor)

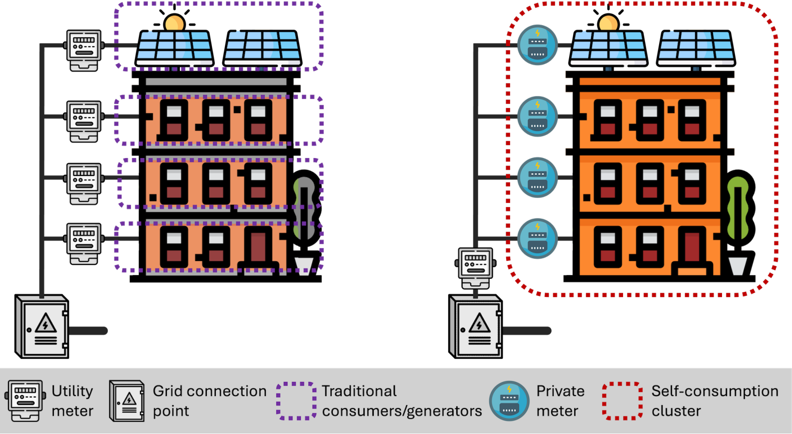
**Liberalization of electricity markets at two levels:**

- **Wholesale market:** open to producers and electricity buyers. In Switzerland, producers and large distributors participate in the common European day-ahead market, EPEX Spot.
- **Retail market:** consumers can choose their electricity supplier (in Switzerland, not yet implemented, except for large consumers).

**Ancillary services** (Systemdienstleistungen | Services système | Servizi ancillari) to maintain reliable real-time operation. In Switzerland, these are procured by Swissgrid, sometimes via partially open markets.

# More recent constructs in the Swiss regulatory framework

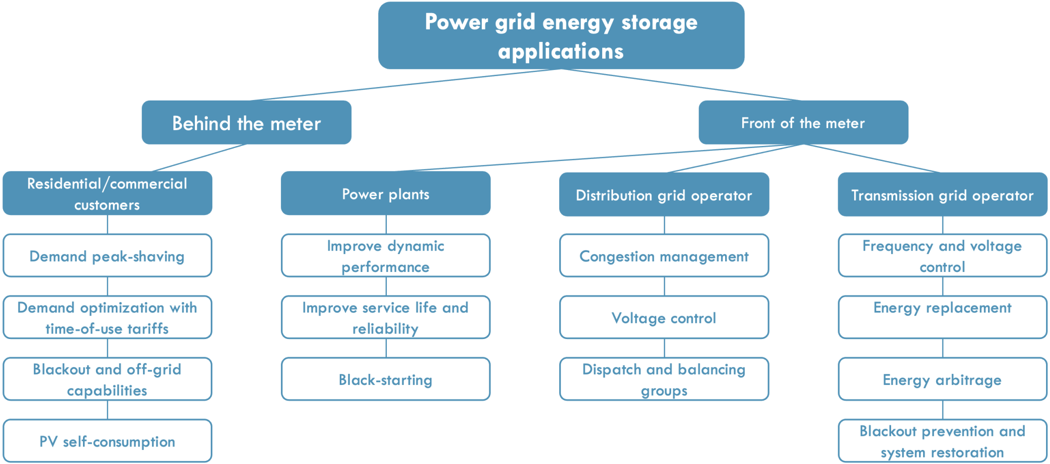
Constructs such as RCP (self-consumption clusters ) and CEL (energy communities) alter the classic electricity retailer/consumer paradigm, allowing different accounting mechanisms than the classical ones.



For more: Link, and official legislation (in German, French, or Italian)

# Energy storage applications in power systems

# Taxonomy of energy storage applications in power systems



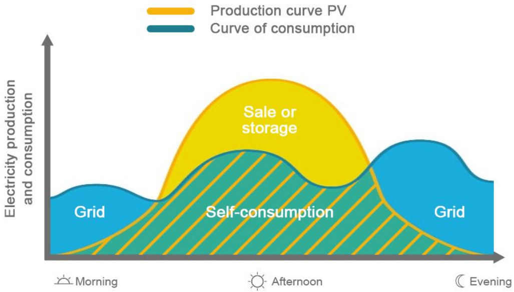
**Power grid energy storage applications**

- **Behind the meter**
  - **Residential/commercial customers**
    - Demand peak-shaving
    - Demand optimization with time-of-use tariffs
    - Blackout and off-grid capabilities
    - PV self-consumption
- **Front of the meter**
  - **Power plants**
    - Improve dynamic performance
    - Improve service life and reliability
    - Black-starting
  - **Distribution grid operator**
    - Congestion management
    - Voltage control
    - Dispatch and balancing groups
  - **Transmission grid operator**
    - Frequency and voltage control
    - Energy replacement
    - Energy arbitrage
    - Blackout prevention and system restoration

PV = Photovoltaic

# Example of applications: PV self-consumption

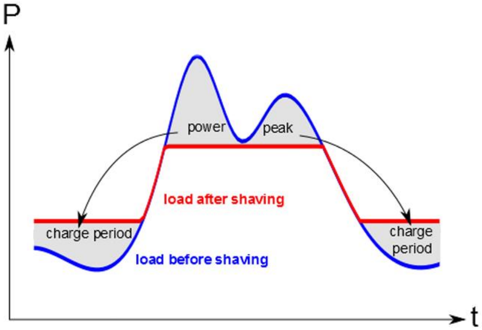
Consider a household with a roof-top PV system.



- 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.



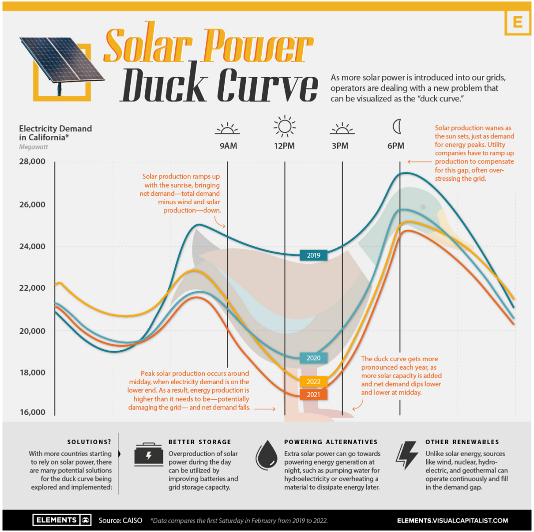
- Peak-shaving refers to trimming peaks of consumption
- Useful when one has contractual obligations on the maximum power that can be drawn from the grid connection
- Large consumers ([1]) are subject to not only electricity tariffs but also to power tariffs (CHF/kW per month applied to the largest power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

---

[1] Customers supplied with either high and medium voltage, or with low voltage and consumption $\geq$ 50 MWh/year (BKW).

# Example: Battery energy storage in California

# Example: energy storage in California, US – Duck curve



**Solar Power Duck Curve**

As more solar power is introduced into our grids, operators are dealing with a new problem that can be visualized as the "duck curve."

Solar production ramps up with the sunrise, bringing net demand—total demand minus wind and solar production—down.

Solar production wanes as the sun sets, just as demand for energy peaks. Utility companies have to ramp up production to compensate for this gap, often over-stressing the grid.

Peak solar production occurs around midday, when electricity demand is on the lower end. As a result, energy production is higher than it needs to be—potentially damaging the grid— and net demand falls.

The duck curve gets more pronounced each year, as more solar capacity is added and net demand dips lower and lower at midday.

**SOLUTIONS?**

With more countries starting to rely on solar power, there are many potential solutions for the duck curve being explored and implemented:

**BETTER STORAGE**

Overproduction of solar power during the day can be utilized by improving batteries and grid storage capacity.

**POWERING ALTERNATIVES**

Extra solar power can go towards powering energy generation at night, such as pumping water for hydroelectricity or overheating a material to dissipate energy later.

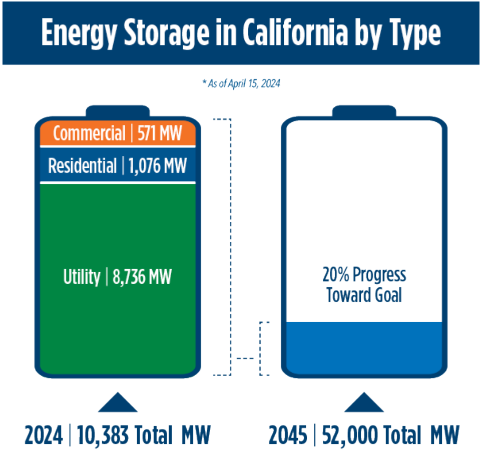
**OTHER RENEWABLES**

Unlike solar energy, sources like wind, nuclear, hydroelectric, and geothermal can operate continuously and fill in the demand gap.

ELEMENTS Source: CAISO *Data compares the first Saturday in February from 2019 to 2022.

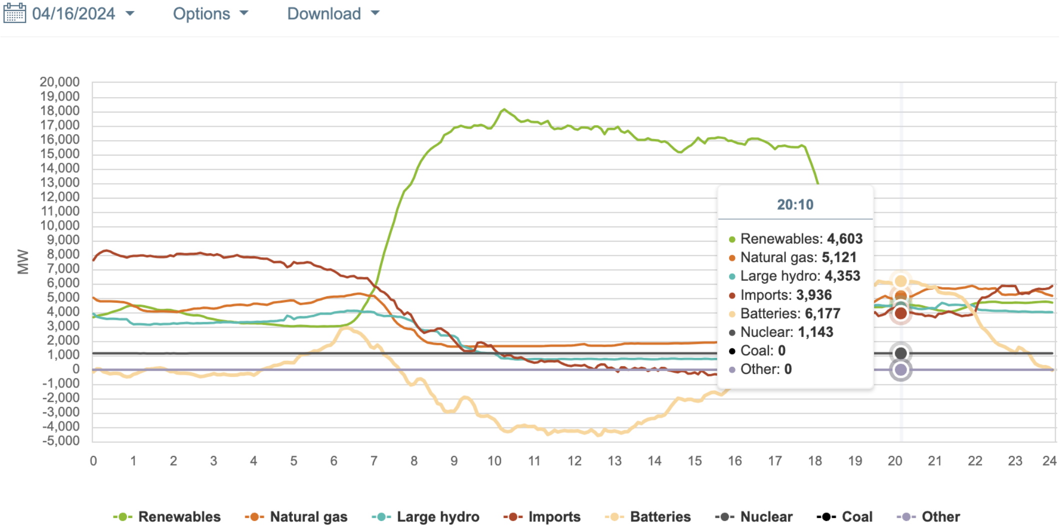
ELEMENTS.VISUALCAPITALIST.COM

# Example: energy storage in California, US



*Hydropower installed capacity in CH amounts to 17 GW.

# Recent empirical evidence: energy storage in California, US



# 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 effiency.
- 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.

---

[1] This 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 liner 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 SOC energetic model with efficiency

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

calculate the round-trip efficiency as a function of the (you can assume it symmetric, for this exercise) charging/discharging efficiency $\eta$.