A.T. Kearney | Energy Transition Institute

FactBook

Electricity Storage Gaining Momentum

A.T. Kearney Energy Transition Institute

Compiled by the A.T. Kearney Energy Transition Institute

Authors

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About the FactBook – Electricity Storage

This Factbook seeks to capture the current status of and future developments in electricity storage, detail the main technological hurdles and areas for Research and Development, and analyze the economics of a range of technologies.

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It 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 economical 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.

Integrating intermittent sources of energy requires additional flexibility resources and gives new momentum to electricity-storage solutions

Power systems are challenging to operate, since supply and demand must be precisely balanced at all times. Power demand is in a constant state of flux; although it generally follows predictable patterns, it is impossible to forecast with precision. As a result, power systems have always had to be flexible. At present, flexibility comes primarily from the generation side: system operators adjust the output of generators upwards or downwards in response to predefined time frames and ramping rates. By storing primary energy sources, such as coal and gas, or water in hydro dams, system operators have avoided the need to store electricity.

Wind and solar photovoltaic systems make demand-supply matching more difficult since they increase the need for flexibility within the system, but do not themselves contribute significantly to flexibility. The increased need for flexibility is reflected in residual load variations (demand minus intermittent output). The minimal participation in flexibility pool resources is mirrored by the low capacity credits granted by system operators to wind and solar – a measure of the amount of power that they can reliably be expected to produce at peak of demand.

Flexibility management can be optimized by perfecting models for forecasting output from wind and solar plants, fine-tuning market regulations and refining the design of power systems. But additional flexibility will be needed in the form of demand-side participation, better connections between markets, greater flexibility in base-load power supply and electricity storage.

Electricity storage is a three-step process that 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, electricity storage has very different uses, depending on the combination of the power rating and discharge time of a device, its location within the grid and its response time.

The primary purpose of electricity storage consists of ensuring power quality and reliability of supply, whether it is to provide operating reserves, uninterrupted power-supply solutions to end-users, or initial power to restart the grid after a blackout. A secondary purpose of electricity storage is driven more by energy requirements. This involves leveling the load – storing power in times of excess supply and discharging it in times of deficit. Leveling enables the deferral of grid investment on a congestion node and optimal utilization of low-operating-cost power plants, and presents opportunities for price arbitrage. The increased penetration of variable renewables is making these applications more critical. It is also creating a new application, known as intermittent balancing, to firm their output or avoid curtailment. For these reasons, variable renewables have resulted in renewed interest in electricity storage.

The features of storage technologies must match application requirements

Unlike liquid or gaseous energy carriers, electrical energy is difficult to store and must usually be converted into another form of energy, incurring conversion losses. Nevertheless, many storage technologies have been developed in recent decades that rely on mechanical, electrochemical, thermal, electrical or chemical energy. Most of them are currently clustered in the investment “valley of death”, i.e. at the demonstration or early deployment phases, when capital requirements and risks are at their highest.

The applications electricity storage technologies are able to fulfill depend on their chemical and physical characteristics. Technologies must be assessed at the application level, taking into account power rating, storage duration, frequency of charge and discharge, efficiency and response time, and site constraints that determine power and energy density requirements.

In general, pumped hydro storage (PHS) and compressed-air energy storage (CAES) are the most suitable for bulk storage applications. PHS uses the gravitational potential energy of two vertical reservoirs; water is pumped from a lower reservoir up to a higher reservoir during periods of off-peak demand, and the flow is reversed to drive a turbine during peak periods. CAES works by using electricity to compress air into a cavern or pressurized tank and later releasing the air to drive a turbine, which converts the energy back into electricity. However, both technologies face site availability issues.

Batteries are a major component of the storage landscape and can serve a wide range of applications with intermediate power and energy requirements. They differ according to electrode type and electrolyte chemistry: sodium-sulfur (NaS) and lithium-ion (Li-ion) are the most suited for stationary storage because of their higher power and energy densities, and greater durability. Nevertheless, durability remains, together with costs and safety concerns, one of the biggest hurdles to commercial development. In addition to conventional batteries, research is being conducted into flow batteries, such as vanadium redox (VRB) or zinc-bromine (Zn/Br) batteries, which use the same reaction but with two separately stored electrolytes, allowing for power and energy decoupling. They are, for now, more costly due to their complex balance of system, and further development and demonstration efforts will be needed.

For applications where providing power in short bursts is the priority, flywheel, superconducting magnetic energy storage (SMES) and supercapacitors appear to be the most attractive, as a result of their high power density, high efficiency, high response time and long lifespan. However, costs are high and these technologies are currently at the demonstration phase.

Finally, despite its poor overall efficiency and high up-front capital costs, chemical storage seems to be the only way to provide the very large-scale and long-term storage requirements that could result from a power mix generated primarily by variable renewables. Chemical storage consists of converting electricity into hydrogen by means of water electrolysis. It actually goes far beyond electricity storage since hydrogen can also be converted into synthetic natural gas or used directly as a fuel in the transportation sector or as feedstock in the chemicals industry. In contrast to other technologies, chemical storage is mainly driven by excess, rather than a shortage, of renewable energy. Thermal storage is also worth considering, but is mainly being developed as a means of electricity storage in association with concentrating solar power.

With the exception of pumped hydro storage, the deployment of electricity storage is at an embryonic stage

Electricity storage is not a new concept. As of November 2017, the installed power capacity of electricity-storage plants amounted to around 175 GW. However, development has been restricted almost exclusively to one technology: pumped hydro storage. Development of pumped hydro storage started in the 1960s, and the technology accounts for 96% of global installed capacity. China, the U.S. and Japan host the largest amount of pumped hydro storage capacity, with 19%, 17% and 17% of global operating capacity, respectively. Most of the future growth in Pumped hydro storage will be driven by the U.S. (48% of the future storage projects).

The first compressed-air energy storage plant, a 290 MW facility in Germany, was commissioned in 1978. The second, a 110 MW plant in the U.S., was not built until 1991. A few small-scale demonstration plants have been constructed in recent years and some are under construction in North America, as well as a smaller number in Europe, to test advanced or new concepts. However, the outlook is uncertain, given that several other compressed-air projects have been suspended in South Korea and the U.S., including a 2,700 MW venture in Norton, Ohio or 317 MW Apex Bethnel in Texas.

At the same time, battery projects are being developed at a rapid pace globally and the total operational capacity (all battery types) amounts to around 1.5 GW. Driven by developments in the U.S., lithium-ion batteries have recently become dominant, accounting for more than 77% of operational battery capacities (1147 MW), and 80% of planned projects. Several manufacturers, such as Tesla, LG Chem, Samsung, Panasonic, Daimler, Sunverge and Enphase, are now offering commercial battery products for residential energy storage, usually in countries experiencing a boom in solar PV, such as the U.S., Germany and Australia. Sodium-sulfur batteries, which were the dominant technology in the 2000s, seem to be losing momentum. They account for less than nearly 13% of stationary batteries installed (188 MW). Although at a very early phase of deployment, with few projects announced, flow batteries could be a game changer in the medium term; research is being carried out at an intense rate in China and Australia.

Thermal storage has developed in recent years in conjunction with concentrating solar power plants and operational capacity has now reached around 2.7 GW, primarily in the form of molten salt. Thermal storage is therefore the dominant source of electricity storage (excluding pumped hydro), beyond Li-ion batteries and flywheels. Despite the recent increase in the projects being commissioned, flywheels struggle to find a sustainable value proposition; electrical storage technologies, either supercapacitors or superconducting magnetic energy storage, remain at an early phase of demonstration. Finally, interest in chemical storage is high in Europe, with several large-scale demonstration projects in Germany, Denmark and the UK. However, the primary aim of these projects is usually not to inject electricity back to the grid, but to green the gas or provide alternative transportation fuels.

Overall, interest in electricity storage is increasing, as indicated by the development of roadmaps by the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the U.S., the U.K. and China.

Research, Development & Demonstration is making inroads into solving technological obstacles

R,D&D priorities vary according to the technology. For pumped hydro storage, the primary objectives are addressing the constraint of site availability and minimizing environmental impact by using sea-based or underground reservoirs. As a significant proportion of pumped hydro capacity is ageing and not designed to help balance variable renewables, R,D&D is also being directed at upgrading existing plants and increasing their flexibility, using variable-speed turbines, for instance.

Several compressed-air energy-storage concepts, which should become more efficient by reducing or avoiding gas use, are also in development. Adiabatic compressed air involves the storage of waste heat from the air-compression process and its use to heat up the air during expansion. The isothermal design, meanwhile, aims to maintain a constant temperature. Several large-scale demonstration projects are planned or under development; these include RWE’s 90 MW adiabatic Adele plant in Germany. As with pumped hydro storage, artificial reservoirs, especially pressurized tanks, are also being developed in response to the limited availability of natural storage formations.

Battery research is focused on new materials and chemical compositions that would increase lifespan, enhance energy density, and mitigate safety and environmental issues. For instance, lower-cost materials for the negative electrode of the lithium-ion battery are being tested, as are organic solutions to replace the water-based electrolytes of flow batteries. Liquid-air and liquid-metal concepts that use oxygen from the air instead of storing an oxidizing agent internally are often considered potentially disruptive, but their commercial prospects remain uncertain.

Finally, R,D&D of hydrogen-based technologies is highly active. Efforts are focused on: improving the viability of water electrolysis (by reducing the capital costs of proton exchange membranes and increasing efficiency through the use of high-temperature concepts); assessing the suitability of blending hydrogen with gas; developing methods of using hydrogen to manufacture synthetic fuels; and continuing to investigate hydrogen storage in the form of metal hydrides and in underground formations.

Despite growth in activity, funding for electricity storage R,D&D is still lagging behind that of other low-carbon-enabling technologies, such as smart grids. Most of the funding is being channeled into compressed-air energy storage. Hydrogen R,D&D is also benefiting indirectly from growing interest in hydrogen-fueled transportation.

Business cases for electricity storage are highly complex and rarely viable under current market conditions and existing regulatory frameworks

The economics of electricity storage are difficult to evaluate since they are influenced by a wide range of factors: the type of storage technology, the requirements of each application and the system in which the storage facility is located.

Initial investment in a storage facility comprises two principal components: a cost per unit of power (in $/kW) and a cost per unit of energy capacity (in $/kWh). The costs of power of a pumped hydro storage plant, for instance, comprise the cost of the pump/turbine (in $/kW) and the cost of energy capacity, which depends on reservoir capacity and elevation differential (in $/kWh).

These costs vary significantly according to the technology being deployed. Reflecting their attractiveness in power-driven applications, flywheels and supercapacitors are characterized by low capital costs for power ($800 - $1200 per kW) but prohibitively high investment in energy capacity (from <$500 per kWh in applications with low energy needs to $50,000 per kWh for high energy requirements). Conversely, compressed-air energy storage has relatively high capital costs per unit of power (from $1300 to $3500 per kW), but is considerably cheaper per unit of energy (from $2 to $150 per kWh). The combination of power rating and energy capacity is therefore crucial in assessing the competitiveness of different technologies. Applications dictate another major component of storage economics: the frequency of charging and discharging cycles. Cycling affects the amortization of capital costs and annual replacement costs, which have significant impacts on battery economics.

Finally, the price of electricity is equivalent to fuel cost. Consequently, electricity-price distribution – depicted by the location-dependent price-duration curve – is a key factor in storage economics. Usually, storage operators try to take advantage of electricity price spreads (charging when the price is low and discharging when it is high), but this is not possible in all applications.

Overall, compressed-air energy storage and pumped hydro storage are the most cost-effective technologies for large-scale electricity storage with frequent cycles. Flywheels and supercapacitors will be preferred for very short storage periods and frequent use. Batteries are likely to be the cheapest solutions when the number of cycles is low. The cost of lithium-ion batteries is expected to achieve significant cost reductions in the coming years. Given that production costs decline by around 20% for each doubling of production capacity (a learning rate similar to that of solar PV technologies), market development and recent investments by manufacturers should improve the economics of battery storage.

However, the economics of electricity storage remain shaky. The benefits of storage can be evaluated according to three methods, based on: the market (e.g. bidding to supply power to the control market); avoided costs (e.g. deferred investment); or the intrinsic value of storage, using the willingness-to-pay of the customer (e.g. provide reliable power supply). Costs tend to outweigh the financial benefits, although price arbitrage and grid-investment deferral may make investments in storage profitable in some countries. Bundling several storage applications together seems a strong lever in helping electricity storage to become profitable. Recent projects in USA highlight that utilities scale projects can be economical but small scale (commercial/residential) projects remain uneconomic. Removing regulatory barriers, such as making storage plants eligible to participate in ancillary services, rewarding fast response assets, or allowing network operators to own storage facilities, is also required to enable the monetization of storage.

Environmental and social impacts vary according to the technology and might hinder development in some cases

As with the economics, 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. There is, for instance, no environmental sense in storing low-cost power from coal at night to displace electricity generated during the day from gas or hydro peak power plants.

In terms of individual technologies, pumped hydro storage faces the greatest environmental problems. Due to its low energy density – 1 cubic meter of water over a height of 100 meters gives 0.27 kWh of potential energy – requirements for land and water are high. Closed-cycle plants using two artificial reservoirs reduce water use, but increase the flooded area. Higher elevation differentials and new concepts using seawater and wastewater could mitigate the technology's environmental impact.

Compressed air energy storage uses very little land, but is the only technology that directly emits greenhouse gases. That said, emissions are very low (equivalent to roughly one third of those of conventional gas turbines) and have been reduced in newer plants where exhaust gas is used to heat up the air. Moreover, emissions will be avoided in adiabatic and isothermal plants. Compressed-air energy storage also has high water requirements for the formation of underground salt caverns and for cooling during operation.

Meanwhile, there are concerns over the energy intensity of batteries. According to a recent Stanford University study, over their lifetime, batteries store only two to 10 times the energy needed to build and operate them. This compares with ratios higher than 200 for pumped hydro storage and compressed-air energy storage. The relatively low ratio for batteries results from their cycling life and the materials of which they are made, underlining the need for continuing research to improve durability and investigate new materials. Important safety issues that could compromise public acceptance must be addressed in the case of batteries and hydrogen solutions.

Finally, better communication and education are needed to improve the understanding of electricity storage among energy professionals, policy makers, students and the general public.

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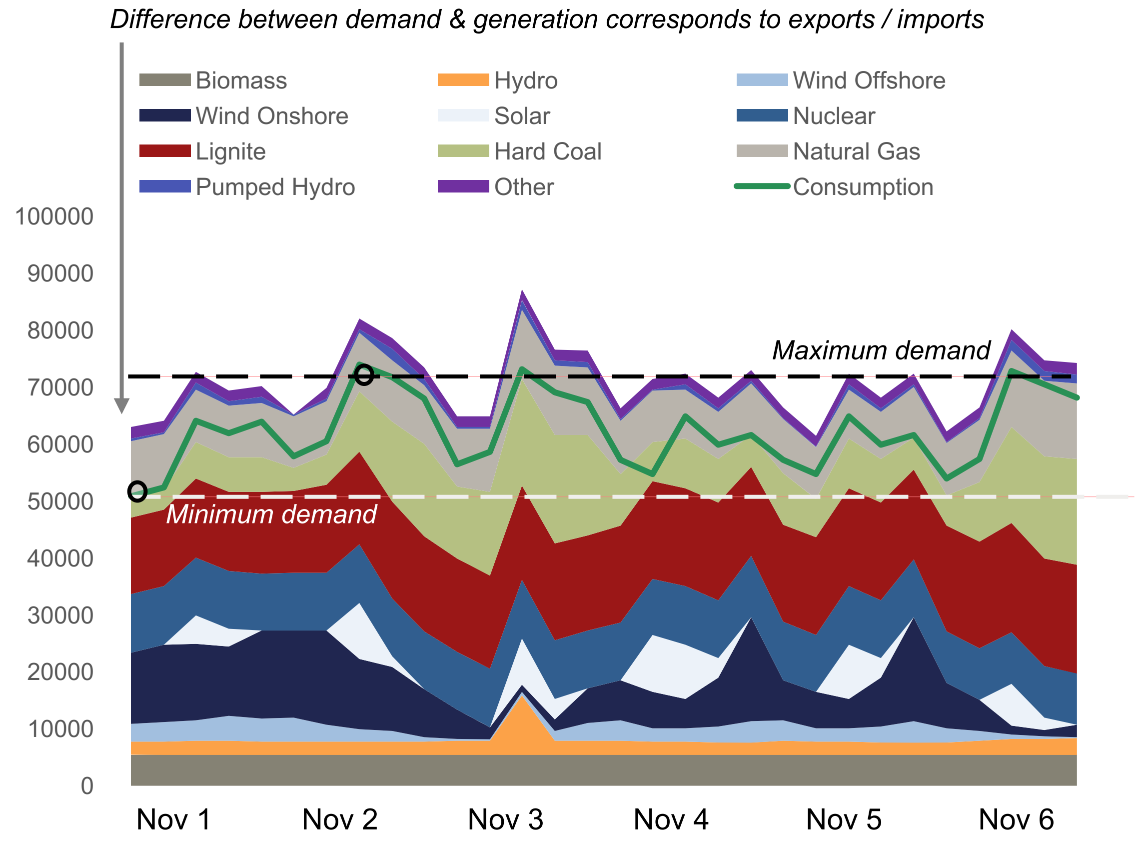
1. Introduction to Electricity Storage

Existing power systems avoid storing electricity by storing primary energy sources that supply flexible power plants

Weekly load and supply curve in Germany, and supply by technology[1]

MW, November 2017



- **Electric power systems are challenging to operate:**
  - They must constantly adapt to demand in order to meet consumption needs and avoid costly blackouts;
  - Power consumption changes all the time. It has a daily, weekly, and seasonal patterns, but is impossible to predict with perfect accuracy.
- **Since demand is imperfectly predictable, in order to follow the load, generators are dispatched at the request of power-grid operators;** generation sources are chosen depending on the flexibility needed and on their marginal costs of production (merit order).
- **Electricity storage is therefore mostly avoided by storing primary-energy resources** such as coal, gas, oil, uranium, biomass or water (hydropower), which can be converted to power at short notice.

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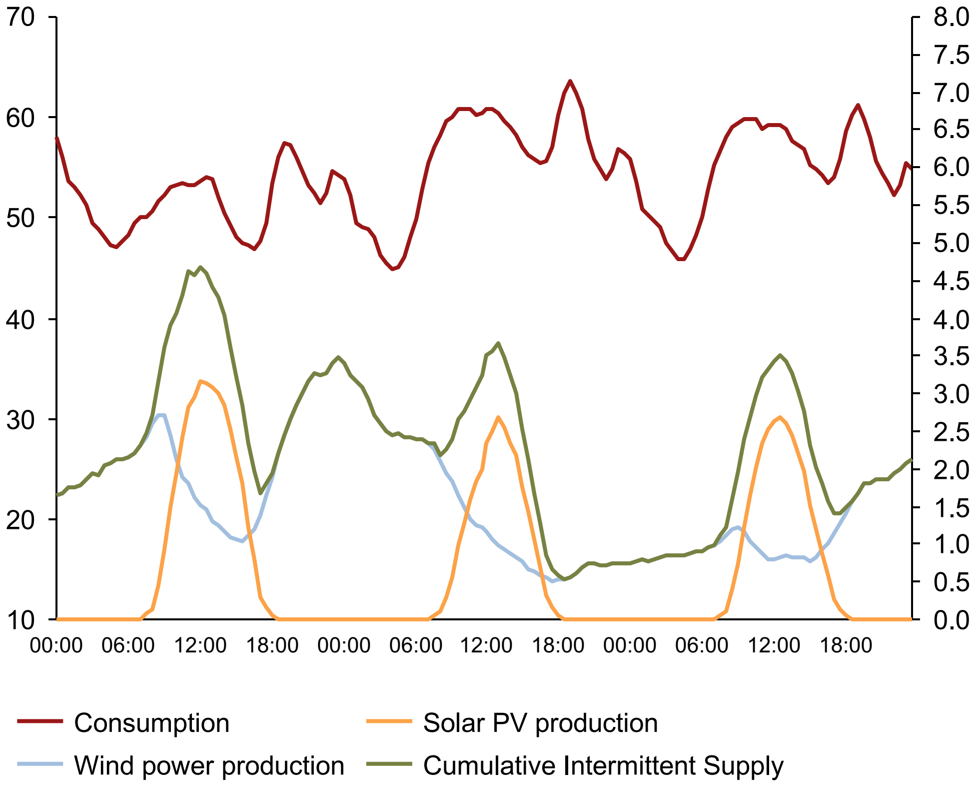
1. The green curve represents demand. Different colors represent production by technology type. The difference between generation and demand represents the difference between exports and imports.

Source: A.T. Kearney Energy Transition Institute analysis based on Agora-energiewende data (accessed 2017), "Power Generation and Consumption", (link)

Wind and solar photovoltaic energy increase the need for flexibility without themselves contributing significantly to the flexibility of the power system

Wind & Solar generation vs. consumption

Consumption (left), generation (right), GW - French grid, Nov 2017



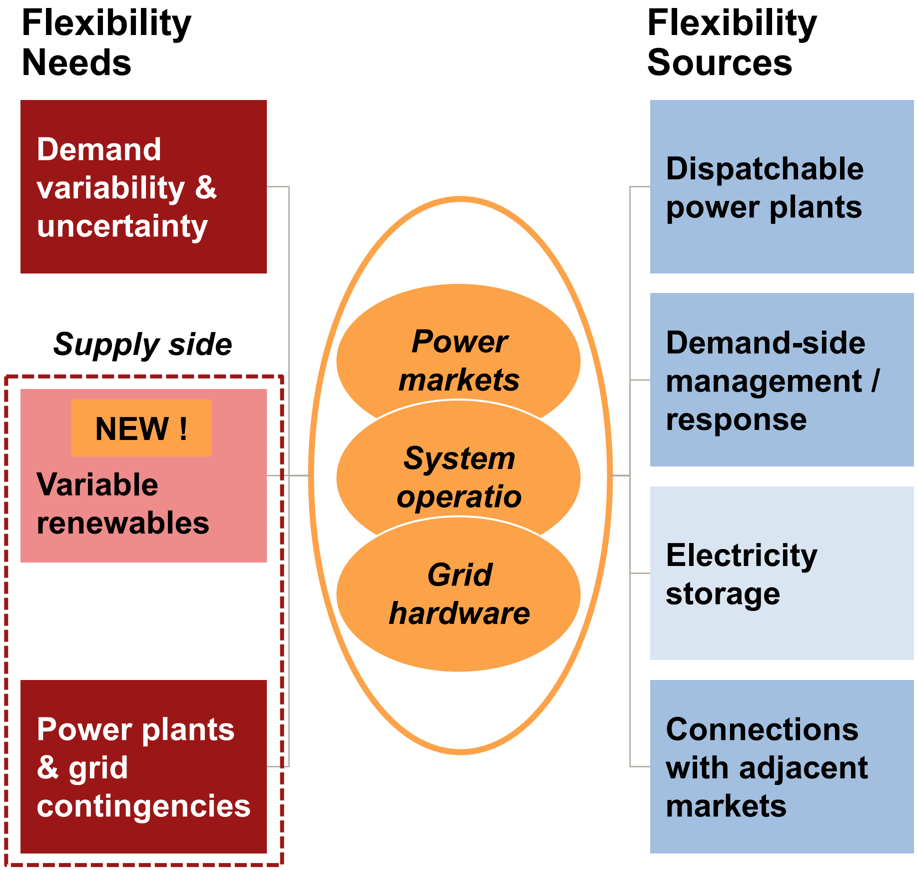
- **Wind and solar photovoltaic (PV) introduce variability and uncertainty to the supply side**. Their output varies according to daily and seasonal patterns, and weather conditions, which are uncontrollable. Output is therefore:
  - Imperfectly predictable (notably harder to forecast than demand);
  - Imperfectly controllable;
  - Subject to steep ramp changes[1].
- **The variable output of wind and solar increases the need for flexibility**. The residual load variations (demand minus intermittent output) on the graph illustrate the need for flexibility. In this example, the residual load variations fluctuate far more widely than the demand curve.
- **Wind and solar make a minimal contribution to the flexibility of the power system** because of uncertainty about their production reliability during peak demand, also known as the capacity credit. The International Energy Agency (IEA) estimates in its New Policies scenario that the capacity credits of wind and solar range between 5% and 20%[2].

1. For instance, a wind farm producing at full load may have to shut down if the speed limit of its turbines is reached; 2. In reality, in Europe, this means that of the 450 GW of installed wind capacity predicted by 2035, only 22.5 GW will be available to power operators as part of the pool of flexibility resources. However, capacity credit varies by region and is typically higher where peak demand occurs during the sunniest hours (e.g. in the Middle East, where demand peaks are caused by the use of air-conditioning).

Source: A.T. Kearney Energy Transition Institute analysis based on RTE eco2mix (accessed 2017), “Production d’électricité par filière”, (link)

Integrating variable renewables requires additional flexibility resources, resulting in the need for electricity storage

Power system flexibility management



Flexibility Needs

Demand variability & uncertainty

Supply side

NEW !

Variable renewables

Power plants & grid contingencies

Power markets

System operatio

Grid hardware

Flexibility Sources

Dispatchable power plants

Demand-side management / response

Electricity storage

Connections with adjacent markets

- **Up to a certain penetration rate[1], the integration of wind and solar into the power mix can usually be managed using existing flexibility sources**. The threshold depends on the system's location and characteristics, and ranges roughly between 15% and 25%.
- **As the penetration of wind and solar within energy systems increases, interest in electricity storage will grow.**
  - Storage enables participants to profit from variations in the peak/off-peak ratio of the residual load arising from the combination of low demand and high variable generation or high demand and low generation. This has, for example, occasionally led to negative prices in some markets in recent years, creating opportunities for price arbitrage;
  - In systems that are highly dependent on variable renewables, electricity storage may be necessary in supplementing primary energy storage and ensuring security of supply. In the short to medium term, electricity storage is likely to be limited to island systems or remote communities, replacing back-up diesel generators. It the longer run, it may also be needed in larger grids*.

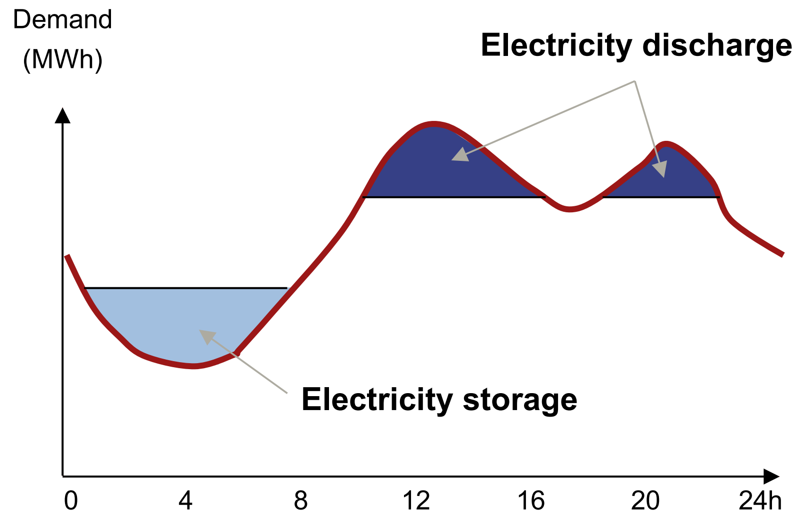
1. Germany has modeled several power mixes for 2050, including one based entirely on renewables; in this case, residual-load simulation projects indicate that the discrepancy between supply and demand is likely to range between a deficit of 84.7 TWh and a surplus of 82.7 TWh. As a result, long-term storage is likely to be needed to store electricity during periods of surplus supply and to release it into the grid when there is a shortage.

Source: IEA (2011), "Harnessing Variable Renewables"

Electricity storage has two primary functions: leveling the demand curve, and ensuring power quality and reliability by providing ancillary services

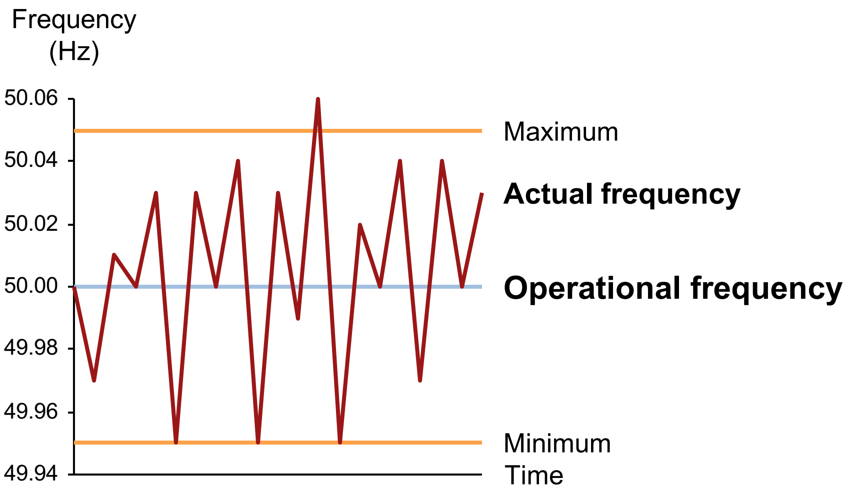
Primary functions for electricity storage - Illustrative

Load Leveling



Electricity storage is used to level the load over various timescales. Typically, electricity is stored during periods of low demand and discharged during periods of peak demand to reduce the peak/off peak amplitude (daily, weekly and seasonal demand). This can also occur over shorter timescales (hourly) to smooth the load and avoid activating peak plants.

Ancillary services

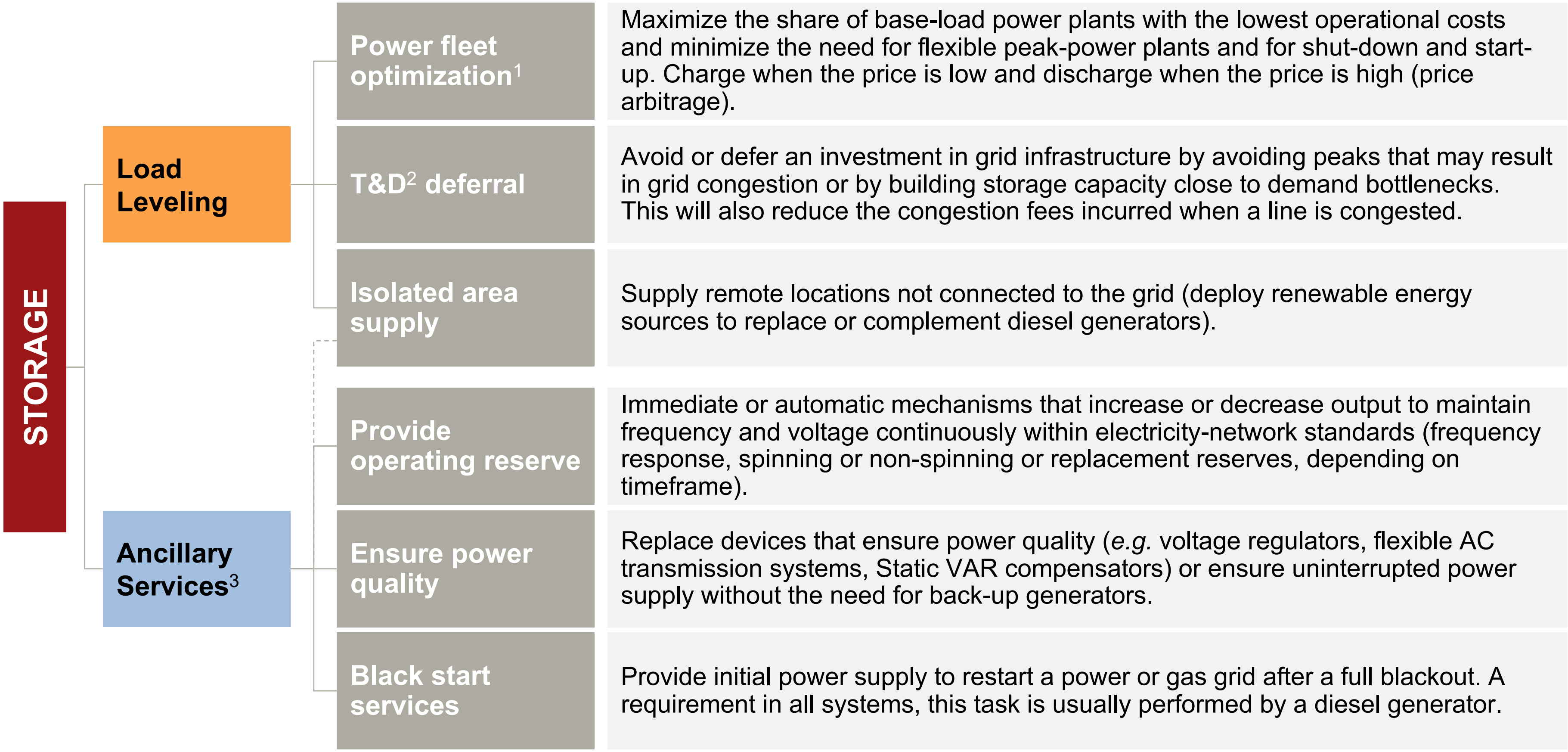


The system’s frequency and voltage need to be maintained within technical limits to avoid instability and blackouts. This could be achieved by using fast-response electricity storage to inject or withdraw power as an alternative to conventional reserves (frequency response, spinning and non spinning, and replacement reserves).

Source: A.T. Kearney Energy Transition Institute analysis based on IRES Proceedings 2012

Electricity storage has several operational applications

Operational applications: main groups



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Load Leveling	**Power fleet optimization**[1]	Maximize the share of base-load power plants with the lowest operational costs and minimize the need for flexible peak-power plants and for shut-down and start-up. Charge when the price is low and discharge when the price is high (price arbitrage).
	T&D[2] **deferral**	Avoid or defer an investment in grid infrastructure by avoiding peaks that may result in grid congestion or by building storage capacity close to demand bottlenecks. This will also reduce the congestion fees incurred when a line is congested.
	Isolated area supply	Supply remote locations not connected to the grid (deploy renewable energy sources to replace or complement diesel generators).
Ancillary Services[3]	**Provide operating reserve**	Immediate or automatic mechanisms that increase or decrease output to maintain frequency and voltage continuously within electricity-network standards (frequency response, spinning or non-spinning or replacement reserves, depending on timeframe).
	Ensure power quality	Replace devices that ensure power quality (*e.g.* voltage regulators, flexible AC transmission systems, Static VAR compensators) or ensure uninterrupted power supply without the need for back-up generators.
	Black start services	Provide initial power supply to restart a power or gas grid after a full blackout. A requirement in all systems, this task is usually performed by a diesel generator.

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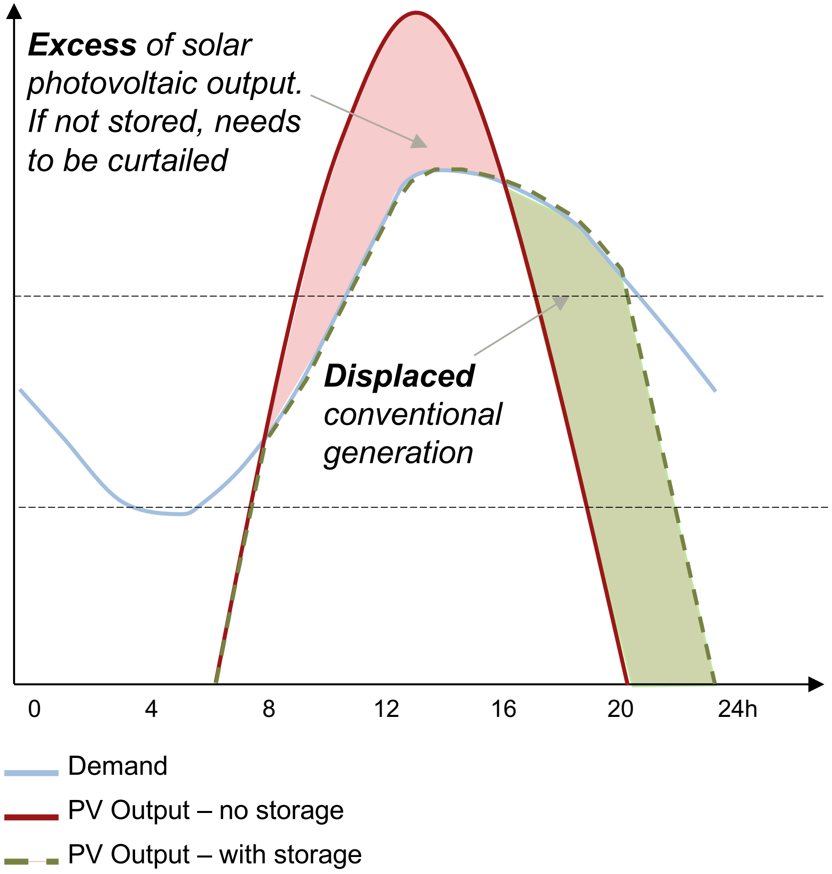
1. Power fleet optimization includes conventional and intermittent balancing (generator side) as well as peak shaving (customer side)
2. T&D for transmission & distribution
3. Ancillary services are usually monetized on the market or through bilateral agreements with the System Operator for provided services

Source: A.T. Kearney Energy Transition Institute analysis

Variable renewables make current applications more crucial and create their own need for storage to balance their intermittency

Illustrative maximization of the daily output of a solar photovoltaic plant with electricity storage



- **Wind and solar are making the existing applications of electricity storage more important:**
  - **Power quality and reliability** is at greater risk because of the variable and non-controllable output of wind and solar (e.g. sudden drops in voltage due to ramp events);
  - **Load leveling** may become essential, as wind and solar power increase the need for flexibility, without themselves contributing significantly to the flexibility of the power system. Variable renewables are likely to increase the price spread between peak and off-peak periods, resulting in price arbitrage opportunities. As wind and solar come first in the merit order, they may displace some of the capacity of baseload power plants and reduce the utilization rate of peak power plants, increasing the complexity of managing and optimizing the power fleet.

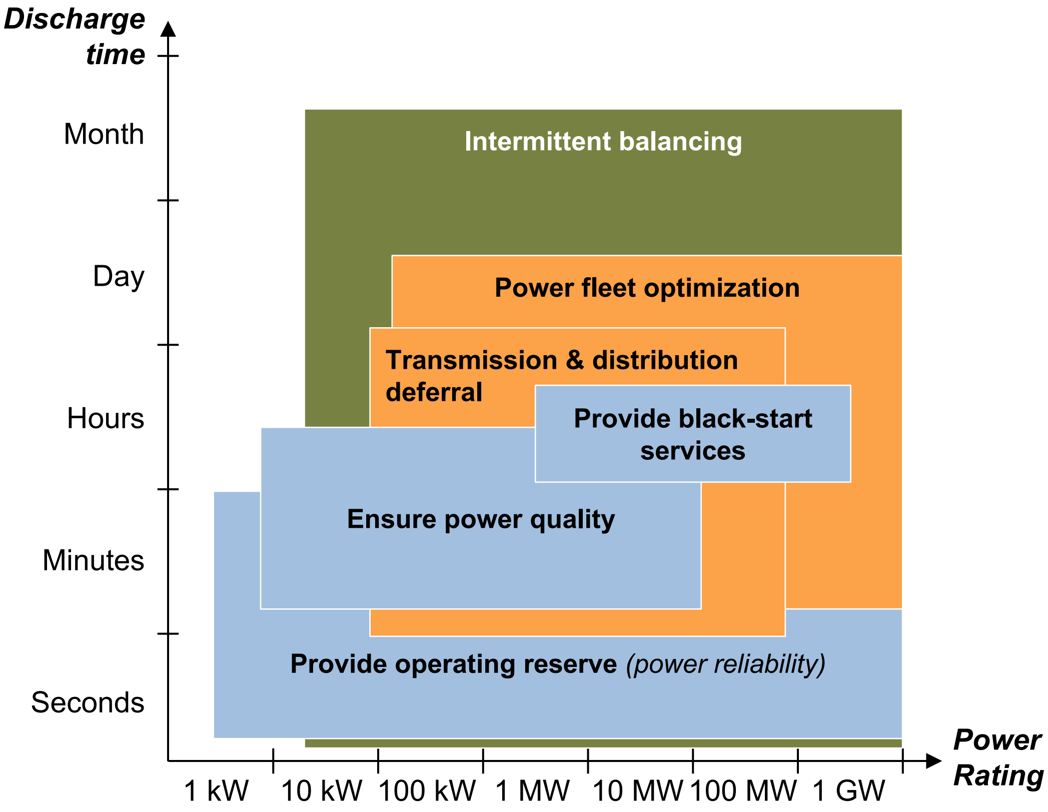
- **Wind and solar are also creating their own electricity-storage applications:**
  - **Firm and smooth output**: increase the reliability of wind and solar farms, and attempt to correlate their output with demand to reduce flexibility needs and/or to participate in flexibility sources;
  - **Integrate distributed generation**: small-scale PV panels can be connected to the distribution grid and create operational challenges (e.g. backflow over the limit);
  - **Avoid curtailment**: for high penetration rates, the combination of low demand and high production can result in an excess of energy. Storage can avoid curtailment and, as a result, energy wastage.

Source: A.T. Kearney Energy Transition Institute analysis

Application requirements depend largely on discharge time and power ratings, which determine cycling time and the importance of efficiency

Applications by power rating & discharge time

Logarithmic scale, power rating in watts

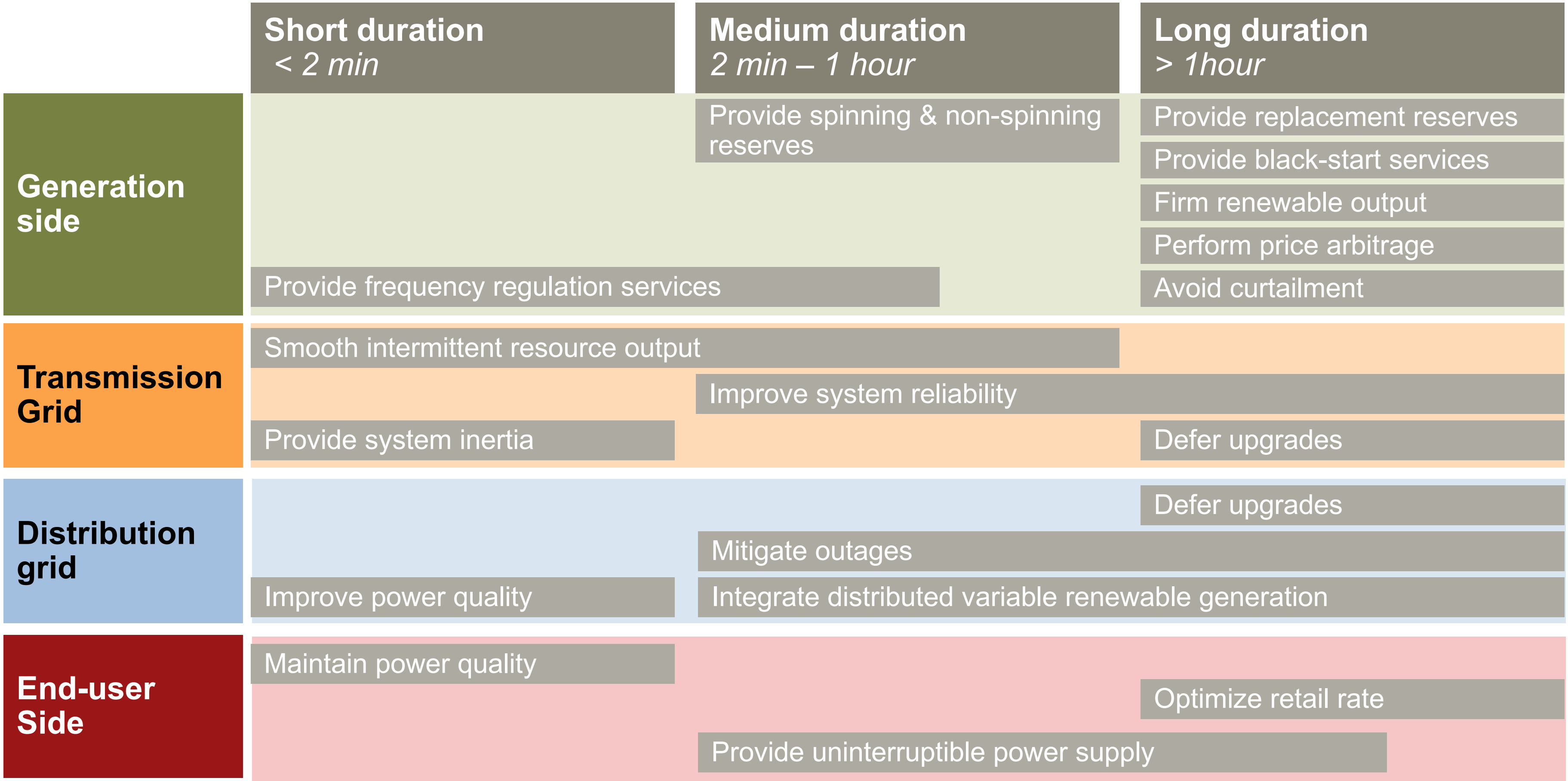


- **Storage applications are broadly classified according to their power ratings and discharge-time requirements:**
  - Power rating rates the storage device's instantaneous ability to withdraw/inject energy from/into the grid;
  - The discharge time indicates the time needed to provide this energy. It is the energy capacity of the storage device divided by its power rating
- **The power-to-energy ratio** is an essential factor in meeting the requirements of different applications. Some applications require output power over a long duration, while others require short bursts of high power

Source: A.T. Kearney Energy Transition Institute analysis based on IEA ECES (accessed 2012), (link)

The type of storage application has a significant impact on its location within the grid

Applications depending on output duration & location on the grid

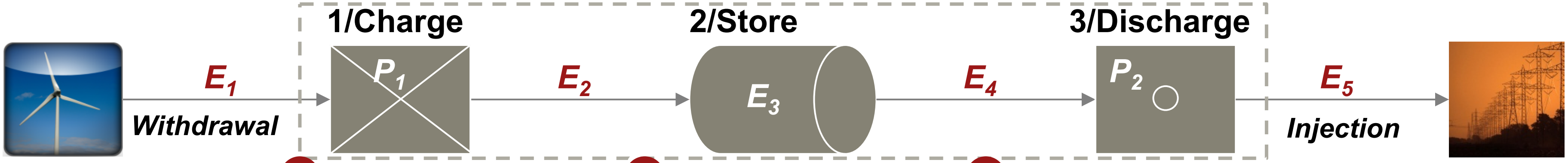


	Short duration *< 2 min*	**Medium duration** *2 min – 1 hour*	**Long duration** *> 1hour*
Generation side	Provide frequency regulation services	Provide spinning & non-spinning reserves Provide frequency regulation services	Provide replacement reserves Provide black-start services Firm renewable output Perform price arbitrage Avoid curtailment
Transmission Grid	Smooth intermittent resource output Provide system inertia	Smooth intermittent resource output Improve system reliability	Improve system reliability Defer upgrades
Distribution grid	Improve power quality	Mitigate outages Integrate distributed variable renewable generation	Defer upgrades Mitigate outages Integrate distributed variable renewable generation
End-user Side	Maintain power quality	Provide uninterruptible power supply	Optimize retail rate Provide uninterruptible power supply

Note: For simplification, voltage & frequency regulation have been merged under power quality.
Source: A.T. Kearney Energy Transition Institute analysis based on Southern California Edison (2010), "Moving Energy Storage from Concept to Reality"

All applications have specific technical requirements that will have to be matched with the characteristics of storage technologies

Storage system properties



① **Charging** can be seen as a form of consumption and is characterized by the rate at which energy can be withdrawn (power) and the time needed to start (ramping rate).

② **Storing phase** adds the time-shifting dimension and is characterized by the amount of energy the system can store (energy being equal to power multiplied by time).

③ **Discharging** can be seen as a form of power generation and is characterized by the rate at which energy can be injected (power) and the time needed to start (ramping rate).

- **The properties of a storage system will determine the breadth of applications that it can serve:**
  - The power-to-energy ratio determines the typical storage cycling time of the system and provides an indication of the cycling frequency (e.g. an 8 MW charging device with 48 MWh electricity storage capacity has a charging time of 6 hours. The same device will have a charging time of 30 minutes for an energy rating of 4 MWh, resulting in a higher cycling frequency);
  - The round-trip efficiency defines the efficiency of the system. It is measured by the energy injected compared with the energy withdrawn. The time-shifting ability can be limited by self-discharge losses (% of energy lost per day). The importance of having a highly efficient system increases with increasing cycling frequency (e.g. ancillary service vs. black start services).

- **Specific energy** (kWh/kg), **energy density** (kWh/l) **and power density** (kW/l) **determine the land footprint**, which, together with safety hazards and environmental impact, could limit the applicability of certain storage systems in certain locations by making licensing and permitting processes more difficult.

Source: A.T. Kearney Energy Transition Institute analysis

2. Electricity Storage Technologies

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

Main electricity-storage technologies grouped by physical or chemical principles

1

Mechanical Storage

- **Pumped hydro storage** (PHS)
- **Compressed air energy storage** (CAES) (& advanced concepts)
- **Flywheel** energy storage (FES)

2

Thermal[1] Storage

- **Hot-water** storage
- **Molten-salt** energy storage (MSES)
- **Phase change material** storage (PCM)

3

Electrical Storage

- **Supercapacitors** (SC)
- **Superconducting magnetic energy storage** (SMES)

4

Electrochemical Storage

- **Sodium-sulfur batteries** (NaS)
- **Lithium-ion batteries** (li-ion)
- **Vanadium redox-flow batteries** (VRB)

5

Chemical Storage

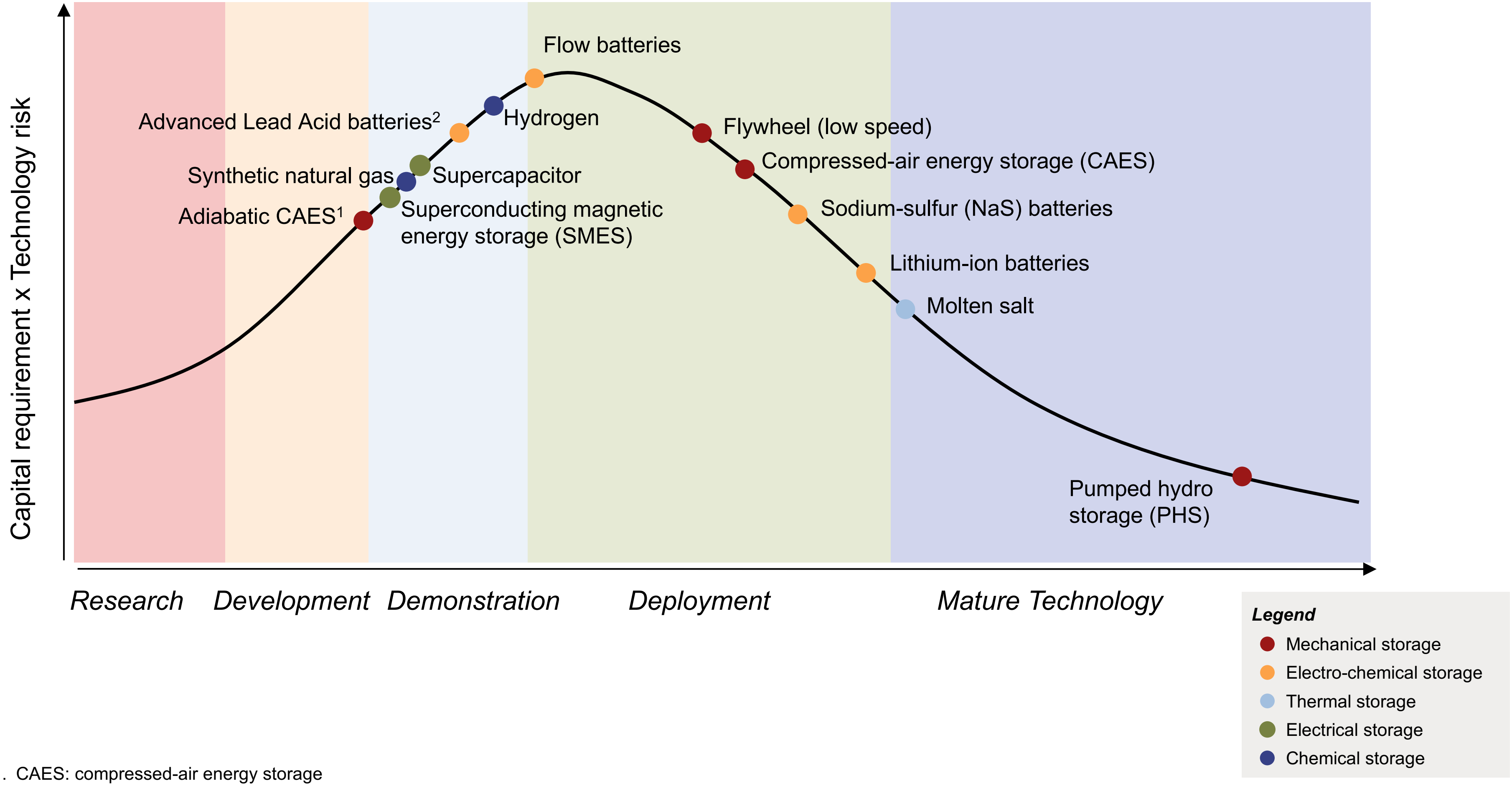
- **Hydrogen**
- **Synthetic natural gas** (SNG)
- **Other chemical compounds** (ammonia, methanol…)[2]

1. This FactBook only describes molten-salt thermal storage, which is the most developed thermal technology for electricity storage. Conventional thermal storage – which aims to supply heat and cooling without re-electrification – includes several other technologies (e.g. aquifer thermal energy storage and ice storage for cooling). Some may interact, support or complement electricity storage (e.g. combining solar-powered desalination plant and thermal storage, or leveraging individual water boilers as a means of electricity storage). For reasons of clarity, those interactions are not discussed in this FactBook, which sticks to pure electricity-storage technologies; 2. Subject to further processing, hydrogen can be stored as ammonia (NH_3), or methanol. These technologies are not covered in this FactBook.

Source: A.T. Kearney Energy Transition Institute analysis

Electricity-storage technologies are at very different levels of maturity, but many face significant risk and extensive capital requirements

Technology maturity curve



1. CAES: compressed-air energy storage
2. Valve regulated Lead Acid batteries is a mature technology

Source: A.T. Kearney Energy Transition Institute analysis

Technologies are constrained by their underlying chemical or physical characteristics

Main technical features of storage technologies

	Power rating (MW)	**Storage duration** (h)	**Cycling or lifetime**	**Self discharge**[8]	**Energy density** (Wh/l)	**Power density** (W/l)	**Efficiency**	**Response time**
PHS[1]	100 - 1,000	4 - 12h	30 - 60 years	0 – 0.02%	0.2 - 2	~0	70-85%	Sec - Min
CAES[2]	10 - 1,000	2 - 30h	20 - 40 years	0 – 1%	2 - 6	0 - 1	40-75%	Sec - Min
Flywheels	0.001 - 1	Sec - hours	100,000 – 1,000,000	20 -100 %	20 - 200	5,000 – 10,000	70-95%	< sec
NaS battery[3]	10 - 100	1 min - 8h	1,000 – 10,000	0.05 - 1%	140 - 300	120 - 160	70-90%	< sec
Li-ion battery[4]	0.1 – 100	1 min - 8h	1,000 - 10,000	0.1 - 0.36%	200 - 620	100 - 10,000	85-98%	< sec
Flow battery[5]	0.1 - 100	1 - 0h	12,000 - 14,000	0 - 1%	15 - 70	1 - 2	60-85%	< sec
Supercapacitor	0.01 - 1	Ms - min	10,000- 100,000	20 - 40%	10 - 20	40,000 - 120,000	80-98%	< sec
SMES[6]	0.1 - 1	Ms - sec	100,000	10 - 15%	~6	~2,600	80-95%	< sec
Molten salt	1 - 150	Hours	30 years	n/a	70 - 210	n/a	80-90%	Min
Hydrogen	0.01 - 1,000	Min - weeks	5 - 30 years	0 - 4%	600 (200 bar)	0.2 - 20	25-45%	Sec - Min
SNG[7]	50 - 1,000	hours-weeks	30 years	negligible	1,800 (200 bar)	0.2 - 2	25-50%	Sec - Min

1. PHS: pumped hydro storage; 2. CAES: compressed-air energy storage; 3. NaS: sodium-sulfur; 4. Li-ion: lithium-ion; 5. Data for vanadium redox flow battery; 6. SMES: superconducting magnetic energy storage; 7. SNG: synthetic natural gas at ambient temperature; 8. Percentage of energy lost per day.

Source: A.T. Kearney Energy Transition Institute analysis, Bradbury (2010), “Energy Storage Technology Review”; IEC (2011), “Electrical Energy Storage – White paper”, IRENA Electricity Storage and Renewables (2017)

The underlying physical features of technologies determine their advantages and drawbacks

Pros & Cons of selected electricity-storage technologies

	Advantages	Drawbacks
PHS[1]	Commercial, large scale, efficient, scalable in power rating	Low energy density, availability of sites, depends on availability of water
CAES[2]	Cost, flexible sizing, large scale, leverages existing gas turbine technology	Lack of suitable geology, low energy density, need to heat the air with gas, possible exposure to natural gas prices
Flywheels	Power density, efficient, scalable	Cost, low energy density
NaS battery[3]	Efficient, density (power & energy), cycling (vs. other battery)	Safety, discharge rate (vs. other battery), must be kept hot
Li-ion battery[4]	Efficient, density (energy & power), mature for mobility	Cost, safety
Flow battery	Independent energy & power sizing, scalable, long lifespan	Cost (more complex balance of system), reduced efficiency
Supercapacitor	High power density, efficient and responsive	Low energy density, cost ($/kWh), voltage changes
SMES[5]	High power density, efficient and responsive	Low energy density, cost ($/kWh), not widely demonstrated
Molten salt	Commercial, large scale	Niche for concentrating solar power plants
Hydrogen	High energy density, versatility of hydrogen carrier	Low round-trip efficiency, cost, safety
SNG[6]	High energy density, leverage current infrastructure	Low round-trip efficiency, cost

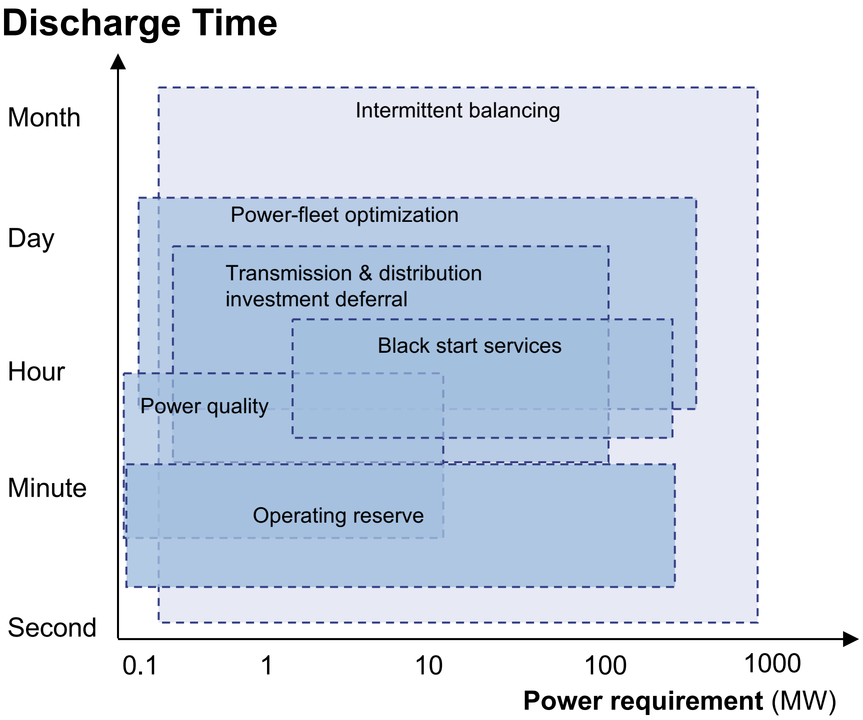
1. PHS: pumped hydro storage; 2. CAES: compressed-air energy storage; 3. NaS: sodium-sulfur; 4. Li-ion: lithium-ion; 5. SMES: superconducting magnetic energy storage; 6. SNG: synthetic natural gas.

Source: A.T. Kearney Energy Transition Institute analysis; IRENA (2012), "Electricity Storage – Technology Brief"

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

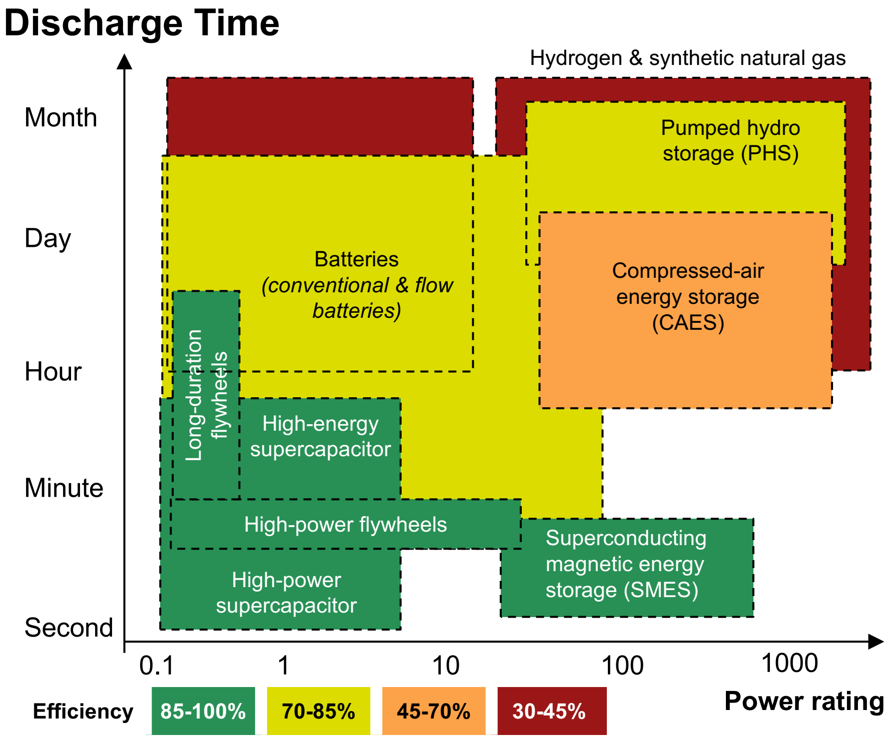
Electricity storage applications

Discharge time vs. power requirements (MW)



Electricity storage technologies

Discharge time vs. power capacity (MW)



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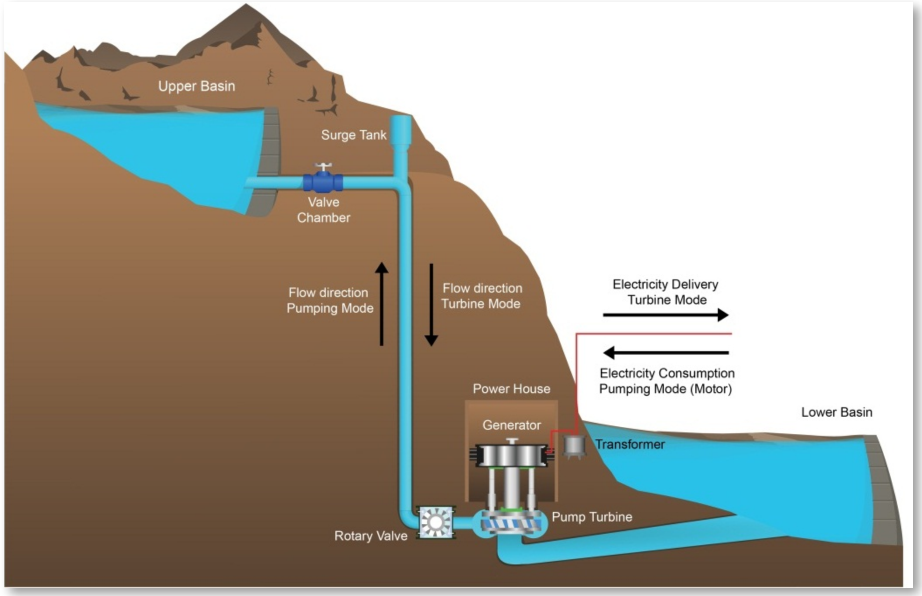
1. Supply to isolated areas has not been included as it is considered a mix of other applications. Technologies that contribute to black-start services only and serve for bridging purposes before other plants kick in have been given a low score. Technologies that balance short-term fluctuations (sec-min) 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.

Source: A.T. Kearney Energy Transition Institute analysis; EPRI (2010), “Electricity Energy Storage Technology Options”, Bradbury (2010), “Energy Storage Technology Review”

Pumped hydro storage uses the gravitational potential energy of water by pumping / releasing water between two vertically separated reservoirs



Pros

- Cheapest and most efficient way to store large quantities of energy over long periods;
- Mature technology.

Cons

- Lack of suitable sites;
- Not suited to distributed generation;
- Relatively low energy density results in indirect environmental impact.

- 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).

Source: A.T. Kearney Energy Transition Institute analysis; Alstom (2012), “Pumped Hydro Storage Plants”

Pumped hydro storage (PHS): Fact card

Examples in use

- **Bath County** in Virginia, (U.S.), with a power rating of 3,003 MW (6 turbines) and an a difference in elevation between the two reservoirs of 385 meters.
- **Guandong** in China, with a capacity of 2,400 MW (8 turbines) and an elevation difference of 353 meters.

Key data

Operational capacity:	**~169 GW**	🟩
Power rating:	**100 - 1,000 MW**	🟩
Discharge duration:	**4 - 12 hours**	⬜
Response time:	**Sec - min**	🟨
Efficiency:	**70 - 85%**	⬜
Lifetime:	**> 30 years**	🟩

High/fast 🟩 ⬜ 🟨 🟥 **Low/slow**

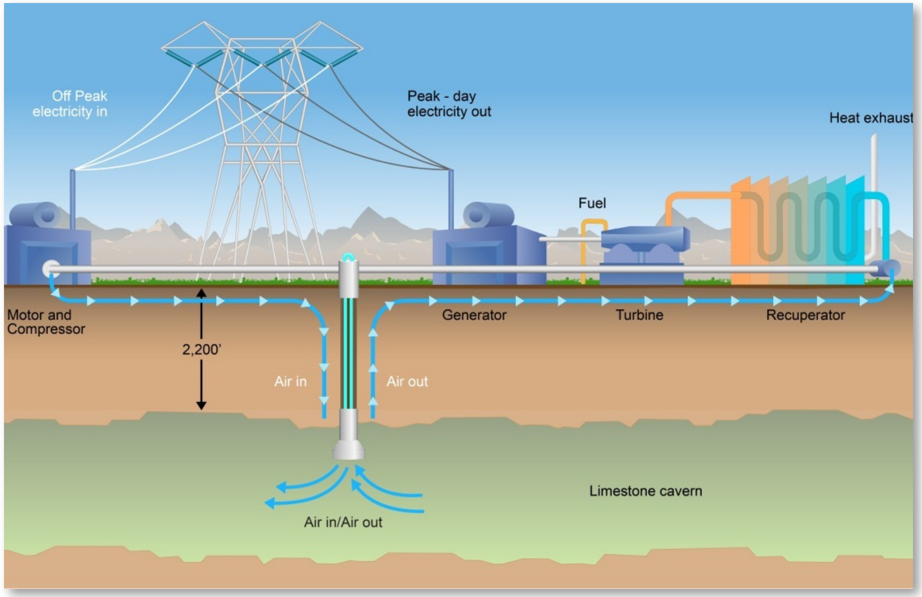
Applications

Power-fleet optimization	🟦
T&D deferral	🟪
Power quality	🟪
Black-start services	🟧
Intermittent balancing	🟧

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; IRENA database extracted on Nov 16th 2015; Alstom (2012), "Pumped Hydro Storage Plants"; Bradbury (2010), "Energy Storage Technology Review", US DOE database (https://www.energystorageexchange.org), November 2017

Compressed-air energy storage mechanically compresses air for storage and releases it during discharge to drive a turbine, producing electricity



Pros

- Large energy and power capacity;
- Competitive, with low costs per kWh;
- Adjustable to decentralized plants with artificial reservoirs.

Cons

- Constraints on availability of suitable geological formations;
- Existing designs rely on gas burners.

- 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.

Source: A.T. Kearney Energy Transition Institute analysis; RWHT Aachen (2011), “Review of Energy Storage Options”

Compressed-air energy storage (CAES): Fact card

Examples in use

Two large-scale commercial plants:

- Huntorf, Germany (above): Power output of 290 MW, two caverns of 150,000 m^3 for production over 4 hours. The power rating of the charging rate is 60 MW (i.e. it takes 12 hours to charge).
- McIntosh, Alabama (U.S.): Power output of 110 MW, discharge time of 26 hours. Air is stored in mined cavern of 283,000 m^3.

Key data

Operational capacity:	**410 MW**	▨
Power rating:	**10 - 1,000 MW**	🟩
Discharge duration:	**2 - 30 hours**	▨
Response time:	**Sec - min**	🟨
Efficiency:	**40 - 75%**	🟨
Lifetime:	**20 - 30 years**	🟩

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

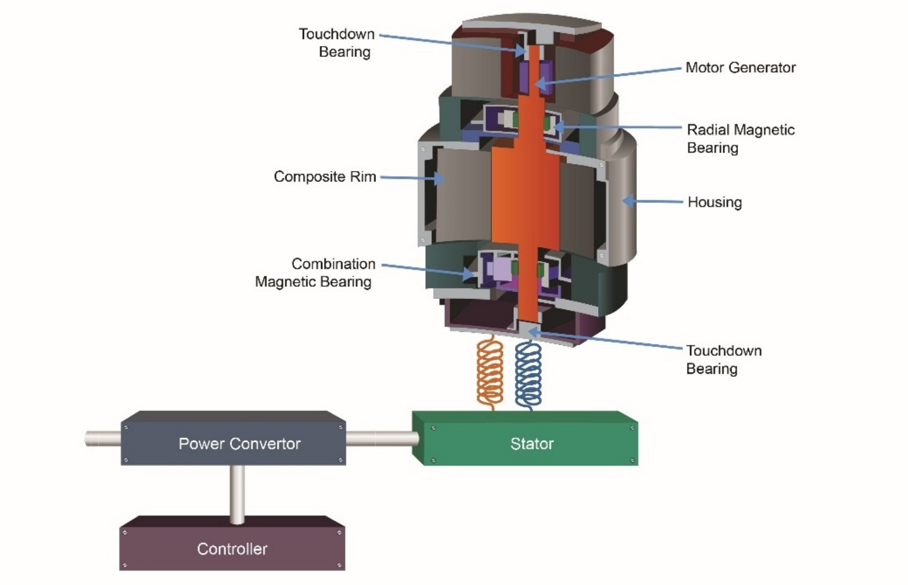
Applications

Power-fleet optimization	🟦
T&D deferral	🟧
Power quality	🟪
Black-start services	🟧
Intermittent balancing	🟧

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; BNEF database, extracted on Nov 16th, 2015; E.ON (2012), "Compressed Air Energy Storage – one promising technology in the future energy storage business", ", US DOE database (https://www.energystorageexchange.org), November 2017

Flywheels store electrical energy in the form of rotational energy via a flywheel rotating in a frictionless container



Pros	Cons
• High power density; • Low detrimental environmental impact; • High cycle life; • Independent power & energy sizing.	• Low energy density; • Difficult / expensive replacement of bearings; • High-energy failures must be contained.

- 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.

Source: A.T. Kearney Energy Transition Institute analysis; Sandia (2010), “Energy Storage for the Electricity Grid: Benefits & Market Potential Assessment Guide”

Flywheel energy storage: Fact card

Examples in use

- Stephentown, New York U.S. (above): 20 MW plant with 200 flywheels providing frequency regulation with 4 second response time, storing 5 MWh over 15 minutes with an 85% round-trip efficiency.
- EFDA JET Fusion Flywheel in Oxfordshire, UK: 400 MW supplied from two large flywheels for 30 seconds, every 20-30 minutes

Key data

Operational capacity:	**930 MW**	🟨
Power rating:	**1 - 1,000 kW**	🟥
Discharge duration:	**sec – hours**	🟨
Response time:	**10 – 20 ms**	🟩
Efficiency:	**70 - 95%**	🟩
Lifetime:	**15 - 20 years**	⬜

High/fast 🟩 ⬜ 🟨 🟥 **Low/slow**

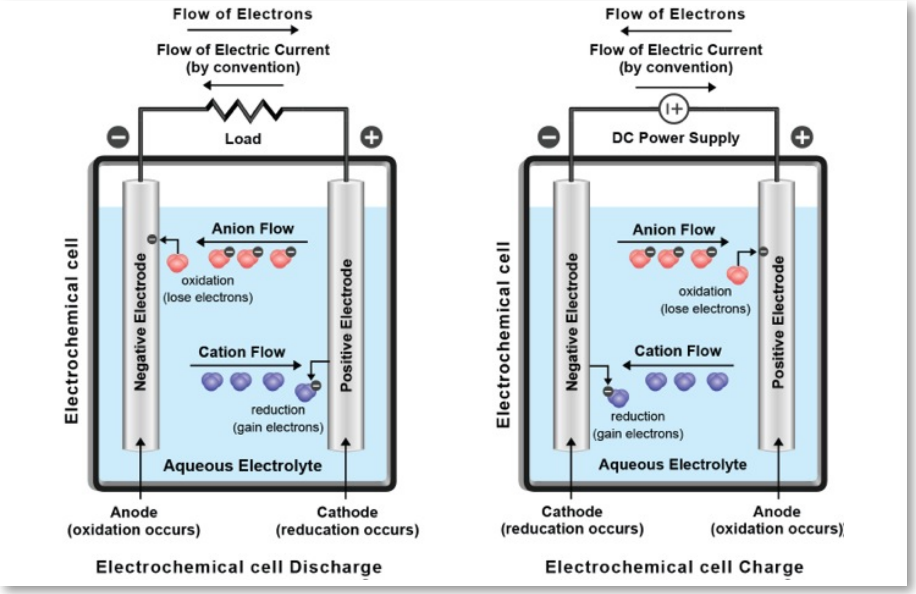
Applications

Power-fleet optimization	🟪
T&D deferral	🟪
Power quality	🟦
Black-start services	🟦
Intermittent balancing	🟧

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; BNEF database, extracted on Nov 16th, 2015; Bradbury (2010), “Energy Storage Technology Review”; IRENA (2012), “Electricity Storage – Technology Brief”, ”, US DOE database (https://www.energystorageexchange.org), November 2017

Batteries, categorized according to their chemical composition, are based on electro-chemical reactions in which electrons flow between two electrodes



Electrochemical cell Discharge

Electrochemical cell Charge

Pros	Cons
• High efficiency; • Extensive experience in portable applications; • Suitable for small-to-medium scale applications.	• Limited lifecycle; • Environmental & safety hazards; • Limited flexibility in power/energy sizing.

- Rechargeable batteries commonly used in mobile and portable applications are based on reversible electro-chemical 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 than 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 lifecycle limitations, present environmental and safety hazards, and are currently costly.

Source: A.T. Kearney Energy Transition Institute analysis; Antonucci (2012), “Battery Energy Storage technologies for power system”; U.S. DoE (2011), “Energy Storage – Program Planning Document”

Sodium and lithium batteries could suit stationary applications thanks to their longer life cycles and higher power & energy densities

Technical performance by battery type

	Sodium-sulfur (NaS)	**Lithium-ion** (Li-ion)	**Nickel-cadmium** (NiCd)	**Lead-acid** (LA)
Efficiency *%*	70 - 90	85 - 98	60 - 80	70 - 90
Self-discharge *% energy / day*	0.05 - 1	0.1 - 0.36	0.067 - 0.6	0.09 - 0.4
Cycle lifetime *Cycles*	1,000 – 10,000	1,000 - 10,000	800 - 3,500	250 - 2,500
Expected lifetime *Years*	5 - 15	5 - 15	5 - 20	3 - 20
Specific energy *Wh / kg*	150 - 240	75 - 200	50 - 75	30 - 50
Specific power *W / kg*	150 - 230	150 - 315	150 - 300	75 - 300
Energy density *Wh / Liter*	140 - 300	200 - 620	60 - 150	50 - 100
Other consideration *(environment & safety)*	Need to be maintained at temperatures of 300°C to 350°C, entailing safety issues and preventing suitability to small-scale applications	Lithium is highly reactive and flammable, and therefore requires recycling programs and safety measures	Cadmium is a toxic metal that needs to be recycled. NiCd also requires ventilation & air conditioning to maintain the temperature	Lead is toxic and sulfuric acid is highly corrosive, requiring recycling and neutralization. Air conditioning required to maintain stable temperature

Source: Antonucci (2012), “Battery Energy Storage technologies for power system”; Bradbury (2010), “Energy Storage Technology Review”, IRENA Electricity Storage and Renewables (2017)

Sodium-sulfur batteries (NaS): Fact card

Examples in use

- Rokkasho-Futamata Wind farm (Japan) (above): 34 MW plant with 17 sets of 2 MW NGK batteries with 238 MWh total storage capacity, used for load leveling and spinning reserves.
- St André La Réunion (France): EDF 1 MW plant (with 7 hours storage).

Key data

Operational capacity:	**188 MW**	▨
Power rating:	**MW scale**	▨
Discharge duration:	**1 min - 8 hours**	▨
Response time:	**10 – 20 ms**	🟩
Efficiency:	**70 - 90%**	▨
Lifetime:	**10 - 15 years**	🟨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

Applications

- 🟧 Power-fleet optimization
- 🟦 T&D deferral
- ▨ Power quality
- 🟦 Black-start services
- 🟦 Intermittent balancing

Stronger application 🟦 🟧 ▨ **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; BNEF database, extracted on Nov 16th, 2015; RWHT Aachen (2011), "Review of Energy Storage Options"; Antonucci (2012), "Battery Energy Storage technologies for power system", US DOE database (https://www.energystorageexchange.org), November 2017

Lithium-ion batteries (Li-ion): Fact card

Examples in use

- Laurel Mountain West Virginia (U.S.): 32 MW plant in an AES wind farm equipped with A123 batteries. Commissioned in 2011, it is the largest of its kind, with 15 minutes of storage capacity.
- La Aldea de San Nicolas in Canaria Island (Spain): 1 MW unit from Endesa with 3 MWh storage capacity equipped with Saft batteries.

Key data

Operational capacity:	**1,147 MW**	▨
Power rating:	**W to MW**	🟨
Discharge duration:	**1 min - 8 hours**	🟨
Response time:	**10 – 20 ms**	🟩
Efficiency:	**85 - 98%**	▨
Lifetime:	**5 - 15 years**	🟨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

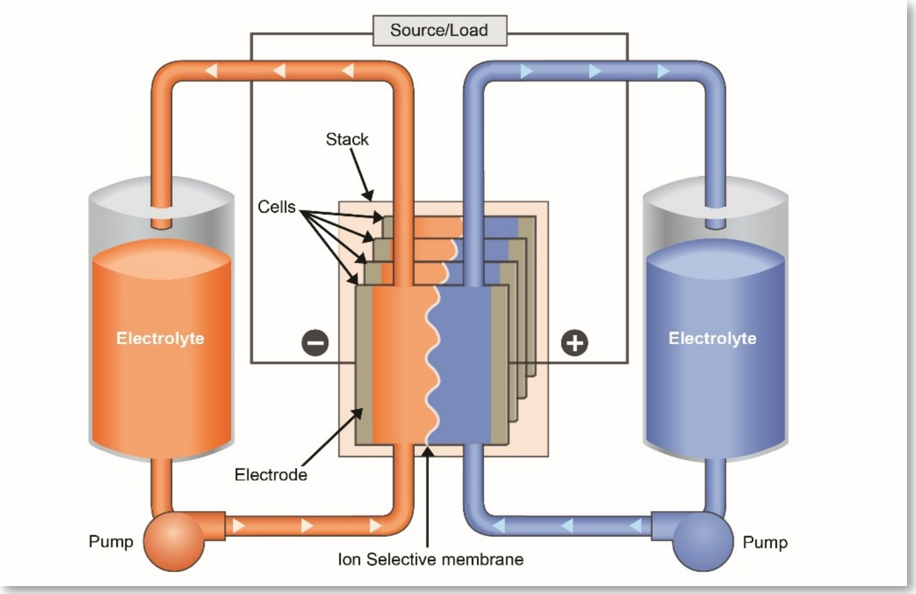
Applications

- Power-fleet optimization
- T&D deferral
- Power quality
- Black-start services
- Intermittent balancing

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; BNEF database, extracted on Nov 16th, 2015; RWHT Aachen (2011), "Review of Energy Storage Options"; Antonucci (2012), "Battery Energy Storage technologies for power system", US DOE database (https://www.energystorageexchange.org), November 2017

Unlike conventional batteries, flow batteries rely on two separately stored electrolytes to decouple their power and energy capacities



Pros

- Independent energy & power sizing;
- Scalable for large applications;
- Longer lifetime in deep discharge.

Cons

- More complex than conventional batteries;
- Early stage of development.

- The electrochemical process in flow batteries is comparable to that in conventional 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 conventional 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.

Source: A.T. Kearney Energy Transition Institute analysis, EPRI (2010), “Electricity Energy Storage Technology Options”

Vanadium redox flow (VRB) batteries: Fact card

Examples in use

- Tomamae, Hokkaido (Japan): 4 MW plant with 6 MWh of storage (90 minutes) composed of 16 modules of 250 kW each, located in a 30.6 MW wind farm.
- Yokohama Works (Japan): 28 units of concentrated photovoltaic (maximum total power generation: 200 kW)* and a redox flow battery (capacity: 1 MW x 5 hours)

Key data

Operational capacity:	**42 MW**	🟨
Power rating:	**100 kW - 20 MW**	🟨
Discharge duration:	**1 - 10 hours**	⬜
Response time:	**10 - 20 ms**	🟩
Efficiency:	**60 - 85%**	⬜
Lifetime:	**5 - 20 years**	🟨

High/fast 🟩 ⬜ 🟨 🟥 **Low/slow**

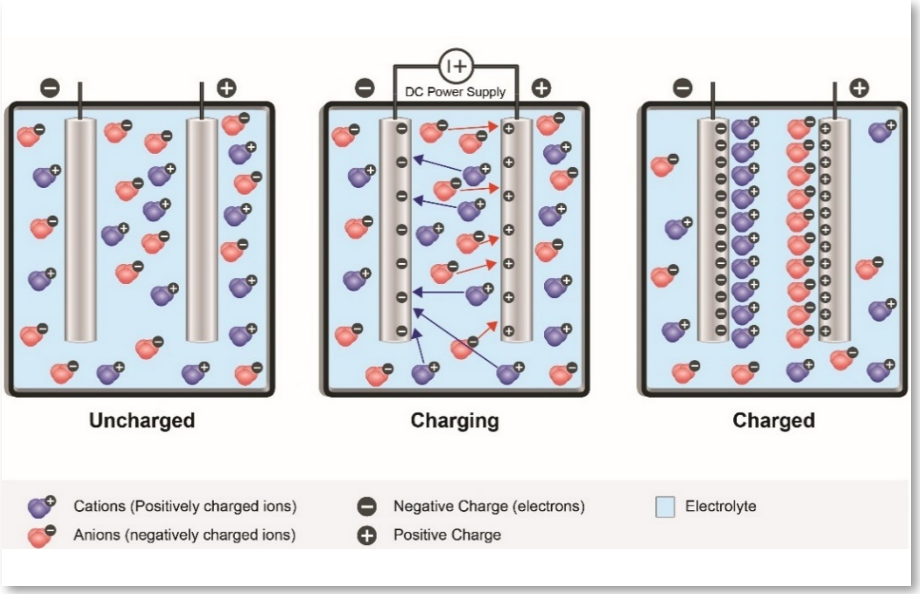
Applications

Power-fleet optimization	🟧
T&D deferral	🟦
Power quality	🟪
Black-start services	🟦
Intermittent balancing	🟦

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; BNEF database, extracted on Nov 16th, 2015; Antonucci (2012), "Battery Energy Storage technologies for power system", US DOE database (https://www.energystorageexchange.org), November 2017

Supercapacitors polarize an electrolytic solution to store energy electrostatically



Pros	**Cons**
• High efficiency;	• Low energy;
• High-cycle fatigue life;	• Requires power conditioning to deliver steady output power;
• Scalable / flexible;	• Expensive per unit of energy capacity.
• High power.	

- 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 (up to 100,000). They are highly efficient (from 80% to 95%), but, because the voltage varies linearly with the charge contained in the system, they require power electronics to ensure steady output.

Source: A.T. Kearney Energy Transition Institute analysis; Bradbury (2010), “Energy Storage Technology Review”

Supercapacitors: Fact card

Examples in use

- Ioxus has fitted its ultracapacitors to the railway wayside traction power on the Long Island Rail Road (LIRR), USA with rated power capacity as 1 MW and 60 seconds storage duration (above)
- La Palma in the Canary Islands (Spain): Endesa’s STORE project, one of few ventures with financing secured, will have a capacity of 4 MW and 6-second storage capacity.

Key data

Operational capacity:	**31 MW**	🟥
Power rating:	**kW – MW**	🟥
Discharge duration:	**ms - min**	🟨
Response time:	**10 - 20 ms**	🟩
Efficiency:	**80 - 98%**	🟩
Lifetime:	**4 - 20 years**	▨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

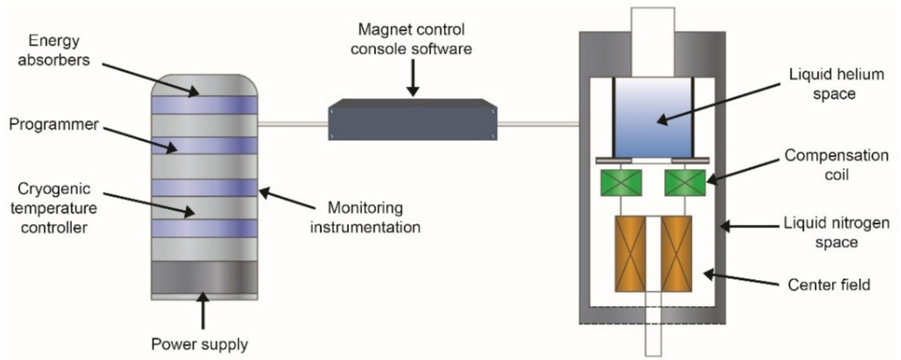
Applications

- Power-fleet optimization 🟪
- T&D deferral 🟪
- Power quality 🟦
- Black-start services 🟧
- Intermittent balancing 🟧

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; Bradbury (2010), “Energy Storage Technology Review”; BNEF database (accessed November 2015), US DOE database (https://www.energystorageexchange.org), November 2017

Superconducting magnets store electricity in a magnetic field



Pros

- High power density;
- Quick response & charging time;
- High efficiency;
- Low maintenance.

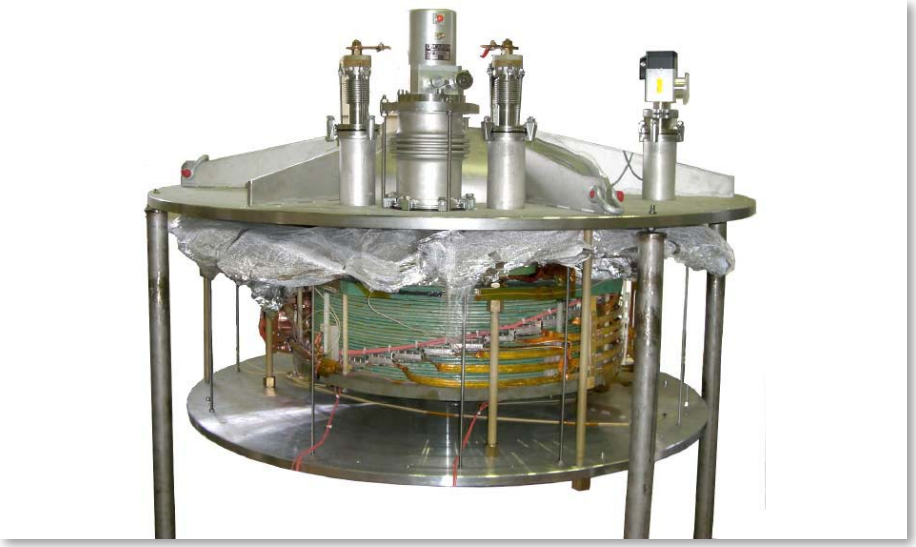
Cons

- High cost of energy;
- Complexity of the system;
- Need to be kept at cryogenic temperatures.

- Superconducting magnetic energy storage devices (SMES) 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.
- As well as 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..

Source: A.T. Kearney Energy Transition Institute analysis; CEA (2009), “Experience in manufacturing a large HTS magnet for a SMES”; EPRI (2010), “Electricity Energy Storage Technology Options”

Superconducting magnetic energy storage (SMES): Fact card



Key data

Operational capacity:	**~40 MW** (2015)	🟥
Power rating:	**MW**	▨
Discharge duration:	**ms – sec**	🟥
Response time:	**< 100 ms**	🟩
Efficiency:	**80 - 95%**	🟩
Lifetime:	**high**	🟩

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

Applications

- Power-fleet optimization
- T&D deferral
- Power quality
- Black-start services
- Intermittent balancing

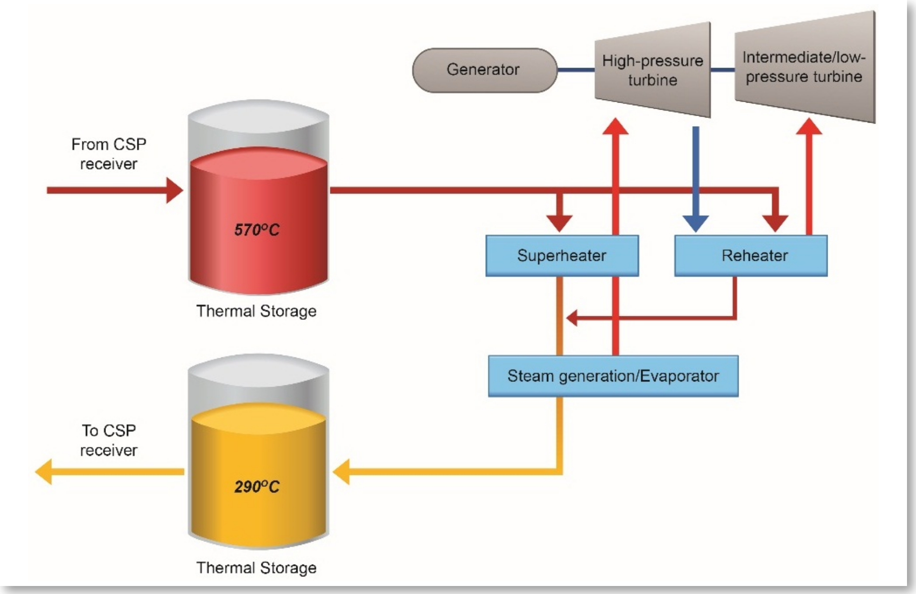
Stronger application 🟦 🟧 🟪 **Limited application**

Examples in use

- Nosoo power station (Japan): 10MW system to improve grid stability and power quality
- Anchorage Alaska (U.S.): 500 kWh project using American Superconductor products for the municipal light & power plant.

Source: A.T. Kearney Energy Transition Institute analysis, EPRI (2010), "Electricity Energy Storage Technology Options"

Molten salts are an energy-storage medium that stores heat from concentrating solar radiation



Pros	**Cons**
• Commercial; • Large scale; • Low cost.	• Niche for concentrating solar plant for power applications; • Molten salts can be corrosive; • Must not be allowed to freeze.

- Thermal storage has been investigated as a method of storing heat generated by the optical concentration of solar energy in concentrating solar power (CSP) plants.
- Indirect storage systems require a heat exchanger to store heat in a separate circuit, usually oil-based. Direct storage systems include a storage tank directly linked to the primary circuit. Molten salts are used as a working fluid since they can serve both as a heat-transfer fluid and as heat-storage medium, making a heat exchanger unnecessary. Molten salts allow the use of higher temperatures, smaller storage tanks and higher steam-cycle efficiency. They have become the dominant technology.
- Molten salt is a mixture of 60% sodium nitrate and 40% potassium nitrate. It is non-flammable and non-toxic, with a low melting point, of 221°C. Salts are kept liquid at 290°C in an insulated cold tank, pumped through pipes, heated to 570°C by the CSP panels and sent to a hot, insulated storage tank. During discharge, hot salts are pumped through a super-heater, and then produce steam in a conventional steam generator, which drives a turbine. The salts are then returned to the cold tank and the process restarts.
- Molten salt is already capable of storing large amounts of energy. It is capable of storing energy for up to 15 hours, and achieving high levels of efficiency. Despite being limited to CSP technology for power applications, it could play an important role in countries with high direct normal irradiance, such as the MENA region[1].

Source: A.T. Kearney Energy Transition Institute analysis; IRENA (2012), “Electricity Storage – Technology Brief”

Molten salts energy storage (MSES): Fact card

Examples in use

- Aldiere, Grenada (Spain): Andasol 150 MW CSP parabolic plant incorporates 7.5 hours of storage (3 series of two tanks containing 28,500 tons of molten salt).
- Tonopah Nevada (US): Crescent Dune 110 MW CSP tower plant include 10 hours storage capacity.

Key data

Operational capacity:	**2,281 MW**	▨
Power rating:	**MW scale**	▨
Discharge duration:	**Hours**	▨
Response time:	**Min**	🟨
Efficiency:	**80 - 90%**	🟩
Lifetime:	**30 years**	▨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

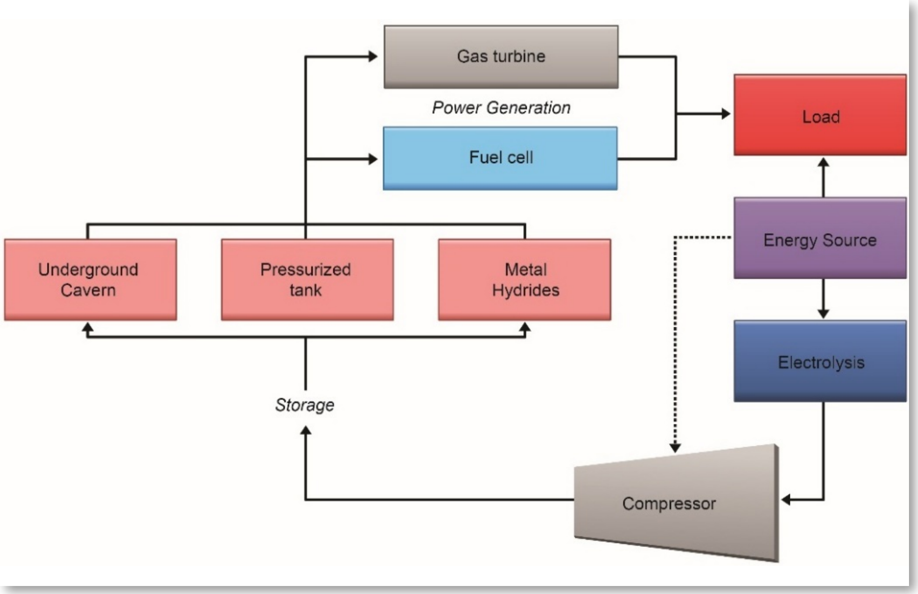
Applications

Power-fleet optimization	🟪
T&D deferral	🟪
Power quality	🟪
Black-start services	🟪
Intermittent balancing	🟧

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute analysis; SolarPace database (accessed 2015); IRENA (2012), "Electricity Storage – Technology Brief", US DOE database (https://www.energystorageexchange.org), November 2017

Hydrogen is the only technology to offer inter-seasonal storage, but it also suffers from low efficiency rates of 35-45%

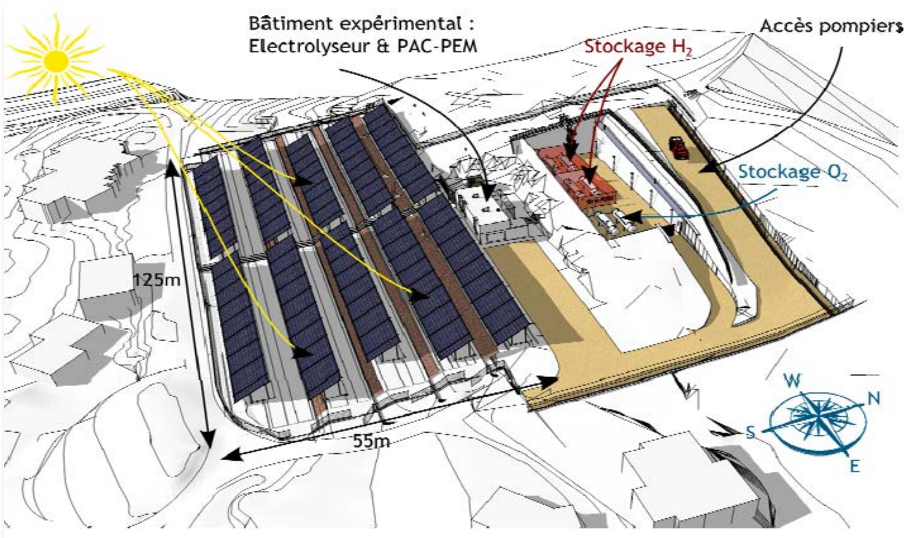


Pros	Cons
• Scalable from distributed to long-term, large-scale storage; • Low detrimental effect on environment.	• Low round-trip efficiency; • High capital cost; • Safety concerns; • Low energy density at ambient conditions.

- Hydrogen energy storage technologies are based on the chemical conversion of electricity into hydrogen. Electrolysis is used to split water (H2O) into its constituent elements, Hydrogen (H2) and Oxygen (O2). 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.

Note: For more information about hydrogen technologies: A.T. Kearney Energy Transition Institute FactBook on hydrogen (link).
Source: A.T. Kearney Energy Transition Institute analysis; FuelCellToday (2013), “Water Electrolysis & Renewable Energy Systems”

Hydrogen energy storage: Fact card



Examples in use

- EnBW Hydrogen Testing Facility (Germany): The system produces hydrogen from water and electricity from renewable energy sources. This hydrogen then powers emission-free fuel cell cars. Rated power: 400 kW for a duration of ~1h
- INGRID Hydrogen Demonstration Project (Italy): A 39 MWh energy storage facility using McPhy hydrogen-based solid state storage (1 ton) and 1.2 MW hydrogen generator

Key data

Operational capacity:	**~15 MW**	🟥
Power rating:	**kW - GW**	🟩
Discharge duration:	**Min - Weeks**	🟩
Response time:	**sec - min**	▨
Efficiency:	**20 - 48%**	🟨
Lifetime:	**5 - 30 years**	▨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

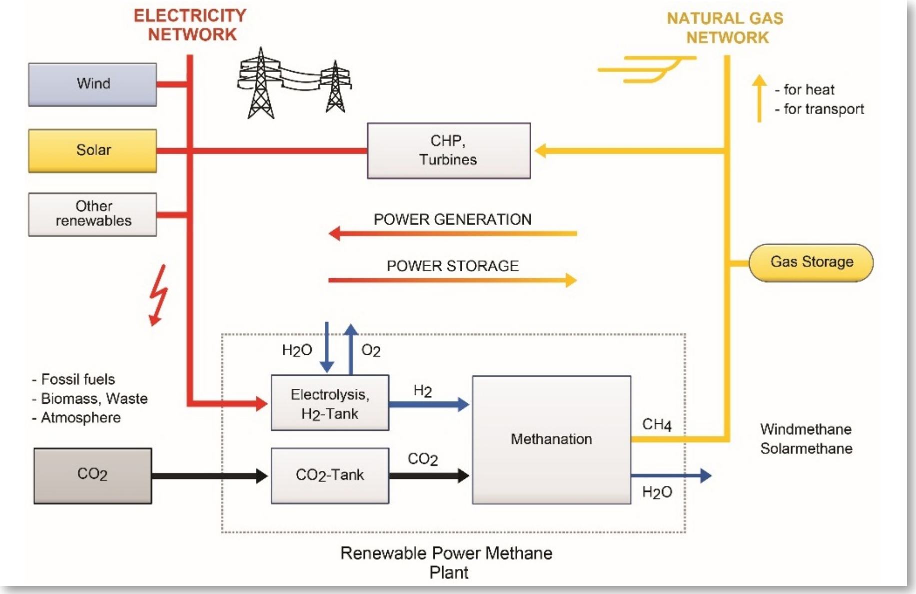
Applications

- Power-fleet optimization
- T&D deferral
- Power quality
- Black-start services
- Intermittent balancing

Stronger application 🟦 🟧 🟪 **Limited application**

Source: A.T. Kearney Energy Transition Institute; FuelCellToday (2013), "Water Electrolysis & Renewable Energy Systems"; plateforme MYRTE, Universita di Corsica Pasquale Paoli (link)

Conversion to hydrogen enables energy to be stored as gas and opens up the use of existing gas infrastructure



Pros	Cons
• Potential for valuable inter-seasonal storage; • Very high chemical energy per unit mass.	• Business case: competition with gas; • Capital costs; • CO_2 source availability; • Low round-trip efficiency.

- Power-to-gas uses electrons to produced synthetic methane or hydrogen-enriched natural gas, which can be sent to consumers through existing gas networks. Power is first converted to hydrogen through electrolysis, which is then either blended directly into the gas grid or synthetized with CO2 to produce synthetic natural gas (SNG) through methanation.
- SNG's main advantage is that it can make use of gas infrastructure, getting round hydrogen's chicken-and-egg dilemma (whether it is necessary to build infrastructure in order to nurture demand or to create demand before building costly infrastructure). In Germany, for instance, underground natural gas-storage capacity is estimated to amount to 212 TWh and gas-grid capacity close to 1,000 TWh/y, compared with power-storage capacity of 0.08 TWh and electrical grid capacity of 500 TWh. Therefore, even if blending is likely to be limited by safety and performance constraints to a rate of 5% to 20% of total volume (depending on system, end-uses, pipeline materials, injection point), gas infrastructure will represent huge storage capacity.
- Methane can also be passed through gas turbines, used in compressed natural gas vehicles or valorized for heat. This versatility leads to the decompartmentalization of energy systems. However, power-to-gas faces strong competition from natural gas. Business cases may be difficult to justify in the short term, as the technology is still developing and is subject to the availability of cheap CO_2.

Source: A.T. Kearney Energy Transition Institute analysis; Specht et al. (2009), "Storing bioenergy and renewable electricity in the natural gas grid"

Power-to-gas: Fact card

Examples in use

- E.ON Falkenhagen project: 2 MW electrolyzers supplied by excess wind power have been built to generate up to 360 m^3 per hour of hydrogen, which is injected into the Ontras gas-transmission network at a maximum pressure of 55 bar.
- Audi E-gas project (Werlte, Germany): 6 MW electricity from wind converted into synthetic natural gas using CO_2 from nearby biogas plant.

Key data

Operational capacity:	**26 MW** (2015)	🟥
Power rating:	**kW - GW**	🟩
Discharge duration:	**N/A**	
Response time:	**N/A**	
Efficiency:	**55-78%**	🟥
Lifetime:	**5 - 30 years**	▨

High/fast 🟩 ▨ 🟨 🟥 **Low/slow**

Applications

Power-fleet optimization	🟧
T&D deferral	🟧
Power quality	🟪
Black-start services	🟪
Intermittent balancing	🟦

Stronger application 🟦 🟧 🟪 **Limited application**

Note: Round-trip efficiency depends to a large extent on end-use (e.g. combined heat & power, combined cycle, but also power or heat applications).
Source: A.T. Kearney Energy Transition Institute analysis; E.ON (2013), “Power to Gas – a promising solution to integrate large quantities of fluctuating renewable power”

3. Status and Future Development

New technologies have continued to emerge since the invention of lead-acid batteries in 1859

Electricity storage timeline

1890s
First PHS plants using separate pump impellers and turbine generators appear in Switzerland, Austria and Italy

1990s
Development of PHS declines due to a drop in gas prices

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

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

2017
Nanotechnology (carbon nanotube) based batteries developed by NAWA Technology

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

1971
First CAES plant built in Huntorf, Germany

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

1991
Second CAES plant built in McIntosh, U.S.

1859 | 1970 | 1980 | 1990 | 2000 | 2010 | **2017**

French physicist Gaston Planté invents the Lead-acid battery

1970s
Li-ion batteries are developed

1983
TEPCO and NGK declare their interest in researching the NaS battery, whose components are abundant in Japan

1986
Sulfuric acid VRBs patented by the University of NSW, Australia

2007-2015
More than 1,500 GW of thermal storage capacity* is developed to provide storage solutions for CSP plants, principally in Spain ad the U.S.

2011
The Laurel Mountain lithium-ion storage project enters commercial operation. It provides frequency regulation and manages fluctuations of the adjacent wind farm.

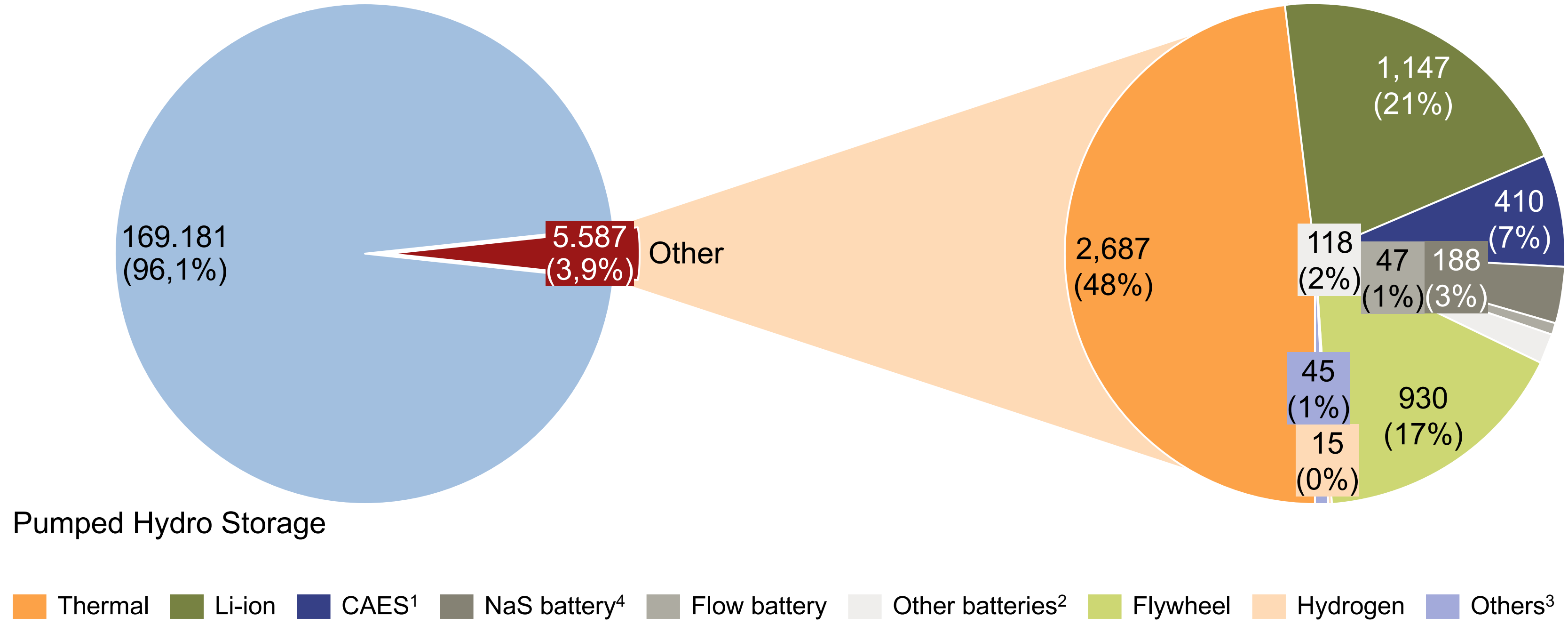
2017
World's First Utility-Scale Hybrid Wind, Solar, & Storage Project announced in Australia

Note: PHS: pumped hydro storage; CAES: compressed-air energy storage; NaS: sodium-sulfur; VRB: vanadium redox battery, Li-ion: lithium-ion battery; CSP for Concentrated Solar Power; *mostly molten salt-based.
Source: A.T. Kearney Energy Transition Institute analysis based on IRENA (2012), "Electricity Storage – Technology Brief"; Chi-Jen Yang (2011), "Pumped Hydroelectric Storage", Press research

Worldwide stationary storage capacity currently stands at 175 GW, 96% of which is pumped hydro storage

Operational worldwide storage capacity
MW and %, November 2017

Operational non-pumped hydro storage capacity
MW and %, November 2017



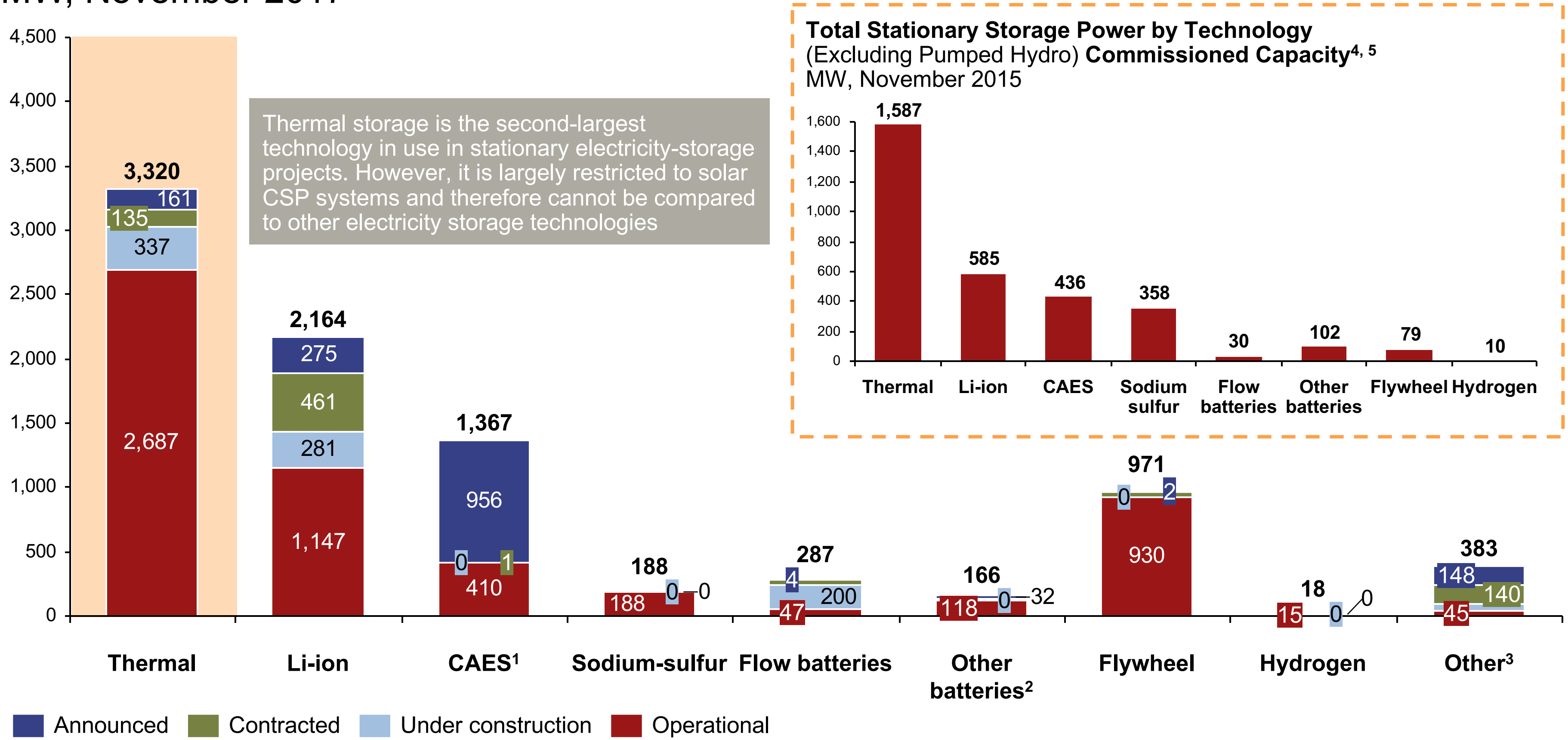
1. CAES: compressed-air energy storage; 2. Other batteries include Lead acid, Hybrid lead acid/electro-chemical, Metal air, Nickel based, Zinc air, Other Sodium based (except Sulfur); 3. Other include Electro-chemical capacitor, Gravitational storage; 4. Sodium Sulfur battery

Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org), November 2017

Li-ion Batteries have registered a strong growth to become the preferred alternatives to pumped hydro storage

Total stationary storage power output by technology (excluding pumped hydro)

MW, November 2017



Thermal storage is the second-largest technology in use in stationary electricity-storage projects. However, it is largely restricted to solar CSP systems and therefore cannot be compared to other electricity storage technologies

Total Stationary Storage Power by Technology (Excluding Pumped Hydro) **Commissioned Capacity**[4, 5]
MW, November 2015

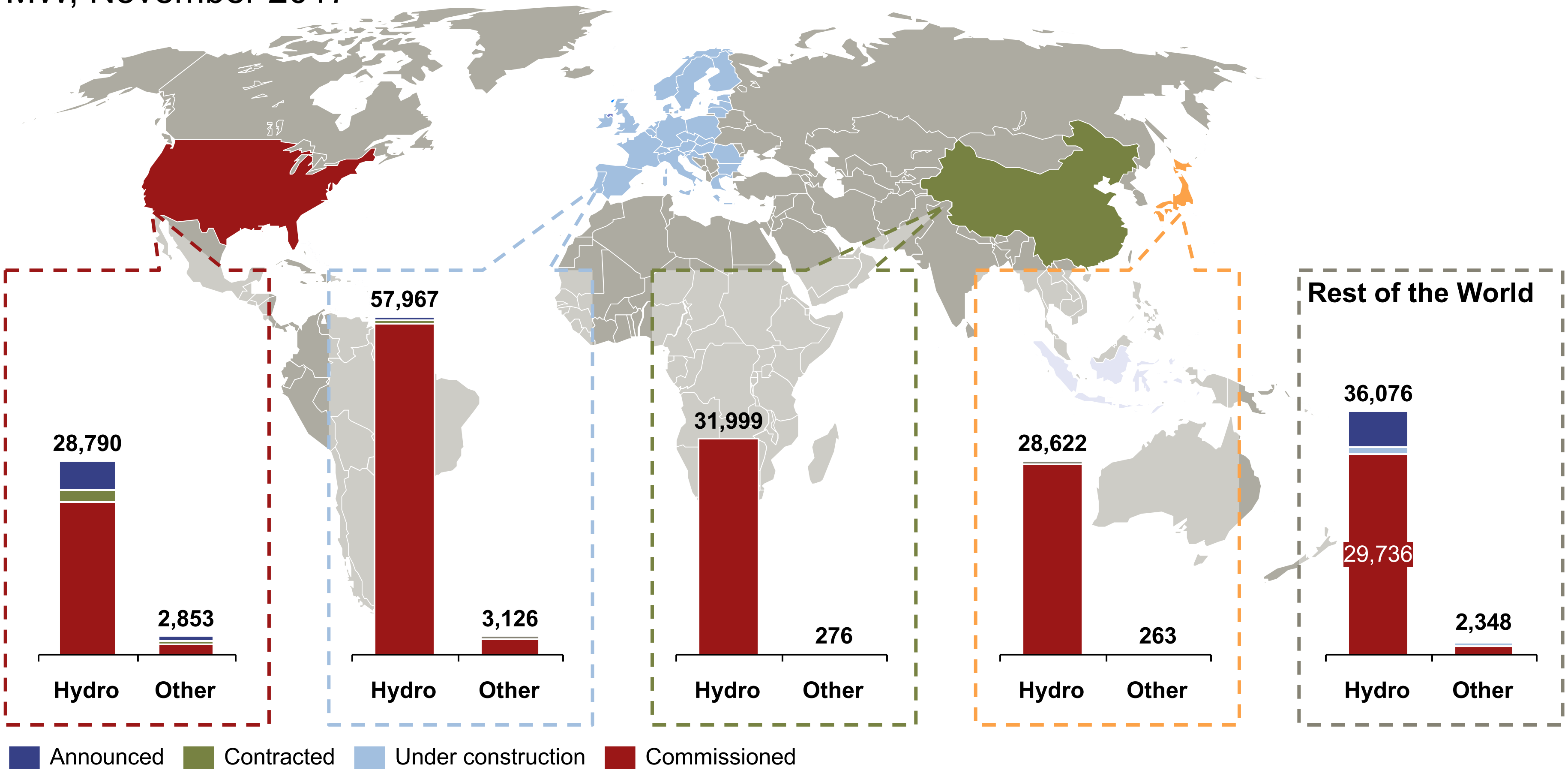
1. CAES: compressed-air energy storage; 2. Other batteries include Lead acid, Hybrid lead acid/electro-chemical, Metal air, Nickel based, Zinc air, Other Sodium based (except Sulfur); 3. Other include Electro-chemical capacitor, Gravitational storage; 4. Commissioned includes commissioned and partially commissioned plants; 5. Variation exists in Bloomberg 2015 dataset and US DOE database 2017 dataset on Flywheel and Hydrogen storage technology

Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org) extracted in November 2017, 2015 figures from Bloomberg New Energy Finance database extracted on 17th Nov 2015

Europe, China, Japan and the U.S. stand out as the market leaders for electricity storage

Stationary storage capacity by region[1] (Pumped Hydro vs. others)

MW, November 2017



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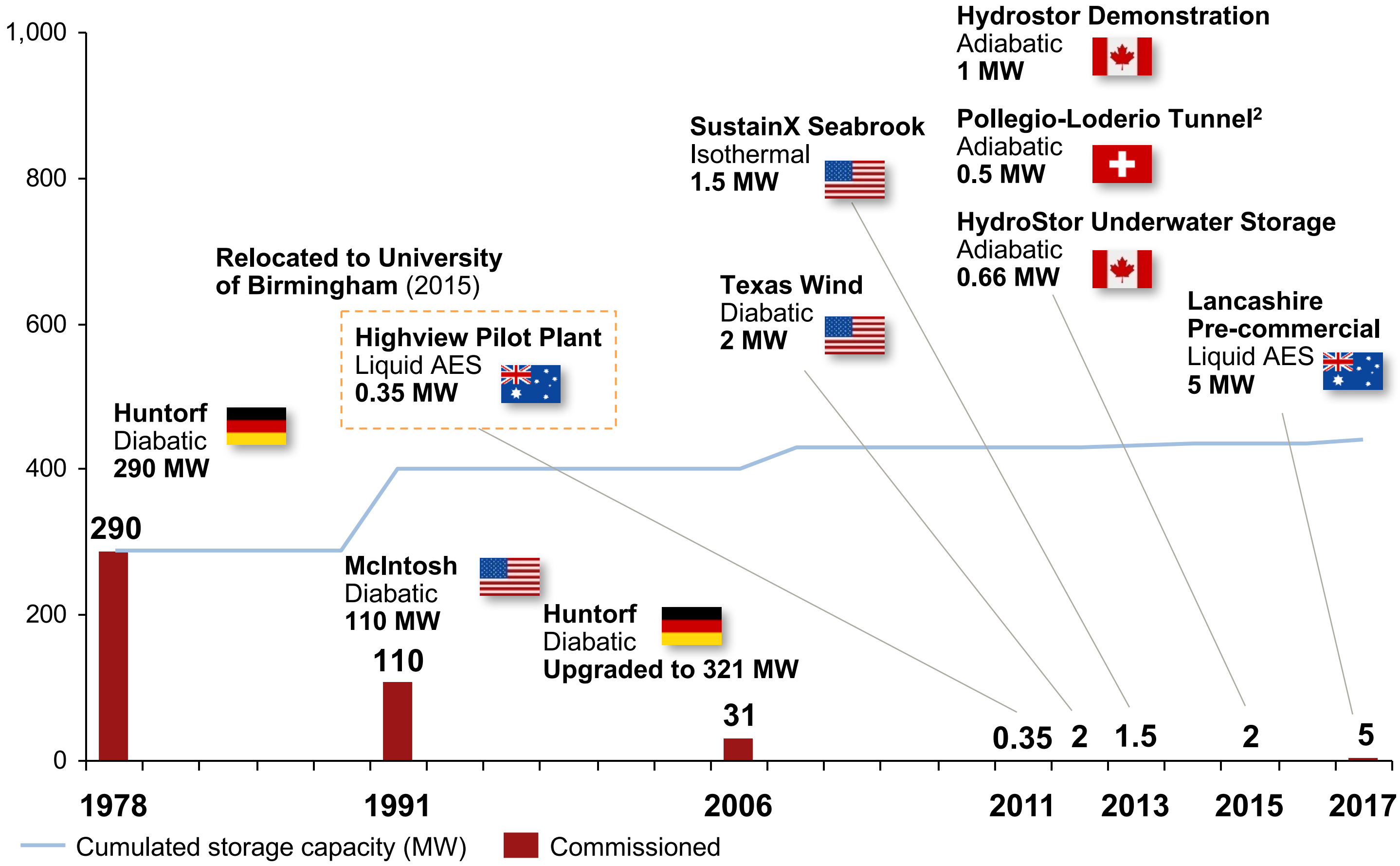
1. Select European countries

Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org), November 2017

Compressed-air energy storage (CAES) is at a standstill with flagship projects being delayed or abandoned

CAES deployment: operational[1]

MW, November 2017



The rights to the largest CAES project in the world, the Norton project, was sold in 2009 to FirstEnergy by Haddington before being suspended because of low power prices and insufficient demand. A project in Iowa was cancelled due to unsuitable geology and several projects have been suspended or delayed in Germany and the U.S., including 317 MW Apex Bethnel and 150 MW Watkins Glen advanced CAES projects in the U.S. and adiabatic 90 MW plant in Germany.

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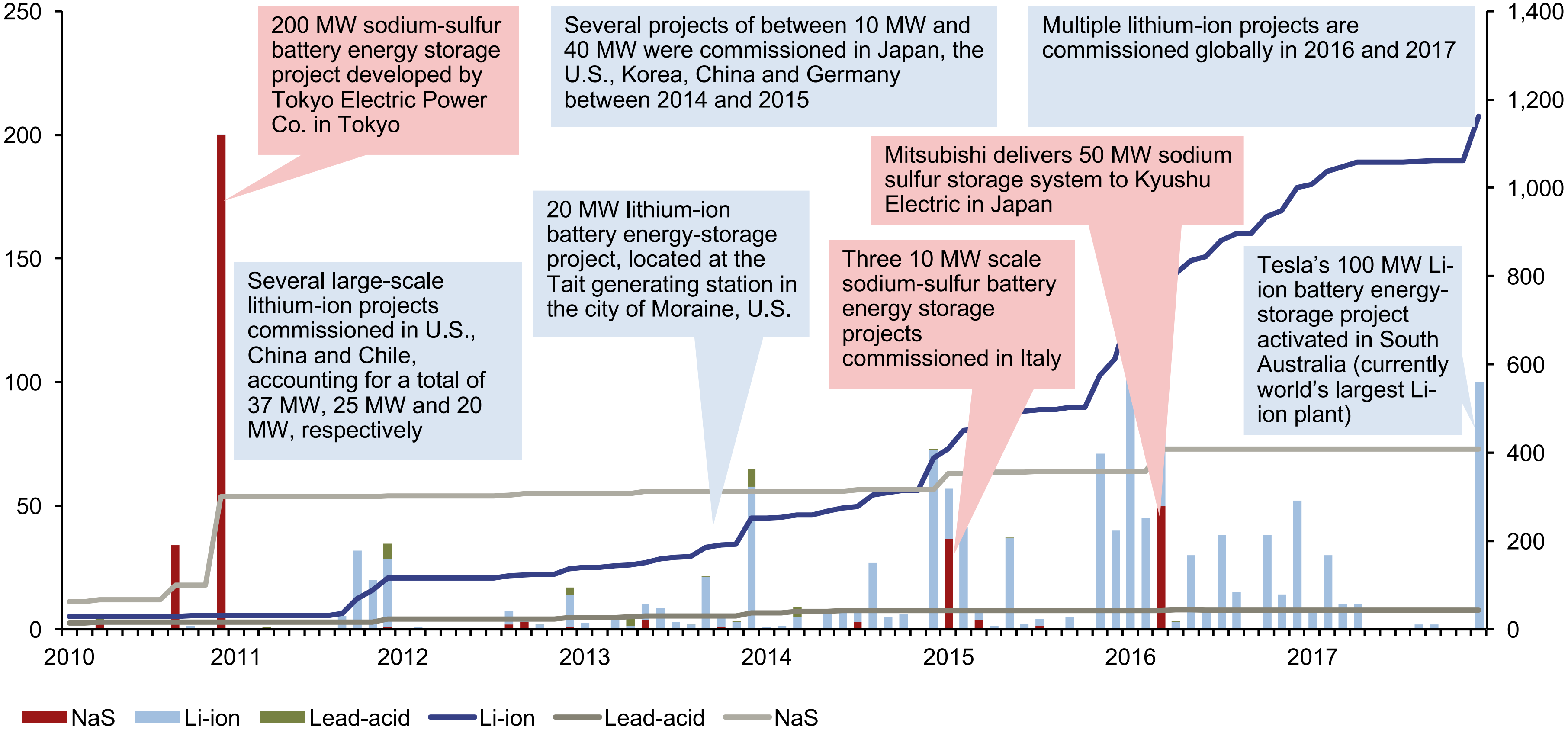
1. Big capacity projects in US (PG&E CAES, etc.) and UK (Gaelectric CAES) have not been commissioned yet despite being announced earlier

Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org), November 2017

Lithium-ion technology has increased in popularity in recent years, whereas sodium-sulfur technology has lost momentum

Historical grid-scale battery deployment (Jan 2010 – Nov 2017)

Individual projects commissioned (MW, left), Cumulated (MW, right)



200 MW sodium-sulfur battery energy storage project developed by Tokyo Electric Power Co. in Tokyo

Several large-scale lithium-ion projects commissioned in U.S., China and Chile, accounting for a total of 37 MW, 25 MW and 20 MW, respectively

Several projects of between 10 MW and 40 MW were commissioned in Japan, the U.S., Korea, China and Germany between 2014 and 2015

20 MW lithium-ion battery energy-storage project, located at the Tait generating station in the city of Moraine, U.S.

Multiple lithium-ion projects are commissioned globally in 2016 and 2017

Mitsubishi delivers 50 MW sodium sulfur storage system to Kyushu Electric in Japan

Three 10 MW scale sodium-sulfur battery energy storage projects commissioned in Italy

Tesla's 100 MW Li-ion battery energy-storage project activated in South Australia (currently world's largest Li-ion plant)

Note: Although the boxes only highlight large-scale projects, this graph also takes into account smaller storage systems installed between 2010 and late 2017.
Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org), November 2017

As of November 2017, lithium-ion technology accounted for the vast majority of grid-scale battery-storage projects

Stationary battery storage projects: operational & in development

MW, November 2017

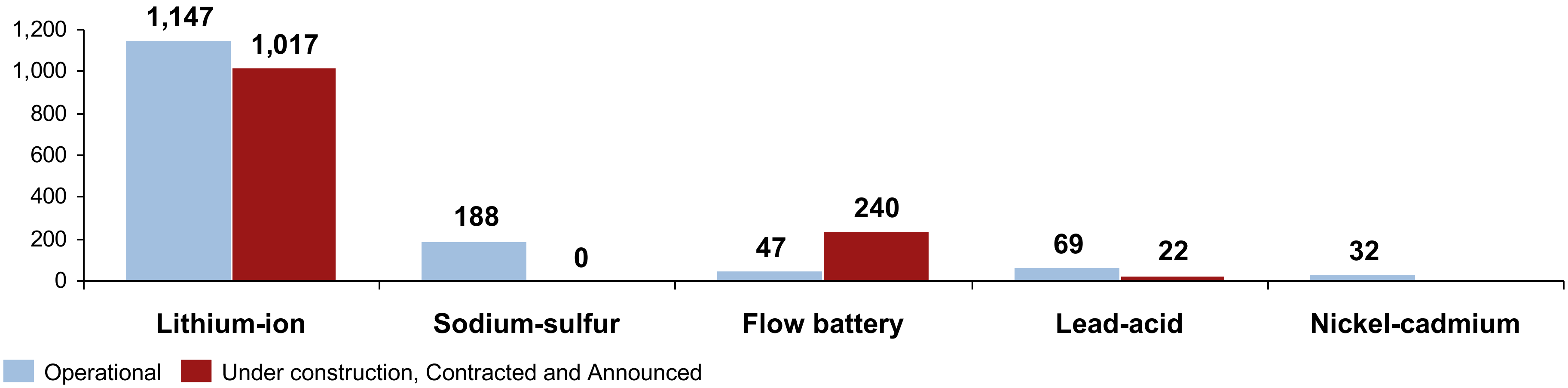
- Li-ion projects have recently gained in popularity. The technology is often preferable to other chemistries with respect to energy and power density, cycle and calendar life, and cost.
- Large projects have been announced in the U.S., Japan, Chile, Korea and Australia

- Until early 2015, Sodium-sulfur accounted for the majority of installed battery-storage capacities.
- The battery storage landscape in the electricity sector is now moving away from this technology.

- Flow technology is at an early stage of development compared with other battery technologies.
- Therefore, growth over the next few years may be slow. However, many predictions show promising potential of the technology as the costs fall

- Lead-acid is the oldest battery type and presents limited potential for growth.
- Recent improvements in carbon-electrode and supercapacitor technology could give lead-acid a new lease of life.

- Nickel-cadmium (Ni-Cad) is not explored in this study as installed capacity is very small and there are few projects in development



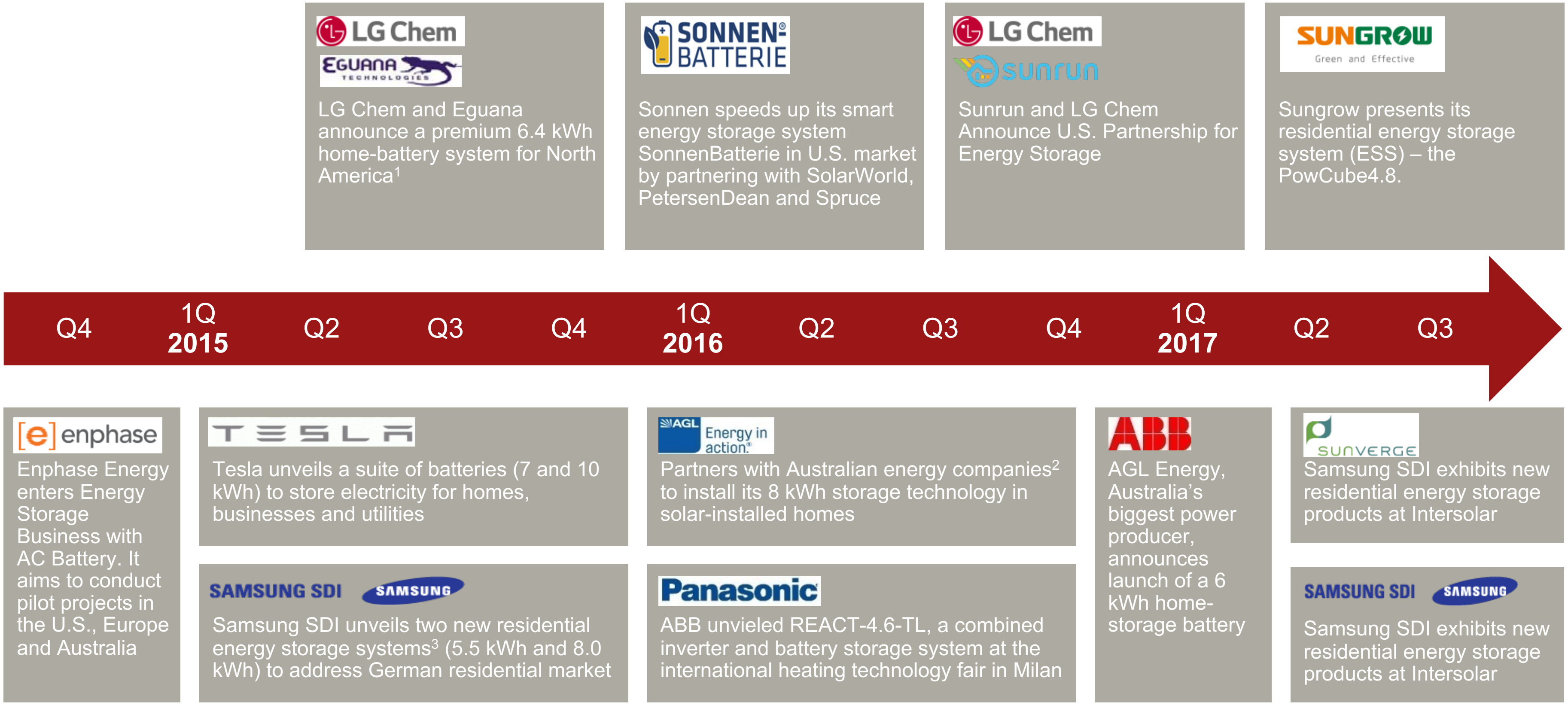
Source: A.T. Kearney Energy Transition Institute analysis based on US DOE database (https://www.energystorageexchange.org), November 2017

Several manufacturers have launched commercial battery products for residential energy storage in Europe – in Germany in particular – the U.S. and Australia

Major residential energy-storage announcements by industrial battery makers

As of November 2017

Not exhaustive



LG Chem, EGUANA TECHNOLOGIES: LG Chem and Eguana announce a premium 6.4 kWh home-battery system for North America[1]

SONNEN BATTERIE: Sonnen speeds up its smart energy storage system SonnenBatterie in U.S. market by partnering with SolarWorld, PetersenDean and Spruce

LG Chem, sunrun: Sunrun and LG Chem Announce U.S. Partnership for Energy Storage

SUNGROW Green and Effective: Sungrow presents its residential energy storage system (ESS) – the PowCube4.8.

[e] enphase: Enphase Energy enters Energy Storage Business with AC Battery. It aims to conduct pilot projects in the U.S., Europe and Australia

TESLA: Tesla unveils a suite of batteries (7 and 10 kWh) to store electricity for homes, businesses and utilities

SAMSUNG SDI, SAMSUNG: Samsung SDI unveils two new residential energy storage systems[3] (5.5 kWh and 8.0 kWh) to address German residential market

AGL Energy in action: Partners with Australian energy companies[2] to install its 8 kWh storage technology in solar-installed homes

Panasonic: ABB unvieled REACT-4.6-TL, a combined inverter and battery storage system at the international heating technology fair in Milan

ABB: AGL Energy, Australia's biggest power producer, announces launch of a 6 kWh home-storage battery

SUNVERGE: Samsung SDI exhibits new residential energy storage products at Intersolar

SAMSUNG SDI, SAMSUNG: Samsung SDI exhibits new residential energy storage products at Intersolar

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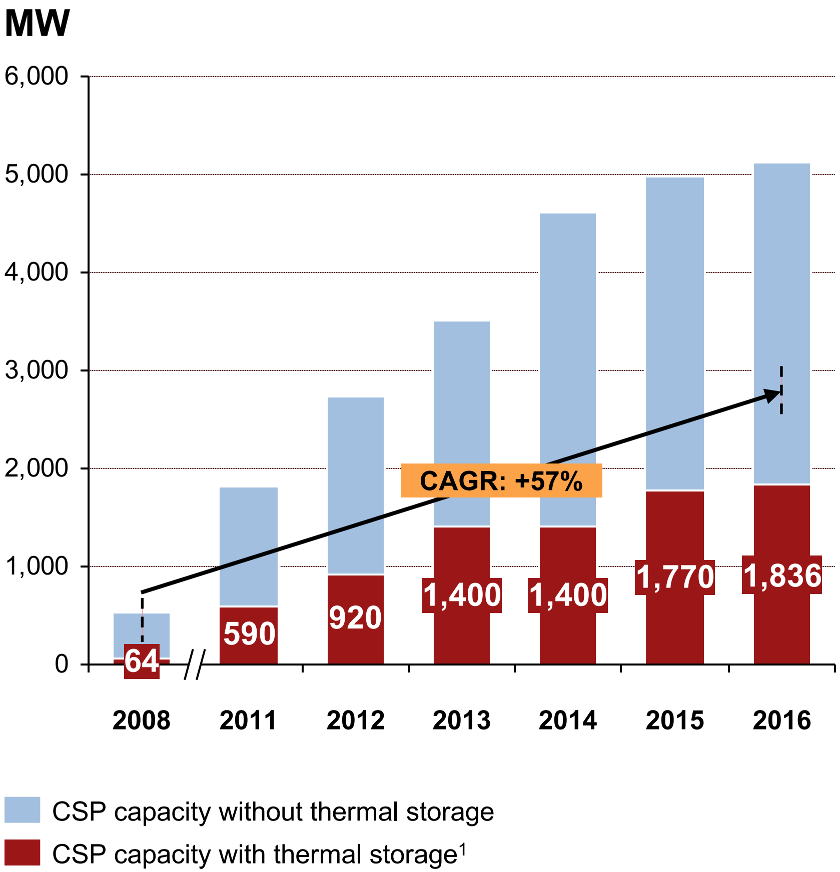
1. LG Chem has said that after North America, its product will be launched in Australia and Europe; 2. ActewAGL, Snowy Hydro's Red Energy, and Ergon Energy;
3. These systems were designed in addition to the existing 3.6 kWh system in 2014; **Note: This list is not exhaustive**

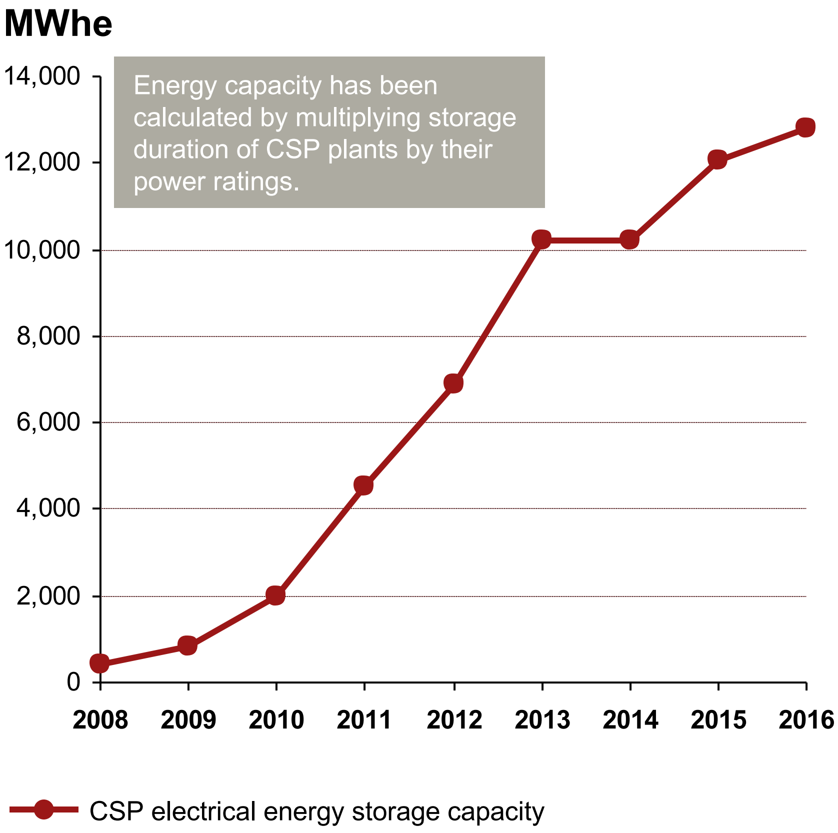
Source: A. T. Kearney Energy Transition Institute analysis based on Enphase (2015), "Enphase Energy Enters into Energy Storage Business with AC Battery"; BNEF News database (accessed 2015), link; Shahan (2015), "LG Chem Trying To Steal Tesla's Home Battery Storage Thunder?"; Steel (2015), "Panasonic To Roll Out Residential Battery To Europe, Starting With Germany"; Sunverge (2015), "Leading Australian Retailer AGL Selects Sunverge for Residential Energy Storage Program"; Business Wire (2015), "Samsung SDI Unveils New Energy Storage Products at Intersolar Europe 2015", Press Search

Thermal storage has become a technology of choice for solar electricity storage due to the development of CSP projects

Cumulated power capacity of operational CSP energy-storage units



Cumulated electrical energy capacity of operational CSP storage units



Energy capacity has been calculated by multiplying storage duration of CSP plants by their power ratings.

1. Note that in CSP plants the same electric turbine is used for both thermal energy coming from the solar receiver and the thermal energy coming from the storage unit. Storage capacity is therefore equal to the power rating of CSP plants.

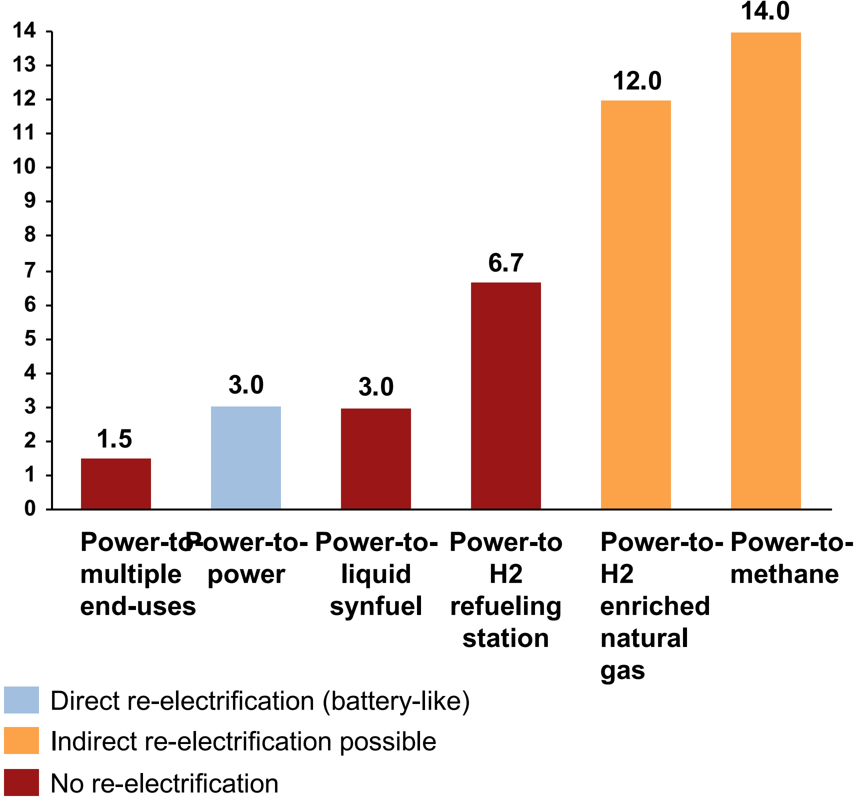
Source: A.T. Kearney Energy Transition Institute analysis based on SolarPaces database (accessed 2017), "Concentrating Solar Power projects" (link)

Hydrogen and synthetic natural gas storage technologies are at the early demonstration phase

Integrated hydrogen-based electricity storage projects

(planned + commissioned)

MW, November 2015



- Chemical storage is part of the re-electrification pathway, in which electrical power that was used for electrolysis and stored as hydrogen is converted back into electricity. However, development seems to be at standstill, with only 3 MW of projects planned or commissioned, mostly very small in scale.
- Chemical storage may yet occur indirectly as a part of power-to-gas processes, if hydrogen-enriched natural gas or synthetic natural gas are used to produce electricity and inject it back to the grid. In fact, power-to-gas applications (injection into the gas grid or methanation) seem to be taking the lead over direct re-electrification, with large-scale demonstration plants operating in Germany, the UK, the Netherlands and Denmark, and demonstration plants announced in France, Switzerland or Canada. However, one should note that the purpose of power-to-gas projects is not necessarily re-electrification: HENG and SNG can also be used to provide low-carbon energy sources for thermal and mobility needs. In the near future, the latter are expected to be favored over re-electrification because of the limited number of alternatives and their lower level of development.

Source: A.T. Kearney Energy Transition Institute analysis; Gahleitner (2013) for data prior to 2013; BNEF, accessed November 2015; U.S. DOE Hydrogen Analysis Resource Center, accessed November 2015

Electricity storage is gaining momentum, with roadmaps recently produced both at national and international levels

Examples of plans and announcements

IRENA International Renewable Energy Agency	The International Renewable Energy Agency released a first Technology Roadmap on electricity-storage systems for renewable power in June 2015. The report highlights several priorities and actions necessary to encourage development of electricity storage, and emphasizes that affordable electricity storage is a key enabler for high penetration of renewable in the power mix
iea	The International Energy Agency released a first Technology Roadmap in April 2014. One of its main goals was to explain the value of energy storage to energy system stakeholders. Since then, the IEA has included energy storage in its decarbonization scenarios
🇪🇺	EU countries have agreed on a new 2030 Framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030. These targets aim to help the EU achieve a more competitive, secure and sustainable energy system
🇺🇸	The Energy Storage Association (ESA) today released its “35x25: A Vision for Energy Storage” white paper, which maps a clear and actionable pathway to reaching 35 gigawatts (GW) of new energy storage systems installed in the U.S. by 2025
🇬🇧	Britain launched a 246 million-pound ($320 million) fund in July 2017, to boost the development and manufacturing of electric batteries, a major growth area for the car and energy sectors
🇰🇷	In 2011, South Korea said it would invest $5.94 billion by 2020 in developing the energy-storage industry – one-third on R&D and the rest on building infrastructure. The government will participate along with private companies.
🇦🇺	Australia has launched new interactive maps of the electricity grid specifically to support decentralized usage of distributed energy resources (DERs) including battery storage, renewable energy and smart demand management
🇨🇳	China National Development and Reform Commission and the National Energy Commission jointly released ""Guidance on the Promotion of Energy Storage Technology and Industry Development“ on Sept. 22, 2017
🇨🇦	Energy Storage Canada highlighted focus on Innovation and Storage in Ontario's 2017 Long-Term Energy Plan

- Unlike renewables, smart meters and carbon capture & storage, there are no targets for electricity-storage development.
- Nevertheless, driven by a recent surge in the use of intermittent renewables and limited growth prospects for electricity-storage projects in the existing regulatory and economic environments, a number of new roadmaps have been produced both at the national and international levels. These roadmaps identify R,D&D gaps and barriers to development (e.g. in terms of regulation, ownership of storage plants and costs). Future roadmaps should also suggest development milestones and business cases.

Source: IEA (2013), “IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop Proceedings”; EASE/EERA (2013), “European Energy Storage Technology Development Roadmap towards 2030”; Guardian (2012), “George Osborne: make UK a world leader in energy storage”; China.com (2011), “S Korea to invest 5.9 bln USD in energy storage industry”; Electricity Storage Association (2013), “Energy secretary nominee Moniz to announce storage timeline soon after confirmation”; IRENA (2015), “Renewable and electricity storage. A technology roadmap for Remap 2030”

4. Research, Development and Demonstration

R,D&D priorities vary by technology

Summary of main drivers of R,D&D axis by technology

Technology	Drivers	Axis of R,D&D
1 **Pumped Hydro Storage** 	• Facilitate intermittent integration • Sidestep site-availability issues	• Upgrade old facilities (e.g. variable-speed turbines) • Develop alternative reservoirs (seawater or artificial underground, underwater and above-ground)
2 **Compressed Air Energy Storage** 	• Avoid/limit natural gas use • Sidestep site availability issues	• Avoid heat losses upon compression (adiabatic, isothermal and hybrid concepts) • Develop alternative reservoirs
3 **Batteries** 	• Increase power & energy density • Lower costs & increase lifecycle • Reduce environmental impact	• Develop lower-cost materials and chemistries • Improve performance of current chemistries • Reuse electric-vehicle batteries for electricity storage
4 **Hydrogen & Synthetic Natural Gas** 	• Adjust hydrogen technologies to intermittent needs (production, storage, end-uses)	• Enhance performance & lower costs of electrolysis • Develop underground and solid storage • Investigate power-to-gas and power-to-liquid

Source: A.T. Kearney Energy Transition Institute analysis

R,D&D efforts are aimed at increasing the flexibility of pumped hydro storage (PHS) in order to support the integration of intermittent renewables

Variable-speed turbine

Variable-speed turbines use an asynchronous motor-generator to adjust the rotational speeds of the pump and turbine.

Its benefits include:

- **Efficiency**: Increased pump-turbine efficiency (~1%)
- **Reliability**: Avoids operation modes subject to hydraulic instability or cavitation to increase durability
- **Flexibility**: faster power adjustment to respond to grid requirements and operate part load pumping, allowing pumped hydro storage to help regulate voltage and frequency (low load).

- **Upgrading opportunities**: a significant proportion of pumped hydro storage plants are aging, notably in Europe, where 80% were commissioned before 1990, and in the U.S. where the last plant was completed in 1995. These plants were not primarily designed to help balance intermittent renewables, but rather to maximize baseload generation (price arbitrage, meet peak demand). R,D&D is therefore under way to upgrade these plants to make them better equipped to respond to the intermittency challenge of renewables by increasing response time in new plants (<15 second).

- **Drivers of R,D&D**:
  - **Increase efficiency**: from 60% to 85%, particularly as a result of the near-optimal efficiency of variable-speed turbines;
  - **Increase reliability**: by using stronger core components (e.g. thrust-bearing and oblique elements in the motor) and improved control systems (software, redundancy…);
  - **Increase flexibility**: faster power adjustment to absorb excess power, thanks in particular to variable-speed turbines.

- **Variable and single-speed turbines**: variable-speed turbines are the focus of R,D&D for pumped hydro storage. Developed in Japan (395 MW installed in 1993 in Kansai unit 2), the technology provides increased flexibility, efficiency and reliability, but increases costs (notably, greater excavation is needed due to a longer shaft).

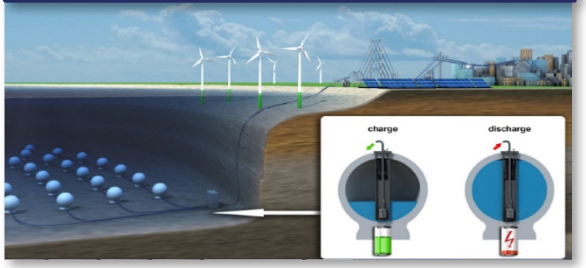
Source: Alstom (2012), “Pumped hydro Storage Plants”; Chi-Jen Yang (2011), “Pumped Hydroelectric Storage”

Alternative pumped hydro storage reservoir types are also being developed to sidestep the constraint of site availability and minimize environmental impacts

Illustration of alternative PHS reservoir

Seawater PHS

Underwater PHS



- **The biggest challenge in establishing pumped hydro storage (PHS) is to find suitable natural sites, notably for lower reservoirs**. Using rivers is not necessarily the best option, as dams have to be erected, changing the water level, which raises safety and environmental issues. R,D&D is focused on developing alternative reservoir types, notably underground (as opposed to the current over ground solutions), storing sea water instead of freshwater and innovating sea-based solutions.

- **Seawater PHS** uses seawater in the lower reservoir. This simultaneously increases the number of suitable locations for PHS, and eliminates concerns over freshwater use. This solution is the most mature alternative to conventional PHS and draws on the experience of the 30 MW Yanabaru Okinawa PHS station, commissioned in 1999, in Japan. Ireland and Hawaii have also expressed interest in seawater PHS, and are planning 480 MW and 300 MW projects, respectively.

- **Underground PHS (UPHS)** has been contemplated since the 1970s, though no large-scale projects have yet been developed and economic feasibility has not been demonstrated. Underground PHS consists of drilling a well and galleries at the bottom of the top reservoir to use as an underground lower reservoir, with an integrated pump/turbine at the surface or just below the upper reservoir. Such a system could allow small-to-medium-scale distributed applications (avoiding large excavations). Underground PHS may be increasingly used thanks to advances in excavating techniques and computer modeling. Gravity Power is already developing a 40 MW facility with 4 hours of storage.

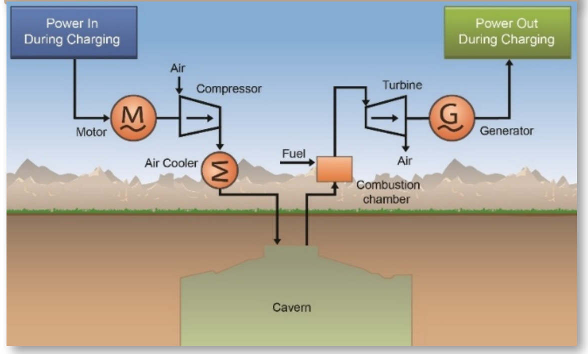
- **Alternative sea-based solutions**: Underwater PHS (Stensea project) pumps water into 30-meter diameter spheres anchored at the seabed, which can store up to 20 MWh each. Another sea-based alternative solution was proposed in Belgium.

Source: Hochtief (2012), “Annual Report”; Gravity Power (http://www.gravitypower.net)

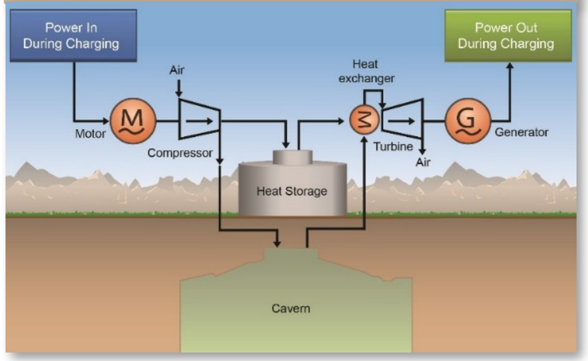
Several new compressed-air energy storage (CAES) concepts are under development to reduce or avoid gas use and thereby increase system efficiency

Conventional Vs. Adiabatic CAES

Diabatic CAES



Adiabatic CAES



- **Compressed-air energy storage R,D&D is largely focused on tackling the reliance on fossil fuels, usually gas, to heat the air during expansion**. Limiting or avoiding gas use has the potential to increase system efficiency (to up to 70%) and limit CO2 emissions. More than energy-storage devices, current CAES facilities are essentially gas turbines that consume 40%-60% less gas than conventional turbines. Two main alternatives to the conventional type are being investigated: Adiabatic CAES and Isothermal CAES.

- **Adiabatic CAES involves** storing waste heat from the air-compression process and using it, instead of gas, to heat up the air during expansion. Although thermal storage is already used in concentrating solar power plants[1], it is still commercially challenging, especially at high temperatures, which require specially adapted components. Several options (oil, molten salts, concrete…) are being investigated. Currently, there are no adiabatic plants in operation, but several projects have been launched, including RWE's 90 MW Adele project. Hybrid designs, which include both heat storage and gas use, or low temperature CAES - which uses water as a heat-storage medium but requires more energy for compression - are also being explored, notably by E.ON in Germany.

- **Isothermal CAES** involves compressing air while continuously removing and storing the by-produced heat to maintain a constant temperature. The stored heat is then used during expansion for the same purpose. SustainX (now merged with General Compression, Inc.) developed a solution in which water is continuously sprayed into the cylinder containing the air to absorb the heat during compression, and the same water is then used to transfer heat back during expansion. A 1.5 MW pilot plant in New Hampshire, U.S demonstrated the process.

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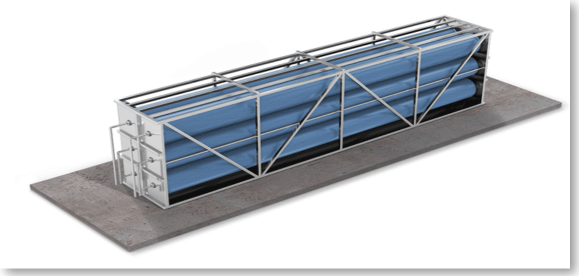
1. For more information on thermal storage, refer to the concentrating solar power FactBook recently published by the SBC Energy

Source: RWTH Aachen (2012), "Review of Energy Storage Options"; E.ON (2012), DOE Energy Storage Database (projects: 146, 318)

Artificial compressed-air energy-storage reservoirs are being developed in response to the limited availability of natural storage formations

Alternative reservoirs

Pressurized tank



Underwater bags

- **Compressed-air energy-storage projects typically use underground salt caverns as a storage vessel** (either man-made or abandoned mines). Salt caverns have the advantage of being gas-tight (no depletion) and of being able to handle frequent charging and discharging cycles[1]. The two CAES plants currently operated by Huntorf and McIntosh make use of salt formations.
- **However, salt deposits do not necessarily occur in the desired electricity-storage locations.** Furthermore, unlike hydrogen or natural gas, CAES can only operate within a specific pressure range, of 50 bar to 100 bar. Since operating pressure is determined by depth, CAES can only be applied in a depth range of 500-1,300 meters..
- **Therefore, artificial pressurized reservoirs are being investigated**. The rationale behind artificial reservoirs is to operate at constant pressure instead of at constant volume, as is the case in salt caverns. For example, 20-meter-diameter underwater bags developed by Thin Line Aerospace could store about 70 MWh at a 600-meter depth. More conventional above-ground pressurized tanks are also being developed by LightSail for its isothermal technologies, allowing for decentralized CAES Plants.

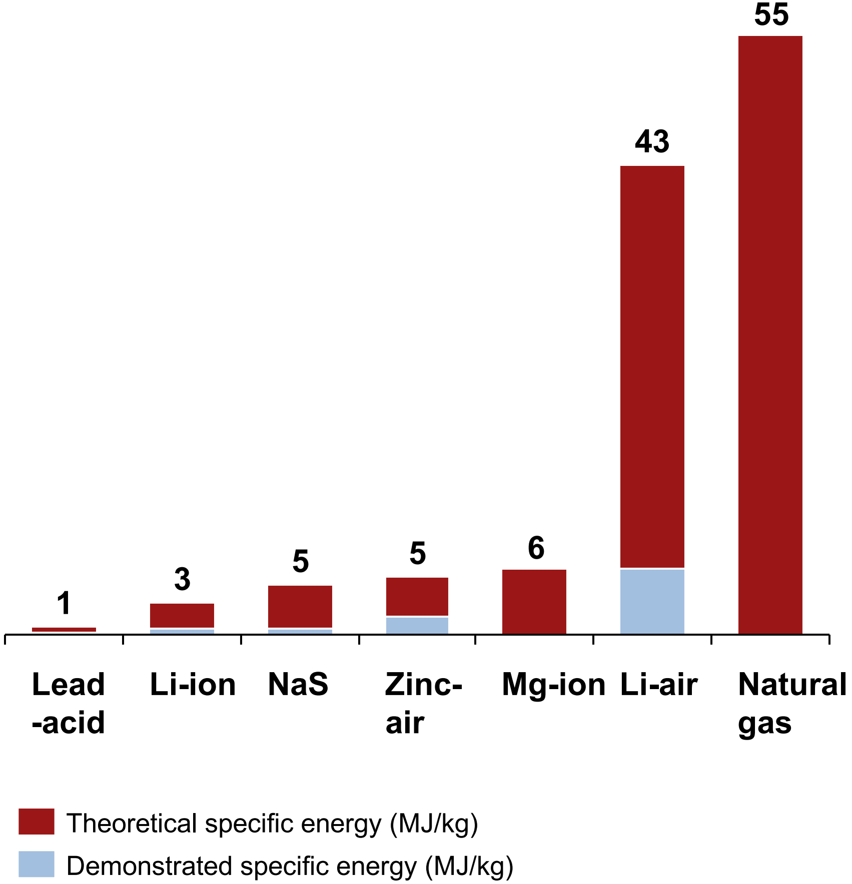
[1] The flexibility of salt caverns regarding withdrawal and injection rates as well their low cushion gas requirement has made them an attractive means of storing natural gas over the past decade.

Source: A.T. Kearney Energy Transition Institute analysis based on Thin Red Line Aerospace (http://www.thin-red-line.com/); Lightsail Energy (http://www.lightsail.com/)

Lower costs, and more durable chemistries and materials are priorities of battery-storage R,D&D

Theoretical specific[1] energy limits by technology

MJ/Kg, 2012



- **For existing battery technologies, priorities and levers are highly specific:**
  - **Lithium-ion:** find lower-cost materials for the negative electrode (e.g. air, titanium oxide) to increase energy density and cycle life;
  - **Lead-acid**: Improve cycle life and depth of discharge;
  - **NaS:** tackle safety issues and lower high operating temperatures, which limit their use at present;
  - **Flow batteries:** replace water-based electrolyte with organic solutions to improve specific energy and cycle life.
- While there is room to bridge the gap between the demonstrated and theoretical specific energy of existing technologies, R,D&D is also trying to identify alternative electrochemical solutions that would achieve higher energy density:
  - **Metal-air**: use oxygen at the cathode, avoiding storing one of the components (e.g. Lithium-air);
  - **Multivalent-ion**: use materials such as magnesium or aluminum that have two or three electrons available for the chemical reaction, which theoretically means two or three times more energy.

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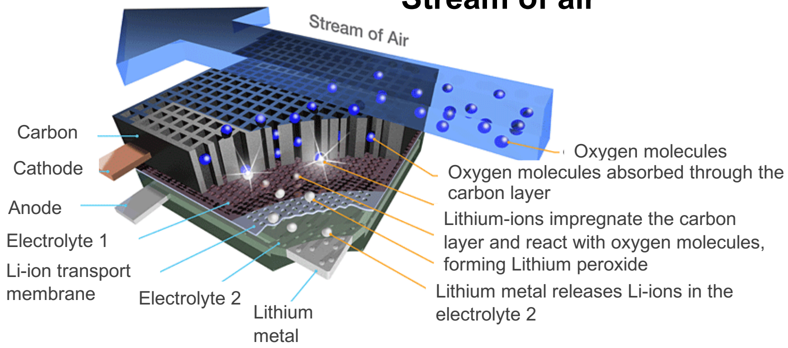
1. Specific energy is defined as the amount of stored energy per unit of mass.

Source: Kurt Zenz House (2009), "The limits of energy storage technology"

Lithium-air batteries are being investigated as a replacement for lithium-ion technology, while liquid-metal batteries are promising for grid-scale storage

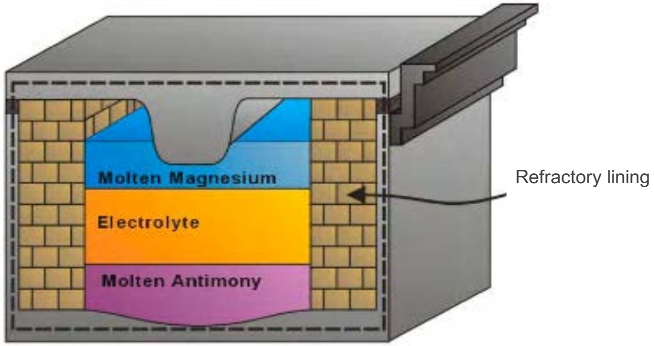
Metal-air batteries

Stream of air



- **Metal-air batteries are being investigated to reduce battery costs and increase their energy density.** They use (di)-oxygen (O_2) at the cathode, eliminating the need to store one of the components (oxygen, which is found in ambient air) and the need for a cathode structure.
- **The anode is a commonly available metal with a high energy density that releases electrons when oxidized**. Many metals, including zinc and sodium, were considered but lithium prevailed (Li-Air) due to its low atomic mass, its superior oxidation ability and its relatively low cost.
- **Despite recent advances in the properties of its materials, li-air is still at an early stage of R&D** and its operation remains challenging because of the degradation that can occur at the cathode (e.g. humidity) and anode (corrosion).

Liquid-metal batteries

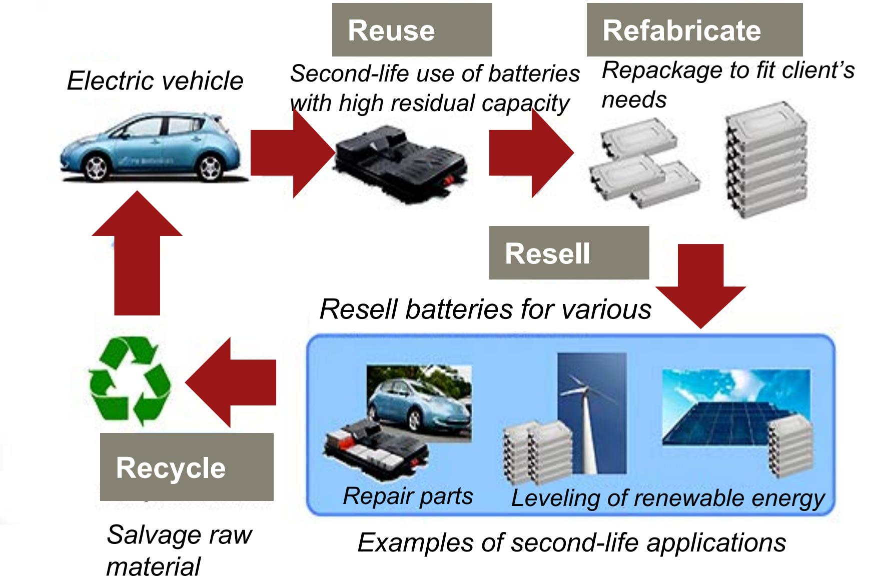


- **Conventional batteries use at least one solid material.** This solid material limits conductivity, increasing the risk of failure and, as a consequence, reduces battery lifetime. R,D&D is turning to liquids to avoid using solid materials.
- **The liquid-metal battery, invented at MIT, uses two layers of liquid metals and a salt (electrolyte).** One fluid layer lies on top of the other because of density differences. During discharge, the liquid metals release two electrons to form an ion that travels through the electrolyte to form an alloy at the cathode (and the reverse happens upon charging).
- This technology is simple to assemble and relies on inexpensive materials, but requires high operating temperatures to keep the metals in a liquid state, which makes it more suitable for large-scale grid storage.

Source: Ambri (2013), http://www.energystorageexchange.org/projects

Giving electric vehicle (EV) batteries a second life by using them for electricity storage would reduce costs and environmental impact

Lifecycle of an electric-vehicle battery with a second life

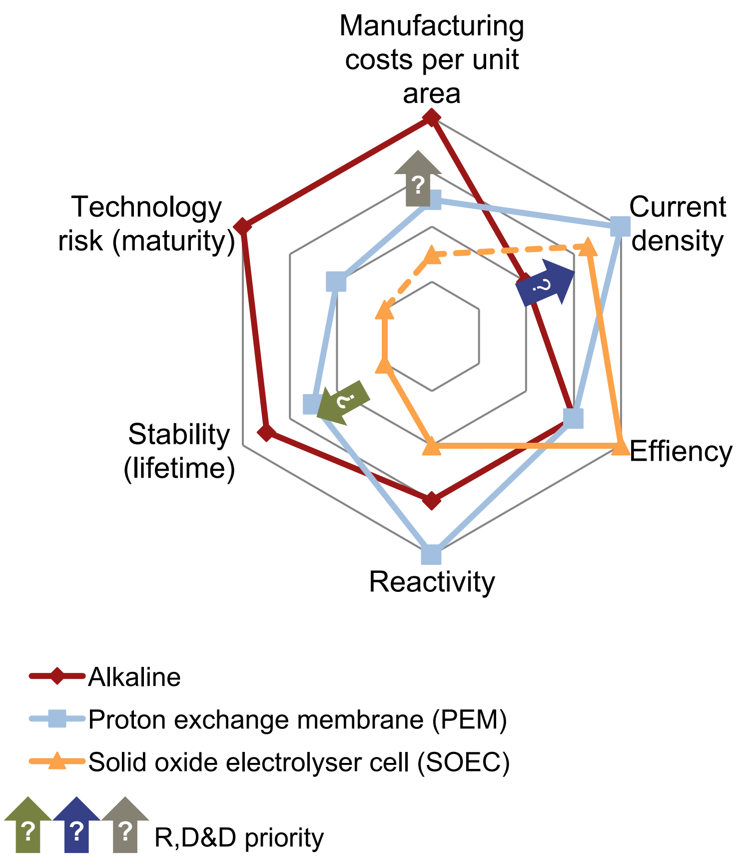


- **If electric-vehicle (EV) deployment were to play a significant role in curbing emissions and achieving climate-change targets, it would result in the use of a very significant number of batteries**. Although uncertainties persist concerning the chemistries that will predominate, lithium-ion (li-ion) batteries account for a majority share of the most recent developments because of their high energy density.
- **Nonetheless, li-ion batteries suffer from a short cycling life** of 5 to 10 years, after which time they approach 70% of their initial capacity, which is too low to power vehicles. The ultimate end-of-life is estimated at around 50% of initial capacity, so batteries unfit for vehicular use would still have a few years of life left that would be suitable for stationary applications, with their lower cycling requirements. This would not only lower the cost of batteries, but also minimize the environmental challenge of battery recycling.
- **The economic feasibility of battery recycling has not yet been proved**, and technical issues concerning reconditioning may arise, since EV batteries are not standardized and probably never will be. However, several energy players and car manufacturers are utilizing used batteries to build utility scale storage capability. For instance, Vattenfall, BMW and Bosch opened a 2.8 MWh energy storage facility built from batteries from over 100 e-cars (Hamburg, 2016)

Note: EV: electric vehicle
Source: Ademe (2011), "Study on the second life batteries for electric and plug-in hybrid vehicles", Press search

R,D&D is under way to lower the cost of hydrogen electrolysis, promote new end-uses and demonstrate the feasibility of large-scale projects

Comparative electrolyzer technologies



- **Hydrogen R,D&D has long been focused almost exclusively on answering demand-side requirements** (i.e. fuel cells, storage for mobility, and combined heat and power applications), but is turning towards the supply side to find a sustainable way to produce clean hydrogen from renewable power. The dominant focus of R,D&D is water electrolysis. R,D&D is also being conducted into laboratory-stage production technologies, such as direct production from bioenergy or solar energy (photolysis), and high-temperature thermo-chemical processes from nuclear.
- **R,D&D into electrolysis seeks to improve performance** (efficiency, lifetime, response-time), **reduce costs** (new materials) **and demonstrate the feasibility of large-scale plants**. It explores ways of improving mature alkaline electrolyzers by developing new membranes or pressurized concepts, reducing the costs of polymer exchange membrane (PEM), electrolyzers (e.g. new catalysts with cheaper material, new engineering processes) and high-temperature solid-oxide electrolyzer cells (SOEC).
- **R,D&D is also working to assess the suitability of large-scale underground storage in geological formations**[1] (salt formations, underground oil & gas[2] fields, deep aquifers) **and to develop metal hydrides for hydrogen absorption**. It also seeks to demonstrate the feasibility of large hydrogen storage solutions and investigates multiple end-uses (re-electrification of stored hydrogen, but also power-to-gas by injecting hydrogen into natural gas grids, or synthetizing methane in methanation processes[1]).

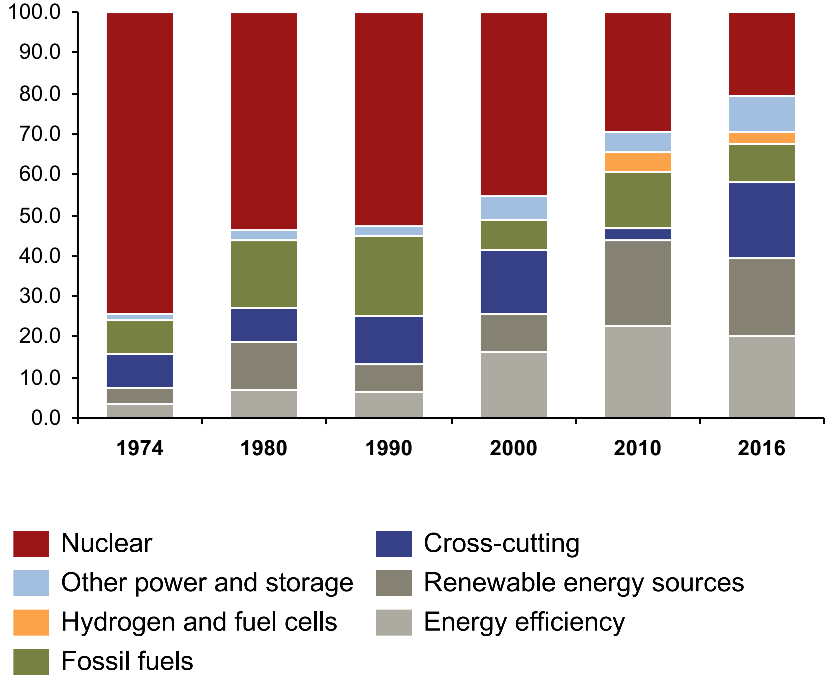
1. For more information, please refer to SBC Energy Institute report on hydrogen-based storage solutions; 2. Cooperative projects for energy storage in depleted oil & gas field could be developed in partnership with oil & gas producers, notably in the Middle East & North Africa.

Source: A.T. Kearney Energy Transition Institute analysis

Public funding of R&D in storage is increasing and is mainly focused on electrochemical batteries

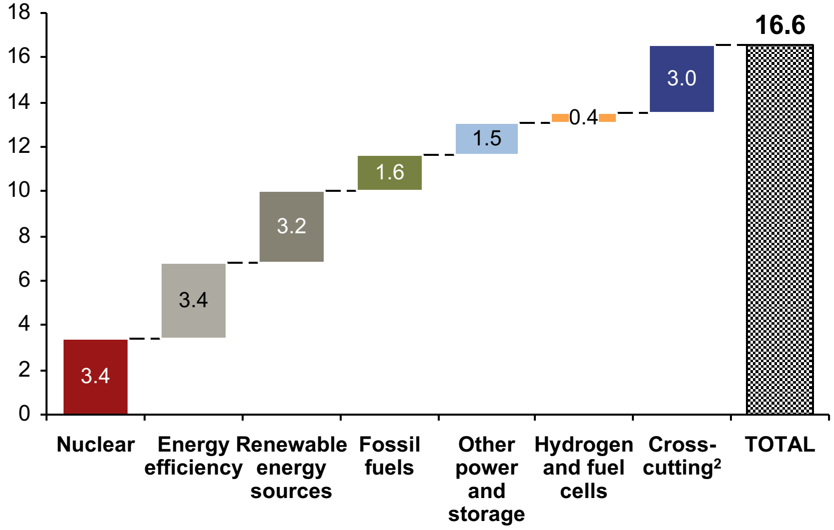
Annual government energy RD&D expenditure[1]

Development by technology (% of total spend)



Breakdown for 2016 spend

($ Billion, US 2016, PPP)



- 2016 spend amounted to $16.6 billions, just slightly below 2015 levels (recent peak was achieved in 2012 with $19.4 billions spend of RD&D)

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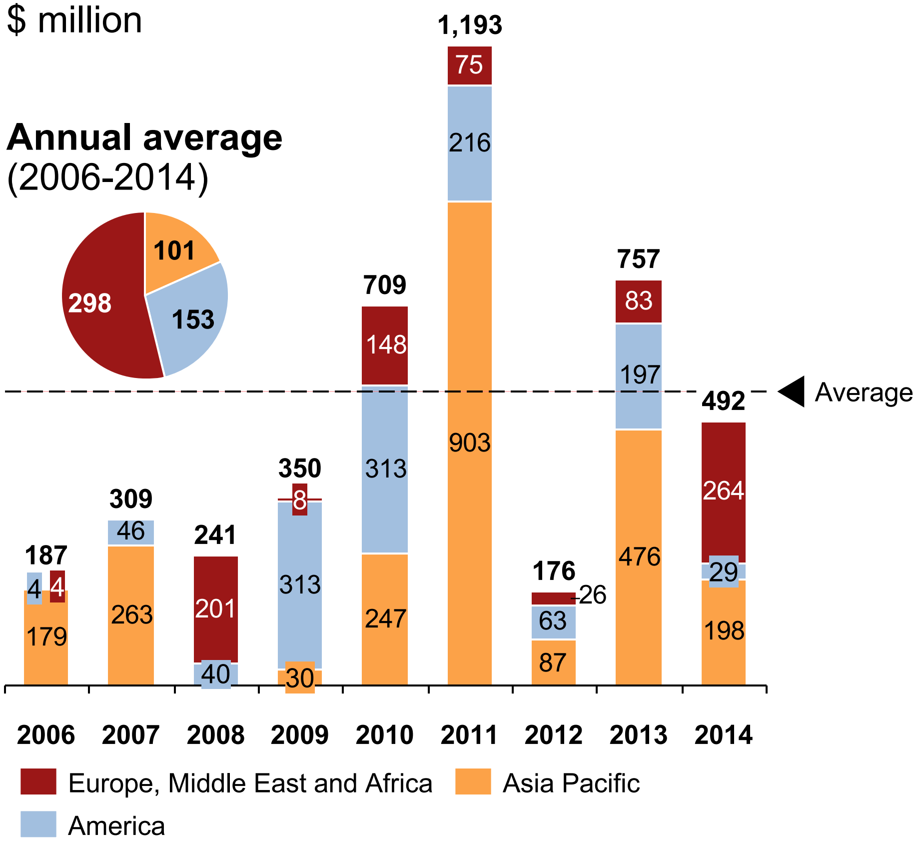
1. IEA member countries only: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States. 2. Cross-cutting represent broad intersectional energy technologies and themes such as Smart Cities and Communities (SCC) in EU, technologies under Science major program of DOE in USA, etc.

Source: IEA data services, accessed on November 2017

Total investments in energy storage have increased since the mid 2000s but vary significantly from year to year

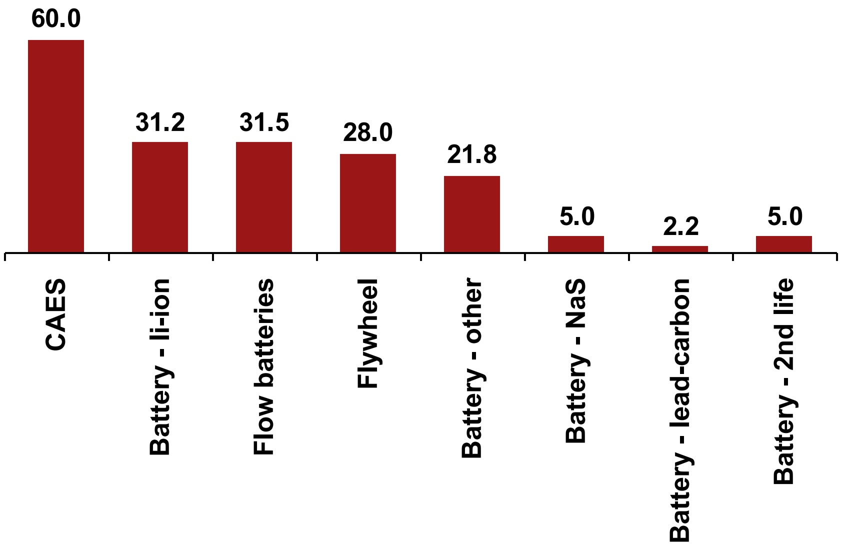
Annual investments in energy storage[1]

$ million



U.S. DOE 2009 storage grant distribution

$ million



- **U.S. investments in energy storage have been supported by DOE grants programs**:
  - – In 2009, the DOE granted $185 million to 16 utility-scale electricity storage projects as part of the American Recovery and Reinvestment Act (see top graph).
  - – In 2012, it announced that $120 million would be made available for research into batteries and electricity storage over the next five years.

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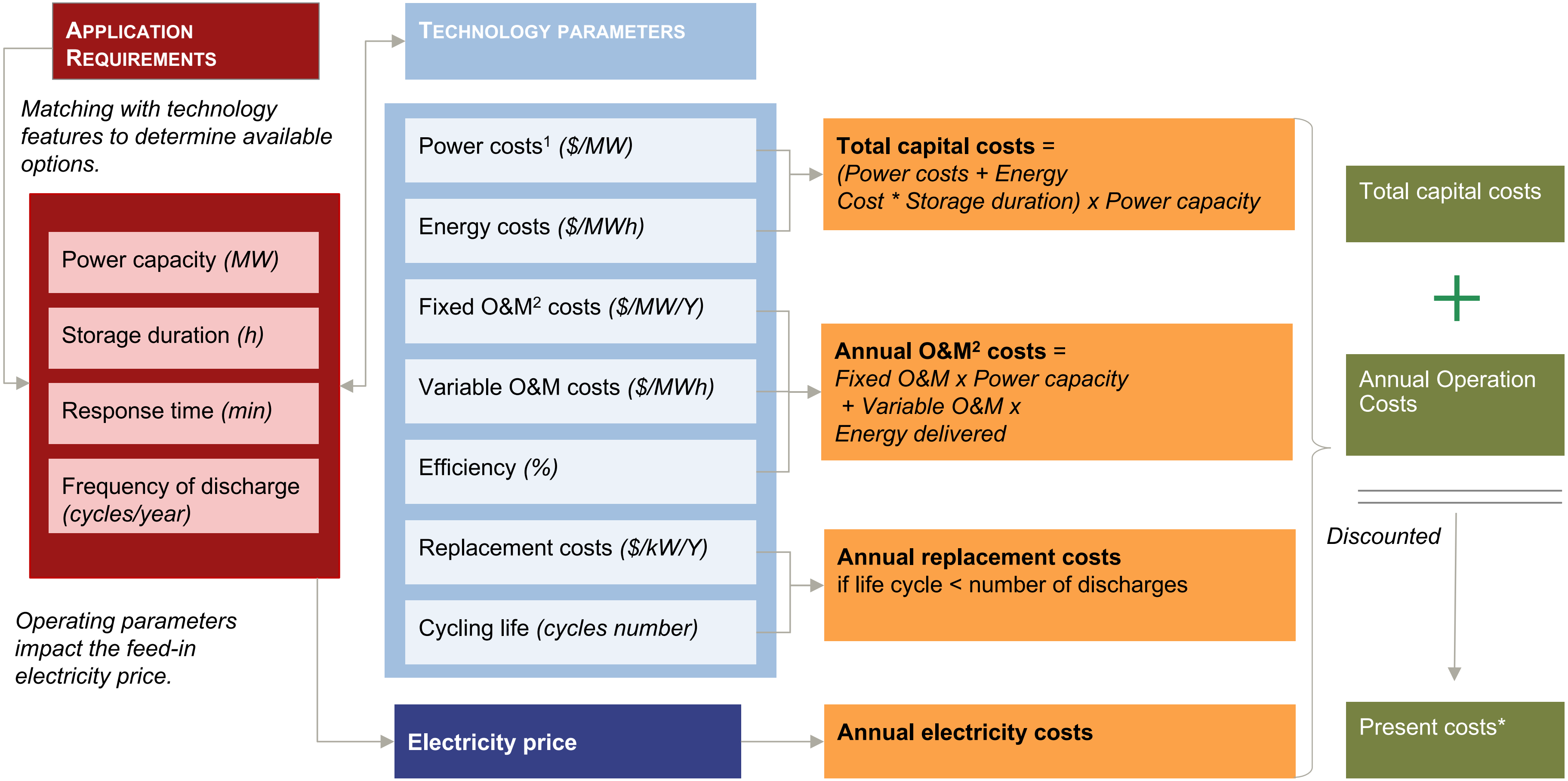
1. Include both private investments and public funding. Exclude large pumped hydro storage capacities.

Source: BNEF database, accessed on November 24, 2015; U.S. Department of Energy website (link)

5. Economics and Ecosystem

The economics of electrical storage are affected both by technological features and applications, making them difficult to assess

Storage-cost parameters



APPLICATION REQUIREMENTS

Matching with technology features to determine available options.

- Power capacity *(MW)*
- Storage duration *(h)*
- Response time *(min)*
- Frequency of discharge *(cycles/year)*

Operating parameters impact the feed-in electricity price.

TECHNOLOGY PARAMETERS

- Power costs[1] *($/MW)*
- Energy costs *($/MWh)*
- Fixed O&M[2] costs *($/MW/Y)*
- Variable O&M costs *($/MWh)*
- Efficiency *(%)*
- Replacement costs *($/kW/Y)*
- Cycling life *(cycles number)*

Electricity price

Total capital costs = *(Power costs + Energy Cost * Storage duration) x Power capacity*

Annual O&M[2] costs = *Fixed O&M x Power capacity + Variable O&M x Energy delivered*

Annual replacement costs if life cycle < number of discharges

Annual electricity costs

Total capital costs

+

Annual Operation Costs

Discounted

Present costs*

---

1. Power costs include storage-device costs, balance of plant costs and power conversion costs
2. O&M: operation & maintenance except electricity price. Include gas price for compressed-air energy storage.

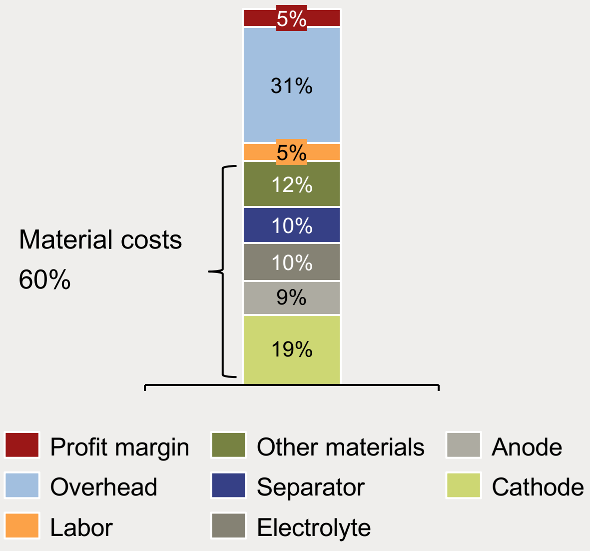
Source: A.T. Kearney Energy Transition Institute analysis

Capital-cost breakdowns are technology-specific, with construction driving CAES and PHS costs, and components driving the cost of batteries

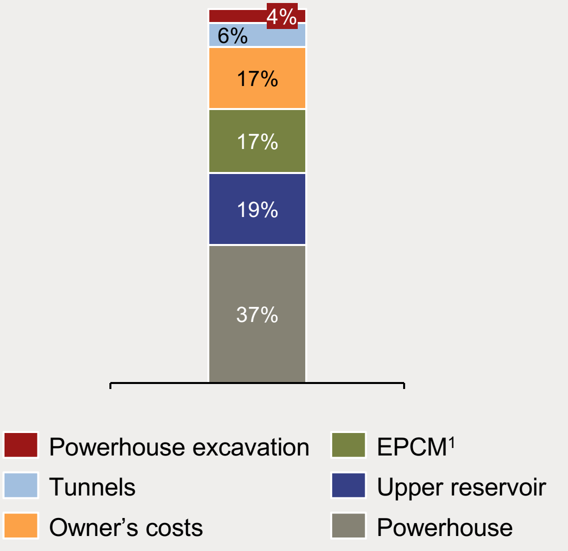
Cost breakdown in three types of storage plant

in percentages, %

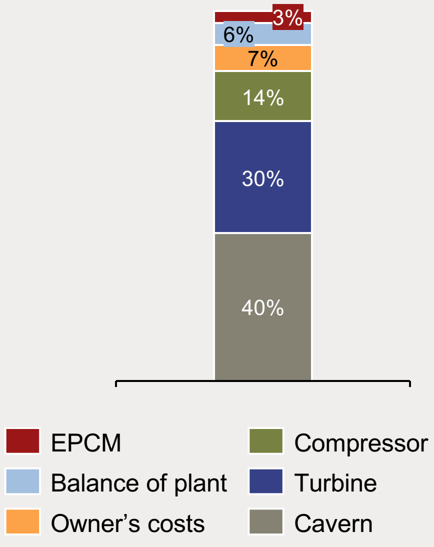
Li-ion battery



Pumped hydro storage



Compressed air energy storage



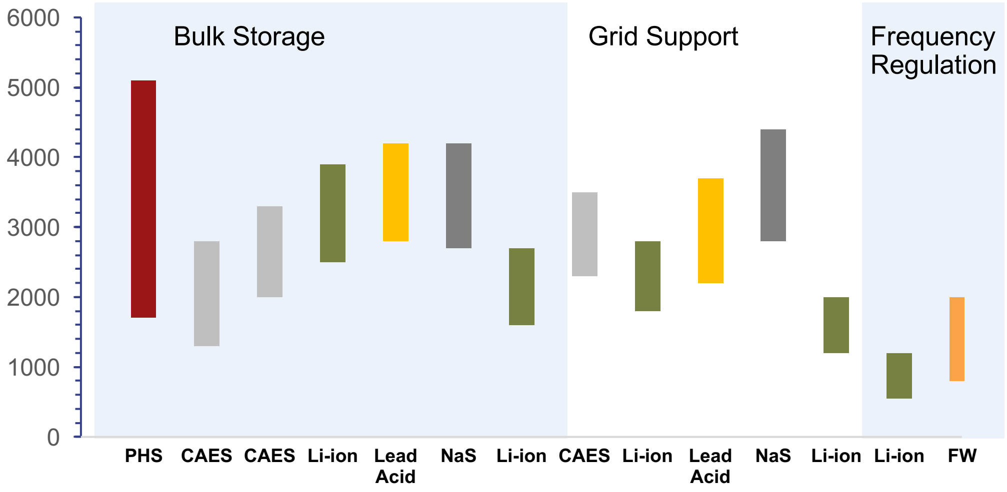
- Civil engineering works make up the bulk of pumped hydro storage (PHS) and compressed-air energy storage (CAES) investment costs, but account for a negligible share of the initial investment in batteries.
- Cutting the capital costs of batteries will most probably involve using cheaper components (material, scale effect…), while pumped hydro storage or compressed-air energy-storage components may have to find cheaper sites or excavation techniques.

1. Engineering, Procurement, Construction and Management

Source: Sandia (2007), "Installation of the first DESS at the American Electric Power"; Black & Veatch (2012), "Cost and performance data for power generation technologies", IRENA Electricity Storage and Renewables (2017), Qnovo – Cost components of a Li-ion battery (2016)

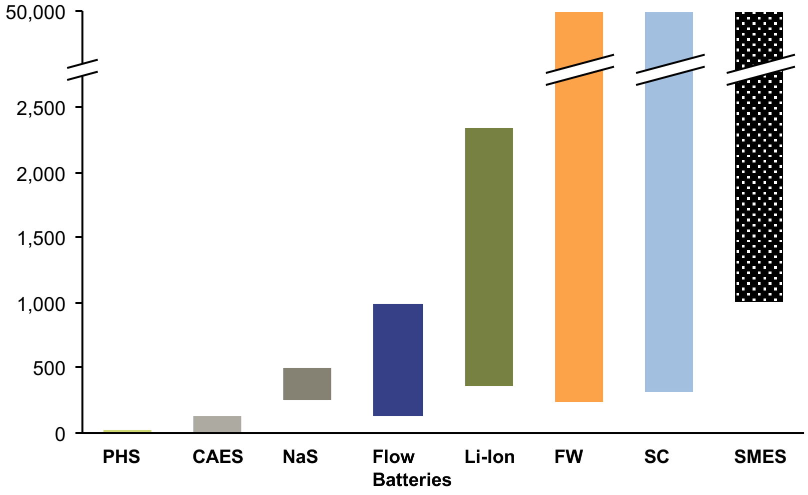
The capital cost of a storage device per unit of power (MW) and per unit of energy capacity (MWh) varies significantly between technologies

Installed costs[1,3] **per unit of power** (2016, $/kw)



Rating (MW)	300 - 1000	100 - 300	30 - 50	30 - 50	30 - 50	30 - 50	50 - 100	10 - 20	10 - 20	10 - 20	10 - 20	1 - 5	20	20
Duration (h)	10	10	6	6	6	6	4	4	4	4	6	2	0.5	0.25

Capital costs[2] **per unit of energy capacity** ($/kwh)



- Flywheels have lower installation costs but suffers from the drawback of high costs per unit of energy capacity. The costs for pumped hydro, compressed air and batteries are more balanced, but the cost per installed power capacity of batteries varies widely.
- This division of costs may imply that power and energy capacities are independent, but this is not true for all systems. This is, for example, true for PHS, CAES and flow batteries but false for conventional batteries and flywheels.

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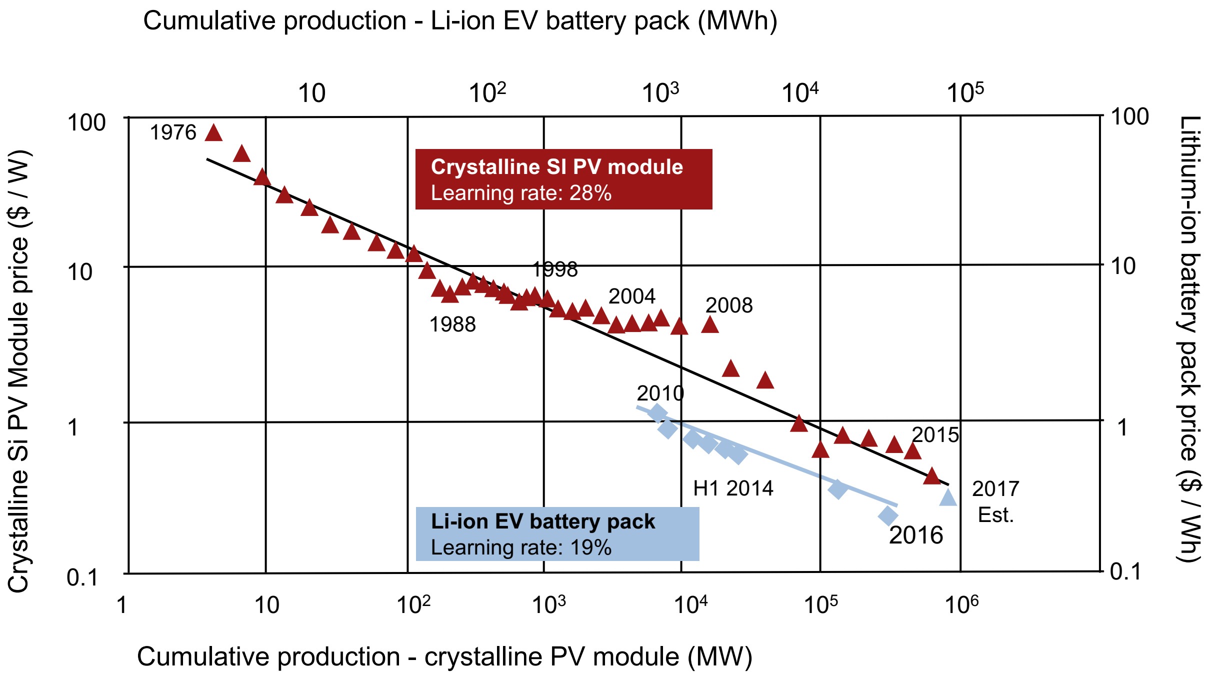
1. Cost ranges are indicative and based on the high and low range of cost estimates provided in the literature. Installed costs exclude land costs, owners costs, project management and contingency. They only take into account the cost of the storage device itself; 2. Energy costs of flywheels, supercapacitors and SMES have been capped at $50,000/kWh but can be significantly higher; 3. PHS: pumped hydro storage; CAES: compressed air energy storage; SC: supercapacitor, SMES: superconducting magnetic energy storage, FW: Flywheel, NaS: Sodium Sulfur batteries, Li-ion: Lithium ion batteries

Source: A.T. Kearney Energy Transition Institute analysis, Energy Storage Cost summary (EPRI, 2016)

Lithium-ion batteries are thought to benefit from a learning rate of roughly 20%, similar to that of PV modules, and from the development of electric-vehicles

Historical price vs cumulative production of lithium-ion[1] battery and cSi PV modules



- The learning rate (%) expresses the average reduction in capital cost of a technology for each doubling of cumulated production capacity.
- Since 1976, the price of crystalline silicon PV modules has empirically followed a learning rate of 28%, mostly due to the increase in size of factories for batch production.
- For 2010-16, the costs of li-ion battery have also followed a regular learning rate of 19%.
- This trend is expected to continue due to the similarity of the production processes of PV and li-ion: Tesla's future Gigafactory, with a production capacity of 35 GWh/year is expected to bring down li-ion production costs by 30% thanks to batch production at a very large scale

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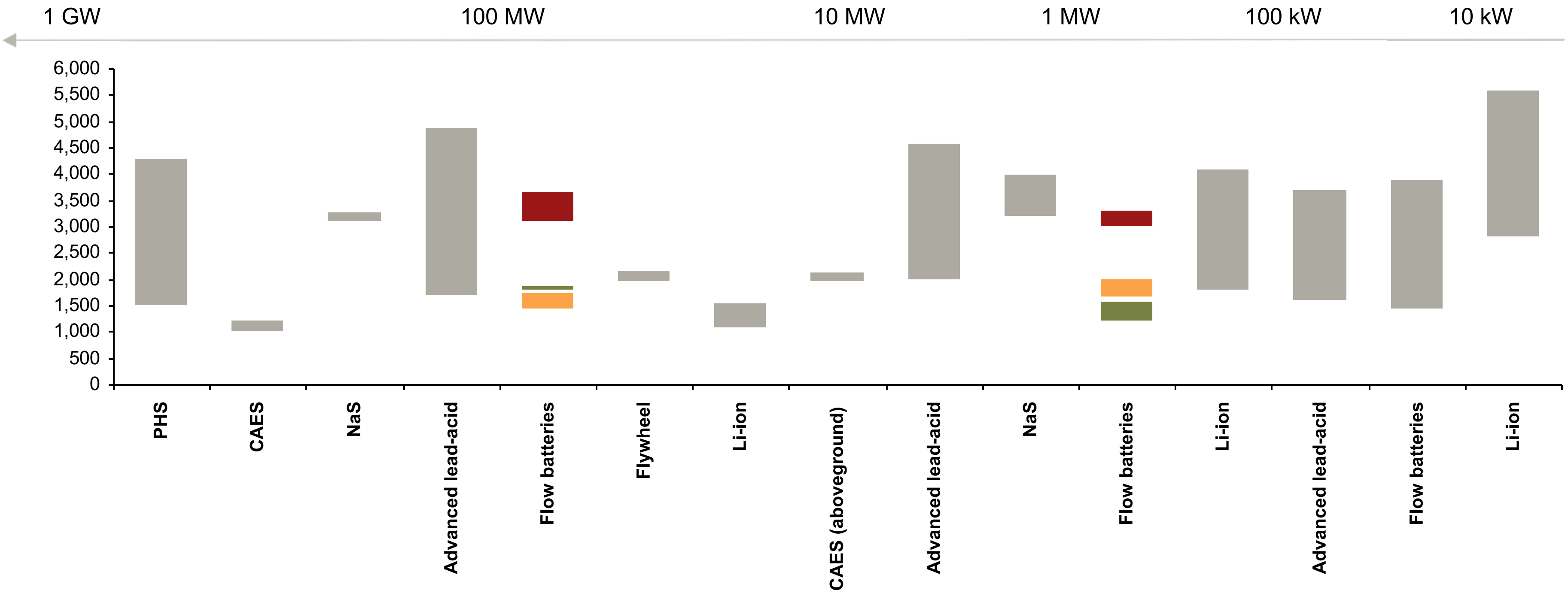
1. Figure is for lithium-ion battery used for electric vehicle.

Source: Bloomberg New Energy Finance (2017), IEA - New Energy Outlook 2017, Presentation by Alejandro Zamorano

Total capital costs vary widely, depending on technology maturity and power capacity

Estimates of total capital cost by technology and capacity[1] $/kW



Storage duration (h)	6-10	8-20	6	4-6	5	0.25	0.25-1	5	3.2-4	7.2	4-5	2-4	2-5	2	1-4

🟥 Vanadium Redox 🟩 Fe/Cr Redox 🟧 Zn/Br Redox

---

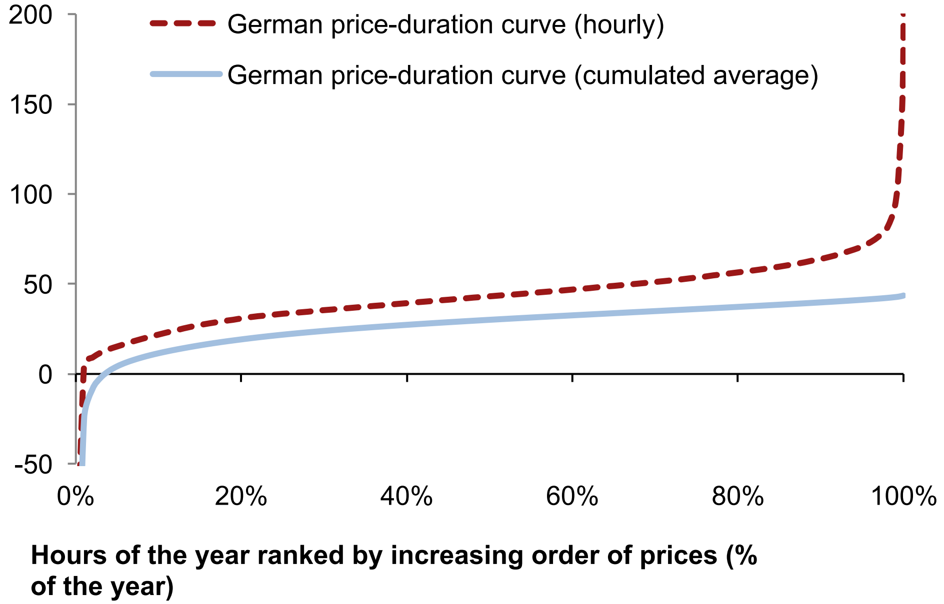
1. Real costs are system- and location-specific and these costs only give an order of magnitude; PHS: pumped hydro storage; CAES: compressed-air energy storage; NaS: sodium-sulfur battery; Li-ion: lithium-ion battery; ZnBr: zinc-bromine; Fe/Cr: iron-chromium battery.

Source: A.T. Kearney Energy Transition Institute based on EPRI (2010), “Electricity Energy Storage Technology Options”

Electricity prices and distribution patterns strongly influence storage costs

Electricity spot price duration curves

€/MWh, 2012 in Germany



There is a trade-off between the cost of feed-in electricity and the utilization of plants to amortize the capital cost. Note that prices are negative during a few hours due to an excess of power from intermittent renewables and to the cost of shutting down non-flexible baseload power plants.

- **The cost of storing electricity is composed of the price of the electricity** that is charged, stored and sent back to the grid[1]. With the exception of storage plants linked to generators that use “free” electricity, most plants purchase power on the spot market. Usually, storage plants try to store energy when electricity prices are low and redistribute it when prices are high. The electricity-price distribution, depicted by the price-duration curve, is consequently a key factor in storage economics.
- **However, the impact of the price of electricity on storage economics varies according to end application**. For some applications, optimizing the buying and selling price is essential for price arbitrage, which takes advantage of the price spread of electricity. Intermittent balancing and power-fleet optimization are also highly dependent on the price structure, as the storage devices are likely to be charged when there is an oversupply of electricity and prices are low, and to be discharged when there is a shortage of electricity and prices are high. The price structure may be of lesser importance for applications that ensure power quality, defer grid investment or provide ancillary services, where revenues are not usually primarily obtained from selling electricity but rather from the remuneration of the services provided (e.g. black start, frequency regulation).

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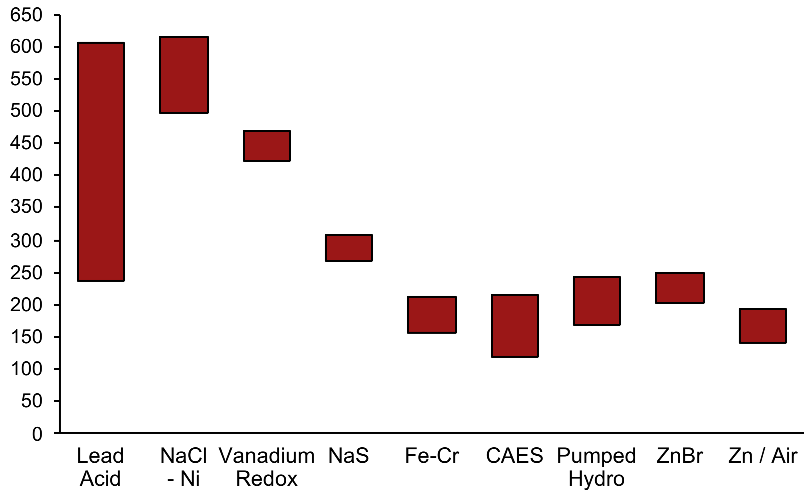
1. Compressed-air energy storage also include the cost of the gas used upon decompression.

Source: EPEX SPOT Market Data 2012

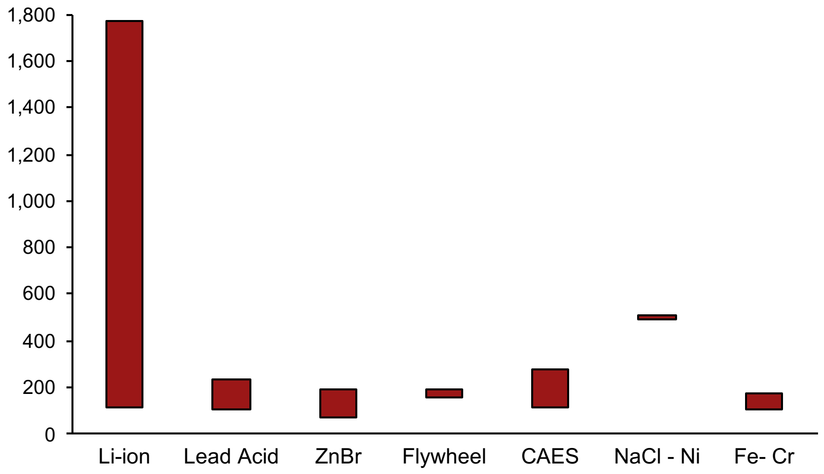
The full costs of electricity storage vary significantly, depending on the application, changing the competitive landscape of technologies (1/2)

Levelized costs of energy[1] for different applications $/MWh

Bulk Storage



Frequency Regulation



Compressed-air energy storage along-with Pumped Hydro provide an economically competitive solution compared to batteries for bulk storage applications

For frequency regulation, batteries with low capital requirements will be favored over Li-ion which is deemed to be high capital-cost technology for this application

---

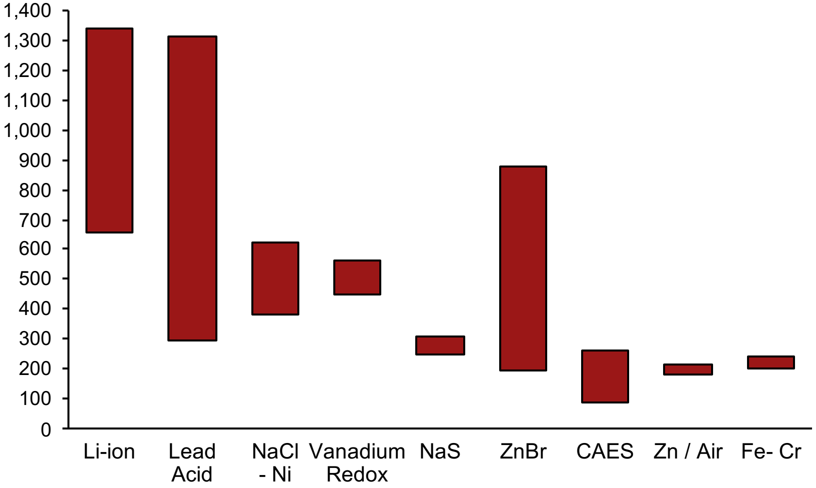
1. Levelized costs take into account discounted annualized operation costs as well as full capital costs. Assumptions about each technology can be found in the source document below.

Source: Sandia (2015), "Electricity Storage Handbook"

The full costs of electricity storage vary significantly, depending on the application, changing the competitive landscape of technologies (2/2)

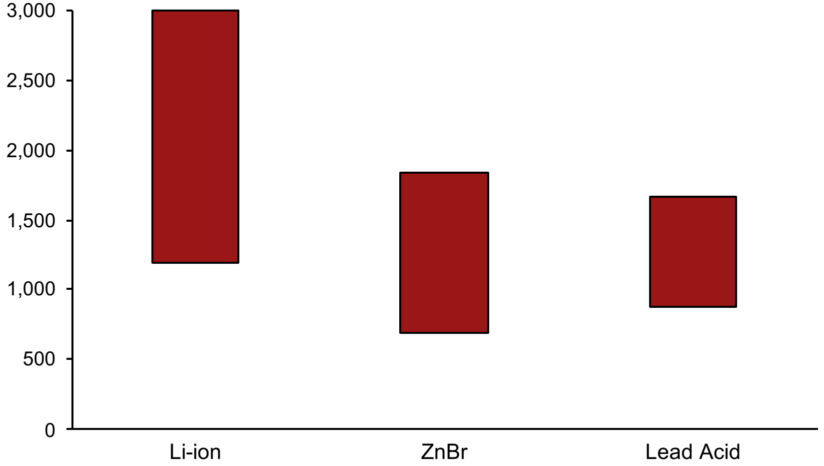
Levelized costs of energy[1] for different applications $/MWh

Transmission & Distribution



Compressed-air energy storage is the most cost-effective technology for transmission & distribution applications. Batteries provide other low cost alternatives

Residential



For residential storage, batteries with the lowest capital costs per unit of power will be the most competitive.

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1. Levelized costs take into account discounted annualized operation costs as well as full capital costs. Assumptions about each technology can be found in the source document below.

Source: Sandia (2015), "Electricity Storage Handbook"

Depending on the end-application, the benefits of storage can be difficult to monetize, making it complicated to build a business case

Approaches to estimating the value of storage

	Approach	Approach
1	*Based on* **Market price**	Revenues correspond to the price in markets where storage operators can bid (e.g. capacity market, frequency regulation market, black-start services). A market-price approach also includes price-arbitrage applications
2	*Based on* **Avoided costs**	In the absence of a market, the benefits of electricity storage can be assessed implicitly by evaluating costs avoided because of investment in storage (e.g. deferral of transmission & distribution investment, reduced transmission congestion charges…)
3	*Based on* **Competing technology / Willingness to Pay**	If electricity storage has an intrinsic value, it can be assessed by comparing alternative technologies (e.g. ensuring power quality for end-users, optimization of the power fleet by storing excess power from renewables instead of shutting down baseload power plants)

- **The financial benefits of storage depend on the application and can be difficult to evaluate**. Market-based applications generate revenues. Their business cases are therefore easier to assess using classic investment tools. However, they may be subject to uncertainty regarding frequency of use and price. Avoided costs are not very difficult to evaluate. The discounted cost of storage can be compared to avoided costs, including risk. Finally, the "intrinsic" value of storage is more complicated to assess. Willingness-to-pay suffers from "free-rider" behavior, while competing technology does not always exist[1].
- **Investors in storage may not necessarily be its main beneficiaries**. Some benefits are social and cannot be allocated to specific players. Storage can also generate positive externalities than cannot be monetized in the absence of specific regulations.
- **Regulation is likely to help determine the value of storage**. Market rules must be put in place to ensure that storage can participate in the capacity market or other ancillary services. System operators should be incentivized to avoid costs, instead of using remuneration pegged to investment budgets. Regulators have to find the most efficient ways to allocate and share storage costs when their benefits are positive.

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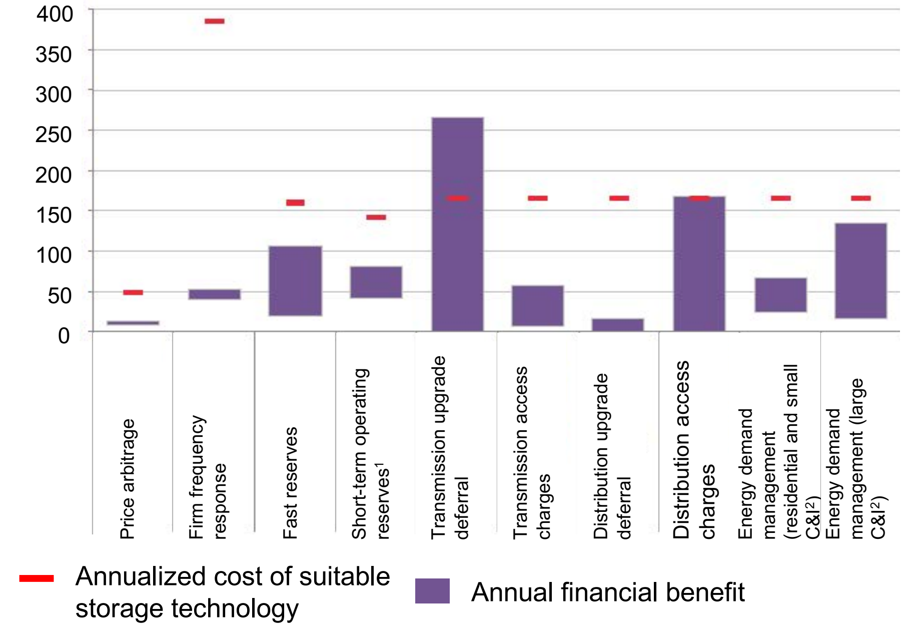
1. Free-riders refers to someone who benefits from resources, goods, or services without paying for the cost of the benefits.

Source: ISEA/RWTH Aachen (2012), "Technology Overview on Electricity Storage. Overview on the potential and on the deployment perspectives of electricity storage technologies"; ETH Zurich (2012), "Economics of Energy Storage"

Currently, the costs of electricity-storage applications outweigh the financial benefits

Annual benefit of storage applications in the UK compared with annualized cost

£/MWh-installed/year



- **Currently, individual electricity-storage applications struggle to generate sufficient financial benefits to cover their costs**. Bloomberg New Energy Finance (BNEF) simulates the current discrepancy between costs and revenues for the UK. According to BNEF analysis, the only activities that may achieve profitability in favorable conditions are the deferral of transmission upgrades and avoidance of distribution access charges.
- **However, the results for the UK cannot be generalized to other systems**. In Switzerland, price arbitrage applications of pumped hydro storage are believed to be profitable thanks to favorable natural conditions and access to cheap German electricity3.
- **The struggle to achieve profitability results from technological maturity, regulatory barriers and from a poor utilization rate**, making it difficult to amortize the high initial investment (e.g. price arbitrage can only be used when the spread is high enough to compensate for energy losses and other operating costs).

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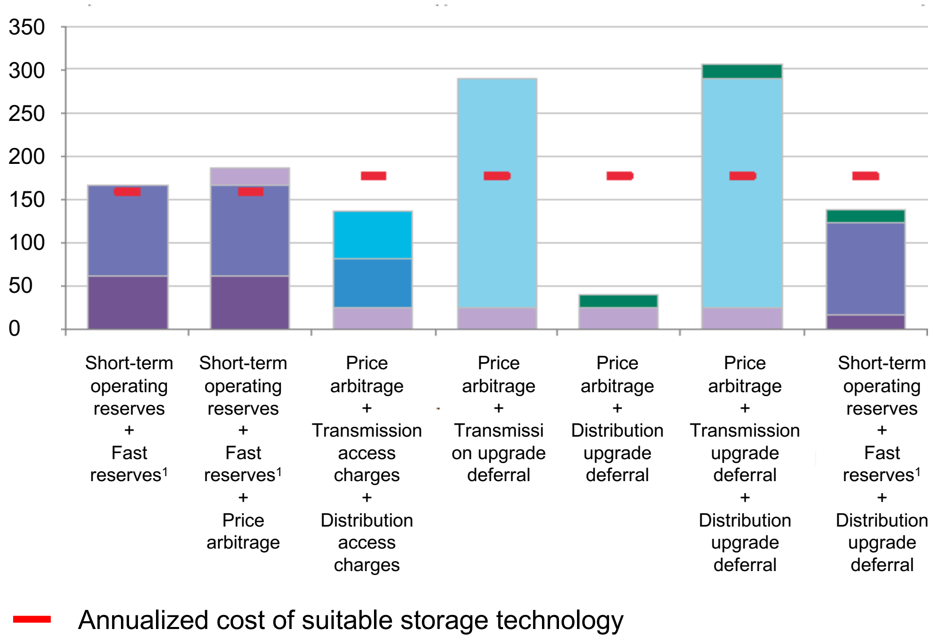
1. Short-term operating reserve
2. C&I: commercial and industrial
3. This occurs in the case of high intermittent production (e.g. good windy day) and low demand (e.g. late at night).

Source: Bloomberg New Energy Finance (2013), "IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop proceedings"

Bundling applications seems to be a strong lever in helping electricity storage become profitable

Annual benefit of storage applications in the UK compared with annualized cost

£/MWh-installed/year



- **Bundling applications is believed to help increase the utilization of storage plants and revenues**. For instance, a very flexible storage plant can provide ancillary services over several different timeframes (fast reserves and short-term operating reserves – STOR), while taking advantage of price arbitrage when it can be achieved. According to a Bloomberg New Energy Finance analysis of the UK market, bundling could make several applications profitable (see graph opposite).
- **Not all applications can be bundled** and potential combinations have to be carefully assessed at the system level because of variations in regulatory frameworks and local specificities (demand curve, intermittency patterns…).
- **Application bundling is challenging** as its efficiency relies on very complex optimization models that are not yet commonly used and still necessitate further R,D&D. It may also be faced with regulatory barriers for ancillary services.

1. Fast reserve is part of the operating reserve (requires to provide at least 25 MW/min within 2 minutes and for 15 minutes).

Source: Bloomberg New Energy Finance (2013), "IEA Energy Storage Technology Roadmap Initial Stakeholder Engagement Workshop proceedings"

Multiple storage applications have been identified to generate revenue streams for the different customer segments

		Customer segments (revenue source)									
		Wholesale Market					Utility			Customer[1]	
	Applications	Energy Arbitrage	Frequency Regulation	Demand Response - Wholesale	Spin/Non-Spin Reserve	Resource Adequacy	Distribution Deferral	Transmission Deferral	Demand Response-Utility	Bill Management	Backup Power
Utility scale	Peaker Replacement	√	√		√	√					
	Distribution					√	√	√			
	Microgrid	√	√	√	√	√	√		√	√	√
Non -utility scale	Commercial		√	√	√	√	√		√	√	√
	Residential			√					√	√	

Energy Arbitrage	Storage of cheaper electricity to be sold at a higher price later
Frequency Regulation	Immediate (4-second) power to maintain generation-load balance
Demand Response - Wholesale	Calling users to reduce/shift demand on the grid to manage high wholesale prices / emergency conditions
Spin/Non-Spin Reserve	Maintaining electricity output during unexpected contingency
Resource Adequacy	Capacity to support electricity requirement at peak load in cases of generation and/or transmission constraints

Distribution Deferral	Extra capacity to meet projected load growth for the purpose of delaying, reducing or avoiding transmission investment
Transmission Deferral	Extra capacity to meet projected load growth for the purpose of delaying, reducing or avoiding transmission investment
Demand Response- Utility	Calling users to reduce/shift demand on the grid to manage high wholesale prices / emergency conditions
Bill Management	Reduction in demand charges through battery discharge and storage during peak hours
Backup Power	Power reserve when grid is down/unavailable

1. Via a competitive retailer or aggregator

Source: A.T. Kearney Energy Transition Institute analysis; Lazard (2017), “Lelelized cost of storage analysis — Version 3 . 0”

Small scale projects are commercially unviable but large scale projects are deemed economical under certain assumptions

Results of selected U.S. energy storage projects

	Peaker Replacement	Distribution	Microgrid	Commercial	Residential
Region	**California ISO**	**New York ISO**	**ISO New England**	**California ISO**	**California ISO**
Owner	IPP in a competitive wholesale market	Wires utility in a competitive wholesale market	IPP in a competitive wholesale market	Customer or financier in a competitive wholesale area	Customer or financier
Revenue sources	Wholesale market settlement, Local capacity resource programs	Capital recovery in regulated rates, avoided cost to wires utility, NY-BEST and other avoided cost incentives	Wholesale market settlement, direct payments from loads within the microgrid, investment tax credit	Wholesale market settlement, tariff settlement, Demand Response participation, avoided costs to commercial customer	Demand Response participation, tariff settlement, avoided costs to residential customer
Energy Storage configuration	Battery Size (MWh): 400 Inverter Size (MW): 100 C-Rating: C/4 Cycles Per Year (Full DoD): 91	Battery Size (MWh): 80 Inverter Size (MW): 10 C-Rating: C/6 Cycles Per Year (Full DoD): 15	Battery Size (MWh): 4 Inverter Size (MW): 1 C-Rating: C/4 Cycles Per Year (Full DoD): 127	Battery Size (MWh): 0.25 Inverter Size (MW): 0.125 C-Rating: C/2 Cycles Per Year (Full DoD): 169	Battery Size (MWh): 0.010 Inverter Size (MW): 0.005 C-Rating: C/2 Cycles Per Year (Full DoD): 200
IRR [1,2]	8.8%	20.8% (3)	N/A	10.9%	N/A (4)
Viability	**Potentially viable**	**Viable**	**Not viable**	**Viable**	**Not viable**

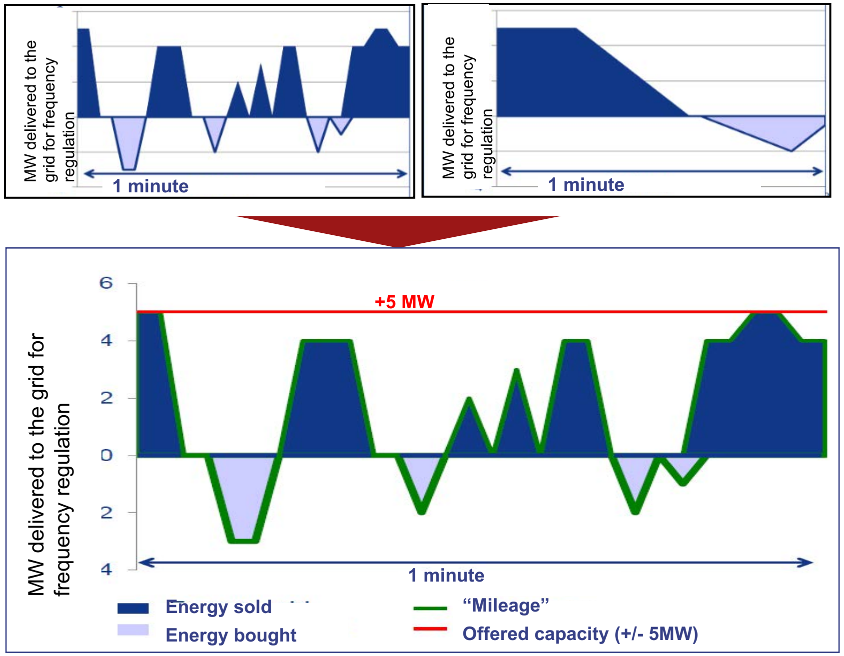
1. Hurdle rate of 10% is assumed, hence Peaker Replacement use case is potentially viable (post-cost reductions/improvements); 2. Estimates only, for a detailed list of assumptions pls refer Lazard's cost of storage analysis – Version 3.0; 3. Includes 50% NYSERDA ("NY-BEST") incentive; 4. Includes 40% Self-Generation Incentive Program ("SGIP") incentive

Source: A.T. Kearney Energy Transition Institute analysis; Lazard (2017), "Levelized cost of storage analysis — Version 3 . 0"

Supportive regulations and policies can help overcome challenges in energy storage market growth

Regulation “mileage”[1]

Equal amounts of energy are provided by two assets over a specified time frame, leading to the same payment, even if the service is very different



Adding remuneration for the mileage as PJM did will help fast-response storage plants to valorize the service they are providing

- Key barriers which affect the ability of developers to monetize electricity storage:
  - **Ability to participate in ancillary services**: storage is not always eligible to participate in ancillary services (markets or bilateral agreements) nor to resource adequacy. This is particularly true for small capacity storage due to a minimum size required;
  - **Ownership of storage plant**: in several unbundled systems, storage is considered a production asset and system operators (transmission or distribution) are not allowed to own storage devices. This is a strong impediment to the implementation of storage devices that would enable the deferral of transmission- and distribution-grid upgrades. The deferral of grid upgrades is considered among the best prospects for revenue generation in the electricity-storage sector;
  - **Monetization of fast-response assets**: frequency regulation usually rewards MW withdrawn or injected to stabilize the grid without taking into account the speed of the response;
  - **Lack of cohesive, transparent and stable framework** increases investment risks.

- **Potential solutions:**
  - Include explicit targets and/or goals to promote procurement of energy storage. Ex: California energy storage procurement targets (i.e. require 1,325 MW by 2020), upfront or performance-based incentive payments to subsidize initial capital requirements ex: California Self-Generation Incentive Programs ($450 million budget available to behind-the-meter storage)
  - Promote regulation “mileage” like PJM did in the U.S. (see graph opposite - Clean Horizon Consulting ©).

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1. Copyright© Clean Horizon Consulting (2012), “Financing hydrogen: focus on an additional value stream”

Source: Joseph Eto (2012), “Renewable Electricity Policies in the US and a Status Report on California’s Energy Storage Procurement Target”; EASE / EERA (2013), “European Energy Storage Technology Development Roadmap Towards 2030”; Lazard (2017), “Levelized cost of storage analysis — Version 3 . 0”

The electricity storage sector is fragmented by technology and composed of small players focused exclusively on storage and large companies diversifying (1/2)

Main actors in electricity storage[1]

Pumped hydro storage

- Alstom / GE 🇫🇷
- China Southern Power Grid 🇨🇳
- Duke Energy 🇺🇸
- Emera 🇨🇦
- First Hydro Company 🇬🇧
- Gridflex energy 🇺🇸
- IMPSA 🇦🇷
- Ukrhydroenerho 🇺🇦
- Voith Hydro 🇩🇪
- MWH Global 🇺🇸

CAES[2]

- E.ON 🇩🇪
- Energy Storage & Power 🇺🇸
- General Compression 🇺🇸
- Lightsail Energy 🇺🇸
- Dresser Rand 🇺🇸
- Hydro store 🇨🇦

Flywheels

- Active Power 🇺🇸
- Amber Kinetics 🇺🇸
- Beacon Power 🇺🇸
- Calnetix 🇺🇸
- Temporal Power 🇺🇸
- Toshiba 🇯🇵

Hydrogen & synthetic natural Gas

- Air Liquide 🇫🇷
- Areva 🇫🇷
- E.ON 🇩🇪
- Electrochaea 🇩🇪
- Giner 🇺🇸
- Hydrogenics 🇨🇦
- ITM Power 🇬🇧
- Linde 🇩🇪
- McPhy 🇫🇷
- NEL Hydrogen 🇳🇴
- Proton OnSite 🇺🇸
- Siemens 🇩🇪
- Hitachi Zosen Inova (HZI) Etogas 🇨🇭
- SunFire 🇩🇪

Thermal Storage[3]

- Abengoa 🇪🇸
- Acciona 🇪🇸
- Infinia 🇺🇸
- General Atomics 🇺🇸
- Terrafore Technologies 🇺🇸
- EnergyNest 🇳🇴
- Ice energy 🇺🇸
- Isentropic 🇬🇧
- World Renewal Spiritual Trust 🇮🇳
- CNIM 🇫🇷

SMES[4] & capacitors

- Maxwell Technologies 🇺🇸
- NEC 🇯🇵
- American Superconductor 🇺🇸
- Endesa 🇪🇸

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1. This list is not exhaustive; 2. CAES: compressed-air energy storage; 3. Associated with CSP; 4. SMES: superconducting magnetic energy storage.

Source: A.T. Kearney Energy Transition Institute analysis based on Bloomberg New Energy Finance database (accessed 2015); US DoE (accessed 2017); Lazard and Press search.

The electricity storage sector is fragmented by technology and composed of small players focused exclusively on storage and large companies diversifying (2/2)

Main actors in battery storage[1]

Pumped hydro storage

- A123
- AES Energy Storage
- Altair Nanotechnologies
- Younicos3
- BYD
- EnerDel
- GE
- GS Yuasa
- Hitachi
- Kokam
- LG Chem
- Mitsubishi
- NextEra Energy
- Powertree Services
- Saft
- Samsung SDI
- SK Innovation
- Panasonic
- Tesla
- Tianjin Lishen Battery
- Toshiba
- Wanxiang Groupl

CAES[2]

- Gildemeister Energy Solutions
- H2 Inc.
- Primus Power
- Prudent Energy
- REDT Energy Storage
- Redflow
- Rongke Power
- Sumitomo Electric Industries
- SunCarrier Omega
- UniEnergy Technologies
- Vionx Energy2
- ViZn Energy
- ZBB Energy

Flywheels

- AES Energy Storage
- Axion Power International
- BYD
- Ecoult
- Exide
- GE
- LG Chem
- Maxwell Technologies
- NGK Insulators Ltd.
- SK Innovation
- Stem, Inc.
- Toshiba Corporation
- Younicos4
- Enersys
- GS Yuasaa
- East Penn Mfg.
- NGK
- Fluidic Energy
- EOS Energy Storage

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1. This list is not exhaustive; 2. Formerly Premium power; 3. Recently bought Xtreme Power.

Source: A.T. Kearney Energy Transition Institute analysis based on Bloomberg New Energy Finance database (accessed 2015) ; U.S. DoE Storage database (accessed 2017); Lazard and Press search.

6. Environmental and Social Impact

The environmental impact of storing energy is difficult to evaluate

Impact categorization

Impact categorization	GHG[1] emissions	Land use	Water use
Direct	No GHG emissions except conventional CAES[2]	Depends on energy density & power density of storage technologies	Can be high for Conventional PHS[3] & CAES[2]
Lifecycle: *Construction*	Depends on the energy intensity and the way it is produced. Some issues with batteries	Depends on the energy intensity and land use during construction. No major issues	No major issues beyond construction of salt caverns for CAES[2]
Lifecycle: *Operation*	Depends on storage efficiency and GHG emissions of upstream energy	Depends on land footprint of electricity stored and storage efficiency	Depends on water use of electricity stored and storage efficiency
Induced	Positive: • Maximize intermittent renewable or nuclear production; • Avoid using peak power plants. Negative: • Increases energy losses in the system (to be compared on a lifecycle basis with alternative solutions).		

- As with “smart energy technologies” such as smart grids or demand-side responses, the environmental impacts of electricity storage are difficult to evaluate. They are a function of the storage technology’s direct impact, but also of the impact of the upstream source of electricity used for charging, of the electricity displaced upon discharging, and of the increase in generation needed to balance storage losses.
- The environmental impact of storage is not restricted to air pollution and GHG emissions, but also encompasses water requirements and land use.
- In some cases, electricity storage can change the emissions intensity of the power mix (e.g. charge by night with coal and discharge during the day, instead of using gas turbines).

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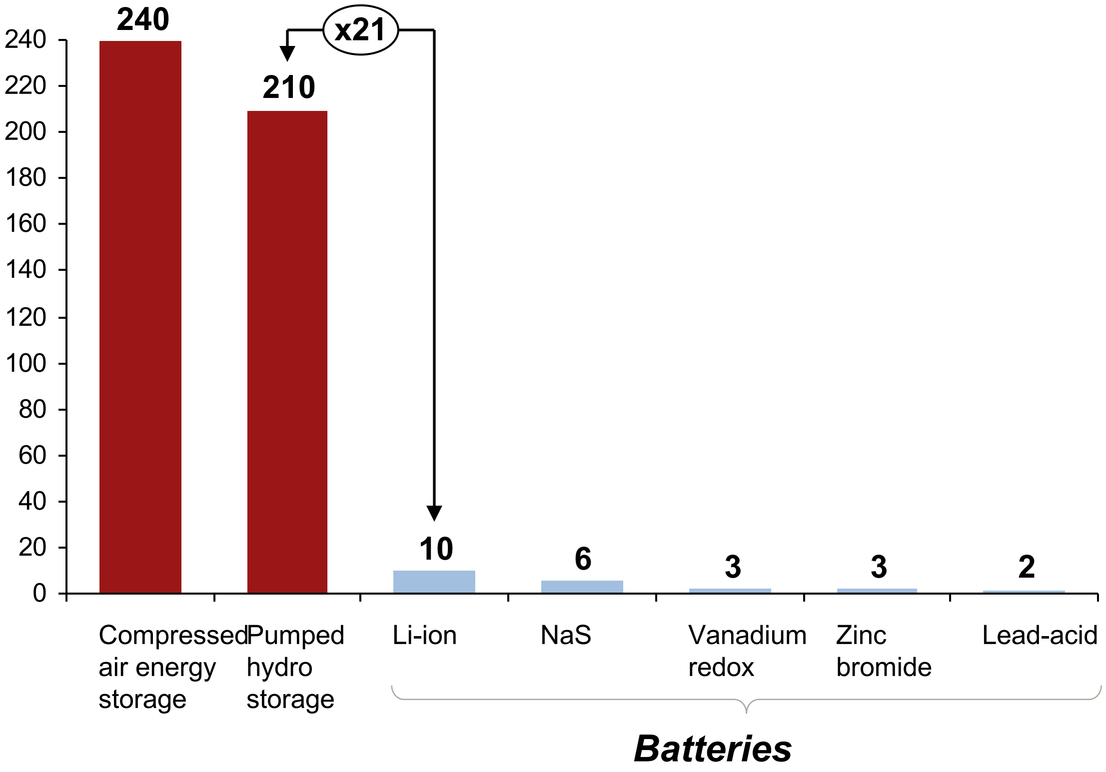
1. GHG: greenhouse gas; 2. CAES: compressed-air energy storage; 3. PHS: pumped hydro storage.

Source: A.T. Kearney Energy Transition Institute analysis; NREL (2012), “Renewable Electricity Futures Study – Volume 2: Renewable Electricity Generation & Storage Technologies”

Recent studies suggest batteries are difficult to deploy as a large-scale storage solution because of their high energy intensity

Ratio of electrical energy stored in the lifetime of the storage device to its embodied primary energy

MJ/MJ



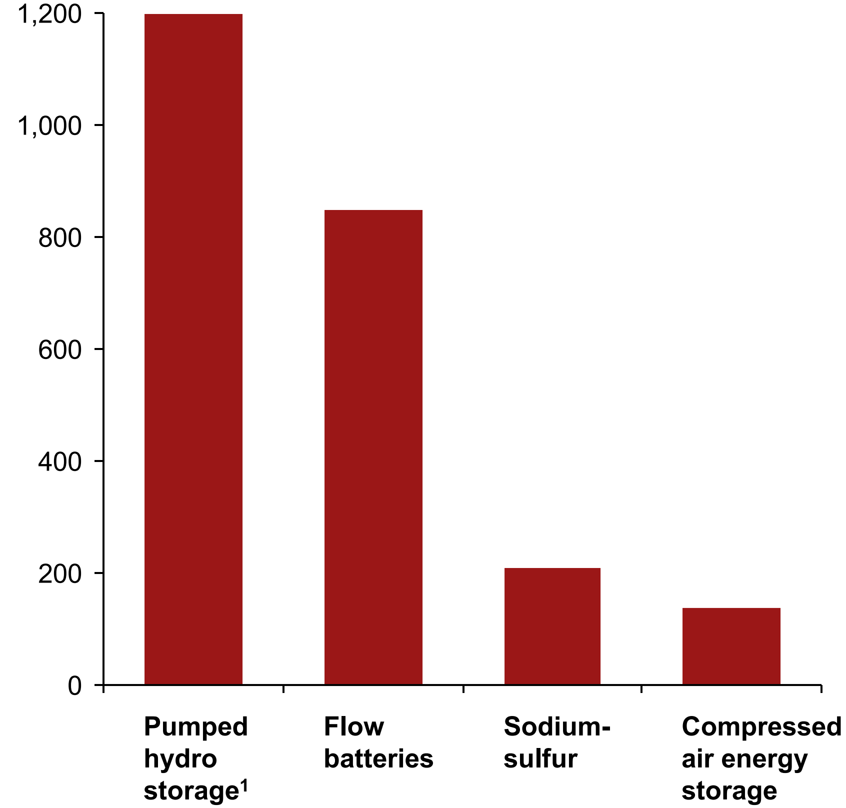
- **Pumped hydro storage** (PHS) **and compressed-air energy storage** (CAES) **plants are on average less energy intensive than electrochemical storage** (batteries) by a factor ranging between 21 and 120.
- **This is mainly a result of the short cycling life of batteries**, but also depends on the 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.
- Although R&D is currently mainly focusing on increasing energy and power density, it seems that improving the cycling life of batteries could greatly reduce their environmental impact, as well as their capital cost.
- Initial research suggests that controlled chemical equilibrium in Zinc-manganese batteries (both abundant metals) could lead to a more viable large-scale energy storage solution (over Li-ion/Lead Acid)

Note: The graph displays the ratio of electrical energy stored over the lifetime of a technology to the energy needed to build it. Stored energy over the lifetime depends significantly on the cycling life, the efficiency and the depth of discharge.
Source: Charles J. Barnhart (2013), "On the importance of reducing the energetic and material demands of electrical energy storage", Pacific Northwest National Laboratory research on Zinc-manganese battery (link)

Pumped hydro storage uses extensive amounts of land and raises social acceptance issues

Land use by technology

m²/MW



- **Pumped hydro storage (PHS) has a high land footprint** because of its poor energy density (1 cubic meter of water over a height of 100 meters gives 0.27 kWh of potential energy). The footprint depends to a large extent on the nature of the reservoirs and the date of construction. According to the National Renewable Energy Laboratory, the total flooded area of old plants with man-made upper and lower reservoirs can exceed 4,000 m²/MW, while more recent projects have significantly lower land requirements, averaging around 1,200 m²/MW.
- **PHS requires a substantial volume of water**. For example, a 1,300 MW closed-cycled facility would require 3 billion liters per year, or 1.1 liter/kWh, mainly due to evaporation. Pumping can disrupt the local environment by increasing the temperature (affecting water quality and aquatic life) and trapping aquatic life in the system.
- **Construction has an impact on local ecosystems, wildlife, and modifies landscape** by blocking the natural flow of a river or flooding a previously dry area.
- **Developers are hoping to avoid these environmental impacts** by using seawater, underground PHS or recycled wastewater.

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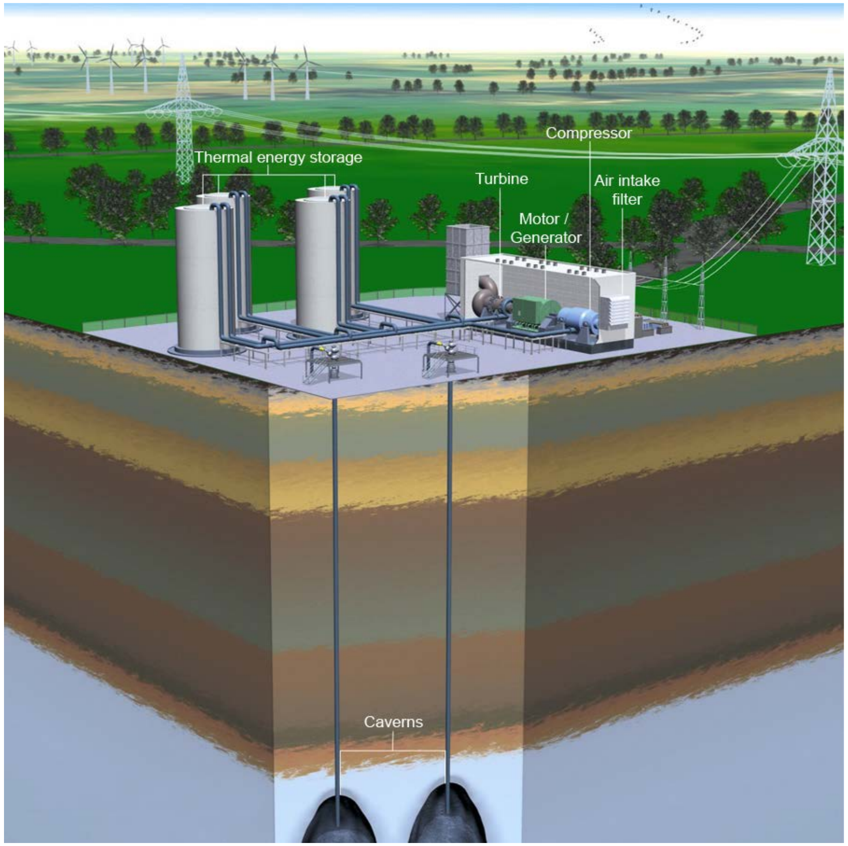
1. Pumped hydro storage footprint refers to recent projects.

Source: A.T. Kearney Energy Transition Institute Analysis based on NREL (2012), “Renewable electricity futures study”

Although compressed-air energy storage (CAES) uses very little land, it is associated with greenhouse gas emissions and high water consumption

Adiabatic CAES, exemple of *RWE Adele project*



- **Conventional compressed-air energy storage (diabatic CAES) requires fuel to heat up the compressed air upon decompressing**, for which it usually relies on natural gas. Therefore, CAES causes air pollution, mainly in the form of nitrogen oxide (NOx), and also emits carbon dioxide (CO2), in amounts roughly equivalent to only one-third emitted from a conventional gas turbine with the same power rating, i.e. around 100 grams and 150 grams per CO2eq./kWh. Recent projects (EPRI 2012) focus on reducing emissions by virtue of a loop that uses exhaust gas to heat up the air.
- **Conventional CAES (diabatic) requires high volumes of water to cool down the compressed air before storing it**. It is estimated that a 2,700 MW facility would use almost 3.5 billion liters of water every year for this purpose, or 0.75 liter/kWh. Furthermore, if the air is stored in man-made salt caverns, water will be needed to dissolve the salt formation (about 8 m3 for each cubic meter excavated). This will also result in large quantities of brine, which will need to be disposed of.
- **Developing adiabatic and isothermal technologies1 could significantly reduce the environmental impact** of CAES by avoiding the need for external fuel and lowering water requirements.

1. Refer to the R,D&D section on CAES for more information on adiabatic and isothermal concepts.

Source: NREL (2012), “Renewable electricity futures study”; RWE (2010), “ADELE – adiabatic compressed-air energy storage for electricity supply”

Appendix and Bibliography

Acronyms

AC: Alternative Current
A-CAES: Adiabatic Compressed Air Energy Storage
ARPA-E: Advanced Research Projects Agency-Energy
ARRA: American Recovery and Reinvestment Act
BNEF: Bloomberg New Energy Finance
CAES: Compressed Air Energy Storage
CAPEX: Capital Expenditures
CO$_2$: Carbon dioxide
CSP: Concentrating Solar Power
DC: Direct Current
DoE: Department of Energy
DSO: Distribution System Operator
EV: Electric Vehicle
GHG: Greenhouse Gas
H$_2$: Hydrogen
Hz: Hertz
IEA: International Energy Agency
kWh: kilowatt hour
Li-ion: Lithium-ion
LA: Lead-acid
Mg: Magnesium
ms: milli-second
MSES: Molten Salt Energy Storage
NaS: Sodium-sulfur
NSW: New South Wales
NiCd: Nickel Cadmium
OPEX: Operational Expenditure
O&M: Operation and Maintenance
P2G: Power-to-Gas
PCM: Phase Change Material
PHS: Pumped Hydro Storage
PJM: Pennsylvania-New Jersey-Maryland
PV: Photovoltaic
R,D&D: Research, Development & Demonstration
SC: Supercapacitor
SNG: Synthetic Natural Gas
SMES: Superconducting Magnetic Energy Storage
SVC: Static VAR Compensator
T&D: Transmission & Distribution
TSO: Transmission System Operator
UHVDC: Ultra High Voltage Direct Current
VRB: Vanadium Redox Batteries
W: Watt
Zn/Br: Zinc-bromine

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Picture credits

- **Slide 9, 33**: Rokkasho-Futumata 34 MW sodium-sulfur (NaS) battery storage system, Japan, NGK
- **Slide 19**: Linthal pumped hydro storage (PHS) 1,000 MW expansion project, Switzerland, Axpo Group
- **Slide 26, 47**: Seneca 435 MW pumped hydro storage plant in Pennsylvania, U.S., FirstEnergy
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- **Slide 88**: Bluffton 2 MW sodium-sulfur (NaS) battery storage system, U.S., S&C

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