**Technical assessment for**

**Utility Scale Energy Storage**

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# Acronyms and Symbols Used

* AC – Alternating Current
* CAES - compressed air energy storage
* CCGT – Combined Cycle Gas Turbine
* CSP - concentrated solar power
* DOE – Department of Energy
* EES - energy storage systems
* FERC - Federal Energy Regulatory Commission
* GW – Gigawatts
* IEA – International Energy Agency
* LCOE – Levelized Cost of Electricity
* PHS - Pumped hydroelectric energy storage
* T&D - transmission and distribution

# Executive Summary

Project Drawdown defines energy storage (utilities) as: new technologies and practices to store energy on a utility level. This solution does not replace a conventional practice, but is key to the development of variable renewable energy sources. Energy storage allows for power to be generated at a time different from when it is consumed (a process known as “time shift”). In a power system with significant amounts of large-scale energy storage, every type of generation can be used in the most optimal fashion. Large centralized generators can run at a steady rate, with no need to undergo inefficient cycling to respond to changes in demand. If the power generated by solar or wind installations exceeds demand, it can be stored for later use rather than rejected by the grid (or “curtailed”). The most rapidly-responding forms of energy storage can account for fluctuations in demand in a second or less, far outpacing even the natural gas-fired plants currently used to respond to demand peaks. In addition, energy storage can provide a number of other valuable services. Storage can relieve congestion on transmission lines, increasing reliability and performance and allowing for the efficient use of existing infrastructure. Moreover, storage makes the power system more resilient, reducing outages and aiding in emergency preparedness.

While it is not possible to store energy in the form of electricity, it is possible to convert electrical energy to another form that can be stored. There are many possible forms in which the energy can be stored, including: (1) gravitational potential energy (pumped hydroelectric energy storage); (2) chemical energy (batteries); (3) mechanical energy (flywheels or compressed air energy storage); (4) thermal energy storage (molten salt); or (5) hydrogen storage.

According to the U.S. Department of Energy’s global energy storage databases (2016), there are around 188 gigawatts of large-scale energy storage currently installed, announced, or under construction in electricity grids worldwide by 2020. The vast majority (99 percent) of this capacity is comprised of pumped hydroelectric technology. The primary use of energy storage at present is power arbitrage (time shift): pumped hydropower facilities buy electricity when prices are low (i.e. at night), and use it to pump water from a low reservoir to an elevated one. During the day, when prices are high, the stored water is allowed to run downhill through turbines, generating electricity that can then be sold back to the grid. This has been the primary mechanism through which energy storage projects earn revenue. Currently, more than 94 percent of this technology’s capacity is used for the time shift application. The remaining energy storage technologies are used to enable penetration of variable renewable generation sources: 25 percent of the compressed air installation capacity is used for wind energy application, 28 percent of the batteries’ capacity is used for solar, and 100 percent of molten salt storage is used for concentrated solar power.

This solution is key for: integrating variable renewable generation sources into the electricity grid; balancing the supply and demand for electricity; replacing natural gas peaking plants; allowing increased reliance on base load generation; and avoiding the need to cycle base load units. Without storage, variable renewable energy technologies face high curtailment rates; thus, storage is a crucial aspect of enabling a low-carbon grid. To avoid double-counting, the climate impact of the bulk of the technologies under the energy storage (utilities) solution is accounted for in the adoption of distributed electricity generation technologies such as wind and solar. Molten salt storage is accounted for in the impact of increased adoption of concentrated solar.

Current and future investments in utility-scale storage units are important when considered in the context of the infrastructure, including transmission and distribution upgrades, expansion of natural gas-fired peaking capacity that storage can replace, and the revenue streams available to storage operators both now and under prospective policy frameworks. Utility-scale energy storage transforms the way we produce, deliver, and consume electricity toward a cleaner and more efficient energy mix. While energy storage increases energy demand due to its inefficiency, the increased efficiency of the grid offsets this, meaning that all carbon savings from the use of clean, renewable variable generation sources can be fully realized.

# Literature Review

## State of Utility Scale Energy Storage technologies

In the present day, electricity is the only major commodity product that is not stored in large quantities (Boos, 2014). Although energy storage technologies such as batteries and pumped fluid reservoirs have existed for generations, current-day electricity grids are designed to be basically synchronous in their operation (European Commission, 2015). Large, centralized generation facilities respond in real-time as load on the grid fluctuates over the course of a day, in order to match supply to demand. A complex system of contracts, hour-by-hour bids, and iterative prediction algorithms has been developed to regulate this system, as it is essential that the electricity supply not fall short of demand.

Energy storage has the potential to disrupt this system and make the operation of power grids asynchronous. Just as the transmission and distribution system delivers electric power where it is needed, energy storage enables the grid system to deliver power when it is needed (Gyuk, 2015). For example, imagine a week in June in New England where only one day is above 85°F. On this day, many more residents will be using their air conditioners than the days immediately before and after, increasing the load on the grid. Efficient energy storage capacity can enable fossil fuel-driven power plants to run at a steady rate instead of ramping up and down to meet demand, which is a less efficient and more carbon intensive mode of operation in conventional generators (Black, 2012).

With the advent of clean, renewable energy sources such as solar and wind power, energy storage has become of crucial importance. Solar and wind power are both “intermittent” or variable sources, meaning that the availability of power from these sources can change from moment to moment. When the energy mix supplying power to the grid consists only of a small percentage of renewable sources, conventional generators can easily make up shortfalls (IEA, 2014). Due to the limited ramp rates possible for conventional generators, however, a rapid increase in the availability of wind or solar power can often lead to “curtailment,” a practice in which the grid rejects energy generated from clean sources in favor of the steady supply from conventional sources (US DOE, 2013). Moreover, in an energy mix with a high percentage of intermittent, renewable generation capacity, the opposite problem can arise: there might not be enough conventional capacity available to meet demand given a sudden shortfall in the wind or solar resource, leading to a lack of reliability (Denholm et al., 2010).

Electricity storage can be deployed to any of the five major subsystems in the electric power system: generation, transmission, distribution, and final consumers (see Figure 1.1).

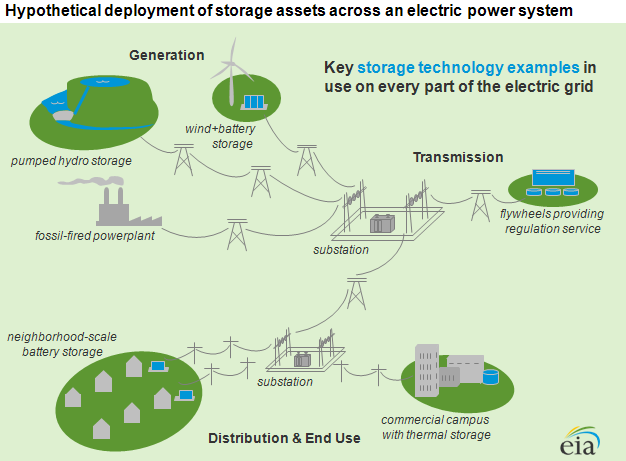


Figure 1.1. Hypothetical deployment of storage assets across an electric power system (Source: U.S EIA, 2012)

The availability of large storage reservoirs has the potential to end or significantly reduce the practice of curtailment, and enable energy mixes that rely heavily on clean generation sources. Although the use of energy storage in and of itself does not reduce carbon emissions directly, its ability to enable full usage and high penetration of renewable sources, as well as the decreased carbon intensity of remaining conventional power generators due to a lessened need for power cycling and ramping, show that energy storage is an important part of decarbonizing the electricity generation system. Moreover, energy storage systems (ESS) can add significant resilience to grid systems, reducing an area’s vulnerability towards power outages in the case of grid faults, generator failures, or the severe weather events that have only increased in frequency due to global climate change (US DOE, 2013).

A wide variety of technologies exist that can be used to store power on the grid, include; pumped hydroelectric energy storage (PHS), batteries, flywheels, compressed air energy storage (CAES), thermal energy storage (molten salt), and hydrogen storage. The vast majority of storage capacity (more than 99% out of 140 GW) is presently in the form of pumped hydropower (J.P. Morgan, 2015)

A PHS storage system, which is used primarily for power arbitrage buy electricity when the electricity rate is low (during off-peak hours) to pump water to higher altitude where it is stored as gravitational potential energy. When the electricity price is high (during on-peak hours), the water is released and passes back through a turbine/generator to convert the stored energy back to electricity (see Figure 1.2).

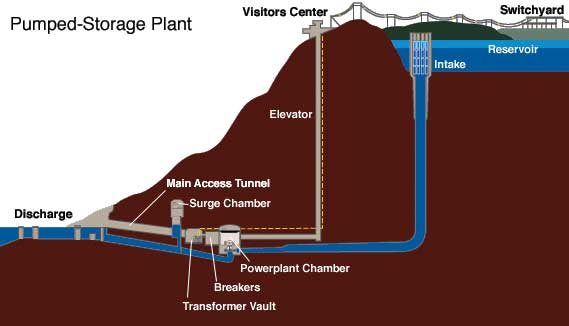


Figure 1.2. Diagram of a pumped hydropower storage plant. (Directorate-General for Energy, 2013)

Other pumped-fluid systems, such as compressed-air energy storage (CAES), operate on similar principles. CAES systems can be very cost-effective when based on an existing air reservoir, such as a subterranean cavern, but are often prohibitively expensive and inefficient otherwise, with round-trip efficiencies on the order of 50-60% (US DOE, 2013). One other mechanical storage system of note is that of flywheels, large wheels with significant inertia that store rotational energy. Flywheels are operated with very low friction to minimize losses, which can be significant for long storage durations. As a result, flywheel systems are rarely used for energy management, but they are very well-suited to power conditioning due to their rapid response times (US DOE, 2013).

Finally, energy on the grid can be stored electrochemically, in batteries or supercapacitors. Batteries store energy using chemical reactions, while supercapacitors (a new technology, also called Ultracapacitors) store static electricity. Although batteries are a very familiar technology to consumers, their relatively high costs have prohibited their usage on the scale of bulk storage. Recently, the cost of advanced batteries (especially of lithium-based battery chemistries) has dropped (Nykvist & Nilsson, 2015), leading to hopes that they may be able to supply significant grid-scale storage capacity at a reasonable price (Dunn, Kamath, & Tarascon, 2011).

Different storage technologies can be compared to one another by comparing how much energy they can store versus the charge/discharge times they can achieve (Figure 1.3). The suitable applications of each different energy storage technologies is depicted on Figure 1.4.

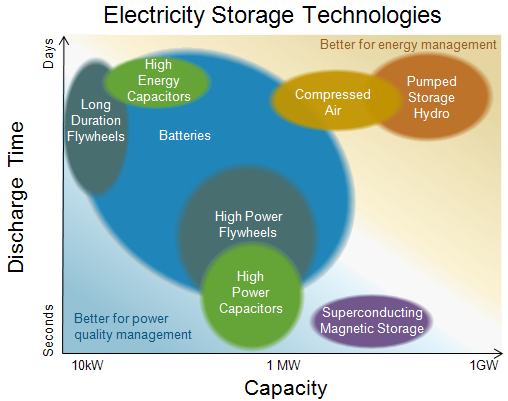


Figure 1.3. The maximum power output of different energy storage technologies versus their discharge times (EIA, 2011)

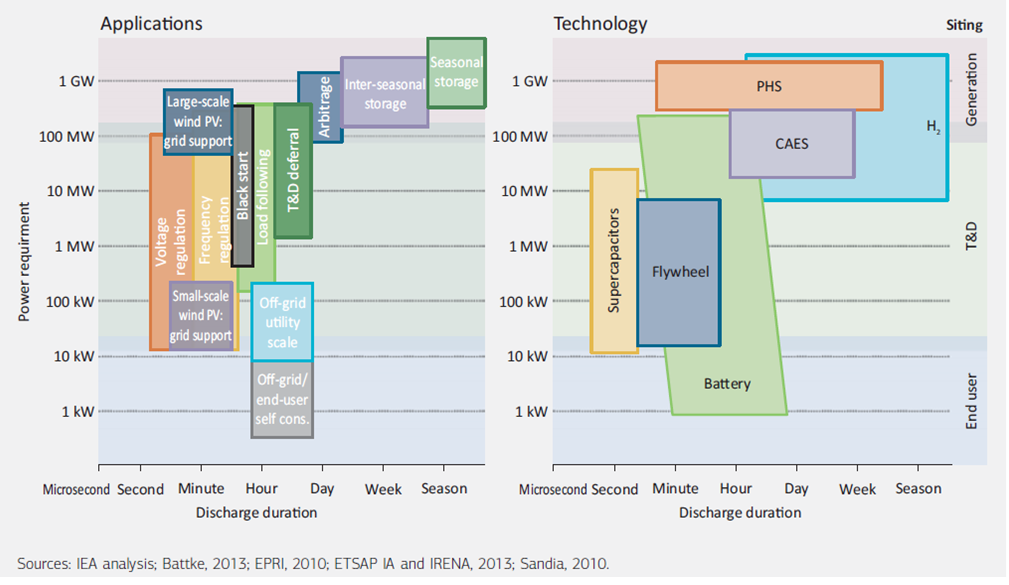


Figure 1.4. Energy storage applications and technologies (IEA, 2014)

## Adoption Path

### Current Adoption

Figure 1.5 shows top 10 countries by installed capacity for different utility-scale Energy Storage Technologies (US DOE, 2016). As shown, the PHS is found Worldwide where China, Japan, United States are the leaders. The electro-chemical (batteries) storage are mainly in United States, Japan and Germany. The electro-mechanical energy storage in terms of CAES and flywheels are mainly found in US and Germany. The thermal storage is mainly in U.S. and Spain, it worth mentions that there are many forms of thermal storage and only the molten salt technology is considered here as a technology can be connected to the grid. However, molten salt thermals storage works only with concentrated solar power (CSP) technology. Only PHS is considered mature technology, while the other technologies are in the deployed stage. The hydrogen storage is still in demonstration stage and mainly found in Germany with few MW projects. Table 1.1 summarizes the total utility-energy storage worldwide capacity installed, announced, or under construction by 2020 and number of projects (US DOE, 2016).

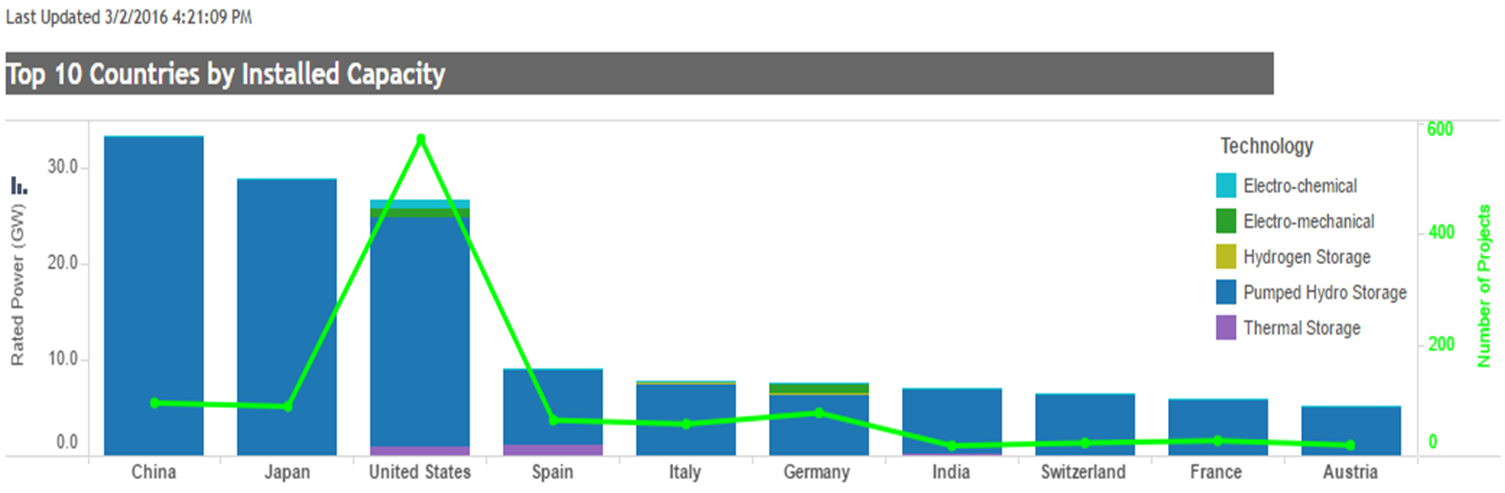


Figure 1.5. Top 10 countries by installed Utility-scale Energy Storage Technologies and capacity (Data Source: US DOE 2016)

Table 1.1. Utility-energy storage capacity and projects Worldwide, Installed, announced, under construction by 2020 (US DOE, 2016)

|  |  |  |
| --- | --- | --- |
| Technology Type | Projects | Rated Power (MW) |
| *Electro-chemical (Batteries)* | 928 | 2,707 |
| *Pumped Hydro Storage (PHS)* | 350 | 179,740 |
| *Thermal Storage (All types)* | 203 | 3,615 |
| *Electro-mechanical (CAES and Flywheels)* | 69 | 2,611 |
| *Hydrogen Storage* | 9 | 6 |
| *Liquid Air Energy Storage* | 1 | 5 |

### Trends to Accelerate Adoption

Energy storage technologies can act as a generator, a load, or a provider of services depending on how it is operated. While ESS installations can currently participate in the utility-scale power market through arbitraging (buying and storing power when it is cheap and selling stored energy to the grid when prices are high), the myriad other services provided by energy storage have yet to be addressed with pricing regulations (Bhatnagar et al., 2013). These include the load balancing and reliability considerations mentioned above as well as other ancillary services such as power conditioning (making sure that AC power signals are supplied at the proper voltage and frequency) and relieving congestion on transmission lines. Since these services do not involve selling power per se, governments and utilities have struggled to determine pricing models that would allow for operators of ESS facilities to be appropriately remunerated for providing them. As a single ESS may be equipped to provide multiple types of ancillary services, this gap is a major impediment to the economic viability of utility-scale energy storage (Bhatnagar et al., 2013). The need to determine pricing models is made more urgent as opportunities for arbitrage will disappear as ESS penetration increases.

Governments have attempted to address this gap but progress has been slow. In the United States, a number of states and utilities (most notably in California and Texas) have set installation targets for ESS projects. Moreover, the Federal Energy Regulatory Commission (FERC) has begun the process of adjusting its regulations to allow ESS operators to be paid for providing multiple types of services at once (e.g., both congestion relief and load balancing), which is not allowed for other types of entities under current policies (Bhatnagar et al., 2013). The payment models open to ESS operators vary upon the service provided, ranging from payment based on providing a certain rate of return on capital investments to “pay for performance” to payment based on the marginal cost of the power that would have had to be generated in the absence of ESS. FERC has issued several directives to regional power system operators indicating that these groups must develop models by which ESS facilities are paid for providing reliability and performance services (Bhatnagar et al., 2013). However, the ISOs themselves have been given freedom to shape their own rules, leading to variability in regulations across regional markets that also serves to complicate the business proposition of utility-scale ESS.

Globally, a number of governments (including those of China, Japan, and South Korea) have agreed to partially or entirely fund demonstration-scale projects with an aim toward reducing cost and risk (US DOE, 2013). Similarly to the situation in the United States, the European Network of Transmission System Operators has begun shaping rules to regular the power balancing market (Directorate-General for Energy, 2013). The situation is complicated by the patchwork nature of the world’s electricity markets. In nations with vertically-integrated utilities or state control of the electric power system, pricing regulations may be unnecessary as utilities will reap the benefits of ESS without market transactions. In regions where power is traded between nations, however, such variations can lead to difficulty for ESS developers that may need to be able to operate in multiple markets to be profitable.

Given the many benefits of energy storage and the recent developments in energy storage technology and related policies, it is reasonable to predict that energy storage capacity will increase in the coming years. In 2014, there was around 141 GW of utility-energy storage installed worldwide (IEA, 2014) which will increase to more than 188 GW by 2020 (US DOE, 2016).

### Barriers to Adoption

There are three main barriers inhibiting the widespread adoption of bulk energy storage systems. First, some technical hurdles have yet to be overcome. These include updating the electricity transmission and distribution system to be able to handle more dynamic, multi-directional power flow patterns (an effort which falls under the larger heading of “smart grid”) as well as improvements in ESS technologies themselves. For example, a number of new companies are attempting to commercialize a new form of CAES that combines air compression with heat exchange to improve round-trip efficiencies. If successful, such innovations will make CAES a much more favorable and cost-effective storage option. Similarly, many stakeholders anticipate future improvements in battery technology to improve power capabilities, energy densities, cycle lifetimes, and (above all) cost (Dunn et al., 2011).

The relatively large expense associated with ESS is a second major barrier. Battery ESS, in particular, are generally 2-4 times more expensive than capital cost targets of ~$250/kWh. As target prices (which include balance-of-system costs for components such as power electronics), ESS can successfully compete with natural gas “peaking plants,” conventional generators that are used primarily to respond to very high loads on the grid. Recently, however, battery ESS have been significantly dropping in price due to a combination of technology improvements and learning curve gains. The extensive use of lithium-based batteries in personal electronics and electric vehicles, in particular, has led to cost reductions that can be leveraged by the electric power industry (Dunn et al., 2011; Nykvist & Nilsson, 2015).

These cost reductions, however, are difficult to leverage presently due to a lack of regulation. The technologies and policies that govern the electrical power grid were both shaped by an expectation that power would be generated by large, centralized power plants and then synchronously transmitted and distributed to passive consumers.

### Adoption Potential

The IEA energy storage roadmap estimated an energy storage increase by 2050 in United States, Europe, China, and India by three different scenarios; “2DS scenario” assumed an 80% chance of limiting average global temperature increase to 2°C, "breakthrough scenario”, with aggressive cost reductions in storage technologies, "EV scenario”, where demand response from "smart" charging of the electric vehicle fleet in the 2DS provides additional flexibility to the system (IEA, 2014). The 2DS scenario is a conservative approach compared to Breakthrough scenario, which estimated 310 GW of additional grid-connected electricity storage capacity would be needed by 2050 (Figure 1.6) (IEA, 2014).

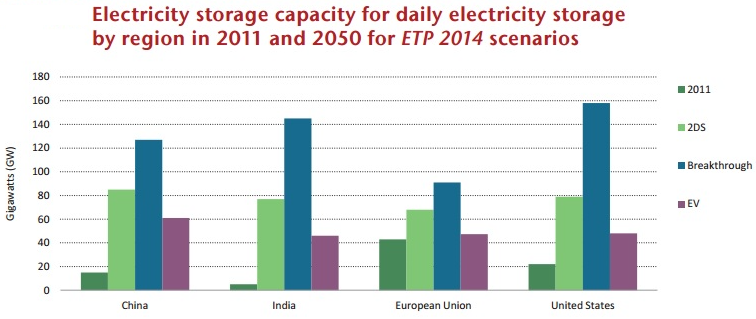


Figure 1.6. Electricity storage capacity by region in 2011 and 2050 Scenarios (IEA, 2014)

## Advantages and Disadvantages of Utility Scale Energy Storage

### Similar Solutions

Utility-scale ESS has several competitors, however. The first is so-called “behind-the-meter” storage. These are small energy storage installations that lie on the consumer side of the power system and can be used for shaving peaks in electricity demand. Behind-the-meter storage can also allow a building to rely primarily on its own on-site solar or wind capacity (such as rooftop photovoltaic installations or micro-wind turbines). Due to economies of scale, however, batteries are by far the most practical technology for behind-the-meter storage. It is likely that the power system of the future will incorporate both large, utility-scale ESS in the form of pumped hydropower, CAES, and others as well as predominantly battery-based behind-the-meter storage.

What is conventionally thought of as energy storage must also compete with ways to store energy services, such as heating and cooling. In France, for example, power demand is managed partially through in-home electric water heaters, which consumer electric power at low-demand times and store hot water until it is needed by domestic consumers (IEA, 2014). Similarly, Australia has begun large-scale implementation of wind-powered water desalination plants, which leverages the high wind resource often found in coastal areas (“Wind-Powered Desalination”, 2013). Such practices reduce or eliminate the concerns associated with intermittency as desalinated, heated, or frozen water can be produced whenever power is available and stored until it is needed. However, these technologies cannot return power to the grid and as such cannot provide power conditioning, resiliency, or related services.

### Arguments for Adoption

The benefits of ESS are numerous, as enumerated above. To summarize, there are six potential benefits of incorporating bulk energy storage systems into the electricity grid as discussed in Carnegie *et al.* (2013) are: 1) allowing time-shift of energy delivery; 2) providing capacity credit to postpone investments in electricity generating capacity, 3) delivering grid operational support to facilitate smooth of the electricity supply system, 4) providing transmission and distribution support to delay investments to upgrade components of the transmission and distribution system, 5) maintaining power quality and reliability, and 6) allowing integration of intermittent renewables generation by smoothing their energy output over time.

Table 1.2 and Figure 1.7 show the energy storage technology characteristics. The pumped hydro land and water footprints are higher than other energy storage technologies, however it still less than Nuclear, Coal, and gas turbines.

Table 1.2. Energy Storage Technology Characteristics (IEA, 2014)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Technology | Pumped Hydro | CAES | Flywheel | Battery | Thermal- Molten Salt | Hydrogen |
| *Maturity Stage* | Mature | Deployed | Deployed | Deployed | Deployed | Demonstration |
| *Limitation* | Geographically limited, large land footprint, large Water footprint around 350 gallons/MWh (see Figure 1.6) | Geographically limited (e.g., Air, large land footprint | Limited energy storage time | High Energy Cost, Deep Discharge | Limited to CSP | Low Efficiency |
| *Round-trip Efficiency* | 80% | 60% | 90% | 90% | 85% | <40% |
| *Lifetime (Years)* | 40 | 35 | 25 | 15 | 30 | 20 |
| *Investment Cost (2014$/kW)* | 2,550 | 1,000 | 2,750 | 2,200 | 550 | - |

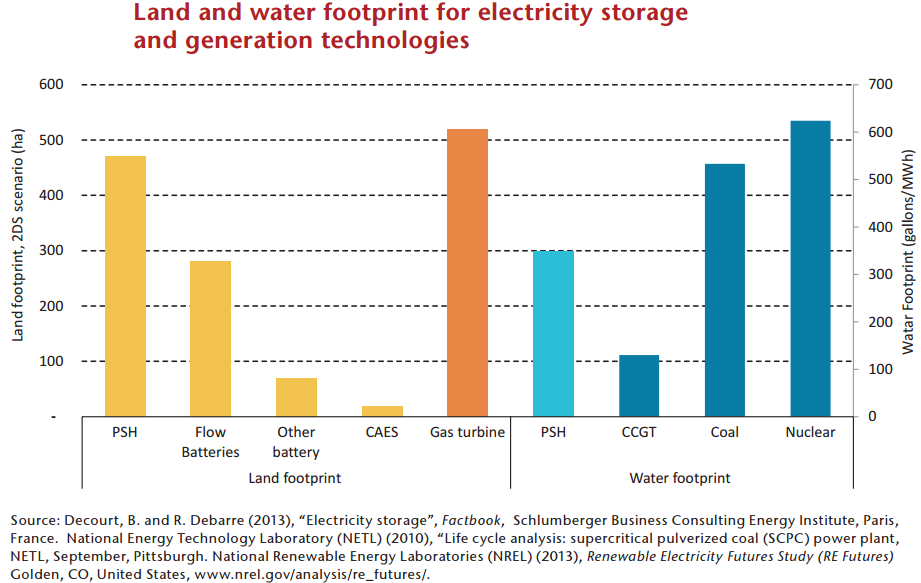


Figure 1.7. Land and water footprint for electricity storage and generation technologies (IEA, 2014)

# Discussion

The technical variables associated with pumped hydropower storage may differ significantly from the parameters associated with other forms of storage. Most lithium batteries, for example, have round trip efficiencies on the order of 90% or above, significantly higher than the average used in the model. However, they also have very low cycle lives, generally leading to a calendar life of between 10 to 15 years (depending on application) rather than the forty-year calendar life assumed here for an “average” ESS.

Newer forms of energy storage, such as lithium and flow batteries, are relatively untested on the grid. Most services provided by energy storage, including arbitrage, power conditioning, and congestion relief cannot be easily provided using other technologies. Natural gas peaking plants, however, can compete with energy storage in its function of responding to periods of unusually high demand on the grid (California Energy Storage Alliance, 2011). Indeed, the use of peaking plants is standard practice in the current day. Energy from peaking plants tends to be expensive, as they have very low capacity factors. Because they operate for so little time, the LCOE of these facilities must be high in order for a given project to turn a profit over its lifetime. However, as a primary objective of grid operators is to avoid power supply falling short of power demand, peaking capacity is presently required to be added to the grid as demand increases. Installation of energy storage effectively avoids the need for further additions of peaking capacity, while still providing the ancillary services listed above.

Similarly, capacity improvements to the transmission and distribution (T&D) capabilities of the power grid have been continually necessary with increasing demand. Storage capacity at various levels in the T&D system can have the effect of relieving congestion on T&D lines and, therefore, allowing deferral of T&D capacity increases (US DOE, 2013). This provides a significant financial benefit, albeit one that cannot be easily harvested in power markets where the providers of T&D services must be separate entities from power generators.

Finally, to individually account for carbon impact of storage assuming a mix of generation technologies with a very high percentage of variable generation capacity, assumptions that using storage reduces the carbon intensity of generation on a moment-by-moment basis may not hold. For example, if natural gas plants are not uses to meet peak demand in the first place, that carbon cannot be displaced through storage. If base load is assumed to come predominantly from nuclear power rather than coal, the carbon implications of varying heat rate are negligible. However, it is crucial to take into account that very high (>30%) proportions of variable renewable generation are impossible without either significant curtailment or significant storage capacity (European Commission, 2015). In the former case, although the installed capacity mix may be very “clean”, the actual generation mix is more carbon intensive as steady and reliable fossil sources must be relied on over variable sources to ensure demand is met. In the latter case, carbon savings are attributable to the presence of clean, renewable generation sources but storage plays an integral role in allowing those sources to be effectively utilized. As such, although the direct impact of utility-scale energy storage on carbon emissions may be small, it might be a key component of moving to a decarbonized power grid. It may transform the way we produce, deliver, and consume electricity toward cleaner and more efficient energy mix.

Estimating grid storage requirements remains challenging mainly because it depends completely on system-wide development, since the related applications span diverse months to seconds and are very location-specific, the modelling requirements are quite complex. However, grid-scale electricity storage technologies have attracted growing attention in recent years, with significant investments focused on decreasing the costs of technologies.

It also allows a smaller capacity of load-following natural gas plants to meet demand while operating at higher efficiencies and reduces future use of baseload generation, instead increasing reliance upon load-following natural gas plants.

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# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

**Approximate PPM Equivalent** – the reduction in the atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario** and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused by the lifetime use of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by the use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a good drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for the adoption of the solution.

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for the adoption of the solution against which all **PDS scenarios** are compared.

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of the grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** - are considered till better technologies and less impactful are more cost-effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours.