## Technology Advisory

# Electrical Energy Storage – A Lexicon

Electrical energy storage is an increasingly important topic in discussions about the future of the grid. The purpose of this document is to provide a common vocabulary for talking about electrical energy storage systems. It is focused on grid-connected systems, but many of the terms also apply to off-grid systems.

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## ❖ Technical Terms

### ❖ Battery

An electrochemical energy storage device which is usually DC. This is one part of an energy storage system.

### ❖ Battery Cell

This is the smallest individual electrical component of a battery. It may be a separate physical device (such as an "18650" cell commonly used with lithium batteries), or it may be part of a larger package, yet electrically isolated (a 12V lead acid car battery actually has six two-volt cells connected via bus bars).

### ❖ Battery Management System

This is a system which manages and monitors the battery to ensure even charging and discharging. This may be part of a system controller or may be a separate subsystem controller.

### ❖ Charge Rate

The ratio of the charge power to the energy capacity of an energy storage system.

For example, a 2 MWh system being recharged at 400 kW would have a charge rate of 0.2C (or C/5), while the same battery being charged at 8 MW would have a charge rate of 4C.

There are often limits as to how fast a system can be charged / discharged.

- **Depth of Discharge**

  This is the inverse of Battery State-of-Charge (BSOC), and is usually abbreviated as DOD. This is usually used to describe battery cycling characteristics.

- **Discharge Rate**

  The ratio of the discharge power to the energy capacity of an energy storage system.

  For example, a 2 MWh system being discharged at 500 kW would have a discharge rate of 0.25C (or C/4) while the same system being discharged at 4 MW would have a discharge rate of 2C. There are often limits as to how fast a battery can be discharged. These limits can be a function of the battery (e.g., plate thickness in solid state batteries, membrane size in a redox flow battery), or it may be a limitation of the power interface (e.g., inverter or motor generator rating).

- **Energy**

  The capacity of a physical system to perform work.

  Electrical energy is measured in Joules (J) or more commonly watt-hour (Wh), kilowatt-hour (kWh), or megawatt-hour (MWh). A 5 kW generator running for 12 hours per day would produce 60 kWh/day.

- **Energy Storage System (ESS)**

  In this context, this is typically used to describe the entire system, including the energy storage device (battery or other) along with any motor/generators, power electronics, control electronics, and packaging.

- **Islanding**

  Islanding occurs when a system continues to generate power and export it, even after the failure of the main electric grid.

  There are two types of islanding – unintentional and intentional.

  - **Unintentional Islanding**

    This would happen if a system were to somehow continue to export power into the grid after the main grid had failed. This is a serious safety problem and would be dangerous both to the crews working to repair the lines and to other consumers sharing that line. Fortunately, all interconnected energy storage systems are subject to IEEE 1547, which requires that distributed generation systems (including energy storage systems which can act as generators) disconnect from the grid in the event of grid failure. Assuming that the equipment is listed to UL-1741 (which incorporates IEEE 1547) or otherwise certified to IEEE 1547 standards, this should prevent unintentional islanding.

- **Intentional Islanding**

  This is a special case where the system disconnects from the electric grid as per UL-1741, but still continues to power a set of loads behind the system disconnect. To do this, the inverter has to switch from "grid interactive mode" to "load following mode". The system would continue to monitor the grid and reconnect when the grid is available and stable per IEEE 1547.

❖ **Power**

The rate at which work is done upon an object.

Electrical power is the rate at which electrical energy is transferred by an electric circuit. Electric power is measured as Joules per second (J/s), or more commonly watt (W), kilowatt (kW) or megawatt (MW).

❖ **Power Subsystem**

This is the device that converts the energy storage in the battery (or other device) into AC power for interaction with the grid.

Most modern energy storage systems use solid state power electronics (inverters), while some compressed air and other systems use rotating motor-generators. All interactive power electronics should meet IEEE 1547 and applicable UL and NEC standards.

❖ **State-of-Charge**

Typically abbreviated as SOC or BSOC (battery SOC). The amount of capacity remaining in a battery.

A fully charged battery is 100% SOC; a fully discharged battery is zero percent SOC. Note that some technologies have different capacities available depending on discharge rate, so it may be a little difficult to completely describe the SOC at any given time.

## ❖ Types of Energy Storage Systems

### ❖ Electrical

Category includes capacitors (often described as "super" or "Ultra" capacitors) and Superconducting Magnetic Energy Storage (SMES).

### ❖ Electro-chemical flow

Battery that uses pumped electrolyte to transfer energy, typically involving a membrane.

There are two primary types of flow batteries generally available – the "redox" battery, where the electrolyte is pumped through a membrane, and the Zinc Bromide battery, where zinc is plated from the electrolyte onto a membrane.

Theoretically the energy capacity is determined by the volume of electrolyte and the "power rating" is determined by the size of the membrane and some other factors. These batteries have moving parts (pumps) and "plumbing" which introduces failure mechanisms which are not present in solid state batteries. Redox batteries are very similar in concept to hydrogen fuel cells.

### ❖ Electro-chemical solid state

Category includes lead acid, lead-carbon, nickel-metal-hydride, various lithium technologies, sodium nickel chloride, and "liquid metal" batteries, among others.

Typically, there is an electrolyte that interacts with an "electrode" with no moving parts or pumps. (The liquid metal battery uses layers of molten metals and complex salts, but there are still no moving parts.)

### ❖ Electro-mechanical

Category covers rotating energy storage (flywheels) and compressed air energy storage (CAES), as well as pumped-hydro and other gravity-based storage systems. These systems rely on mechanical processes, rather than electrochemical interactions, to store energy, and can thus have nearly infinite cycle life, provided proper maintenance is done on components.

### ❖ Electro-thermal

Category refers to reversible electric storage systems which store energy using heat.

An example of this is Isentropic Systems in the UK, which uses a piston powered heat pump to heat ($500^0$ C) and cool ($-160^0$ C) argon gas. This gas is circulated through beds of gravel to store the heat/cold. When electricity is needed, the system is reversed and the stored heat/cold is used to drive the heat pump to produce electricity. Other proposed systems use $CO_2$ as the working gas.

- **Thermal**

Category is distinguished from electro-thermal in that it is one way. Electrical energy is converted into either heat (as in a water heater) or cold (as in ice storage), and then the thermal energy is used directly without reconverting to electricity. This creates what Amory Lovins famously called “Nega-watts” – using the thermal energy directly means that you will not have to use the equivalent amount of electrical energy.

Some modern solar thermal systems store thermal energy in molten salts, which are then used to create steam to drive generators. This is one-way electrical energy storage in the opposite direction.

One form of thermal energy storage varies the hourly use of electricity to produce hot water or heat in the home, and is the simplest and lowest-cost form of energy storage. Electricity can be used to produce hot water from 11 PM to 7 AM when electricity prices are cheap. During the off peak time while the hot water is being produced, the electricity used can be varied to provide valuable spinning reserve and frequency regulation service to the grid. The stored hot water is then used during the morning peak hours or during the daily peaks when needed.

Thermal energy storage can also be used to heat up ceramic bricks at night with the heat released during the daytime during peak periods of electricity use.

- **Other**

There are other methods which can potentially serve as energy storage – creating and storing hydrogen or ammonia using excess electricity, and then using that fuel to power either a generator or a mechanical device (automobile or tractor, for example).

Another method called Liquid Air Energy Storage (LAES) uses excess electricity to cool and liquefy air or nitrogen which is stored in an insulated tank at low pressure. The process is reversed by pressurizing the liquid air and then allowing it to evaporate and expand, creating a high pressure gas which is heated and then used to drive a turbine/generator.

## ❖ Specifications

There are seven primary specifications associated with energy storage:

### ❖ Cost – specified in dollars ($)

It is important to note whether the specified cost is for the entire system (including storage subsystem, power and control electronics, housing and interconnection transformer), or just for the energy storage subsystem / battery.

It is also important to note whether the cost is ex-factory (not including shipping) or shipped and installed.

There are four types of costs typically used to describe energy storage systems:

- **Capital Cost –** the simple initial cost of the system.

- **Cost per kW (MW)** – the cost of the system divided by the output power rating of the system. Must specify as $/kW-AC (preferred) or $/kW-DC.

- **Cost per kWh (MWh)** – the cost of the system divided by the amount of energy storage. Must specify as $/kWh-AC (preferred) or $/kWh-DC. Also must specify whether this is based on the useable storage capacity versus the rated storage capacity, if different.

- **Cost per kWh Throughput –** the cost of the system divided by the product of the useable capacity of the system and the cycle life of the system:

  $$(kWh\_throughput = Cost / (useful\_kWh * \#\_cycles)$$

  This is not very useful since it assumes that the battery will be used to 100% of its technical capacity, which is not usually achieved in actual applications.

### ❖ Cycle Life

This is the number of times an energy storage system can be discharged and recharged before end-of-life.

Cycle life may vary with depth of discharge (DOD) and/or discharge rate. It is usually specified as a number of cycles to a certain depth-of-discharge (e.g. 5,000 cycles to 80% DOD), or even as a table or graph. A sample is provided in Figure 1.

Cycle life may also vary based on the charge rate.

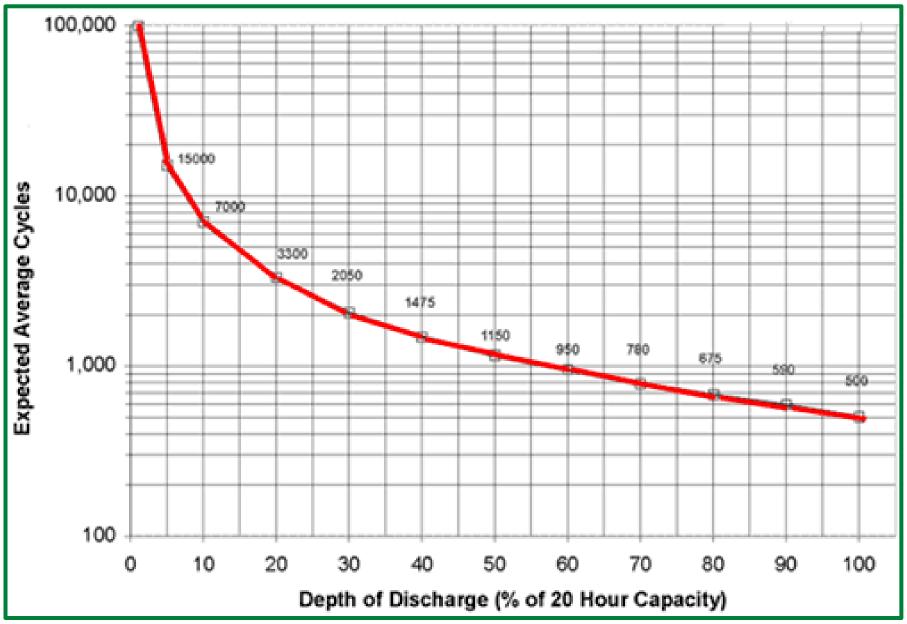


**Figure 1 - Sample Cycle Life vs. Depth-of-Discharge Graph**

### ❖ Energy Capacity

This is the amount of energy which can be stored in the device for delivery to a load and is described in kilowatt-hour (kWh) or megawatt-hour (MWh).

It is important here to note the difference between direct current (DC) and alternating current (AC) ratings, and between the "rated capacity" and the "useable capacity." Many energy storage devices (especially those called "batteries") are rated in DC, while an energy storage "system" – which interacts with the electric grid – is rated in AC. So, it is important to note which one is being discussed by specifying "kWh-DC" or "kWh-AC".

It is also important to note whether this is the "nameplate rating" or the "useable capacity." Some technologies (e.g. lead-acid and lithium) have a theoretical rating based on 100% discharge. However, using this capacity repeatedly would cause physical damage to the battery, so manufacturers recommend using only some percentage (i.e., 50% or 80%) of the nameplate rating. There are other energy storage systems, especially flow batteries; that can do 100% depth of discharge (DOD) without physical damage to the battery.

- **Power Rating**

This is the amount of power which can be delivered from the energy storage system, and is measured in kilowatts (kW) or megawatts (MW).

This must also be specified as DC (if discussing the battery alone) or AC (if discussing an energy storage system).

This rating is a function of the battery itself and of the power electronics (inverter), which are used to convert the battery energy into AC power. The most common specification is for continuous power, but different devices may also be rated for short-term or "surge" power. The power rating is usually the same for both discharge and recharge, but it can be different in special circumstances, especially when discussing the battery alone.

- **Round Trip Efficiency**

This is the ratio of the amount of energy which can be discharged from the energy storage system to the amount of energy it takes to recharge to the initial state. It is usually abbreviated as RTE, which must be specified as DC (if discussing the battery alone) or AC (if discussing an energy storage system).

$$\text{ACRTE} = \text{DCRTE} * \text{inverter efficiency} * \text{charger efficiency}$$

Round-trip efficiency may vary based on charge / discharge rate.

Note that all energy storage systems have a round-trip efficiency of less than 100%.

Actual DCRTE can be between 65% and 95%, depending on the battery technology.

- **Size**

Dimensions and weight of the device.

It is important to note whether the specified size is for the entire system (including storage subsystem, power and control electronics, housing and interconnection transformer) or just for the energy storage subsystem / battery.

- **System Life**

  This is the number of years that the system is expected to operate within specified parameters. For example, some systems may be specified to operate for five or ten years and then be replaced / recycled, while others may be specified to operate for 25 years, assuming certain maintenance and component replacements along the way.

  Inverters and pumps/motor drives and flow-battery membranes are examples of components that may need refurbishing and/or replacement over the life of the system.

There are also other specifications which may be described on a datasheet, including:

- **Degradation**

  Some energy storage systems (especially electrochemical) will experience a reduction in capacity over their life. Such systems are often rated using terminology such as "5,000 cycles to 80% final capacity."

  Note – this is the reason why people are looking at selling used electric vehicle (EV) batteries for home energy storage after they have outlived their specified life in the vehicle.

- **Hazardous Waste Category**

  Many batteries contain hazardous materials, and the battery specification should list these materials, typically in a "Material Safety Data Sheet" or MSDS.

- **Included Recycling**

  Some energy storage manufacturers are starting to offer recycling at the end of system life, either as part of the initial cost or as an added service. Lead acid batteries have a recycling infrastructure in place.

- **Interconnection Voltage**

  This is the AC voltage at which the system will interconnect with the grid.

  Residential systems will interconnect at 120/240 single phase, commercial systems at 480 3-phase, substation-sized systems at distribution voltage (15 kW class), and large grid support systems at higher voltage.

- **Response Time**

  This is the time it takes the system to respond to either a ramping signal (e.g., "change from 50% discharge to 100% discharge") or to a reversal in direction of power flow (e.g., "change from current discharge rate to full recharge"). This is usually specified either in milliseconds (ms) or cycles (1 cycle = $1/60^{th}$ of a second in the US).

- **Self-Discharge**

  This is the rate at which an energy system will lose capacity if left unconnected to a charging source.

  It important to note that some technologies (lead acid, lithium, flow batteries) are suitable to standby use (long periods of inactivity followed by use), while others (sodium nickel chloride, liquid metal batteries) are designed to be used continuously, since their "losses" help provide the heating for the high temperature elements of the battery.

- **Standby / Tare Loads**

  The "tare load" is the amount of energy used by the energy storage system to maintain itself at a specific state when it is not being used. This could account for energy to keep the battery "topped up," circulating pumps for flow batteries, climate control to keep the battery / system within a certain temperature range, or "background" power for control and power systems.

- **Temperature Range / Derating**

  A good specification will include an operating ambient temperature range and a "storage" range. The temperature range may include derating (e.g., "100% up to 40 deg C, 2% per degree up to 55 deg C") which is due to the effect of temperature both on the battery chemistry and on the ability to cool the power electronics.

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## Business Terms

- **End-of-life**

  This is the condition which defines the end of the useful operation of the energy storage system. In electrochemical systems, this is typically expressed in percent of original capacity.

- **FMEA -- Failure Modes and Effects Analysis**

  This is a formal study of a complex system to examine the effects of different types (modes) of failure on a system.

- **Reliability**

  All physical systems are subject to failures at some point during their operational life. Reliability of a system is typically described with two numbers: MTBF and MTTR

  - **MTBF – Mean Time Before Failure**
    This is the number of hours of operation expected before the system experiences a failure resulting in a loss of operating capacity. Note that a failure may cause complete shutdown of a system, or only degradation in system capabilities.

  - **MTTR – Mean Time To Repair**
    This is the mean number of hours needed to repair a system in order to restore operation.

- **Warranty**

  A written guarantee, issued to the purchaser of an article by its manufacturer, promising to repair or replace it if necessary within a specified period of time.

  Note that a warranty period is not the same as the useful life of that product.

  Note also that a warranty may only pay for partial replacement if failure occurs before the warranty period. For example, if a battery fails 5 years into a ten year warranty, the warranty might only pay for half of the original cost.

  A completely packaged system would typically have a single warranty, while a system which is engineered out of separate components may have multiple warranties (i.e., battery, power electronics, workmanship).

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## Applications

This is a partial list of the most common applications. The full list and definitions are available in the NRECA Document "Financial Screening for Energy Storage" and in the DOE/Sandia Energy Handbook.

- **Demand Side Management / Peak Reduction**

  Use energy storage to reduce electricity demand during peak demand periods, recharging during low demand periods. May be implemented by the customer or the utility.

- **Electric Service Reliability / Resilience**

  Provide backup power during outages, including integration with distributed generation sources.

- **Energy Arbitrage**

  Purchase off-peak electricity at low prices for charging the storage plant, so that stored energy can be used or sold at a later time when the price of purchased electricity is high. This is sometimes referred to as Electric Energy Time–Shift.

- **Fast Response Frequency Regulation**

  Manage the interchange flows between control areas, especially to support frequency regulation.

  FERC Order 755 promotes ES as an option for frequency regulation, allowing for a higher premium to be paid where there are markets for ancillary services for the rapid response of energy storage in maintaining system frequency.

- **Micro-grids**

  The use of dispatchable and non-dispatchable generators, often combined with energy storage, and intentional islanding, to produce energy for distribution to a local set of loads. Usually done for energy independence or economic optimization purposes.

- **Off-grid systems**

  Systems which are not connected to a utility grid.

  These range from solar-powered streetlights and mountaintop microwave repeaters to individual homes and even whole communities which are powered by local generation sources.

- **Renewables Firming**

  Use ES in tandem with intermittent wind or solar to provide a more constant power source.

❖ **Transmission / Distribution System Deferral**

Defer and/or reduce the need to build new generation / distribution capacity or purchase generation capacity in the wholesale electricity marketplace. Distribution applications include deferral of transformer upgrades or line reconductoring.

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