

Energy Storage

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November 4, 2025

1. Introduction

Energy storage consists of equipment that receive electrical power from the power distribution, convert that power into stored energy of some type (charging), then when needed, convert that stored energy back to electrical power (discharging) that is provided either back to the power distribution system or to a select number of protected loads. Energy storage may fulfill a variety of functions; the properties of the energy storage vary depending on the functions fulfilled. These functions are largely related to fulfilling survivability and quality of service requirements. The technology used to store the energy includes batteries, flywheels, and supercapacitors. Other technologies are possible, but have not been, or rarely been, used onboard ships.

Depending on the functions fulfilled, energy storage may be integrated into shipboard power systems in either a centralized or decentralized manner. Furthermore, energy storage may have different power interfaces for charging and discharging; these types of energy storage are often called uninterruptible power supplies (UPS). Other energy storage may employ a single power interface for charging and discharging; these types of energy storage are often called energy storage systems.

2. Definitions

2.1. Discharge and charge rate

The C-Rate measures how quickly energy storage is or can be charged or discharged. Energy storage charges or discharges at 1C when its rated energy capacity (kWh) is completely charged or discharged in 1 hour. 2C corresponds to completely charging or discharging in $\frac{1}{2}$ an hour. The maximum C-Rate for either charging or discharging (they may be different) should not be exceeded in order to prevent thermal degradation or mechanical overstressing.

2.2. Rated energy capacity

The rated energy capacity is the amount of electrical energy that can be provided by energy storage when new and when discharging at a specified C-Rate. The amount of energy that can be provided while discharging at other C-Rates may differ. The actual energy capacity generally degrades over time and the number of charge-discharge cycles. End of life is usually defined as when the actual energy capacity has degraded to a specified (typically 80%) percentage of the rated energy capacity.



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2.3. State of charge (SOC)

State of charge is the fraction of the rated energy capacity that the energy storage can provide. Fully charged energy storage has a SOC of 1.0; fully discharged energy storage has a SOC of 0.0.

2.4. State of health (SOH)

State of health is the fraction of life remaining before energy storage has reached its End of Life. SOH may be measured in different ways. One way is to estimate the amount of degradation in actual energy capacity and compare this to the degradation used for defining End of Life. Another way is to count the charge-discharge cycles and comparing this to the rated number of charge-discharge cycles.

2.5. Reconfiguration time (t_1)

As defined in IEEE Std 45.1, reconfiguration time (t_1) is the maximum time to reconfigure the electrical distribution system or to clear faults without bringing on additional generation capacity. Reconfiguration time is thus the maximum length of time that a load could experience power quality outside of steady-state interface requirements due to circuit breakers clearing faults, or transients from circuit breakers changing the configuration of the electrical distribution system. Reconfiguration time is usually less than 2 seconds and depends on the technology employed for circuit breakers and other circuit protection components.

2.6. Generator start time (t_2)

As defined in IEEE Std 45.1, generator start time (t_2) is the maximum time to bring the slowest standby generator set online. Generator start time is usually between 10 seconds and 5 minutes depending on the technology used for the generator sets.

2.7. Service interruption

A service interruption occurs when the length of time that power quality is outside of prescribed standards (or power is lost altogether) is greater than the amount of time a load can tolerate the power quality being outside of prescribed standards.

2.8. Mean time between service interruption (MTBSI)

The average amount of time between service interruptions that a load experiences.

2.9. Uninterruptible load

If a load would experience a service interruption with power outside of power quality requirements of duration t_1 , it is classified as an uninterruptible load.

2.10. Short-term interrupt load

If a load would not experience a service interruption with power outside of power quality requirements of duration t_1 , but would with duration t_2 , it is classified as a short-term interrupt load.

2.11. Long-term interrupt load

If a load would not experience a service interruption with power outside of power quality requirements of duration t_2 , it is classified as a long-term interrupt load.

2.12. Zonal survivability

Zonal survivability is achieved if damage to one or two adjacent zones does not result in service interruptions in undamaged zones.

2.13. Compartment survivability

Compartment survivability incorporates provisions to quickly recover electrical power to undamaged critical loads in damaged zones that can be energized safely.

3. Energy storage functions

The following energy storage functions are an extension of those defined by Doerry and Amy (2011).

3.1. ESM-F1

Energy storage fulfilling ESM-F1 provide power of the requisite power quality to loads (uninterruptible loads primarily) during short term power disruptions of up to the reconfiguration time (t_1).

3.2. ESM-F2

Energy storage fulfilling ESM-F2 provide power of the requisite power quality to loads (uninterruptible and short term interrupt loads primarily) during power disruptions of up to the generator start time (t_2).

3.3. ESM-F3

Energy storage fulfilling ESM-F3 provide power for the emergency starting of generator sets.

3.4. ESM-F4

Energy storage fulfilling ESM-F4 provide load leveling for pulsed loads, generator sets with slow dynamics, and generator sets operating near their capacity.

3.5. ESM-F5

Energy storage fulfilling ESM-F4 provide primary power with or without other generator sets online. Used to implement zonal or compartment system survivability. Also used when limiting airborne emissions in sensitive environments, or when limiting infrared or acoustic signatures for limited periods of time.

4. Power system architecture considerations

4.1. Centralized energy storage

Centralized energy storage is intended to serve many loads; it often has a large energy capacity and may connect to the power distribution system at a switchboard. Centralized energy storage is compatible with fulfilling ESM-F2, ESM-F4, ESM-F5 and possibly ESM-F3. It likely is not compatible with fulfilling ESM-F1.

4.2. Decentralized energy storage

Decentralized energy storage is intended to serve a few loads; it may have a small energy capacity, or in special cases, may have a large energy capacity depending on the protected loads it serves. Decentralized energy storage is compatible with ESM-F1, ESM-F2, ESM-F3, and some applications of ESM-F4. It likely is not cost competitive with centralized energy storage for fulfilling ESM-F5.

5. Energy storage technologies

While there are many possible energy storage technologies that could be incorporated into a shipboard power system, the three most mature technologies are batteries, flywheels, and supercapacitors. As depicted in Figure 1, these technologies offer a trade-off in energy density and power density. Another dimension is that of cost; although lead-acid batteries are dominated with respect to power and energy density by other technologies, they are the least expensive and therefore are found in shipboard applications. Some energy storage applications include multiple technologies to take advantage of the strengths of each.

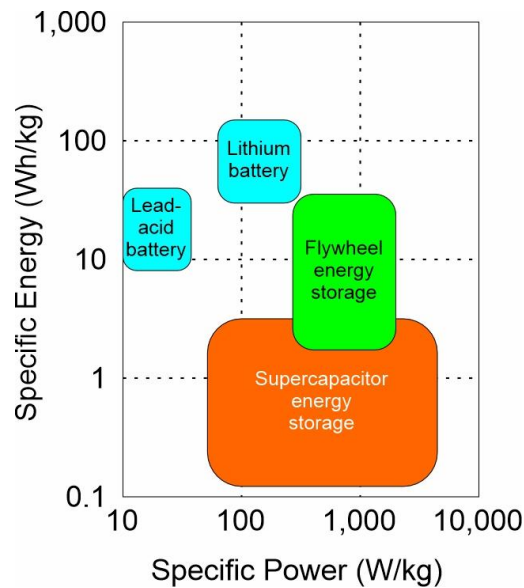


Figure 1: Ragone plot of energy storage technologies (approximate)

5.1. Batteries

Batteries are the most common technology used for energy storage onboard ship today. Low power UPSs have historically used lead acid batteries, but lithium-based batteries are increasingly being used in these applications. Battery energy storage systems (BESS) intended for higher power and energy capacity are increasingly using lithium-based batteries. Higher power battery systems incorporate series and parallel configurations of individual battery cells along with a battery management system to monitor and optimize the battery's SOC and SOH while ensuring safety. To maximize battery life, batteries typically are not fully charged or discharged, resulting in a working capacity less than the rated capacity.

One of the key factors for end of life is the number of charge and discharge cycles. Different battery technologies result in different numbers of charge and discharge cycles before the end of life condition is met. In most cases, the end of life for the batteries is less than the service life of the ship; provisions should be provided to easily replace the batteries.

Large batteries usually require special off-gas vent systems, cooling systems, and firefighting systems.

See IEEE Std 45.1, ABS (2025) and Sun, Patel and Hou (2020) for additional details on battery installations onboard ship.

5.2. Flywheels

Flywheels use rotational kinetic energy to store energy. A combination motor/generator driven by a bi-directional power electronic converter performs the conversion between electrical

energy and rotational kinetic energy. Compared to lithium batteries, flywheels usually can support higher charge and discharge rates but have lower energy capacity. Flywheels can be designed to have a service life consistent with the service life of the ship; they likely will not require replacement during the ship's life. While a flywheel is likely to be more expensive than the initial installation cost of a comparable battery system, the need to replace the batteries multiple times over the ship's life may result in the flywheel having a lower total ownership cost.

See Sun, Patel and Hou (2020) for additional information on shipboard flywheel applications

5.3. Super-capacitors

A super-capacitor stores electrical energy in the electric field of the capacitor. Super-capacitors have very high charge and discharge rates, but their energy density is typically lower than batteries or flywheels. Similar to a BESS, a capacitor energy storage system is composed of series and parallel combinations of individual supercapacitors and employs a capacitor management system. The life of a capacitor depends on the voltage applied to it and its temperature; by controlling the voltage and temperature, it is possible to design a super-capacitor energy storage system to have a life longer than the service-life of the ship.

See ABS (2022) and Sun, Patel and Hou (2020) for additional information on shipboard super-capacitor applications.

6. Types of Energy Storage

Energy storage is typically implemented as either an UPS or an energy storage system. An UPS typically has different interfaces for charging and discharging. The loads connected to the discharging interface are often called protected loads because they are protected from disturbances on the power system. An energy storage system typically has only a single interface for charging and discharging. When discharging, it may behave similar to a generator set or any other source of power. Individual loads are not protected by an energy storage system, rather the power system itself is protected from collapse due to insufficient generation online.

In general, it is desirable for the UPSs and energy storage systems to have a monitoring and control network connection to the ship's overall electric plant monitoring and control system. The SOH and SOC of each energy storage component should be able to be remotely monitored by the watchstander. If the SOH is below a threshold, the operator should be notified to take corrective action.

Four broad categories of energy storage internal architectures are commonly found: standby UPS, line-interactive UPS, double conversion UPS, and energy storage system. The desired functions should influence which architecture to use.

6.1. Standby UPS

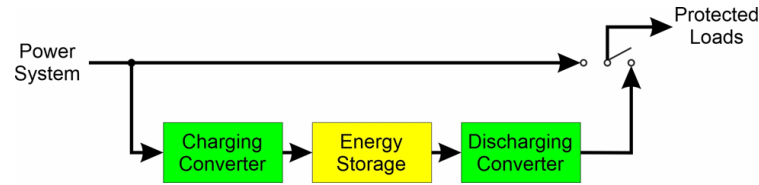


Figure 2: Standby UPS

As depicted in Figure 2, a standby UPS has distinct power interfaces for charging and discharging. Under normal conditions, a fast switch directly connects the charging interface to the protected loads. The charging converter can also charge and maintain the SOC of the energy storage under normal conditions. Should the power system power be interrupted or not meet power quality requirements, the fast switch quickly switches the protected loads to the discharging converter. This switch typically can switch sources in less than 5 ms; fast enough for most protected loads to ride through. Because a direct connection is made between the charging interface and the interface to the protected loads under normal conditions, the power quality interface standards at the two interfaces are the same.

Standby UPSs typically use batteries for their energy storage. Standby UPSs are usually effective for fulfilling functions ESM-F1 and ESM-F2; Standby UPSs may or may not be effective for fulfilling function ESM-F3. Standby UPSs are likely not suitable for fulfilling functions ESM-F4 and ESM-F5. Standby UPSs are usually employed as decentralized energy storage.

6.2. Line-interactive UPS

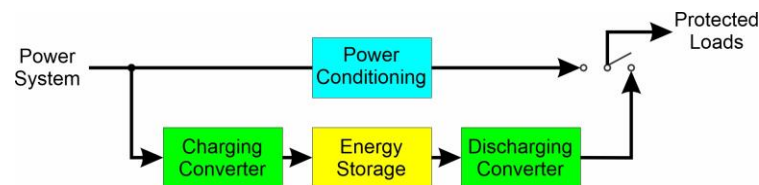


Figure 3: Line-interactive UPS

As depicted in Figure 3, a line-interactive UPS is the same as a standby UPS except power conditioning has been added between the two power interfaces under normal conditions. This power conditioning element can correct small deviations in power quality from the power system, thereby reducing the number of times the energy storage and discharging converter are used. The reduction in charging and discharging cycles should lengthen the life of the energy storage. The addition of the power conditioning element usually increases the initial acquisition cost of the line-interactive UPS as compared to the standby UPS.

As with standby UPSs, line-interactive UPS typically use batteries for their energy storage. Line-interactive UPSs are usually effective for fulfilling functions ESM-F1 and ESM-F2; Line-interactive UPSs may or may not be effective for fulfilling function ESM-F3. Line-interactive UPSs are likely not suitable for fulfilling functions ESM-F4 and ESM-F5. Line-interactive UPSs are usually employed as decentralized energy storage.

6.3. Double conversion UPS

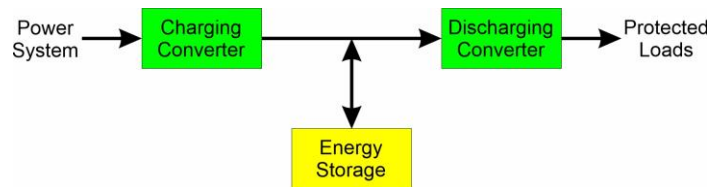


Figure 4: Double conversion UPS

As depicted in Figure 4, a double-conversion UPS converts all of the power from the power system interface to an intermediate voltage with a charging converter, then converts the power needed by the protective loads by a discharging converter. The difference between the power provided by the charging converter and used by the discharging converter goes into or comes from the energy storage. One advantage of the double conversion UPS is that it is truly uninterruptible, a switch is not required to switch between normal and backup modes. Another advantage is that the power quality standard for the two interfaces need not be the same. For example, the power system interface could be 4.16 kV three phase ac power and the protected load interface could be 1 kV dc. This capability to support differing power interface standard allows the double conversion UPS to be a good match for supplying pulsed power loads. A disadvantage is that under normal conditions, the efficiency of the double conversion UPS is likely to be less than the standby UPS or the line-interactive UPS.

Batteries, flywheels, and supercapacitors are all appropriate for double conversion UPSs. Double conversion UPSs are suitable for ESM-F1, ESM-F2, ESM-F3, and ESM-F4 functions. Double conversion UPSs are likely not suitable for ESM-F5. Double conversion UPSs may be used as either centralized or decentralized energy storage.

6.4. Energy storage system

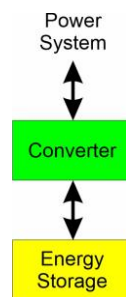


Figure 5: Energy storage system

As depicted in Figure 5, an energy storage system has a single interface to the power system. A bidirectional power converter controls charging and discharging the energy storage. Controls of the converter determine how the energy storage system behaves with respect to the power system; these controls implement the desired functionality of the energy storage system. Energy storage systems may employ batteries (BESS), flywheels (FESS), or supercapacitors (CESS).

For dc systems, one variation of the energy storage system is to directly connect batteries or capacitors to the dc bus without a converter. The charging and discharging of the energy storage is determined by the bus voltage and SOC of the energy storage.

Since energy storage systems operate at the power system level, they generally are employed as centralized UPSs. Because specific loads are not protected, energy storage systems typically are not used for ESM-F1 functionality. Energy storage systems are suitable for fulfilling ESM-F2, ESM-F3, ESM-F4 and ESM-F5 functionality.

7. Energy storage studies

Each energy storage function may call for one or more studies or analyses to evaluate whether a given design adequately fulfills the function. These studies may employ tools such as spread sheets, steady-state system solvers (such as load flow analysis tools), or quasi-steady-state system solvers (such as discrete event simulators). In some cases, more detailed waveform level transient analysis may be called for.

7.1. UPS vs fast circuit breaker studies (ESM-F1)

A natural trade-off exists between using energy storage (typically a UPS) and fast circuit breakers. If coordinated circuit breakers can clear a fault within about 5 ms, then few loads would experience a service interruption due to faults within the distribution system or loads. Circuit protection based on coordinating circuit breaker trip curves using traditional circuit breakers is likely not going to achieve fault clearing within 5 ms. Fast solid state based circuit protection, although more expensive, may be capable of this level of performance. With traditional circuit breakers, UPSs may be employed to provide the ESM-F1 functionality.

In conducting this trade study, one of the first tasks is identifying the values of t_1 that are achievable with traditional circuit breakers and fast solid state based circuit breakers. The next step would be to identify which loads would be classified as uninterruptible under both values of t_1 . Most loads can tolerate interruptions of several seconds, hence these loads would not be uninterruptible for either traditional or fast circuit breakers. The loads of concern are those critical loads that cannot tolerate interruptions of length t_1 for conventional circuit breakers. Typically these critical loads have a computer of some sort that requires a significant time to reboot following an interruption in power. If there are relatively few such loads, then

distributed UPSs are likely to be the lowest cost option to ensuring QOS. If there are many such loads, and they are distributed throughout the ship, then it may be cost effective to use the fast circuit breakers. Since both solutions are likely feasible, the choice as to which to use usually is an economic decision.

Since a failure within a protected load may cause a service interruption of other protected load, the number of loads protected by an UPS should be limited. If the number of protected loads for a UPS is large (say 30), then one should examine the failure rate of the loads and estimate a Mean Time between Service Interruption (MTSBI); if this MTSBI is below specification, or below 30,000 hours if not specified, then the loads should be split among two or more UPSs.

7.2. Standby generator start simulation (ESM-F2)

This scenario assumes that initially there are at least two generator sets online. At some point, one of the generator sets trips offline and the remaining online generator sets do not have sufficient capacity to serve all the loads. Typically, the study employs quasi-steady state simulation to evaluate the system response. Normally one would expect load shedding to occur, and energy storage discharging to fulfill ESM-F2 functionality. Some electrical power is required to start the standby generator. Once the standby generator is online, the energy storage recharges. The energy storage is evaluated to determine if its power and energy capacity ratings are sufficient.

Within this study one can trade-off centralized and decentralized energy storage. If decentralized energy storage is already required for ESM-F1 functionality and this decentralized energy storage has enough capacity for ESM-F2 functionality, it makes sense to take advantage of this energy storage. Any additional demand for energy storage could be fulfilled by either centralized or decentralized energy storage.

7.3. Reserve power studies (ESM-F2)

Reserve power is online generation capacity (power) that is available but not being used. Reserve power includes energy storage designated for ESM-F2 functionality. Reserve power studies typically examine the following scenario:

The total load increases significantly to a level beyond the rating of online generator sets. Energy storage provides power until one or more standby generators are brought online to service the new total load and charge the energy storage. A quasi-steady state analysis is used to evaluate the adequacy of the energy storage power and energy capacity.

7.4. Dark ship start simulation (ESM-F2 and ESM-F3)

A dark ship occurs when all online generator sets trip offline, but energy storage is available. This may occur for example, if a single generator set is operating with energy storage providing reserve power. It could also happen if two generator sets are initially online, but both trip offline nearly simultaneously. A quasi-steady state simulation is used to evaluate the adequacy of the energy storage power and energy capacity. Generally, the system responds by shedding load, starting the standby generator sets, and using energy storage to supply power to remaining loads. Once the standby generator sets are online, the energy storage switches from discharging to charging. The simulation evaluates whether the proper loads have been shed (not shed) and that the correct loads to enable the standby generator sets to start and operate are provided power.

7.5. Load-leveling study (ESM-F4)

A load-leveling study is used to examine several scenarios where load-leveling may be used. These scenarios include:

- a. Enabling sources (such as fuel cells) that are not capable of fast enough dynamic response to achieve power quality requirements by themselves. Energy storage essentially serves as a low pass filter by supplying and receiving the high frequency content of the power, thereby enabling the source to only provide the low frequency content.
- b. Enabling sources to operate near their power rating by providing power when the load temporarily exceeds the power rating. The sources provide the average power up to their rating while the energy storage provides (either sources or sinks) the momentary deviations from that average power.
- c. Compensating for pulsed loads by providing (either sourcing or sinking) the deviations around the average power for the pulsed load.

Depending on the details of the scenario, these studies may employ either quasi-steady state analysis or a full transient analysis.

7.6. Zonal and compartment survivability analysis (ESM-F5)

Zonal survivability analysis evaluates whether there is sufficient power generation, energy storage and connectivity in each zone to enable zonal survivability. In zonal survivability analysis, each zone and pair of adjacent zones is examined separately. One assumes the zone(s) are damaged and evaluates whether there is sufficient generation and connectivity in the undamaged zones to power all surviving mission critical equipment. If the architecture incorporates multiple cross-zone busses (typically port and starboard) that are sufficiently separated and protected such that the likelihood of both busses being inoperative is low, then one normally assumes one of the two busses will be operable following damage. Energy storage may be employed to provide power to an otherwise underpowered zone if it has

sufficient connectivity and energy capacity. The energy capacity should be sufficient to last until an alternate means (such as casualty power) is employed to provide sufficient long term power to the zone.

Compartment survivability enables restoration of power to undamaged mission critical equipment within a damaged zone. This may be implemented with normal and alternate power feeds as well as the possible inclusion of casualty power. As with zonal survivability, if there is insufficient power capacity from generator sets in undamaged zones, then energy storage with the requisite energy capacity and power may be employed.

7.7. Endurance energy calculations (ESM-F5)

Endurance energy calculations are performed similar to endurance fuel calculations as defined in DPC 200-1. The economical transit distance and operational presence time are likely to be much smaller than for the fuel calculations. Instead of determining fuel rates and required fuel tank capacity, endurance energy calculations determine the power and energy capacity rating of energy storage. The useable capacity of the energy storage should be sufficient to meet the applicable endurance condition; the loads should include service life allowance and margins. The plant deterioration allowance should be consistent with the end-of-life loss in capacity (typically 1.25). Unless the energy storage is intended to be used in conjunction with generator sets, specific fuel consumption curves and tailpipe allowances are not applicable.

8. References

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