

Applications For Short-Term Energy Storage Using Ultracapacitors

Michael Howard, Tom Key¹— Michael R. Ingram²

Abstract

Growing need for power quality and reliability are driving technology development in short term energy storage. New ultracapacitor technology can store enough energy to compete with batteries in many short-term energy storage applications. Ultracapacitors best fit in applications requiring relatively high cycle life and round-trip efficiency, wide temperature variations and fast charge/discharge response. These performance characteristics compliment other power system components such as small generators and fuel cells with low-power capacity, fluctuating or high-inrush loads, etc. This paper examines different short-term energy storage application and the electrical parameters such as power and energy performance that should be considered when selecting a storage option. It also identifies applications where the unique characteristics of ultracapacitors make them a new and viable short-term energy storage solution.

Introduction

New ultracapacitor technologies can store enough energy to compete with batteries in many short-term energy storage applications. Ultracapacitors are best suited for applications requiring relatively high-cycle life and round-trip efficiency, wide temperature variations and fast charge/discharge response. These performance characteristics compliment many other power system components such as small generators, low-power capacity fuel cells or flow batteries, fluctuating or high-inrush loads, etc. Consequently, effective application of the ultracapacitor is expected to make a wide range of energy system applications more practical. Several short-term storage applications that were not technically or economically viable in the past should be reconsidered using ultracapacitor technologies.

This paper identifies applications where ultracapacitors should be considered as a viable short-term energy storage solution. The paper also defines the electrical parameters that should be considered when selecting a short-term energy storage application. Relationships and trade offs between different technical parameters are also discussed for short-term energy storage applications.

The ultracapacitor energy storage application area is defined as any use of an ultracapacitor that supplements normal AC electric power or utility power for devices or systems. One dimension of the power application is how the electric power is supported or enhanced by the energy storage. Five different ultracapacitor application areas that should be considered supplemental relative to the electric power parameters of voltage (V), current (A), real-power (W) and energy (W-H) include:

- Voltage stabilization where the ultracapacitor system returns post-disturbance voltage to equilibrium status. Voltage stabilization duration is typically cycles to seconds.
- Current in-rush support where the ultracapacitor system is throttled to serve an inrush of local real or reactive current needs. Current in-rush support is usually less than 5 seconds.
- Missing-voltage replacement where the ultracapacitor system supplements low voltage during a fault or a severe overload condition, normally less than 15 cycles or 250 milliseconds.
- Bridging power where the ultracapacitor system carries or serves the local load, both real and reactive power, during transfer between alternate power sources. Bridging power is typically required for a few seconds for spinning reserve up to 30 seconds for generator starting and transfer.
- Short-term energy replacement where the ultracapacitor returns energy to the electric power system during an interruption with duration in the range of a few seconds to 5 minutes and depends on the energy rating and level of power demand for the application. Based on IEEE Standard 1366 on distribution reliability indices, a momentary interruption is not to exceed 5 minutes and a sustained interruption is greater than 5 minutes. IEEE Standard 1159 on monitoring power quality defines a short duration or temporary interruption as less than 1 minute and a long duration or sustained interruption is greater than on 1 minute.

¹ EPRI PEAC Corp., Knoxville, Tennessee. Email: mhoward@epri-peac.com

² Tennessee Valley Authority, Chattanooga, Tennessee.

Energy Storage Technologies

The increased demand for electric power and the limited growth of the power system capacity during the past decade have created energy shortages in several regions of the country. These shortages result in an increase in electric power disturbances such as momentary interruptions and short-term voltage sags. These disturbances will become more widespread and their consequences will be more severe if the electric power system is not significantly enhanced. Energy storage technologies can be part of the solution to prevent electric power disturbances and offer one solution to improved reliability and power quality for digital-quality, mission-critical electric customers.

Energy storage technologies can be used for a wide range of energy management, control and conditioning functions from the transmission and distribution system to end-user facilities. Potential energy storage applications include:

- Power quality enhancement (voltage sags, momentary and temporary interruptions)
- Reliability enhancement (momentary, temporary and sustained ,interruptions)
- Load leveling (both short-term and long-term peak shaving)
- Load following (full time)
- T&D system support (reactive power compensation and voltage regulation)
- Area frequency control (real power compensation)
- Transient and dynamic stability control
- Generation and load-matching (such as a daily load cycle)
- Energy storage for intermittent generation(such as wind and solar)

For the applications listed above, the required “duration” of energy storage determines whether the application requires a short burst of power or a longer-term dispatch of energy. For example, voltage sag mitigation and transient stability control may require only a few seconds of energy storage, momentary interruption mitigation may require several minutes and mitigating sustained interruptions could require up to several hours of energy storage. Transmission and distribution system support functions such as peak shaving and load leveling must dispatch stored energy into the power system to offset the load during peak periods. Peak load periods may last for many hours and the storage required to successfully shave the load will need to operate for the duration of the peak loading period. Energy storage for peak shaving applications is particularly advantageous if the T&D system is capacity constrained, the load factor is poor, and there is significant peak-to-off-peak energy price difference. For example, energy storage located near a load center can help defer new T&D infrastructure and in areas where air-pollution is an issue it may even help reduce local emissions by avoiding the need for more generation.

There are three energy storage technologies that are widely applied today. These are battery based UPS, flywheel-based motor-generator sets and their derivatives, and hydroelectric pumped storage systems. The former two energy storage technologies are used for power quality applications at end users while pumped storage is used for bulk power system support. Other than pumped storage, there have been few utility-scale long-term energy storage projects. This is due to the high cost and/or maintenance of the available energy storage technologies. There have been many demonstration projects and a niche market has developed using various battery technologies where other solutions are unattractive, however, the industry is still waiting for an improved technology to emerge that is reliable and cost effective for longer duration applications. Meanwhile, the short-term energy storage market, such as power quality, is growing and service entrance or feeder scale applications are broadening in this market area. The ultracapacitor is a relatively new and emerging technology that is ideally suited for short-term (less than 5 minutes) energy storage requirements found in many power quality applications, and may have applications in transmission voltage stability.

A fundamental difference between the economics of power quality energy storage applications and long-term energy storage applications is that for power quality applications, the cost of the energy storage medium plays much less of a role in the total “storage system cost.” The total “storage system cost” is the cost of the storage medium (batteries, flywheels, ultracapacitors, etc.), plus the balance of system that includes the power conversion system (typically an inverter), switchgear, and other ancillary equipment. For power quality applications, since only seconds of energy storage are typically required, the storage medium cost may be as little as 10 percent of the total storage system cost. Whereas, with long-term storage applications, the cost of the storage medium can represent much more than 50 percent of the system cost. Another key difference is that long-term applications compete directly against low-cost

conventional solutions such as adding more bulk generation, distributed generation and/or upgrading T&D – these are generally less costly than current energy storage technology. Still, long-term energy storage may be the preferred option if these other solutions cannot be applied due to siting or environmental reasons. In the case of power quality applications, the opposite is true - voltage sag and momentary interruption mitigation is usually very costly to resolve with conventional equipment; therefore, energy storage approaches such as a UPS are usually more cost effective than T&D upgrades.

The past decade has been a period of great innovation in energy storage and the next decade promises even greater advances. New emerging energy storage technologies are now entering or will soon enter commercial service. These technologies include advanced battery technologies, composite high-speed flywheels, ultracapacitors, and improved superconductor magnetic energy storage devices (SMES). Table 1 lists some energy storage technologies and their current commercial status.

Table 1 – Available Energy Storage Technologies for Bridging Power Applications

Energy Storage Technology Type	Specific Energy (WH/kg)	Specific Power (W/kg)	Commercial Availability
Batteries:			
Lead Acid	45	300	Very mature and readily available
Nickel Cadmium	65	200	Mature and available
Lithium-Ion	130	180	Available
Nickel Hydride	80	200	Available
Zinc-Air	90	150	Available
Sodium Sulfur	110	260	Available
Zinc Bromine	70	75	Available
Ultracapacitors (electrochemical capacitors)	5-15	2,000-10,000	Commercial Now for pulse power. Lower cost products in 1-5 years for longer duration applications
Flywheels (steel and composite low and high speed)	10-100	1,000-10,000	Short term Storage Products Available Now, Long Duration Products Emerging
Superconducting Magnetic Energy Storage (SMES)	?	300-1,000	Short term Storage Products Available Now, Longer Duration Products in Development

Many of the technologies listed in Table 1, including some of the exotic battery technologies, are being developed to overcome the deficiencies found in standard lead acid-batteries. Currently, the lead-acid battery remains the dominant short-term energy storage technology due to its low initial cost (about \$150 per kWh) and maturity. But it suffers from a number of disadvantages that include, limited cycle life, about 20 percent power losses during charge/discharge cycle, use of hazardous metals and chemicals, slow recharge rates, sensitivity to high or low temperature, and relatively high maintenance.

Technologies such as ultracapacitors avoid many of these problems and can already compete at replacing batteries for short-term energy storage applications and may even play a role in long-term applications if the cost per watt-hour can be reduced. Ultracapacitors can have a cycle life that is 10 times greater than lead acid batteries. They also have a much higher specific power (albeit a lower specific energy) and are better than 98 percent efficient in the charge/discharge cycle. In addition, they can be charged much more rapidly than batteries. Many contain materials that are much more benign from an environmental perspective.

The main issue hindering widespread adoption of ultracapacitors is cost and lack of application experience. Ultracapacitor's initial capital cost is 10-30 times more than lead-acid batteries for longer duration applications but when life cycle costs are considered, the cost factor is in the range of 3-10 times more expensive. Furthermore, for short-duration applications less than 5 seconds, they are already cost competitive due to their higher specific powers and other attributes. As ultracapacitor costs continue to decrease, it is very likely they will challenge batteries for short-term energy storage applications in the 5 to 30 second timeframe.

Parameters Used to Compare Energy Storage Technologies

The technical parameters used to compare energy storage options vary depending on the specific application. However, some of the more important technical parameters include those listed in Table 2 below.

Table 2 - Technical Parameters Used to Compare Energy Storage Options

Energy and Power per kG Energy and Power liter	Useful Voltage Range
Discharge Characteristics	Equalization
Recharge Characteristics	Power Electronics
Environmental Friendliness	Life Cycle Cost
Recharge Efficiency	Reliability
Self-Discharge Rate	Cycle Life
Maintenance	State-of-Charge
Design Complexity	Temperature Range

Of the technical parameters listed in Table 2, energy and power discharge characteristics are typically the most significant factors in the design of any energy storage system and will be discussed in more detail below.

Specific energy describes, on the basis of weight, the amount of energy that can be taken from an energy source and is given in units of watt-hour per kilogram or kilo-Joules per kilogram. Energy density is given in watt-hours per liter or kilo-Joules per liter. The example below will illustrate the concept of specific energy by comparing two automobile energy storage systems with the following characteristics:

1. Electric powered automobile with 500 kilograms of lead-acid batteries and a range of 150 miles
2. Internal combustion automobile with 50 kilograms of gasoline and a range of 300 miles

In this illustration, the internal combustion automobile has 20 times higher specific energy than the electric car (150 miles/500 kilograms versus 300 miles/50 kilograms or 20 times higher energy). This assumes that the work done to move each vehicle is proportional to the distances that the total weight of the two vehicles is roughly the same.

Specific power describes, on the basis of weight, the rate at which energy can be removed from an energy source. Specific power is generally shown in units of watts per kilogram. The example below will illustrate the concept by considering two automobile power systems with the following characteristics:

1. Race car with a 4.3 liter V6 engine and a top speed of 180 mph at 230 horsepower
2. Passenger car with a 4.3 liter V6 engine and a top speed of 90 mph at 100 horsepower

Assuming both engines weigh the same, the race-car engine delivers more horsepower and thus has higher specific power. Note that the measure of power does not consider fuel type, consumption or system efficiency. It is likely that the higher power engine is less efficient and uses more energy per mile than the standard engine.

The specific energy and power for different energy storage technologies can be plotted on the same graph as shown in Figure 1. As with automobiles, each energy storage technology has its unique energy versus power profile. Some energy storage applications may require high energy and low power, while other applications may require higher power. In general, higher energy systems have slower discharge rates, while higher power systems have faster discharge rates. For example, for many power quality applications, the short duration of the power quality event requires that the energy storage system provide a quick release of power necessary to “ride-through” a power quality event (usually 5 seconds or less). However, for peak shaving applications, it is much more important to have higher specific energy and provide sufficient load power for longer periods, perhaps hours of system peak loading.

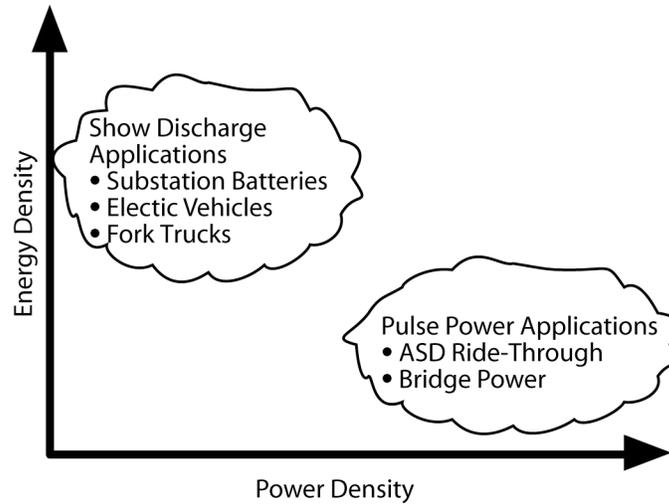


Figure 1-Comparing storage applications requiring more W-Hs to those requiring more kW.

The discharge time of an energy storage technology depends on the power or load level and is the amount of time energy can be delivered within an allowable voltage-operating window. For example, Figure 2 shows two different voltage discharge curves labeled A and B. The useful voltage window is shown in the vertical axis while the resulting discharge time is shown on the horizontal axis. In the example shown in Figure 2, the discharge time for curve A (t_2) is much longer than curve B (t_1).

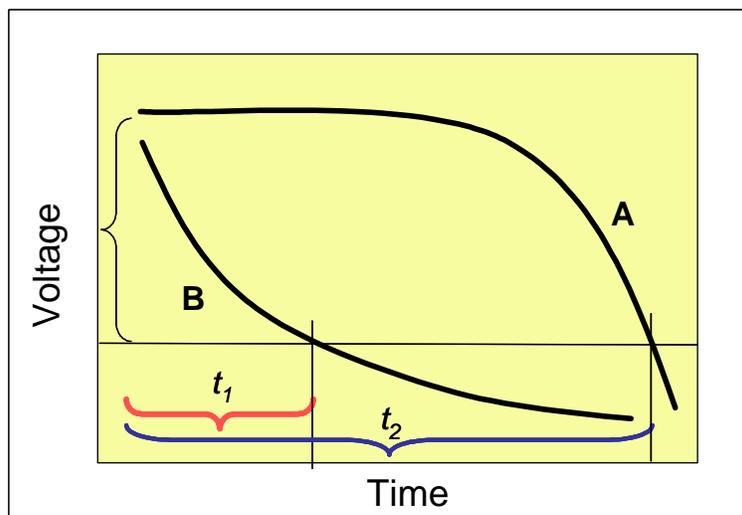


Figure 2 - Voltage Discharge versus Time

Just like different energy storage technologies have different energy and power, they also have different discharge characteristics. Different energy storage applications require the selection of appropriate energy and power for the use or discharge times. Typical discharge time for various energy storage technologies is shown in Figure 3. Power quality applications typically require low to medium power and low discharge times while energy management applications require higher power and longer discharge times.

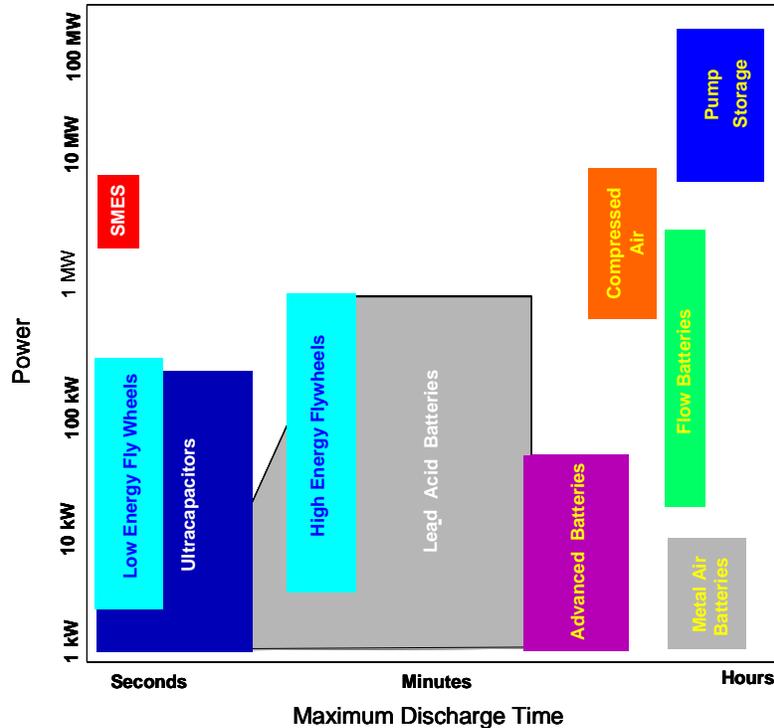


Figure 3 – Typical Discharge Times versus Power for Different Energy Storage Technologies

Performance Characteristics of Short-term Energy Storage Options

Application areas ideally suited for ultracapacitor energy storage solutions include voltage stabilization, current in-rush support, missing-voltage replacement, bridging power, and short-term energy storage. These application areas are discussed in more detail below.

- Voltage stabilization refers to the use of an ultracapacitor system to return post-disturbance voltages to equilibrium status.
- Current in-rush support refers to the use of an ultracapacitor system to provide inrush support local real or reactive current needs.
- Missing-voltage replacement refers to the use of an ultracapacitor system to supplement voltage during a fault or a severe overload condition.
- Bridging power refers to the use of an ultracapacitor system to carry or serve the local load, both real and reactive power, during transfer between alternate power sources.
- Short-term energy storage refers to the use of an ultracapacitor to temporary store and return energy to the electric power system on demand.

As previously stated, short-term energy storage problems have been solved using lead-acid batteries. More recently, mechanical flywheels have emerged as a viable solution for many short-term energy storage applications. With the advent of higher energy and power ultracapacitors currently being developed by several companies, the price per Joule of energy storage are now becoming economically viable. The performance characteristics of energy storage options are shown in Figures 4 and 5 below.

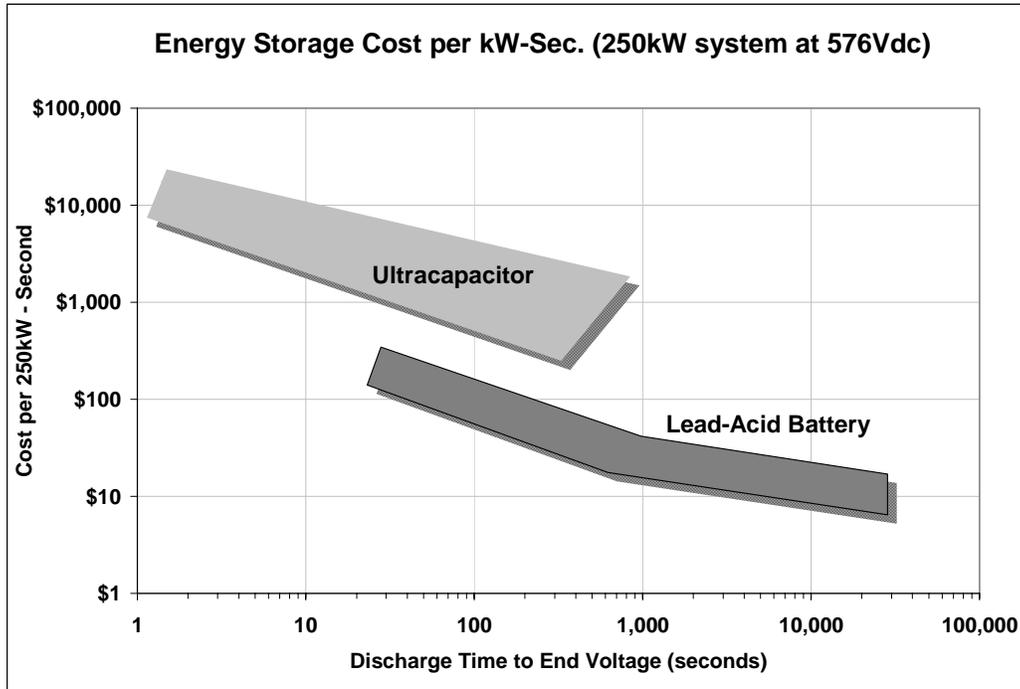


Figure 4 – Energy Storage Cost per KW-Sec.

Figure 4 shows the energy storage cost per kilowatt-second versus discharge time to the end voltage for two energy storage options: ultracapacitor and lead-acid battery. Note that the performance of lead acid battery at less than 30 seconds duration is not specified and does not extrapolate linearly from the characteristic shown. The cost per kilowatt for lead acid increases rapidly for durations less than 10 seconds. It is expected to equal or exceed the ultracapacitor at less than one second because of significantly higher equivalent series resistance (ESR).

For short-term energy storage options (under approximately 30 seconds), the ultracapacitor may become the preferred choice due to higher specific power, low roundtrip losses, better cycle life, and wider tolerance to temperature. For longer-term energy storage options (greater than 30 seconds), the lead-acid battery remains the most economical option. Lead-acid battery's relatively lower power output (See Figure 5) is due to the chemical reaction kinetics, which results in a slower response than the capacitor. Note the battery will provide a good output in the 1-30 second time frames, however the level of the output is not provided in battery rating. Based on the growing interest in short-term energy storage for power quality applications a 1-second rating for conventional batteries would be useful to application engineers.

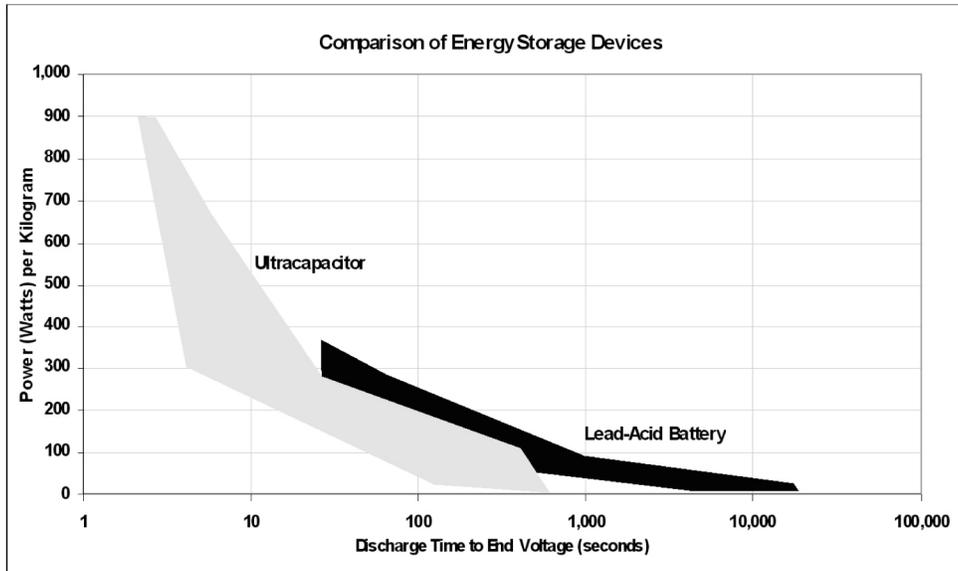


Figure 5 – Specific Power versus Discharge Time.

Figure 6 shows the energy storage (megawatt-second) versus discharge time to the end voltage for a 250kW system for three energy storage options: ultracapacitor, flywheel and lead-acid battery. For short-term energy storage options, the ultracapacitor and the flywheel are the preferred choice, again due to their higher specific power. For longer-term energy storage options (approximately greater than 15 seconds), the lead-acid battery is lower cost and most likely the preferred solution.

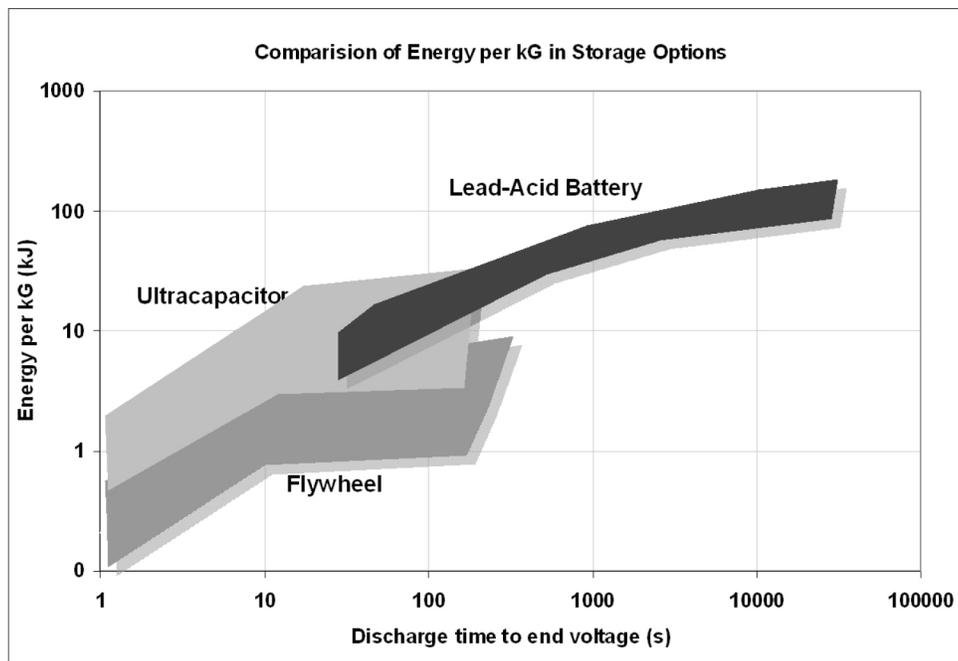


Figure 6 – Comparison of Storage Options.

Conclusion

Ultracapacitors are best suited for applications requiring relatively high cycle life and round-trip efficiency, wide temperature variations and fast charge/discharge response for discharge times under 15 seconds. These performance characteristics compliment many other power system components such as small generators, low-power capacity fuel cells or flow batteries, fluctuating or high-inrush loads, etc. Consequently, effective application of the ultracapacitor is expected to make many distributed energy resources and power quality system applications more practical.

Several short-term energy storage applications that were not viable in the past should be reconsidered with ultracapacitors today. Widespread introduction of the ultra capacitor systems for longer duration applications will require further improvements in the first cost per kW-H of these emerging technologies, further reductions in balance of system cost, and development of an experience base of applications.

Overall, new electric energy storage options add significant value to many power system applications and are already seeing an expanding market for short-duration storage applications. Even traditional lead-acid batteries such as automotive cranking batteries would likely benefit if the manufactures would provide a short term rating in the one to 5 second range. New power system requirements, new technologies and new applications are slowly being realized and by the end of this decade, electric energy storage is likely to be more of a mainstream part of the power system operation and control.