

# Considerations for Selecting a Lithium-ion Battery System for UPSs and Energy Storage Systems

## White Paper 284

Version 1

by Scott Daniels

### Executive summary

“Why do these batteries cost more?”, “How large are these batteries?” and “How long will these batteries last?” are some of the more common questions posed from UPS and energy storage stakeholders. These questions increase in importance and complexity as the industry transitions from VRLA to lithium-ion batteries. This paper does not teach you how to specify or design a battery system, but rather it explains the key variables that drive battery decisions. Having this knowledge also prepares you for vendor discussions, especially when you’re presented with trade-offs. Informed battery decisions lead to optimized solutions that drive long-term value.

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## Introduction

As UPS systems transition from VRLA to lithium-ion batteries, it's important to know the right evaluation metrics to ensure the optimal solution is selected for a particular application. There are two popular and vastly different characteristics of lithium ion (li-ion) batteries with many supporting cell designs and chemistries – energy batteries and power batteries – and although UPSs use power batteries, we generally hear in the popular press about metrics that relate to energy batteries. Most battery news focuses on energy systems such as new introductions of electric vehicles with ever increasing range, energy storage systems with longer runtimes, and the decreasing energy battery system costs. **This spotlight on energy batteries is creating confusion in the marketplace regarding price and performance of power battery systems.**

Power battery systems, although not in the news nearly as much, have several applications – UPSs systems are one, but they also can be found in hybrid electric and micro-hybrid electric vehicles (otherwise known as idle reduction), cordless power tools, automotive starter batteries and battery jump packs.

UPS battery systems are typically designed for high power, short duration events, since the traditional application of a UPS is to provide backup power to the load in the event of a utility power outage. But there are extended run and emerging UPS applications that are enabled by the improved performance of li-ion energy batteries. These energy-targeted UPS applications include peak-load shifting, demand response, generator substitution, peak shaving and frequency regulation. UPS applications use various types of power and energy batteries and the key is to use an optimized battery system that is matched to the application. Optimizing batteries is very important for all battery powered systems including small portable electronics and large grid scale energy storage.

In contrast to lead-acid batteries, li-ion batteries are significantly more complex. Therefore, **the purpose of this paper is not to teach you how to specify and design a battery solution, but rather to explain the key variables that drive battery decisions. Having this knowledge prepares you for vendor discussions, especially when you're presented with trade-offs.**

## Energy and power metrics

As the names suggest, power batteries are designed to provide a large amount of power over a short period of time while energy batteries are designed to provide a small amount of power over a long period of time. Note that power batteries are generally specified in watts whereas energy batteries are generally specified in watt-hours. While all the metrics below apply to all types of batteries, power and energy battery applications each have a set of metrics that helps identify the best battery for job.

### The energy and power metrics

**Table 1** shows a list of battery metrics and their definitions.

**Table 1**  
Battery metrics and their definitions

Metric	Units	Definition	Notes
<b>Energy Density</b>	<b>Wh/L</b>	<b>Energy for a given volume</b>	<b>When volume is a concern</b>
<b>Specific Energy</b>	<b>Wh/kg</b>	<b>Energy for a given mass</b>	<b>When mass is a concern</b>
<b>Power Density</b>	<b>W/L</b>	<b>Power for a given volume</b>	<b>When volume is a concern</b>
<b>Specific Power</b>	<b>W/kg</b>	<b>Power for a given mass</b>	<b>When mass is a concern</b>
<b>“Cost” - Power</b>	<b>\$/W</b>	<b>Cost of each Watt delivered from a cell</b>	<b>Power applications</b>
<b>“Cost” – Energy</b>	<b>\$/Wh</b>	<b>Cost of each Wh delivered from a cell</b>	<b>Energy applications</b>
Self Discharge	% / Yr	Self discharge over time	Discharge when not connected
Elevated Temp	°C	Service/operational temperature	Elevated temp applications
Cold Temp	°C	Service/operational temperature	Cold temp applications
Cycle Life	Cycles	Cycles before EOL* is reached	Temp, Rate, DOD influence
Shelf Life	Years	How long can the cell sit on a shelf before EOL*	Temp influence
Calendar Life	Years	How long can the cell be connected/on before EOL*	Temp influence
Safety	0-7	Per SAE Standards: 0=Safe, 7=Explosion	Refer to SAE, EUCAR & UL
Roundtrip Efficiency	%	The total efficiency of both charging and discharging	Very important for Peak Load Shift
Disposal	\$	The cost to recycle and/or dispose	End of life cost

\* Note: End of life (EOL) is typically 80% of initial battery capacity for automotive and 70% for stationary

The first bolded 6 items in **Table 1** are the metrics that help differentiate energy and power batteries. The remaining metrics are still very important to matching a battery for a given application, however these metrics do not differentiate power versus energy batteries.

The two most common metrics used in battery systems are focused on energy applications and the first common metric is energy density (watt hours per liter). Energy density is often misused in place of specific energy where specific energy is how much energy is available per unit mass (watt hours per kilogram). The second common metric is cost of energy (dollars per watt hour). These two common metrics do not accurately define power batteries but are still commonly used when evaluating power batteries. This misuse of energy metrics when comparing power and energy batteries for power applications creates confusion between the value of these battery systems

### How is value measured?

Not only in monetary terms i.e. \$/Wh and \$/W, but also in energy density (Wh/l), specific energy (Wh/kg), power density (W/l) and specific power (W/kg).

### What drives value for energy cells?

The value of an energy battery is measured in \$/Wh and this is in direct correlation of the amount of active material that is in each battery cell and system. In other words, is derived from how much active material is in a unit of volume and weight.

## What drives value for power cells?

The value of a power battery is measured in \$/W and this is driven by how fast energy can be extracted from a battery cell and system. Active material still plays a role, but in power batteries there is much less active material when compared to the thicker electrodes of the energy batteries. These thicker electrodes found in energy batteries result in more internal resistance which equates to less power.

## Levelized performance

Levelized performance is a method of normalizing battery metrics such as \$/Wh, Wh/kg, and Wh/L to more accurately compare power and energy batteries for the same application. The main variable that impacts levelized performance for typical UPS applications is discharge efficiency. Discharge efficiency is defined by the amount of energy that is extracted from a battery system for a given application at a set discharge rate. Faster discharge rates equate to lower efficiencies especially for energy batteries. Roundtrip efficiency includes both charge and discharge efficiencies, but we only need to focus on discharge efficiency for typical UPS applications that have slow charge rates and fast discharge rates.

A prime example of levelized performance is to apply it to lead acid battery systems that are used in both energy and power applications. Typical energy extraction of a lead acid battery at a 20-hour discharge rate is near 100%, but energy extraction from a lead acid battery at a 5-minute discharge rate is ~33%. For example, if the cost of a lead acid battery is \$100/kWh at 100% discharge efficiency, then at 33% discharge efficiency that levelized cost would be  $\$100/\text{kWh} / 33\% \text{ efficiency} = \$303/\text{kWh}$ . Note that there are other important metrics including size and weight of the battery system. The same holds true with energy and power lithium-ion battery cells and systems. Energy li-ion cells that are used in power applications will have lower discharge efficiencies when compared to power li-ion cells used in the same application at similar rates.

## Application constraints

There are many important application constraints that impact battery system design including size, formfactor, cooling and efficiency. These external design constraints can lead to a selection of a battery system that is not intuitive or obvious.

**Space limitations** may prevent the use of larger size batteries resulting in higher priced battery systems. This is a challenge that many smaller battery systems face and is an area primed for innovation and new disruptive technologies.

**Operating temperature** constraints are magnified when applications require sealed enclosures and may be in elevated temperature environments. These challenges can lead to compromises in battery selection where a higher power battery will be used in an energy application resulting in less heat generation due to the native higher charge and discharge efficiencies found in power batteries.

**Roundtrip efficiency** is defined by the total amount of energy extracted from a battery during discharge divided by the total energy applied to the battery during charge. Roundtrip efficiency is very important for applications such as energy arbitrage, peak load shift and renewables integration. Just like in cooling challenges round trip efficiency can be improved by using more powerful batteries. In typical stable grid UPS applications roundtrip efficiency may not seem that important since power outages are very infrequent, but efficiencies will impact battery system cooling requirements and life. Lower efficiencies often equate to higher cooling loads.

### Battery charge and discharge characteristics

Batteries are charged and discharged at various rates and these rates help define energy versus power batteries. UPS and energy storage batteries are specked at full load discharge even though these products may not be fully loaded. For example, a power battery for a UPS may be specked for a full load 10-minute discharge but the UPS may only be loaded at 50% resulting in more than 20 minutes of runtime when the application calls for 10 minutes of runtime. This extra runtime can lead to questions about whether battery systems are truly optimized. UPS products need to support a range of loads that are often dynamic resulting in various runtimes.

C-Rate is a very popular term used in the battery industry to define charge and discharge rates of batteries and applications. C-Rates are defined by “C” and “C” is a standard unit of time that is recognized throughout the battery industry equating to 1 hour (unity). C-Rate is representative of how long it takes to either charge or discharge a battery from 0 to 100% or 100 to 0%. Below are some common battery C-Rates

- 1C = 1 hour Mid-Rate
- C/2 = 2 hours Energy
- 2C = ½ hour (30min) Power
- 10C = 6 minutes High Power

Differentiating between energy and power batteries is generally easy but can be difficult near the midpoint of 30 minutes to 1 hour. Power batteries are typically 30-minutes or less and energy batteries are typically more than 1-hour. 1-hour batteries happen to define “C”, and this is often considered the mid-point or mid-rate. Lead acid batteries are commonly used in power applications, but their efficiencies are very low at these high rates resulting in a battery that is not optimized for an application. Lead acid batteries are more efficient at the very long run-times required in energy applications. Optimized solutions must satisfy the required metrics for a given application. Please note that applications are also defined by C-rates and when the C-rates do not match you often have a non-optimized solution.

### Optimized battery systems are not a given

Energy batteries used in power applications often occur when the costs for energy batteries is much lower than the costs for power batteries and the external design constraints are flexible.

An example would be if an optimized power system at the container level is 2MW of power and 1MWh of energy in one container (equating to a 30minute system) cost ‘X’ and an energy system of 4MWh of energy and 2MW of power from two containers cost ‘0.8X’. This would be financially preferred if the external design constraints allowed for 2 containers.

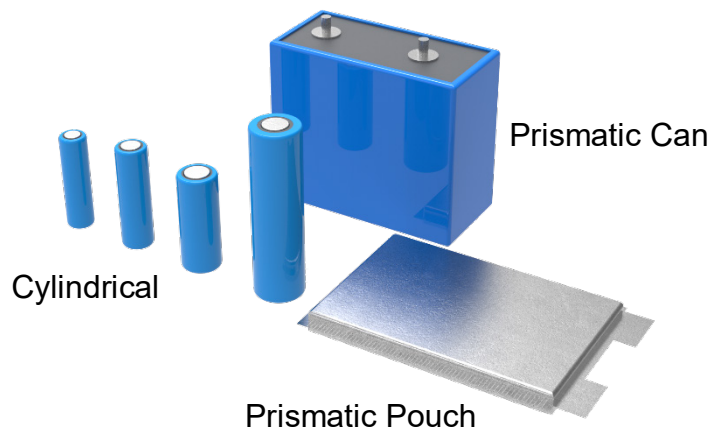
There are compromises made where the power density metric and specific power metrics are not as significant to the system cost metric of \$/W. There can be other non-intended benefits from using energy batteries such as having extra energy capacity that would provide longer run-times.

### Battery cell formfactors

There are three main lithium-ion cell formfactors that will impact battery system design, performance, and cost. These three formfactors are cylindrical, prismatic can and prismatic pouch (see **Figure 1**). The first commercialized lithium-ion battery cell

was the small format 18650 cylindrical formfactor. The 18650 cells became a standard for notebook computers in the 1990's and it experienced rapid growth in demand that resulted in a very large manufacturing base that significantly drove down prices.

**Figure 1**  
Battery formfactors



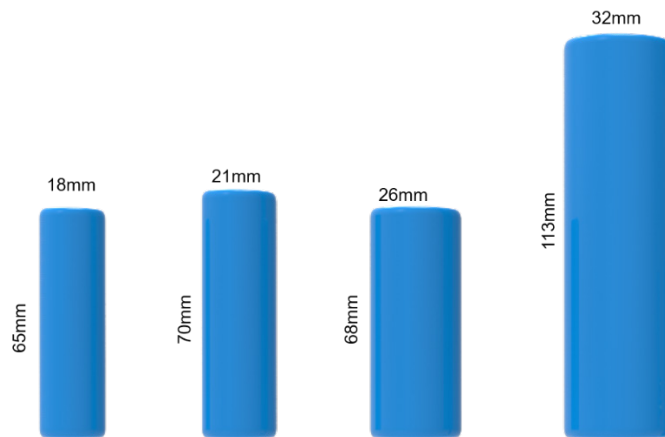
Cell formfactors have evolved quite a bit over the last couple of decades that influence the size, shape and packaging of the battery systems. The prismatic cell emerged out of the growing need for condensed energy sources for the rapidly growing market of small handheld devices such as cell phones and other portable electronics. The portable electronics markets grew exponentially, and the prismatic Lithium-ion battery cell enabled this growth. Prismatic cells include both pouch and can formfactors. The prismatic can was often used where the user can change or replace batteries in the device, whereas prismatic pouches were used in devices where battery performance and life were enough to warrant a permanently installed battery. The standard cylindrical cell was not the right formfactor to use in these thin devices.

The prismatic cell formfactor enables thin portable electronic devices. However, the prismatic pouch formfactor through recent improvements in electrode technologies allow for even thinner and lighter devices. The key for the evolution of prismatic pouch is the ability of the device to provide the necessary function and protection that rigid can-style formfactors normally provide.

Cylindrical cells are the only format that has been standardized and this was due to the massive manufacturing capacity that was installed in the 1990's and early 2000's. There are three common standard sizes for cylindrical cells starting with the most popular 18650, the newly introduced 21700 (as an upgrade to the 18650), and the 26650.

The name for a cylindrical cell, such as the 18650, represents the dimensions of the cell itself. The "18" is referencing the diameter of the cell in millimeters and "the 65" refers to the cells overall length in millimeters. These cell standards helped drive down battery system costs and allowed for multi-sourcing cell suppliers. The reason for the "0" in the 18650 has nothing to do with this cell itself, but has everything to do with keeping a consistent standard as the less common 32113 cell requires 3 significant digits for the 113 millimeters of length, as illustrated in **Figure 2**.

**Figure 2**  
Cylindrical cell dimensions



Larger formfactor cells have a tremendous impact on battery system design, performance and cost. In fact, even moving to a slightly larger cell formfactor can dramatically reduce battery system complexity and cost. Moving from an 18650 cell to a larger 21700 cell, for example, using the same basic internal cell components will have a cost savings. These savings are attributed to having a reduced number of cells, connections and other supporting components. For example, if you had a large li-ion battery pack that contained 8,000 18650 cells and switched those cells to the larger formfactor 21700 cells, you would effectively reduce the battery cell count by approximately 1,600 cells.

## Battery design characteristics

The root building block of a li-ion battery is the li-ion cell and the various li-ion cell designs have significant impact on battery system performance including cost. The goal of this section is not to cover the details of cell design and make you an expert, but rather to introduce the basics of cell design that impact total system value.

**Electrode chemistries** have the greatest impact on cell performance. There are many different cathode and anode chemistries and these chemistries will steer the cell design towards energy or power battery systems. Cell chemistries have varying voltages that impact the total energy the cell can store. Some common cathode cell chemistries are NMC, LFP, and NCA, while anode chemistries are typically carbon-based.

**Electrode thickness** has a drastic impact on whether a cell is better suited for power versus energy. Thicker electrodes mean that there is more active material in the cell resulting in more energy, but these thick electrodes create more internal resistance lowering the power capabilities of the cell. The opposite holds with thin electrodes that result in less active material, lower energy, but have lower internal resistance and more power. Cylindrical cells use wound electrodes that can limit the electrode thickness and the amount of active material a cell can have where prismatic cells employ flat electrodes that can have much thicker electrodes.

**Cell size** is influenced by both the electrode and formfactor. Very large cell sizes are typically used for energy batteries and small cell sizes are used for both energy and power. The larger the cell the more active material the cell can hold. The electrode thickness limitations of the wound electrode result in the common use of prismatic cells where thick electrodes can be leveraged.

**Quality of materials and cell manufacturing processes** have a drastic impact on cell performance and safety. Not all battery components perform the same even though their names may be identical. A cathode material from one supplier can perform differently from a cathode material from another supplier even though both

cathode materials are the same chemistry. The methods of cell manufacturing can significantly impact cell quality. For example, a fully automated process versus a manual process can result in different quality performance. A poor manufacturing process can result in cell defects that can cause failures. Process controls, automation, materials handling, and materials tracking are crucial to ensure high quality lithium-ion battery cells.

**Safety** is always important and the more energy a battery system has leads to greater system volatility. Power cells and power battery systems often employ more stable chemistries resulting in safer battery cells and systems. Please note that energy cells and battery systems are quite safe with recent innovations such as ceramic additives and ceramic safety layers.

## Technology evolution of battery cells and systems

### Rapid innovation and invention

Lead acid battery systems have been around over 100 years and are very mature systems within an industry that is very consolidated. We do periodically see incremental improvements with lead acid batteries, but no recent improvements have been disruptive. In fact, lead acid batteries are often treated as a commodity product today. Lithium-ion battery systems, on the other hand, are relatively new when compared to lead acid battery systems and there are numerous chemistries and technologies making the landscape very challenging to evaluate and predict. There is tremendous growth and innovation occurring within this industry along with some possible disruptive technologies on the horizon. The lithium-ion industry is just starting to experience consolidation with a few major companies starting to gain separation from the competition in the marketplace, but the industry is nowhere close to the maturity of the lead acid industry.

Electric vehicle batteries are very similar to stationary batteries and they often employ the same li-ion cell chemistries and formfactors satisfying similar application metrics and external design constraints. The demand for lithium-ion batteries for electric vehicles is orders of magnitude greater than the demand from stationary applications and innovation is often driven by the electric vehicle industry. There are several types of electric vehicle batteries ranging from energy to power just like we see in stationary applications.

### Migration to larger formfactors (18650 to 21700)

Another form of innovation is to work with what you have, and we are seeing that with the introduction of the new 21700 cylindrical formfactor that will eventually replace the 18650 cylindrical formfactor. The global manufacturing capacity for cylindrical cells is quite large and not fully utilized as most portable electronics are migrating to larger formfactor cells such as pouch cells. For cylindrical cells to compete with the ever increasing large formfactor cell technology, manufacturers have determined that they can increase the physical size of the 18650 cells without the need to purchase new electrode manufacturing equipment. The ability to use existing manufacturing equipment will have a significant impact for lithium-ion cell manufactures that have a tremendous amount of sunk cost in equipment that is designed to make small format cylindrical cells. This allows legacy li-ion cell manufacturers to remain competitive in the near term, but this is only a stop gap solution as larger formfactor cells and other disruptive technologies are on the horizon.

### Game changers

There are disruptive technologies on the horizon that may alter the landscape of li-ion batteries. Solid state batteries are now being introduced in wearables such as smart watches. Solid state batteries do not have a liquid electrolyte and are much



safer than conventional li-ion batteries with a flammable liquid electrolyte. There are several unique characteristics to this technology that may revolutionize the way we approach battery design. For example, solid state batteries do not need stack pressure or rigid packaging for protection and will provide new possibilities for system designs and flexibility with installations. There are and will be other disruptive technologies that can significantly alter this dynamic industry.

## Conclusion

As UPS and energy storage systems continue the transition from VRLA to lithium-ion batteries, decision makers need to clearly understand the correct evaluation metrics to ensure that an optimized battery system is selected for a given application. The complexity and numerous types of lithium-ion batteries can make this task challenging, but the results of making informed battery decisions are extremely important.

### About the author

**Scott Daniels** is a Technology Business Strategist and Energy Storage Systems Senior Technical expert at Schneider Electric. Scott has over 20 years of experience in the energy and clean technology sectors. He held recent positions at A123 Systems as the competitive intelligence lead for advanced battery technologies and at EnerNOC as a product owner for remote energy management and demand response software platforms.

Scott holds a Bachelor's Degree and a Master's Degree in Mechanical Engineering from Northeastern University graduating Magna Cum Laude with a focus on Materials Science and he holds a full-time MBA with Honors from Boston University with concentrations in business analysis, strategy and entrepreneurship.

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