Annual Update on Lithium-ion Battery Technology

White Paper

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Introduction

Engineers and supply chain stakeholders need to be informed regarding the latest trends in battery technology and associated electronics to ensure an innovative, high-performance design and a continuity of supply.

Seasoned design engineers understand the importance of carefully selecting, designing, and implementing the right power system solution for each application. When products have demanding power requirements, the battery, charger and power supply's design are key to the overall performance of the device and will influence the customer's experience and a company's brand equity. Engineers and supply chain stakeholders need to be informed regarding the latest trends in battery technology and associated electronics to ensure an innovative, high-performance design and a continuity of supply.

This is a dynamic time for the battery industry and these changes will extend beyond the coming years. The last fifteen years have seen radical adoption of new mobile technologies. Enabled by lighter and smaller battery systems, there has been unprecedented growth in the use of smart phones, laptops and tablet PCs. In turn, the portable electronics industry has driven Lithium-ion (Li-ion) battery technology to provide the lightweight and long runtimes required by these applications. There are now several new important applications on the market; everything from lawn and garden equipment to electric bikes are adopting Li-ion technology, but the largest by far are electric vehicles and energy storage systems. These new applications are demanding new form factors and new capabilities from battery technology, so while there are new options available from cell suppliers, there is also allocation due to short supply and part number rationalization for traditional technology. Many of these applications are replacement for lead-acid batteries, so the required electronics are changing as well.

In this white paper, we outline the recent and upcoming changes for cell technology and roadmaps and some electronics innovations that are allowing Li-ion technology to replace lead acid. Recent changes to legislation and regulatory requirements are also outlined. This white paper is part of a series, published each year. The reader may want to refer to past issues for industry changes that occurred previously.

Market Dynamics

The battery industry is currently experiencing an unprecedented confluence of events which is creating major supply chain challenges. There are a few significant market trends that are dramatically impacting both the availability and costs associated with lithium-ion cells. The electric vehicle and energy storage markets are growing significantly and are now the largest consumers of lithium cells with growth projected to continue over the next 10 years.

Suppliers had invested in capital to build higher volumes of 18650 cells but there was a drop in the consumer electronics demand for cylindrical cells and then an unexpected increase in many other applications, especially electric vehicles. While there is a diversification of offerings, there is a corresponding shortage of cylindrical cell supply due to this higher than expected demand in the electric vehicle market which has seen a 75% increase in consumption. In turn, this market shift is driving the cell manufacturers to focus their technology and product lines around electric vehicle and energy storage applications. The impact is a significant rationalization and consolidation of Li-ion cell product lines and part numbers for those used in applications other than electric vehicles and energy storage. In addition to price increases, the industry is seeing allocation of available cell capacity to preferred direct and large OEM customers. The evolving difference between supply and demand is shown in the graph below.

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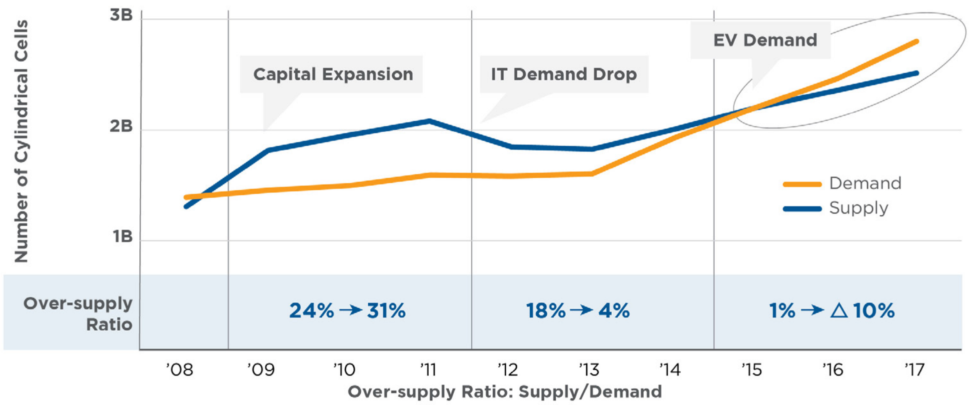
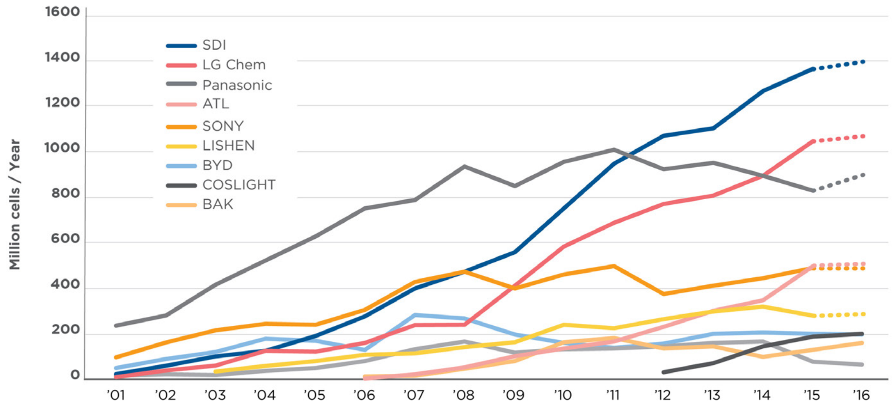


Raw material costs are increasing across the board. The largest increases are related to cobalt, which has doubled in cost, and lithium, which has tripled in cost over the past year. Cell manufacturers can no longer absorb these increases and the majority of suppliers are now passing these costs on and leveraging the over-demand situation to increase prices and offset capital investments.

The graph below shows various cell suppliers' market share over the last fifteen years. We continue to see aggressive growth from SDI (Samsung) and LG Chemical. ATL continues growth in the polymer market, but generally, we see most of the competition holding steady.



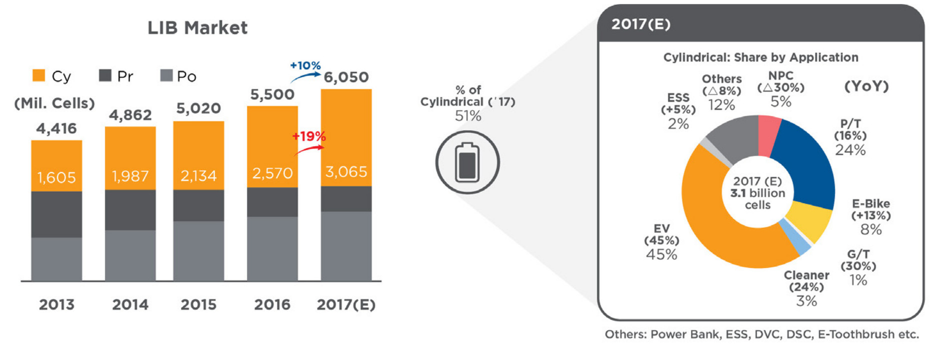
Cylindrical cells used to be almost exclusively available in an 18650 size, but now there are some others that have become common such as the 21700.

Li-ion Classification

Every Li-ion battery consists of the fundamental building blocks of anode material and cathode material. Early in the development of this technology, this was referred to as a "rocking chair" with the Li-ions shuttling back and forth in the electrolyte between the carbon (and now sometimes silicon) based anode and the transition-metal oxide cathode. A separator prevents shorting and provides basic safety.

There are three fundamental form factors for Li-ion cells: cylindrical, prismatic and polymer (sometimes called pouch). In both cylindrical and prismatic, the anode and cathode are deposited on current collectors, wound around a central mandrel and inserted into a metal can and the assembly is filled with liquid electrolyte. The difference between cylindrical and prismatic is mainly the shape; prismatic cells are brick shaped for improved mechanical efficiency in some applications. Cylindrical cells used to be almost exclusively available in an 18650 size, but now there are some others that have become common such as the 21700. Li-polymer cells have a thin form factor, enabled by their flexible packaging material and gel electrolyte. They are available in some standard sizes and are able to be custom made in relatively low (compared to hard sided cells) quantities for an optimized size or shape.

The charts below show the gain in market share for the cylindrical and polymer products and the share by application for the cylindrical market, which shows how important the EV market is in this industry.



While each piece of the Li-ion cell performs a critical function, it is the cathode that largely determines performance, voltage capacity.

Another way to classify cells is by their rate capability. C-rate is a rating of the rate capability as a function of cell capacity. Generally, there is a direct trade-off between rate capability and capacity. High capacity and low rate capable cells are used in consumer electronics products. Mid-rate cells have a design that compromises capacity and rate capability and are used in applications like e-bikes. High-rate cells are designed specifically for high power applications like power tools.

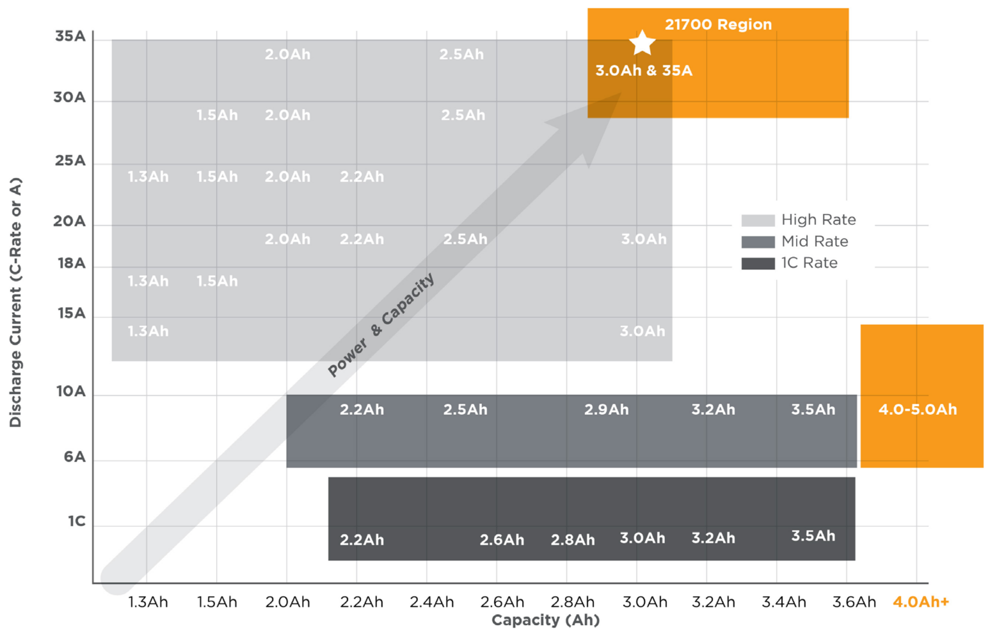
While each piece of the Li-ion cell performs a critical function, it is the cathode that largely determines performance, voltage capacity. The other components such as electrolyte concentration and current collector thickness are engineered to reflect the design enabled by the cathode. Therefore, one sees applications like power tools being fundamentally enabled by the high-power Li-iron phosphate material. The chart below shows each available cathode material and its features. Each of these could be implemented in any of the three mechanical shapes.

Cathode Material	Average Voltage	Voltage Range	Specific Energy Density	Safety Index	Comments
	V	V	mAh/g		
LCO $LiCoO_2$	3.7-3.80	4.2, 4.3-4.35, 4.45V) -2.75, 2.5V	~140	♦♦	First commercial cathode material yields high voltage - common in Polymer cells
NCA $Li(Co_xAl_yNi_{1-xy})O_2$	3.6	4.2-2.75V	~190	♦♦	Doping with Ni and Al improves capacity and rate capability - common in mid-rate cells
NCM $Li(Ni_xMn_yCo_z)O_2$	~3.65-3.75	4.2, 4.3-4.35V) -2.75, 2.5V	~155(~170)	♦♦♦	Doping with Ni and Mn improves rate capability and safety- common in mid and high-rate cells
LMO $LiMn_2O_4$	3.8	4.5-3.0	~110	♦♦♦♦	Low capacity and high-rate capability- used in niche applications
LFP $LiFePO_4$	3.2	3.65-2.5(2.0)V	~145	♦♦♦♦♦ very safe	Low voltage, low capacity, high-rate capability, best cycle life- used for high-rate or direct lead acid replacement

The high-rate 21700 cells are available in many combinations of capacity and rate capability, but there is a new generation of cells capable of 35A at 3Ah capacity.

Li-ion Roadmaps and Technology

The figure below is a consolidated cell supplier roadmap that indicates where the market is in terms of 18650 cylindrical cells' performance in both rate capability and capacity. The dark gray section at the bottom of the chart represents the 1C rate type of cells. These are cells that were designed for the laptop market. In terms of the mid-rate cells, availability ranges from 2Ah up to 3.5Ah and capacities of greater than 4Ah are emerging. The high-rate 21700 cells are available in many combinations of capacity and rate capability, but there is a new generation of cells capable of 35A at 3Ah capacity.



It is also important to look at the various technologies in terms of energy density. The image on the next page is a representation of the various chemistries, with reference to specific cell model examples. The chart references chemistries to where they are in watt hours/kilogram and watt hours/liter.

On the vertical axis there is Wh/L. This is the amount of energy by volume. On the horizontal scale, energy is measured by weight in Wh/Kg.

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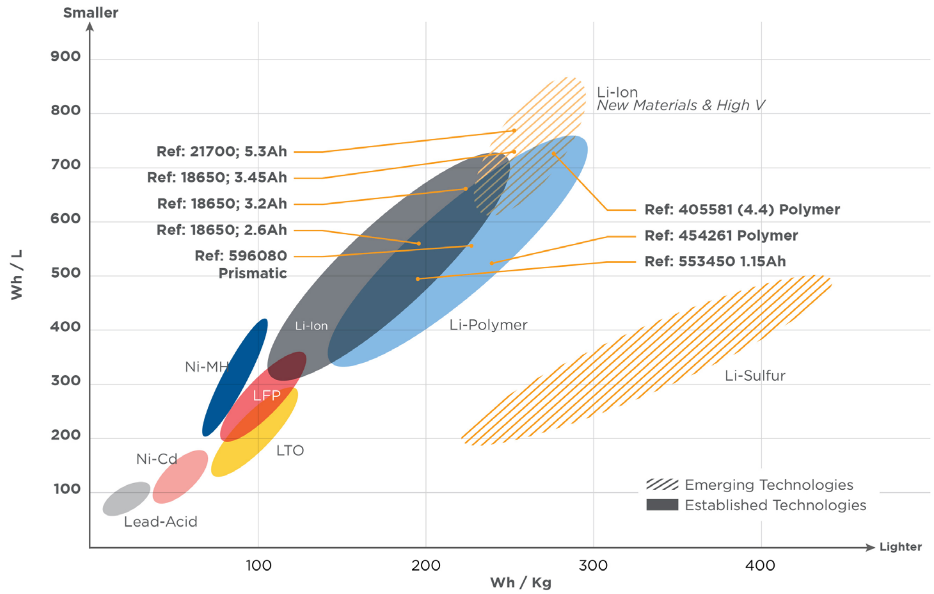

Battery Management Electronics Market

The main function of the Battery Management System (BMS) is to ensure the Li-ion battery is being used within its recommended operating conditions and ensuring that the current, voltage, and temperature are within the cell specification. If they are not, then it shuts off the battery to the load or charger.

As with cell supply, there are constraints on the electronic components of a battery, electronics' lead times, including those for ICs, FETs and other components, have increased dramatically in recent months and this constraint is expected to continue through 2018. For example, resistor lead times are now at 52 weeks. The high demand and low availability are driving price increases for some components, such as memory ICs, which are up 63% in lead time and 68% in price in Q3 alone. The industry has not seen a constraint this dramatic since the 1990s.

BMS for Lead Acid Replacement

Many new applications that are adopting Li-ion are direct replacement of lead acid batteries. Applications such as material handling equipment and other low speed vehicles are seeing the benefits of higher productivity with faster charging and longer runtimes. There are some challenges to using Li-ion in these situations.

One challenge is that putting lead acid batteries in series and parallel to make high voltage and capacity systems is simple and straight forward, but this is not the case for Li-ion. For example, take three, 8V lithium-ion batteries connected in series. Each battery will have its own battery management system. The bottom battery will provide 8V, the second battery will bump it up to 16V and the 3rd battery will output 24V. When everything is working normally, the system is functional. But if, for example, the 2nd battery detects an overtemperature on the cells and shuts off its output, the series connection is basically severed. The bottom and top battery again will see 8V difference on each battery. The battery in protection will detect the full stack voltage on the MOSFETs. If the MOSFETs are not rated for the full stack voltage of the system, they will be damaged.

In order to design a lithium-ion battery pack than can be put in series, we need to ensure the BMS circuitry can handle the full stack voltage. Theoretically a user can put an unlimited number of batteries in series. As a general rule, lithium-ion battery packs cannot be put in series unless the data sheets say otherwise. There are similar challenges with putting Li-ion batteries in parallel to increase capacity. For example, battery packs in series powering up a load with each battery pack and sharing the full load current equally, will need to be designed for each to accommodate the full load in the event other packs shut off. The other concern in putting battery packs in parallel is backfeeding, in which a higher state-of-charge battery may discharge into a lower state-of-charge battery. This can be resolved by putting diodes in discharge path.

Inventus Power has a line of batteries that can be used in parallel and series just like a lead-acid battery. The battery is designed to put up to four in series and ten in parallel. These batteries can be connected in series for a maximum of 48V and up to 10 in parallel to provide over 500Ah. The specifications are outlined below.

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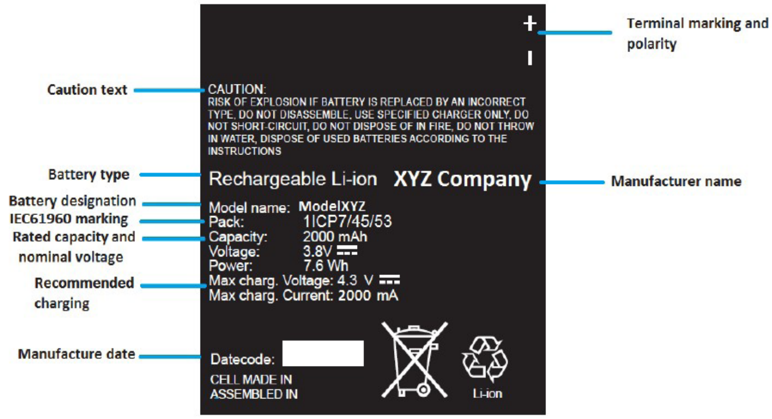
Specifications			
Series Module Support	Up to 4 in series	**Weight**	6.0Kg
Parallel Module Support	Up to 10 in parallel	**Dimensions (LxWxH)**	209x137x186mm
Nominal Voltage	12.8 Volts	**Communication**	SMBus, CANBus, Bluetooth, NFC
Nominal Capacity	51.2 Amp Hour (655.36Wh)	**Battery Terminals**	1/4-20 Female Thread
Continuous Discharge Current	80 Amps	**Shipping Classification**	Class 9

Regulatory Updates

IEC 62133 is the main standard for lithium-ion batteries for international compliance. The new version, which is called IEC 62133:2017, is broken into two parts for nickel based systems and lithium systems.

One of the major changes in 2017 was the release of a new version of IEC 62133. IEC 62133 is the main standard for lithium-ion batteries for international compliance. The new version, which is called IEC 62133:2017, is broken into two parts for nickel based systems and lithium systems. The current spec will be withdrawn by March 14, 2020. The new version has made several updates to some of the testing requirements needed to pass.

- Short Circuit Testing: This test will require a single fault applied to protective component. Once a component is faulted, an external 80mohm short is applied to the battery terminals and needed to ensure no explosion or fire. With this caveat of single fault testing, the circuit design will need to have a secondary protection element added. This can be a fuse or another MOSFET or PTC in series in the discharge path.
- Mechanical Testing: Currently this was covered by showing compliance to UN38.3 testing. That has been removed from the spec and specific vibration mechanical and shock testing are required per the spec.
- Overcharging: The current spec requires to charge at the maximum voltage of the charger which can be 4.2V per cell. The new spec calls out to apply 1.4 times the max charging voltage for 1S battery packs.
- Labeling: The new spec calls out labeling per the IEC 61960 requirements. The requirement states that the label is to include type of battery, the polarity markings, manufacturing date, name of manufacturer, rated capacity and nominal voltage. These are shown in the image below.



While the current market dynamics represent a challenge to our industry, we are working closely with our customers to develop long term strategies that mitigate component and cell sourcing issues.

Conclusion

At Inventus Power, we aspire to be the most trusted and innovative power solutions company in the world. While the current market dynamics represent a challenge to our industry, we are working closely with our customers to develop long-term strategies that mitigate component and cell sourcing issues. Inventus Power's close partnerships and proactive communication with both our suppliers and customers will allow us to continue to provide innovative solutions to complex power problems. Awareness of the latest roadmaps and changes to the industry allows engineers to anticipate and accommodate the new technology available.

About Inventus Power

Inventus Power, founded in 1960, is the leading provider of advanced battery systems for global OEMs. We specialize in the design and manufacture of battery packs, chargers, and power supplies across a broad range of portable, motive & stationary applications.

With multi-country locations across four continents and manufacturing facilities in the U.S., Mexico, Brazil, China, & Malaysia, we are strategically positioned to support the needs of global brands.

From design & engineering to performance testing & mass production, Inventus Power provides accelerated end-to-end solutions. Our broad market/application expertise, technology agnostic approach, global footprint, and vertical integration allow us to deliver safe, reliable & innovative power solutions at an exceptional speed to market.

For more information, visit **inventuspower.com** and follow @inventuspower.

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