INVENTUS™ POWER

Cell Roadmap Update:
The Evolving Cylindrical Cell

A White Paper

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Introduction

For many years, laptop batteries drove the standard in cell size, the 18650. Now, electric vehicles, e-bikes and power tools are driving cylindrical Li-ion designs, resulting in new opportunities and challenges.

At one time, when a designer wanted to ensure a cost competitive supply, superior testing and safety for a long life cycle piece of equipment (i.e. medical, military or industrial product), the 18650 had been the way to go. Today, Li-ion cylindrical cell sizes are changing; their power capabilities are more diverse and, for now, there is not a single standard in place. In this white paper, we will discuss the cylindrical cell market dynamics, cell suppliers, and new options available to design engineers.

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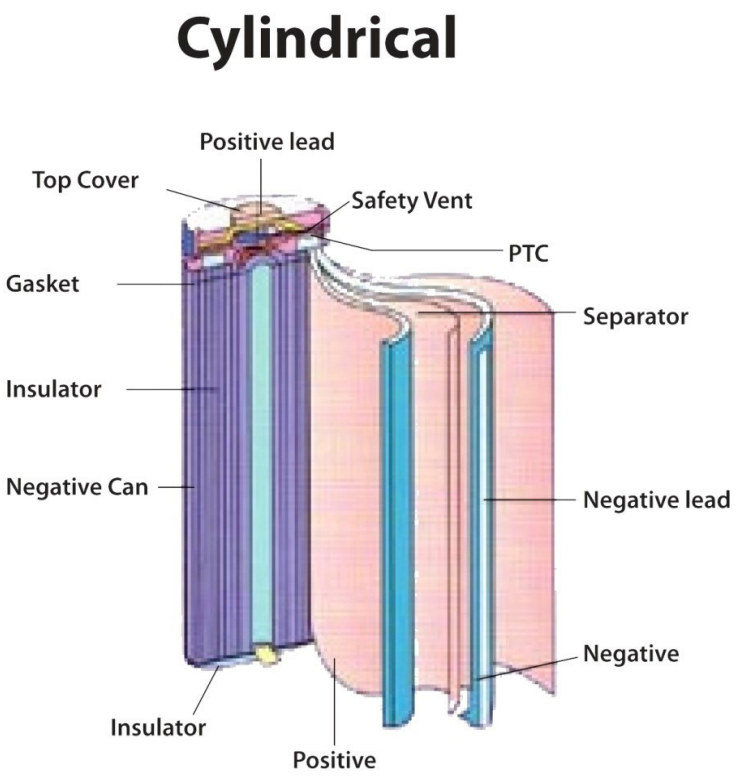
Features of Li-ion Chemistry

There are many reasons why Li-ion chemistry is the default choice for almost all applications today. The points below outline the commonalities between these cells that are the driving force for their adoption. The focus of this white paper will be the emerging differences between the cells available.

- Conventional Li-ion cells are designed to offer the highest energy density by size and weight.
- Cycle life is generally 300 to 500 cycles, but can be in the thousands for Li-iron Phosphate cells.
- The operating temperature is relatively narrow.
- A variety of cell sizes, shapes and current capability are available.
- Maintenance cycling is not required and self-discharge is low.
- Safety circuitry and complex charging algorithms are required.
- SOC measurement is complex because of the flat voltage discharge curve.

Cylindrical Cell Construction & the 18650 Standard:

Every Li-ion battery consists of the fundamental building blocks of the anode material and cathode material. Early in the development of this technology, this was referred to as a “rocking horse” 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. The basic construction of every cylindrical cell is the same. The anode and cathode are deposited on current collectors, wound around a central mandrel and inserted into a metal can. A separator prevents shorting and the assembly is filled with liquid electrolyte. This assembly is shown in cross section below.



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The cylindrical cell has been the work horse of the industry since the beginning of Li-ion adoption in the late 1990s. While researchers pursued other form factors such as flat Li-polymer cells or niche industries utilized the brick shaped prismatic cells based on the same construction methods, the strength and integrity of a cylinder can’t be beat and allowed more and more aggressive energy density roadmaps required by the laptop industry. As the laptop industry grew, fueled by the longer enabled run-times, the 18650 (18mm diameter, 65mm length) utilized by this application became the only true battery industry standard size, so other applications, from medical devices to barcode scanners, adopted this form factor, knowing that a stable supply chain would be assured.

The traditional 18650, or laptop cell, is optimized for energy density and cycle life due to the long runtimes and use models required by laptops and other consumer electronics equipment.

Cathode Chemistry

There are subtle differences in construction and design of a cell that are determined by specific application requirements and can affect the performance of a Li-ion cylindrical battery. These may include the electrolyte composition, sizing of the current collector and particle size of the anode & cathode materials. These subtle differences are reflected in the market requirement changes reflected in the next section, but it is first worth noting the variety of cathode chemistries available since these tend to affect a more gross change in the cell performance. Cathode chemistries commonly available and their characteristics and performance are outlined in the chart below.

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	♦♦	Excellent cathode Mainly for polymer cell. High voltage
NCA - $Li(Co_xAl_yNi_{1-x-y})O_2$	3.6	4.2-2.75V	~190	♦♦	High capacity for middle rate cell, EV and garden tool etc.
NCM - $Li(Ni_xMn_yCo_z)O_2$	~3.65 – 3.75	4.2,4.3-4.35V) -2.75, 2.5V	~155(~170)	♦♦♦	High capacity High rate and middle rate, 111 532 and 811 etc.
LMO - $LiMn_2O_4$	3.8	4.5-3.0	~110	♦♦♦♦	Low capacity, for large batteries
LFP - $LiFePO_4$	3.2	3.65-2.5(2.0)V	~145	♦♦♦♦♦ very safe	Low energy density, for large batteries such as EV, HEV, high rate and storage

Cylindrical Cell Diversification and Market Drivers

The traditional 18650, or laptop cell, is optimized for energy density and cycle life due to the long runtimes and use models required by laptops and other consumer electronics equipment. The rate capability of these cells is generally only 1C to 1.5C on the top end, meaning a 3Ah cell could be discharged at 3 Amps. In order to maximize cycle life, these cells need to be charged more comfortably, which is usually less than 1C. There are minor adjustments in charge voltages and rates to optimize performance for a specific device, but they are small compared to the more radical changes required by other industries.

Because the 18650 was so ubiquitous, it was also adopted by the pioneers of the Electric Vehicle (EV) market - Tesla most notably. This was a wise choice on the part of their engineers. The technology was proven, especially the safety and quality track record, which is very important in a battery system that consists of thousands of cells. In addition, the capacity to build cells at a rate required to meet the rapid EV adoption rate was already in place. As seen in the chart below, the EV and other motive and high power markets have grown rapidly in recent years, while the IT, or consumer electronics market is relatively flat. In addition, the consumer electronics market is universally moving to a flat Li-Polymer form factor, so the new driver for cylindrical cells is in these emerging markets, with different requirements than the traditional 18650, in terms of power, capacity and even the size itself.

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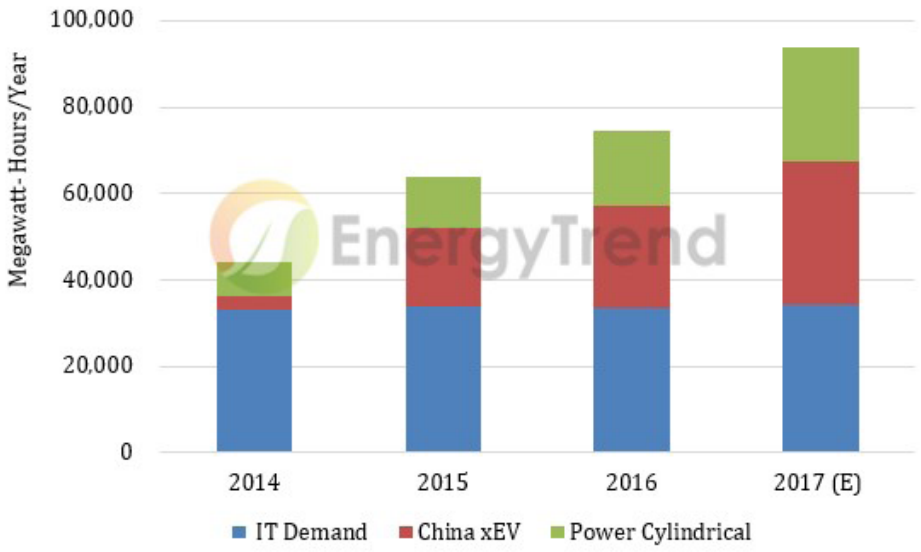
Figure: Global Lithium-Ion Battery Demand, 2014~2017



Notes:

[1] IT demand includes batteries for notebooks, tablets and mobile phones.

[2] Power cylindrical demand includes worldwide cylindrical battery demand for light electric vehicles (LEVs or electric bicycles), personal transports (PTs such as Segway) and x-electric vehicles (xEVs or plug-in hybrid and battery electric vehicles). However, this demand specifically excludes xEV battery demand from China.

[3] China xEV includes xEV battery demand from commercial (e.g. electric buses) and

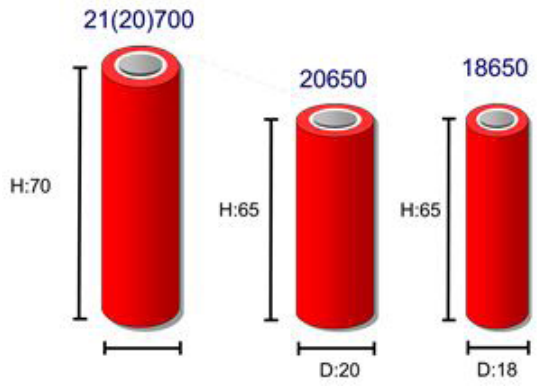
A mid-rate cell was introduced initially for e-bikes, particularly in Europe where lithium-ion batteries for e-bikes have proliferated. These cells are characterized by a compromise of rate and capacity.

The new markets generally fall into two categories for rate capability. In both cases, these originated from the 18650 form factor, but have since developed unique sizes specific to the industry requirement:

High Rate (Power Tool Cells): These cells were optimized for the discharge rate and intended for the consumer power tool class, at a capacity around 1.1Ah and a rate capability of 10 to 15 Amps for an 18650. Compared to the traditional 18650 cells at 2Ah, these cells were about half the capacity but featured a significantly higher discharge rate capability. Today there are NMC/NCA 18650s in this class that are 3.0Ah and can do 15Amps and 2.5Ah cells that can do 30Amps. However, in addition to the 18650 versions, now there is a general transition to 20650s for many suppliers.

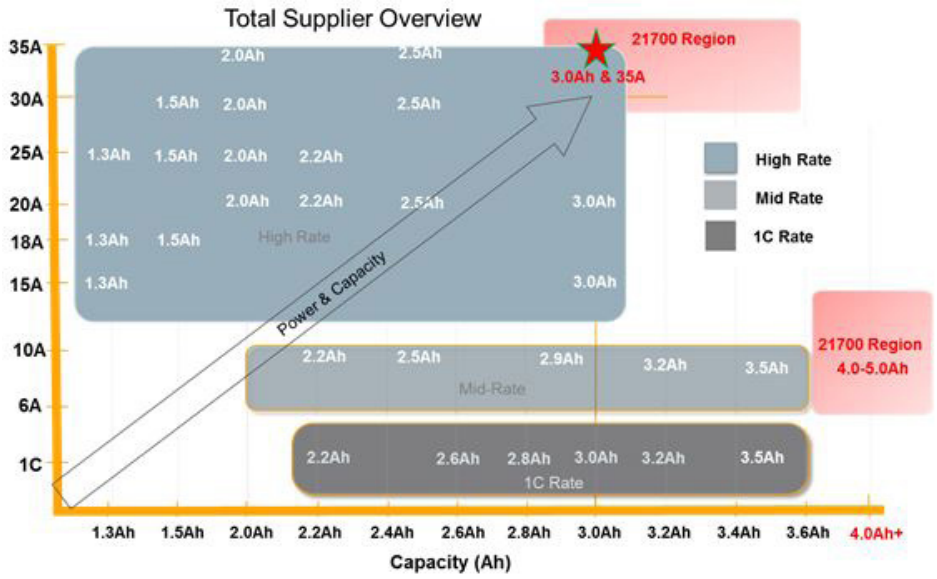
Mid-Rate (E-Bike Cells): A mid-rate cell was introduced initially for e-bikes, particularly in Europe where lithium-ion batteries for e-bikes have proliferated. These cells are characterized by a compromise of rate and capacity. They were initially introduced at 2Ah and up to 10 Amp continuous rate capability. Today, 3.4Ah mid-rate cells are available at a slightly lower 6 to 8 Amp discharge rate capability with 10 Amp pulse certainly capability and longer cycle life as a target. As with E-bike battery packs which need a long life and often have long warranties, many applications can benefit from mid- rate cells. The mid-rate cells are now more commonly available as 21700s than they were in the 18650 form factor originally introduced.

The image below shows the relative sizes of these newer form factors relative to the 18650 cell. While the change in dimensions seems relatively minor, there is a significant change in volume in the cells. This change allows for not only an increase in the amount of active material and a subsequent capacity and runtime improvement, but it also accommodates the thicker current collectors necessary for high-rate applications. In addition, large format applications don't have the size and weight requirements of consumer electronics and other hand held applications.



With these [current capability and capacity] improvements, more and more applications are seeing an reduction in total cost of ownership with the adoption of Li-ion technology.

Whether or not the industry will shift overall to a new standard or remain with these diversified options in terms of physical form factor is yet to be seen. In order to make an informed decision in product design, Inventus Power has developed the unified cylindrical roadmap illustrated in the image below. Here we can see that the cells are improving overall in both current capability and capacity, simultaneously. With these improvements, more and more applications are seeing an reduction in total cost of ownership with the adoption of Li-ion technology and its value, even over gas and propane, is being recognized in applications such as material handling and lawn and garden equipment.

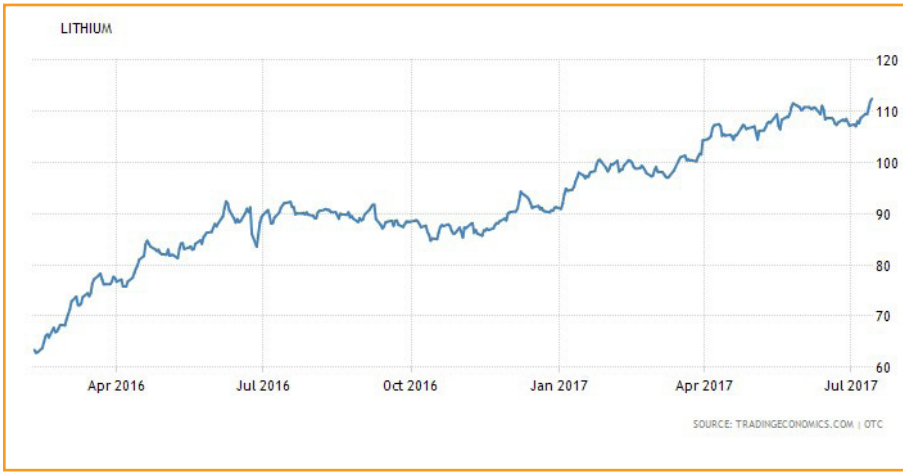


Material Costs and Supply Chain Challenges

In the background of these increasing choices and diversification, 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 the costs associated with lithium-ion cells.

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. These increases are shown in the graphs below. Cell manufacturers can no longer absorb these increases and the majority of suppliers are now passing these costs on and they are leveraging over-demand situation to increase prices and offset capital investments.

Electric vehicle and energy storage markets are growing significantly and are now the largest consumers of lithium cells; this growth is projected to continue over the next 10 years.



As stated previously, the electric vehicle and energy storage markets are growing significantly and are now the largest consumers of lithium cells; this growth is projected to continue over the next 10 years. While there is a diversification of offerings, there is a corresponding shortage of cell supply due to this higher than expected demand in the electric vehicle market; the 75% increase in the electric vehicle market is consuming almost 100% of nickel/cobalt based cells. 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 lithium-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.

Conclusion

Whether designing for extreme temperature resistance, backup power, long cycle applications, intrinsically safe requirements, high reliability, long life applications, or high power requirements, the first line of defense is the cell.

At Inventus Power, we find great value in having access to a variety of cells and chemistries; our purchasing capacity and cell supplier relationships can help our customers navigate this increasingly complex cell supply chain environment. The markets that drive the availability of these cells are tracked by our team of experts, so we can offer both the latest technology as well as a stable and secure supply chain for the long product life-cycles typical in medical, military, industrial and commercial applications. We often look at solving an application or customer's requirements first at a cell level. Whether designing for extreme temperature resistance, backup power, long cycle applications, intrinsically safe requirements, high reliability, long life applications, or high power requirements, the first line of defense is the cell. We are also capable of meeting a need at the system level or battery pack design level, but our first action is to provide the best possible cell solution. Our industry experience in supporting and testing various applications affords us an advantage in identifying proper cells that optimize performance.

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**.

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