# Annual Update on Lithium-Ion Battery Technology

A White Paper

inventuspower.com

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Innovative use of battery technology will differentiate OEM's product designs with tangible improvements in performance.

## Introduction

Many products use batteries for primary and backup power, yet not all batteries function the same. It is important for Original Equipment Manufacturers (OEMs) and design engineers to understand the importance of carefully selecting the right battery solution to power their product. From not selecting the optimal battery chemistry for the device's power requirements to being unable to efficiently dissipate heat under charge, poorly designed battery packs can hamper the total power system's performance. When products have demanding power requirements, the battery design is a key element to the overall performance of the device and therefore can influence the end user's perception of the product as well as the manufacturer/brand. In an age of ever increasing computing-power driving more sophisticated technology, battery technology can be used to innovate and differentiate OEM devices under development and selecting the right rechargeable battery has become one of the most important factors for product developers in designing a successful product.

## The Power of Lithium-Ion

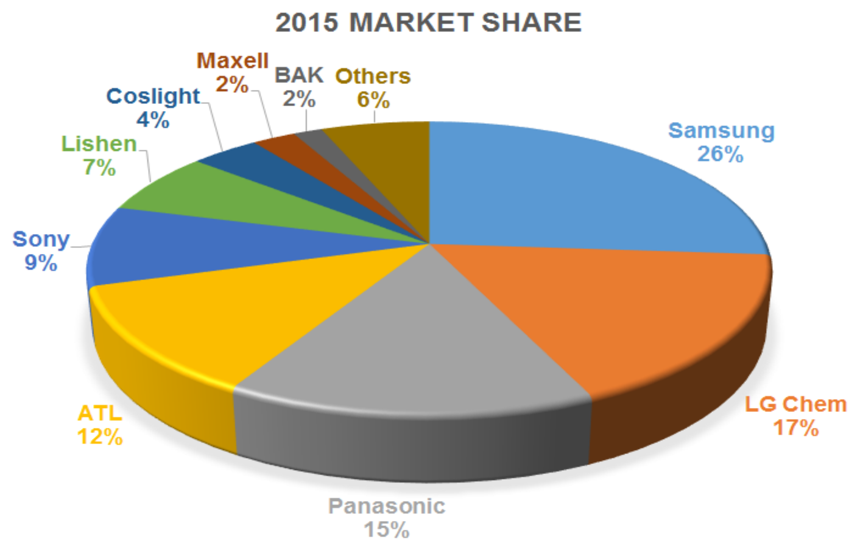
At the point in time when Sony Energy launched the first mass produced Lithium-Ion (Li-Ion) battery cell in 1991, mobile phones were analog devices that ran for 1-2 hours and were able to display one line of text. Medical devices were stationary, plugged into the wall, and in some cases backed up by Lead Acid batteries. Today, Li-Ion dominates every portable product device market and has enabled countless other markets to meet functionality requirements not possible with other chemistries.

Li-Ion cells come in many different chemistry variations delivering dramatic differences in performance depending on how they are applied and used. Cell selection is critical to end equipment performance. Medical devices, for example, have strict compliance standards covering the product development process, design integrity, and quality management system of their suppliers. Few Li-Ion Rechargeable System manufacturers have the processes in place to meet these demands. Developing as a complete rechargeable system producesbetter functioning end products, speeds products to market, and produces a profoundly superior ROI for device manufacturers.

## Battery Market Update

Li-ion is replacing other chemistries in applications from wheelchairs to garden tools.

Samsung, LG Chem, and Panasonic continue to lead the market, while relatively new ATL has gained market share, especially in the Li-polymer market. Traditional markets for portable electronics have remained relatively flat, while automotive and other applications have grown substantially. Of particular interest is the growth in "other" applications for Li-ion, which is gradually replacing lead acid and NiCd in everything from wheelchairs to garden tools.




*Source: B3, a consulting company in Japan*

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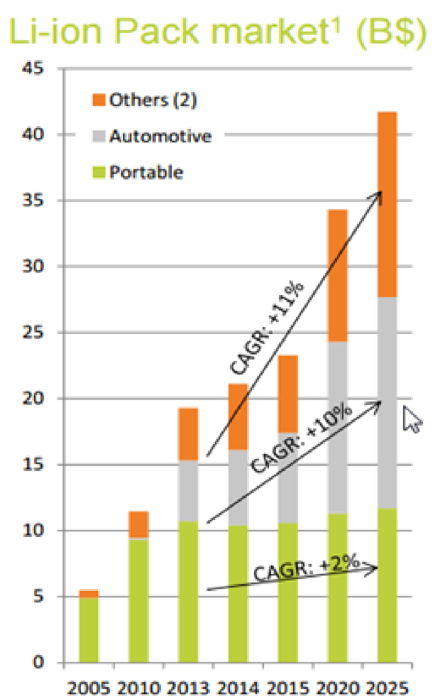


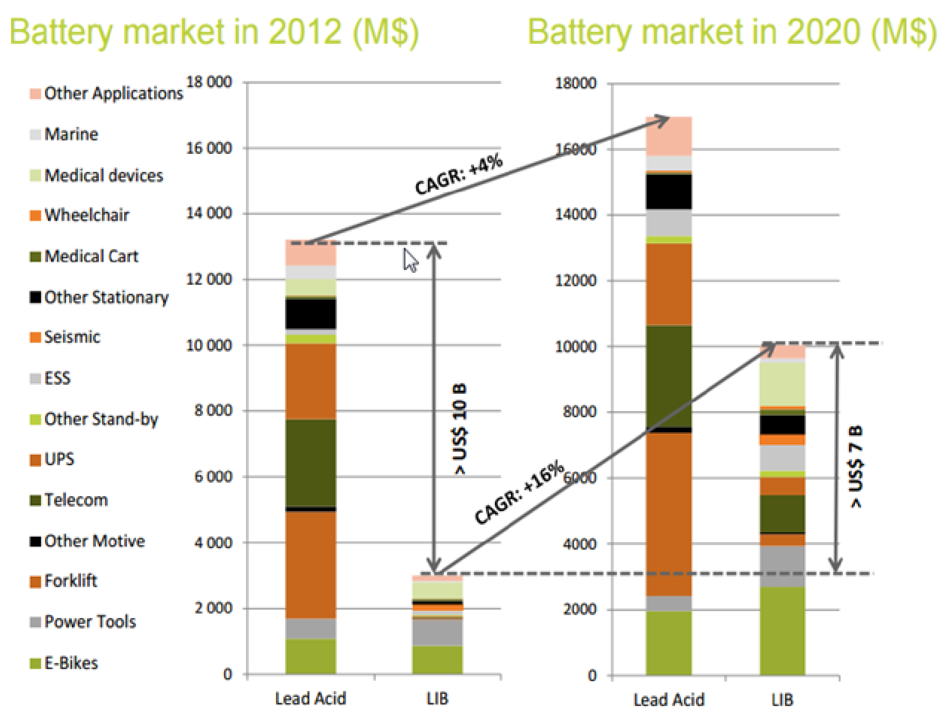


*SOURCE: AVICENNE ENERGY Analyses 2016*

## Cylindrical

The cylindrical Lithium-Ion battery market is predominately made up of 18650 cells (18mm diameter cell by 65mm in length) which is one of the first Lithium-Ion cell sizes to be commercialized circa 1993.

Panasonic, LG Chem, Samsung and Sony make up approximately 93% of the market, with over 1.9 billion 18650 cylindrical cells sold. Over the years, there have been several entrants into this market, or attempts of entry, by many cell manufacturers.

A recent change to this market is the proportion of dedicated supply from Panasonic that is dedicated to Tesla. 20% of the overall market is being used for Tesla's electric vehicles and this represents a higher volume for Panasonic than all the other applications combined.

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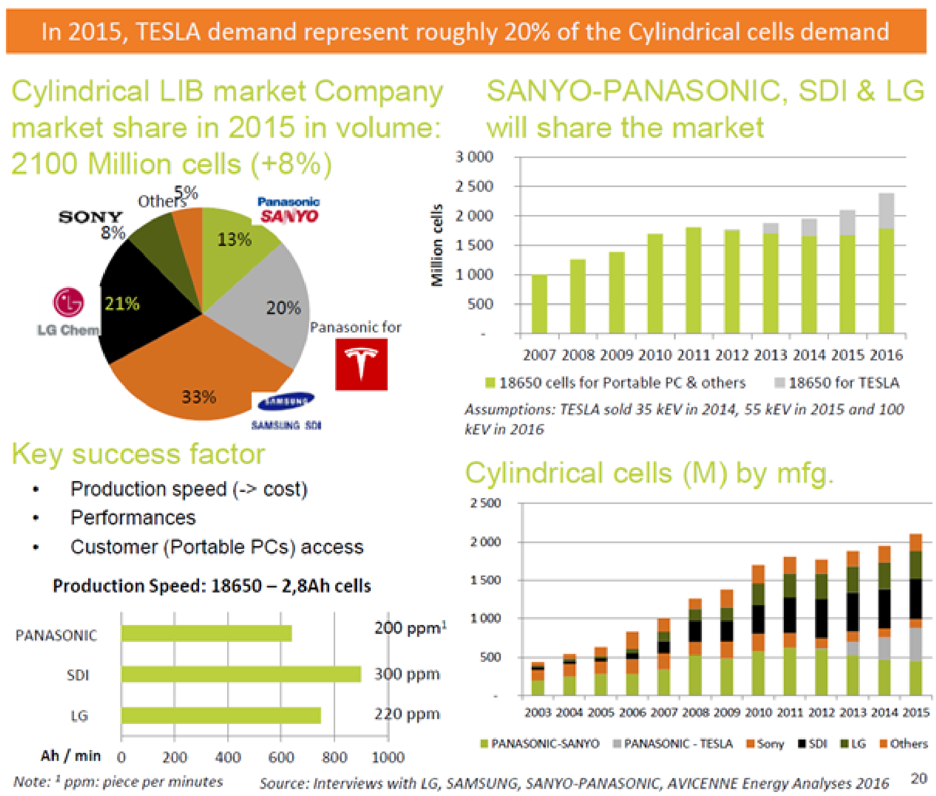


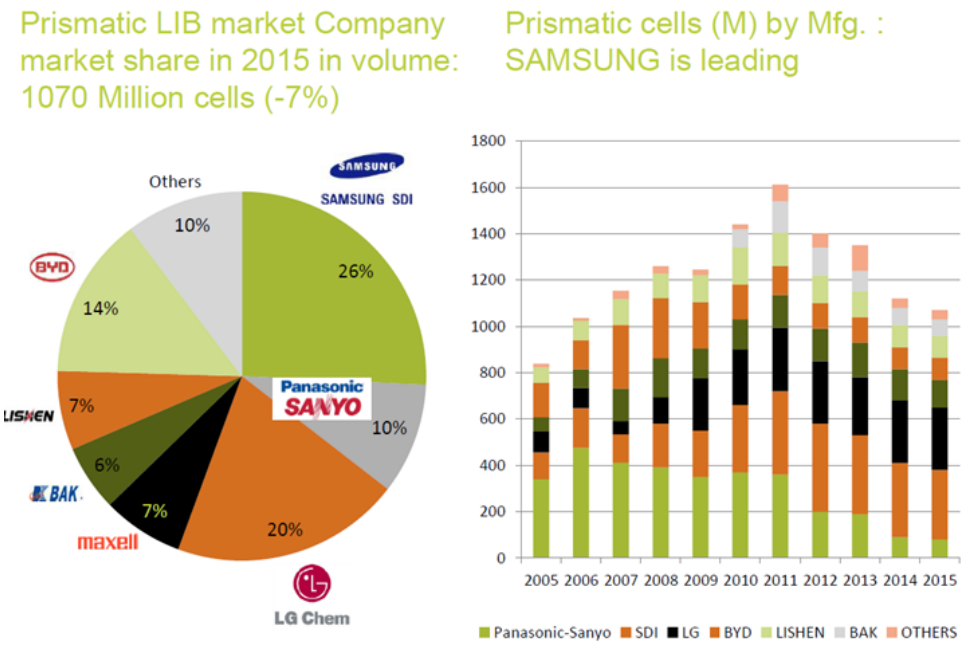

*SOURCE: AVICENNE ENERGY Analyses 2016*

## Prismatic

As shown in the figure below, prismatic cells have been steadily losing production volume since 2011. This is primarily due to the increase in viability, availability and price reductions of polymer cells.

Samsung and LG represent large shares of the prismatic market. Both of these Korean companies have made significant advancements since they started in 2000, despite starting ten years after their Japanese competitors. Part of their market share lead may be attributed to the success of their electronics groups who are supported with these types of cells (i.e. smart phones).

Prismatic cells are starting to lose market share to the polymer cells.




SOURCE: AVICENNE ENERGY Analyses 2016

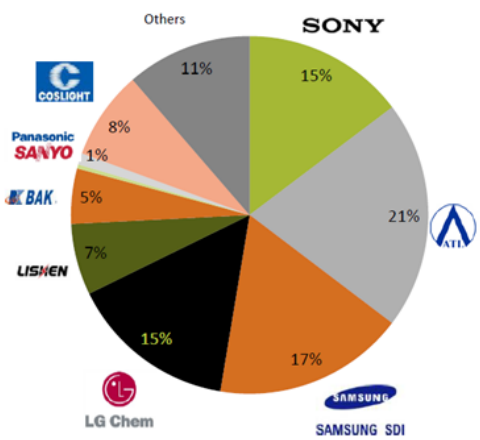
## Laminate

For polymer (laminate) cells, the market becomes a little more diverse. Sony, the first company to commercialize Lithium-Polymer back in 1999, is still essentially holding a large share, closely following ATL, a Chinese company that has been focused on Lithium-Polymer for many years.

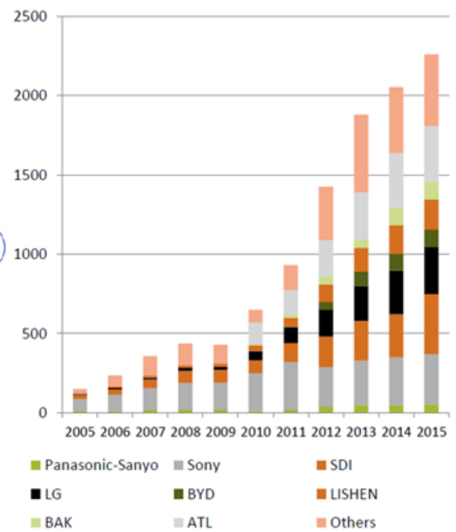
An exciting development in the use of Li-polymer cells is the advancement and prevalence of non-rectilinear shapes and the introduction of curved cells in mainstream applications. Some of examples can be seen in the applications below.

Laminate cells are now common and are produced in unusual shapes and are curved in many consumer products.

Laminate battery market Company market share in 2015 in volume: 2 200 Million cells (+5%)




Pouch cells (M) by Mfg. SONY, ATL and SAMSUNG are leading this market

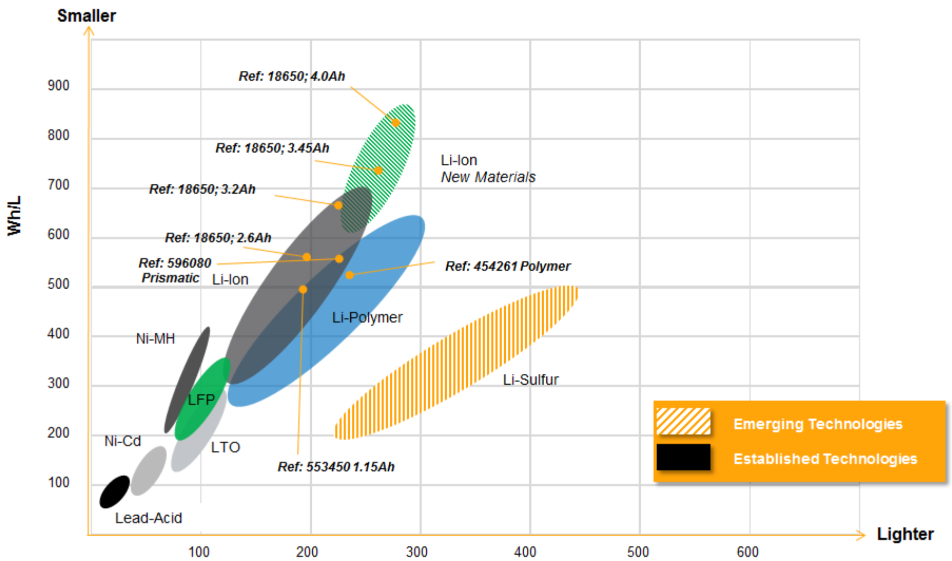



*SOURCE: AVICENNE ENERGY Analyses 2016*

## Energy Density Overview

From a technical position, it is important to start with an overview of various battery chemistries in terms of energy density. The image below 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 we have Wh/L. This is the amount of energy by volume. On the horizontal scale, we measure energy by weight in Wh/Kg.

The main attractiveness of Lithium Sulfur is primarily due to its energy density by weight...In terms of watt hours per liter, however; conventional Lithium-Ion has a significant advantage over this chemistry.




The various 18650 reference points noted above illustrate where the cells are in relationship to energy density. A 2.6Ah, 18650 is approximately 550Wh/L and 200Wh/kg. The more common 3.2Ah cell is over 600Wh/L and over 200Wh/kg. Later in 2016, we expect to see the widespread introduction of 3.5Ah, 18650 cells which puts them over 700Wh/L and starting to approach 300Wh/kg. For several years, there has been a 4Ah, 18650 on this chart which does not exist yet. At this point, there is reason to believe that this cell will not be commercialized due to discussions in the market about developing slightly wider diameter cylindrical cells (i.e. above 18mm), in order to meet a 4Ah threshold. When this transpires, there will most likely be less pressure in the market to engineer an 18650 to a 4Ah level. There may also be a focus shift on further developing other parameters of 18650 cells in terms of rate capability, cycle life, and lower temperature performance.

One additional chemistry important to consider is Lithium Sulfur. Lithium Sulfur has been in development for about 20 years, but there are only a few suppliers which have been able to overcome the shortcomings of Lithium Sulfur through advancement in material science. The main attractiveness of Lithium Sulfur is primarily due to its energy density by weight. Today, the prototype cells are 200 to 300Wh/kg and theoretically reaching 400Wh/kg. In terms of Wh/L, however; conventional Lithium-Ion has a significant advantage over this chemistry.

## Classes of Li-Ion Cylindrical

In terms of 18650 cells, there has been much focus on developing different varieties of cells, yet there is a lack of understanding in the marketplace about the availability of those performance differences.

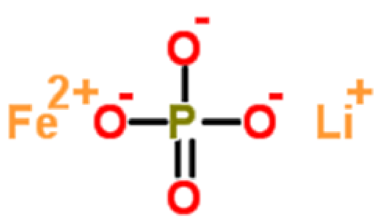
18650s dominate the market, but there is a recent push to change to 20650s for high-rate power tools and 21700 for mid-rate automotive applications.

18650s have dominated the market for many years, but there is a recent push to change to 20650s for high-rate power tools and 21700 for mid-rate automotive applications.

High Energy Density (Laptop Cells): The traditional 18650, often referred to as a laptop cell, is optimized for energy density. The rate capability of these cells is 1C to 1.5C on the top end, meaning a 3Ah cell could be discharged at 3 Amps. In order to reach a maximum cycle life, these cells need to be discharged more comfortably, which is less than 1C. There are charge voltages that can achieve higher capacity over 3Ah which are 4.30/4.35 Volts per cell. This is a trend being seen with higher capacities, where there is a lowering of the charge voltage, but a maintaining of the capacity.

High Rate (Power Tool Cells): A few years ago, 18650 cells for high rate power tools were introduced. 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. Compared to the traditional 18650 cells at 2Ah, these cells were about half the capacity but featured a significantly higher discharge rate capability. 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, 3.2Ah 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.



Iron Phosphate: A Lithium-Ion chemistry but characterized by low energy density. The operating nominal voltage is about 3.2V, it has good rate capability and its strength is in cycle and calendar life. Iron Phosphate is inherently more stable than typical transition metal oxides and because it charges at 3.6V, it provides longer life. While these cells were initially developed for power tools, they have also found homes in backup applications, such as BBUs or Battery Backup Units for UPS type of applications in addition to energy storage, where long calendar life is important and the energy density or lack thereof is not as critical.

A downside to Lithium-Iron Phosphate (LFP) is that there is a limited supply base of Tier One manufacturers. The commitment and development of Lithium-Iron Phosphate in terms of either trying to improve the rate capability or keep the same rate capability, does not seem to be a focus. For example, the 1.1 Amp, 18650 cell has not changed since its introduction. While a 1.5Ah/1.6Ah cell may be available, it will most likely not be supplied by a Tier One supplier.

Another downside is the cost of Lithium-Iron Phosphate relative to conventional Lithium-Ion, which is nickel/cobalt/manganese based and all blends thereof, is still relatively high. This is mostly due to the fact that the scale of adoption of LFP is an order of magnitude less conventional than Li-Ion. While there are billions of 18650s or conventional Lithium-Ion cells being made, Iron Phosphate by comparison is much smaller scale and, therefore, the costs are higher.

## Classes of Li-Ion Prismatic/Polymer

The difference between a prismatic cell and a polymer cell is a slight difference in electrolyte as well as the container.

The difference between a prismatic cell and a polymer cell is a slight difference in electrolyte as well as the container. Prismatic cells are in an aluminum can while polymers are in a form of bag or a sandwich of polypropylene and aluminum that is heat sealed around the outer edge.

These cells are similar in that they are developed primarily to achieve the highest capacity in order to meet the applications which are driving their development, such as consumer electronics, smart phones, tablets, etc. In a Lithium-Ion prismatic case, there has been development to increase the x,y footprint to better compete with laminate form factors. These cells now have a wider footprints (i.e. 60x80mm) and are also being used in multi-cell designs. Again, historically, they have been single cell application cells, but are now being manufactured with a quality level that enables their use in multi-cell battery packs.

In the case of Lithium-Polymer, there are some niche high rate cells that have been on the market, but not through Tier One cell manufacturers. Some Tier One companies are starting to develop a higher rate polymer and prismatic cell in order to compete in new markets, such as higher rate power tools.

## What's New?

In terms of what is new in the marketplace, large format cells are starting to find homes in applications such as energy storage for large grid applications as well as electric vehicles for which they were initially developed. Large format battery applications require larger cells (i.e. 10Ah up to 50Ah) and are attractive for use due to their long calendar and cycle life. There is also a trend being seen towards even higher charge voltages. Traditional Lithium-Ion has charged to 4.2V in the past and now it is up to 4.4V in some prismatic and polymer cells.

In terms of new cell technologies, Lithium Titanate (LTO) is gaining popularity. It is characterized by long cycle life and has been commercialized by companies such as Altair, ATL, and Toshiba. Toshiba continues to promote this cell technology both for energy storage, larger format applications, as well as material handling applications.

Electric Double Layer Capacitors (EDLCs) are making headway in the market in conjunction with Lithium-Ion batteries.

Some companies that are now working with Lithium Sulfur are Oxis Energy, Sion, and Polyplus. Oxis has gained some traction in Europe within applications that perhaps were not targeted initially with Lithium Sulfur but find its high energy density by weight attractive.

Nickel Zinc was initially commercialized for power tools as a replacement to NiCad, but more recently has evolved for use in micro-hybrid type vehicles. PowerGenix is an example of a company utilizing this technology.

Sodium Nickel Chloride is a technology that GE and FIAMM are trying to commercialize and the Hybrid Ion is from Aquion Energy. Sodium Nickel Chloride and the Hybrid Ion are similar in that their chemistries are better suited for mass energy storage (low energy density/long life).

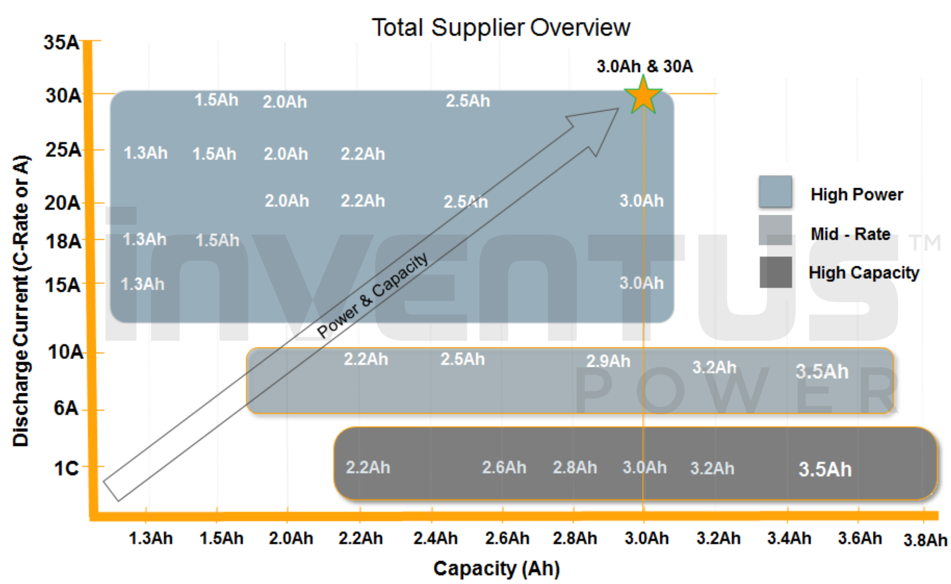
Lastly, Super Capacitors or Electric Double Layer Capacitors (EDLCs) are making headway in the market in conjunction with Lithium-Ion batteries and Lithium Primary batteries, occasionally replacing the entire battery in some applications.

## Cylindrical Li-Ion 18650 Roadmap (Capacity + Power)

The figure below is a roadmap that explains where the market is in terms of 18650 cylindrical cells, which comprise a significant portion of the overall market as well as the battery packs and systems that are available today. The light blue section at the bottom of the chart represents the 1C rate type of cells. These are laptop cells, with the dark blue noting the cells that have been commercialized, and the red noting the capacity that has recently or is going to be commercialized this year. In this representation, we see up to 3.5Ah being available in the market for those needing high capacity.

In terms of the mid-rate cells, availability ranges from 2Ah up to 3.4Ah which will be introduced later this year. Mid-rate cells at 3.2Ah are quite common. Mid-rate and high power cells charge at 4.20V, whereas we see up to 4.35V for 1C rate cells.

We see up to 3.5Ah [in cylindrical Li-Ion cells] being available in the market for those needing high capacity.




From a historical perspective, 1.3-1.5Ah cells are available in the market with a discharge rate capability of 15 Amps up to 25 Amps. More recently, 2.5Ah cells have been introduced with 20A to 30A rate capability which is exciting considering where 18650 cells were not too long ago in terms of rate capability.

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.

## Conclusion

At Inventus Power, we find great value in having access to a variety of cells and chemistries. The markets that often drive the ability of these cells are not necessarily those that we are interested in at Inventus Power, but they are excellent choices for some of the applications that we can support due to having access to these cells.

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 optimizes performance. Our overall cell knowledge and access to Tier One cell suppliers provides great value to our OEM customers.

## About Inventus Power

Inventus Power, formerly ICCNexergy + Palladium Energy, is the world's ONLY power systems manufacturer that integrates and delivers battery packs, chargers & docking stations and power supplies across the consumer, commercial, medical and military & government markets and is located in 10 countries across 4 continents.

With headquarters in Woodridge, Illinois and manufacturing facilities in the United States, Mexico, Brazil, China and Malaysia, we are globally positioned to be a catalyst for our customers' success. Inventus Power utilizes decades of design, engineering and market expertise to apply innovative technology to our OEM customers' devices and ensures a reliable, high-quality product through our vertically integrated processes and performance testing capabilities.

For more information, visit **inventuspower.com**.

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