White Paper

The Goldilocks Problem:

Cell Selection for Emerging Battery Applications

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Introduction

In the classic fairy tale, "Goldilocks and the Three Bears", a girl named Goldilocks walks into a house that belongs to a family of bears. She makes herself comfortable in the house: eats porridge, sits in a chair, and sleeps in a bed. Each time she does something new, she picks the item that best suits her needs – the porridge that was at the right temperature, the chair that was sized right, and the bed that was most comfortable. But what if there had been more than one factor to consider for each object she chose? What if there was a chair sized perfectly for her, but the cushion was too soft? What if there was another chair that was slightly too big, but the cushioning was perfect? Then, Goldilocks would have had to pick what was more important to her: the size or the cushioning.

When choosing the cell for a battery, an engineer must decide what variables are most important to the final application of the battery.

Similarly, when choosing the cell for a battery, an engineer must decide what variables are most important to the final application of the battery. Which factors are essential, and which factors are just nice to have? A cell is defined by its chemistry and form factor, but the chemistry dictates its performance specifications: the energy density, charging profile, discharging profile, cycle life, and temperature limitations. Furthermore, the operating conditions of the battery can affect those performance specifications. Finally, the engineer must navigate the cost, market availability, and cell suppliers' requirements to ensure the chosen cell can be obtained.

This white paper will give an overview of a battery cell's variables and discuss the process of prioritizing them when selecting a cell for an emerging application.

Understanding Cell Form Factor

A cell is defined by its chemistry and form factor, so a general understanding of both is needed in order to select a cell. There are three main formats for cells: the polymer pouch, the prismatic cell, and the cylindrical cell. From these three formats, cells come in various sizes but there are generally a few standard sizes that are more readily available in the industry. When deciding which cell form factor to use, an engineer should consider the mechanical limitations and physical space the battery can take up, but also the market availability.

The cylindrical cell is an excellent choice for many applications due to its high energy density and wide availability.

Prismatic Cells: The prismatic cell is a rectangular cell with a hard, aluminum or steel housing. It satisfies the need for a thin cell and the metal exterior makes it robust. However, it can be more expensive to manufacture. There are only a few manufacturers for prismatic cells and only a few standard sizes currently available on the market. The two most common prismatic cell sizes are the 5.5mm thick, 34mm wide, and 50mm long cell (553450) and the 10mm thick, 34mm wide, and 50mm long cell (103450).

Polymer (Pouch) Cells: Polymer pouch cells are like the prismatic cell, but there is no hard-exterior casing. The pouch cell has the highest packaging efficiency and a great energy density, but the soft pouch tends to swell and leaves the cell more vulnerable to penetration. There are many suppliers of pouch cells, and many are willing to make custom sizes if the volume is high enough. The level of quality of pouch cells varies significantly among suppliers. The engineer really should work with a company experienced in evaluating these suppliers – the stories of swollen "pillowed" pouch batteries and safety incidents are far too common. Smaller volume applications requiring less than one million estimated annual units (EAU) can still use polymer cells, but there is a risk of the cell becoming unavailable as other high volume OEM customers move to new sizes. Pouch cells are a good choice for a high-volume application that requires a thin form factor, but an engineer must select a cell from a reliable manufacturer, protect the cell from external penetration, and have a mechanical design that accounts for swelling when choosing a pouch cell.

Cylindrical Cells: Cylindrical cells are the most common format in the industry. Typical cylindrical sizes are 18650, 21700, and 26650, with 18650 being the most commonly used today.

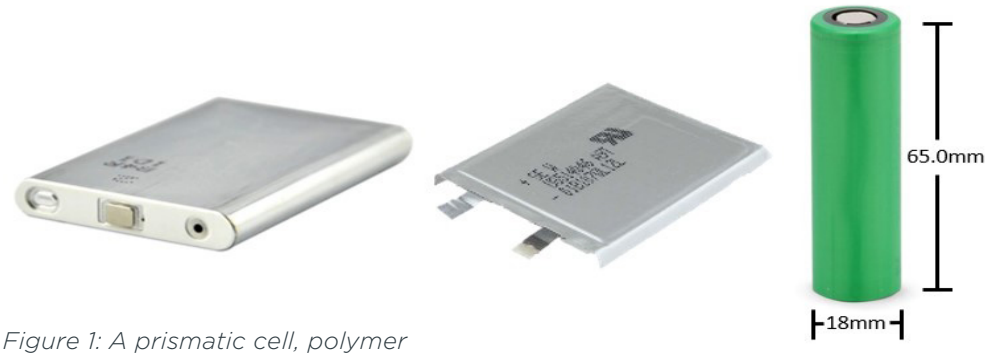

Figure 1: A prismatic cell, polymer (pouch) cell, and 18650 cylindrical cell (from left to right)

There were approximately 5 billion cylindrical cells made in 2019 (out of total 8.5 billion cells). The scale and level of automated production provides lower cost and reliable cells with good cycling ability. Cylindrical cells are the preferred choice for multi-cell configurations commonly needed in today's medical, industrial, and commercial large format applications.

Understanding Battery Chemistry

Lithium-ion (Li-ion) is currently the dominating chemistry as it provides the same amount of energy as many other chemistries while weighing less and taking up less space.

The chemistry of a cell heavily influences and even dictates many key variables, notably the energy density, cycle life, discharge capability, charge profile, and temperature range. Established lithium chemistry cells already far surpass other chemistries in energy density by both weight and volume. Lithium-ion (Li-ion) is currently the dominating chemistry due to the increase in energy density by volume and weight.

Figure 2 shows the energy density of various rechargeable battery chemistries. One can see the progression from the lower energy density (older) chemistries such as Lead-Acid, and Nickel Cadmium to current day Li-ion and including new technologies such as Li-metal Sulfur.

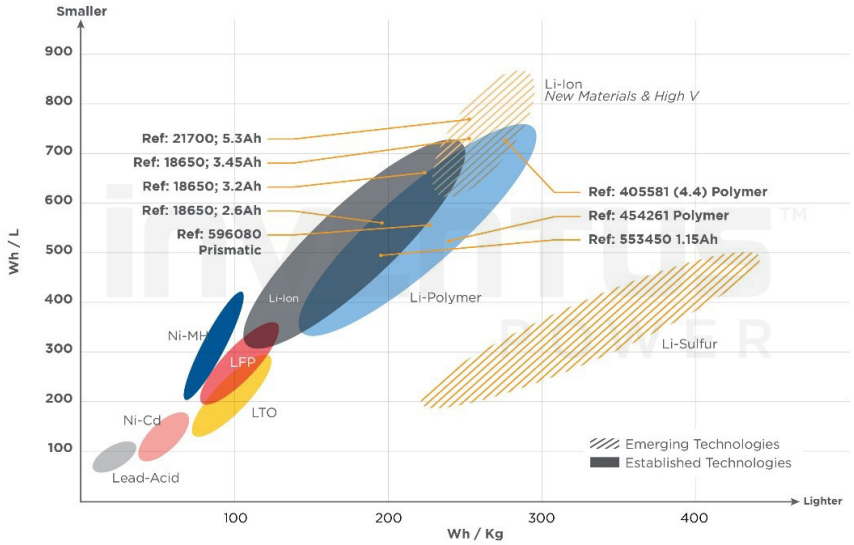

Figure 2: Energy densities by weight and volume of different battery chemistries

It should be noted that even within the Li-ion family there are other examples, such as LFP and LTO, which are not as energy dense as conventional Li-ion (i.e. with LCO, NMC, NCA cathodes), but offer other advantages in safety, cycle life, and rate capability. Energy density is not always the primary deciding factor. Some applications have the luxury of space (i.e. energy/grid storage), but place a higher priority on calendar life of the battery. Other applications like material handling (i.e. forklifts or autonomous mobile robots) may not place much value on the benefit in energy density by weight (Wh/kg) and instead place higher priority on fast charging and/or cycle life.

Understanding the tradeoffs among various battery chemistries can significantly help optimize the battery for the application. Once the tradeoff is understood, it can then be prioritized. To prioritize these factors, the engineer must understand the discharge profile of the particular chemistry used, how much cycle life is needed, how quickly the battery needs to be charged, and in what temperature range the battery will be operating.

Even among similar conventional Li-ion, the choice of NMC, LCO, or NCA cathodes can have a significant impact on actual runtime depending on the discharge cutoff voltage of the end device.

	Lead Acid	Ni-Cd	Ni-MH	Li-ion	LFP	LTO
Voltage	2V	1.2V	1.2V	3.6-3.7V	3.3V	2.4V
Energy Density (Wh/Kg)	35	50	80	200	100	75
Cycle Life	300	500-1000	400-1000	400-1000	2000	10000
Life (Yrs) @ one charge/day	1	2	2	1+	5+	10+
Charging Time	8 hr	1.5 hr	4 hr	1-3 hr	1-3 hr	<1
Self Discharge Rate (%/mo)	5%	30%	30%	3%	3%	3%
Safety	Good	Good	Good	BMS	BMS	BMS
High Temp Performance	Good	Good	Good	Fair to good	Good	Good
Cold Temp (0°F) Charge	Good	Fair	Fair	0-45°C	0-45°C	-30°C
Cold Temp (0°F) Discharge	Good	Good	Poor	Fair-Good	Good	-30°C
Memory Effect	No	Yes	Little	No	No	No
Cost	$	$	$	$$	$$$	$$$$$

Figure 3: Battery chemistries and their various specifications

Discharge Profile

As pointed out earlier, the discharge profile of the end application can be a very important factor. As discharge current requirements increase, the chemistry choice becomes more important. Even among similar conventional Li-ion, the choice of NMC, LCO, or NCA cathodes can have a significant impact on actual runtime depending on the discharge cutoff voltage of the end device. Figure 4 shows the discharge profile at 1C discharge rate for various chemistries. The voltage cutoff for the device (i.e. 3.3V vs 3.0V) could have significant impact on the delivered capacity (runtime).

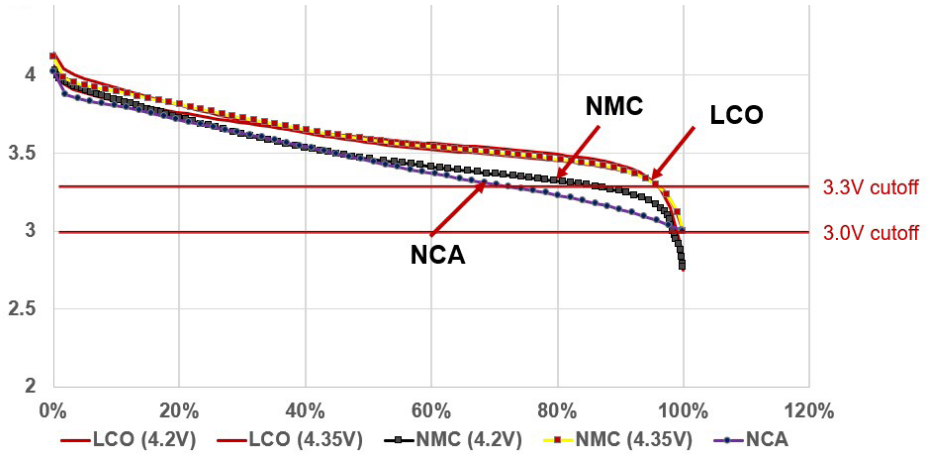

Figure 4: 1C Discharge Curve for Different Chemistry Cathode Material

Mid-Rate Cells are the most common used today in a variety of industrial and medical applications as well as the cell of choice for electric vehicle (e.g. Tesla) and light electric vehicles (LEV) due to their balance of power and energy density.

High Energy Density Cells ("1C Rate"): For applications that require a discharge current lower than 5A per cell, high energy density cells are an easy solution. As its name suggests, high energy density cells can store a lot of energy in the same form factor. In an 18650 high energy density cell, capacities per cell can reach up to 3.5Ah. Their maximum continuous discharge rate is 1 times their capacity per cell (1C) with peaks allowed slightly higher up to 2C rate. Going beyond this 2C rate will significantly impact cycle life of these cells and could present a safety issue. Historically, laptops represented a typical application for these cells. When it comes to 18650s, "1C" rate cells have become less popular due to a laptop market switch to pouch cells. Today, the 'mid-rate' class of cells particularly in 18650 are more prevalent and recommended generally over 1C rate cells that are quickly disappearing from cell supplier roadmaps.

Mid-Rate Cells (Up to 10A per cell): Mid-rate cells initially were developed for applications (i.e. E-bikes) that required higher discharge rates than a laptop, but still maintain reasonably high energy density. A mid-rate cell is capable generally of 3-4C rate continuous with peaks up to 5C. These cells are the most commonly used today in a variety of industrial and medical applications as well as the cell of choice for electric vehicle (i.e. Tesla) and light electric vehicles (LEV) due to their balance of power and energy density.

High Rate Cells (Up to 35A per cell): Lastly, there are high rate cells that can discharge up to 35A per cell. The capacity is lower in this class of cells, ranging from 1.3Ah to 3.0Ah in 18650s and up to 4.0Ah in 21700s. These cells are used in power tools, lawn and garden equipment, and uninterruptible power supplies (UPS). The chemistry and internal mechanical structure of these cells are optimized to lower the impedance improving the discharge rate at the expense of capacity. These cells have also become popular in many applications outside of the originally intended markets.

Cycle Life

Li-ion batteries lose capacity over the course of many charge and discharge cycles and eventually can no longer be used. The cycle life of a cell is the number of times a cell can be fully charged and discharged before the capacity reaches an unusable state or is taken out of service due to reliability concerns. Certain applications, such as cell phones, are replaced after a couple years and do not need high cycle life. On the other hand, applications like electric vehicles can be expected to last up to 10 years and therefore must be able to cycle thousands of times. The actual cycle life can vary depending on the charge voltage and current, discharge rate, and temperature in the application.

All lithium-ion cell manufacturers specify maximum charging voltage for safety and cycle life. Charging above that maximum decreases cell life and can be a safety hazard; charging below the maximum increases cycle life.

When a cell is charged or discharged at higher rates, there is stress on both the anode and cathode – both of which decrease cycle life. All lithium-ion cell manufacturers specify a maximum charging voltage and minimum cut-off voltage for safety and cycle life. Charging above that maximum voltage or current decreases cell life and can be a safety hazard; charging below the maximum increases cycle life. In Figure 5 below, the same type of cell is charged at 4.15V, 4.25V, and 4.35V and then discharged. Charging the cell at a lower voltage results in a lower initial capacity but a higher usable capacity and cycle life in the long run.

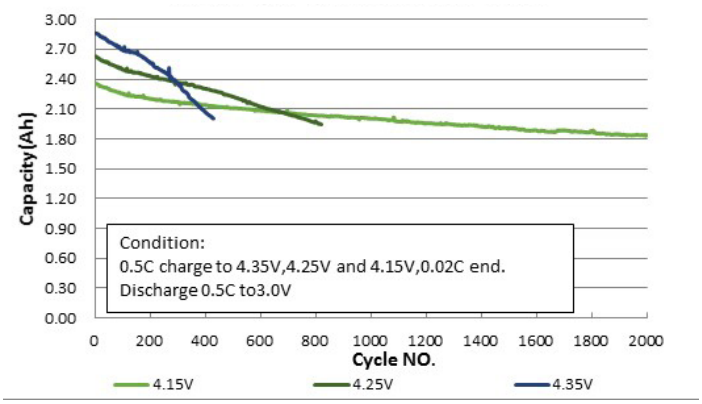

Figure 5: The cycle life of a Li-ion cell changes with charge voltage

Similarly, discharging/charging at a higher current also decreases cycle life. By increasing the cutoff voltage or decreasing the discharge/charge current, the cycle life can be lengthened, as seen below in Figure 6

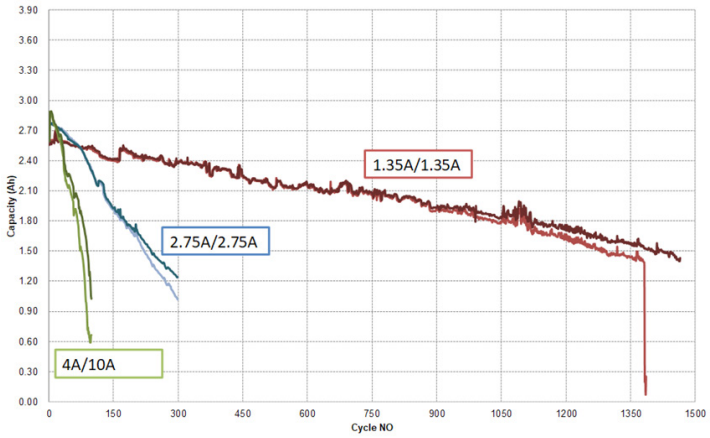

Figure 6: Cycle life at different charge and discharge rates.

For applications where capacity can be sacrificed, charging at a lower voltage and discharging to a higher cutoff voltage with a lower current is an effective method to increase cycle life. When selecting a cell, an engineer must consider and understand the effects of how often the battery will be charged, how long it should take for the battery to charge, and how much power the final application needs in order to accurately assess the calendar life of the product.

Temperature

Elevated temperatures speed up the degradation process of the electrodes and at high enough temperatures, can lead to venting or thermal runaway

The previous section explained how pushing a cell to the upper and lower bounds of its electrical capabilities could be unsafe and decrease the cell's cycle life. To account for this, manufacturers set current and voltage limits for a cell. In the same vein, all cell manufacturers set a maximum and minimum temperature for charging, discharging, and storing. Most batteries prefer and perform better in a room temperature setting between 15-35°C. High temperatures accelerate degradation. Low temperatures, while beneficial for long term storage, result in sluggish electro-chemistry performance and decreases the power density. Figure 7 below gives a general sense of the temperature ranges cell chemistries can operate in. While most applications can adhere to a room temperature range of 0-45°C on charge or -20-60°C on discharge, if a higher or lower temperature cell operation is absolutely necessary, that must be prioritized as there are only a few cell chemistries that will qualify.

For applications that require cells to operate beyond the minimum and maximum temperature, there are options from a system level to mitigate degradation and improve reliability. If the battery pack is going in a lawn mower or EV and is expected to get very hot, an active or passive cooling component like liquid coolant or a heat sink can be added to the battery. Or, if the battery is expected to operate in severely cold temperatures, a heater can be added in parallel to the battery pack to keep the cells at a reasonable temperature. These methods keep the battery pack safe by changing the temperature, but they increase the pack's volume, weight, and cost. If designing a battery pack for extreme temperature conditions, an engineer must be aware of these possible additions early on.

	-40° to -20°C	-40° to 0°C	0° to 45°C	45° to 60°C	60° to 85°C
Charge	• None	• Li-ion* • Lead-Acid*	• Li-ion • Lead-Acid • NiCd/NiMH	• Li-ion	• None
Discharge	• Li-ion* • LFP	• Li-ion • Lead-Acid • NiCd/NiMH	• Li-ion • Lead-Acid • NiCd/NiMH	• Li-ion • NiCd/NiMH	• Li-ion* • LFP

*Figure 7: List of common cell chemistries that support different charging and discharging temperature ranges. *Some cells can be used at reduced power.*

An engineer designing a battery for harsh temperature conditions must also be prepared for the effects of temperature to change the cell's electrical performance. All chemistries have limitations when it comes to temperature. While there are Li-ion cells which can discharge (at low rates) down to -40°C, however, -20°C is considered the normal limit. When Li-ion cells are charged below 0°C, dendrites can form and cause permanent damage to the battery. Inventus Power performed a test on seven different 18650 Li-ion cells with rated capacities of 2.5-3.0Ah to understand their low temperature performance. Each cell was discharged 240mA, or around 0.1C, at -20°C. Most cells were unable to discharge even 50% of their initial capacity before reaching 3.5V cutoff. This test is shown in Figure 8.

When choosing a cell for a battery, it is always better to test the cells to the specific requirements of the end application instead of relying on datasheets

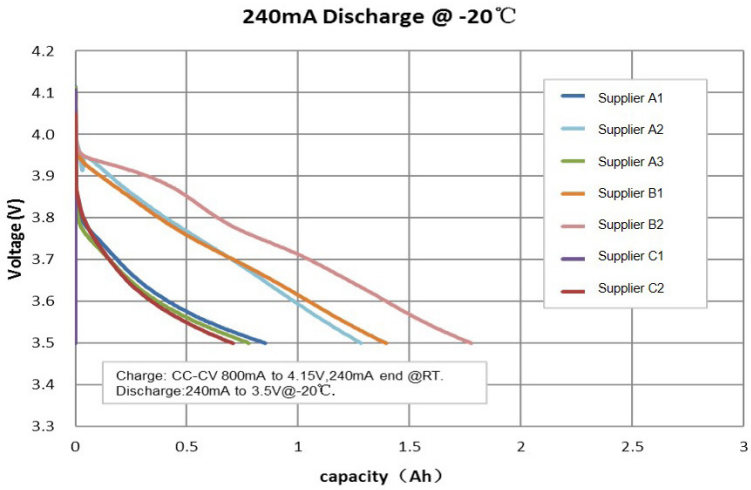

Figure 8: Low temperature (-20°C) performance of various cells.

In another test performed by Inventus Power, various cell models were fully charged to 4.1V, stored at 45°C then checked monthly for capacity loss with some cells on test for up to 5 years. This test is performed to determine the best cell for server, data storage, and UPS type applications that require the battery to be fully charged in a very hot environment: two of the most strenuous conditions for a battery. The results are shown below in Figure 9.

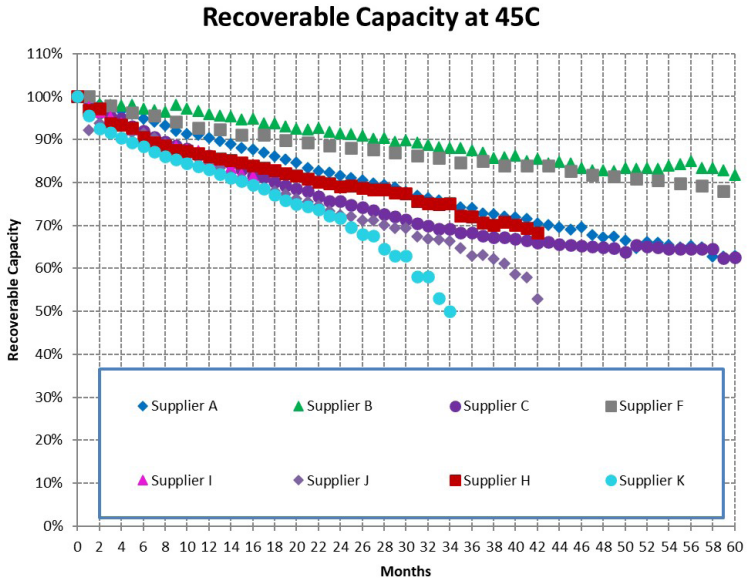

Figure 9: The effects of high temperature (45°C) storage on cell cycle life.

From the tests in Figures 8 and 9, it is evident that temperature affects cells differently and some cells perform better than others in extreme temperatures. These effects should be thoroughly understood before selecting a cell. When choosing a cell for a battery, it is always better to test the cells to the specific requirements of the end application instead of relying on datasheets.

Cell Suppliers

As the demand for cells have drastically increased with the demand for portable power, battery consumers have become more dependent on the cell suppliers.

While an understanding of the influences of cell performance, cell chemistry, and form factor is necessary in order to select a cell, another major consideration is more commercial based. As the demand for cells have drastically increased with the demand for portable power, battery consumers have become more dependent on the cell suppliers. There are limited number of top tier suppliers and they support each market differently. Depending on the intended application, certain suppliers might add more rules (i.e. charge limited to 4.1V for medical applications) or decide the risk is too high and not support certain applications at all. Additionally, the future availability of the cell must be secured to ensure the battery pack will not need to be re-designed for another cell during the lifetime of the product.

There are many cell suppliers around the globe and new ones emerge every day, but not all cell suppliers are equal. Cell suppliers can be divided into tiers. The top tier suppliers are known to be reliable and have the best manufacturing and quality processes, with fully automated lines and world class quality control. If using a cell from another vendor, an engineer must vet the vendor enough to trust in the cell's quality.

It might seem obvious to use a cell from a tier 1 manufacturer to ensure reliability. The real challenge can come from deciding among the lower tier suppliers where "semi-automated" manufactured lines are common. How do you determine which supplier can meet the rigorous standards needed to ensure reliable and safe cells? Without the experience, how do you determine which critical processes should be automated and which ones are ok for limited manual intervention? The factory location where the cell model is being built must be audited by someone experienced in cell manufacturing specifically. Additionally, qualification testing of each model should be performed as variation in reliability can occur even within the top tier manufacturers from cell model to cell model. Auditing and qualification testing are just foundational starting points -- quality is a never-ending process -- ongoing Quality Improvement Plans (QIP) should be implemented with each supplier. Regular 'check-ins' should be made with suppliers to ensure a continual focus on critical parameters for improvement.

Market Availability

When all of the factors have been prioritized and a cell has been chosen from a reliable manufacturer, if the cell becomes obsolete and stops being produced in a few months, then the whole process will have to be repeated. To avoid these situations, an engineer must understand how their cell choice fits into the macro direction of the market. An example is Li-ion prismatic cells. Small prismatic cells at one time were very popular for use in cellphones and digital cameras. Today, most of those applications have transitioned to pouch cells and the market for prismatic cells is declining (Figure 10). While a prismatic cell might fit an engineer's technical requirements perfectly today, there is a big risk of obsolescence with most prismatic models in the future.

A major portion of Li-ion cell sales in the next 10 years are projected to be for electric vehicles. This shift in the battery market has moved the demand for cylindrical cells away from high energy density cells and towards mid-rate cells.

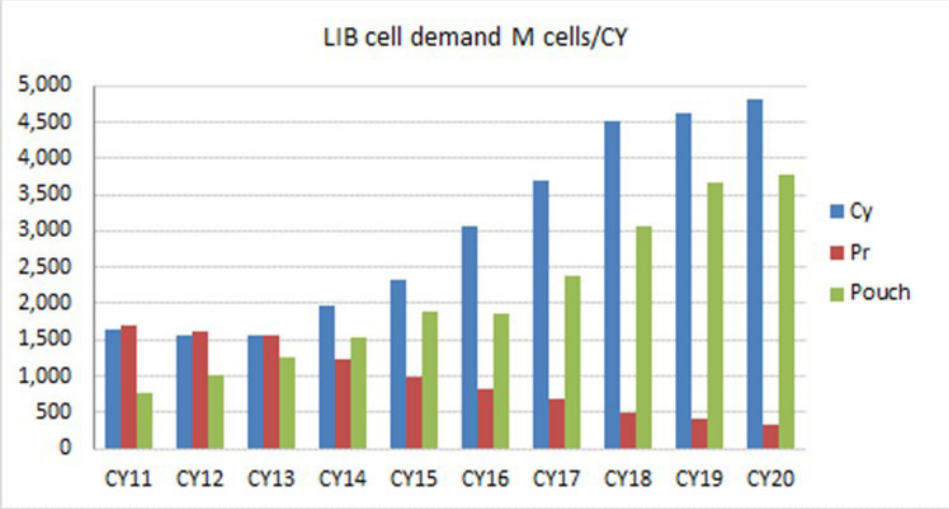

Figure 10: Battery market for small LIB cells by form factor (Source: B3 Corporation, B3 Report 20-21/Chapter 1, page 31)

As seen in Figure 11, a majority of Li-ion cell demand is coming from electric vehicles ("BEV" in the chart) and other markets ("Others" in the chart) generally such as ESS, LEV, and applications converting from Lead Acid or combustion engines to lithium-ion. This shift in the battery market has moved the demand for cylindrical cells away from "1C" rate, lower cycle life cells and towards higher rate and more robust, longer cycle life cylindrical cells. The "1C" cylindrical cells are becoming end of life quickly and might not be the best choice for new applications. And, since 18650 cylindrical cells have plateaued in energy capacity at around 3.5Ah per cell, the 21700 cell is increasing in demand.

An engineer must understand the tradeoffs between different variables and prioritize what is absolutely needed and what is just good to have. At Inventus Power, we perform this type of analysis on a daily basis.

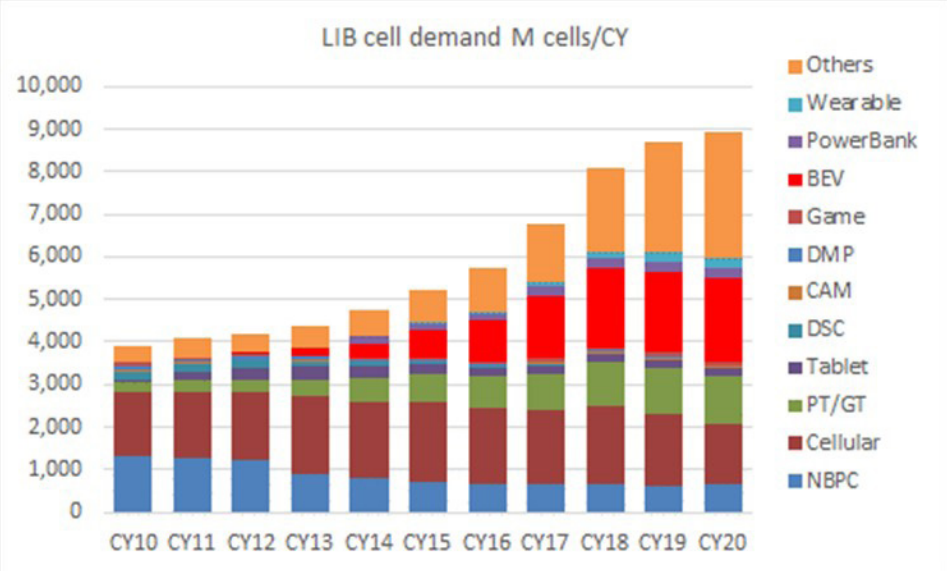

Figure 11: Battery market for LIB cells by application; (Source: B3 Corporation, B3 Report 20-21/Chapter 1, page 31)

The 18650 form factor is expected to continue to be available for many years, however, there is a significant shift in production capacity away from 18650s and towards 21700s which are more desirable for EV and the other applications mentioned. As a result, we see pending supply constraints of 18650s for the foreseeable future until the right balance of 18650 & 21700 supply can be worked out in the market. If your new application can accept 21700s, then this is an option that should be considered.

Conclusion

Even in Goldilocks' fairytale world, there were still things to consider and sacrifice when selecting something as simple as a bowl of porridge. When selecting cells for a battery application, the considerations become much more complex and compromises may need to be made. An engineer must understand the tradeoffs between different variables and prioritize what is absolutely needed and what is just good to have. At Inventus Power, we perform this type of analysis on a daily basis and work with our customers to help them determine the best solution for their application based on our data, experience, and cell supplier relationships.

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 Li-ion battery packs, smart chargers, and efficient power supplies across a broad range of portable, motive & stationary applications.

With 60 years of experience, we understand that different applications have different needs. From advanced concept development, cell characterization & prototyping to complete power system design and BMS customization, our global engineering staff of 300+ degreed mechanical, electrical, software, qualification and compliance engineers have the knowledge and resources needed to design and develop power solutions that operate safely and correctly within their intended environment.

Plus, with global manufacturing facilities and vertically integrated design, tooling and testing capabilities, we are able to manage complex programs from concept to production providing a turnkey solution for our customers.

For more information about our products, experience and capabilities, visit inventuspower.com and follow @inventuspower.

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