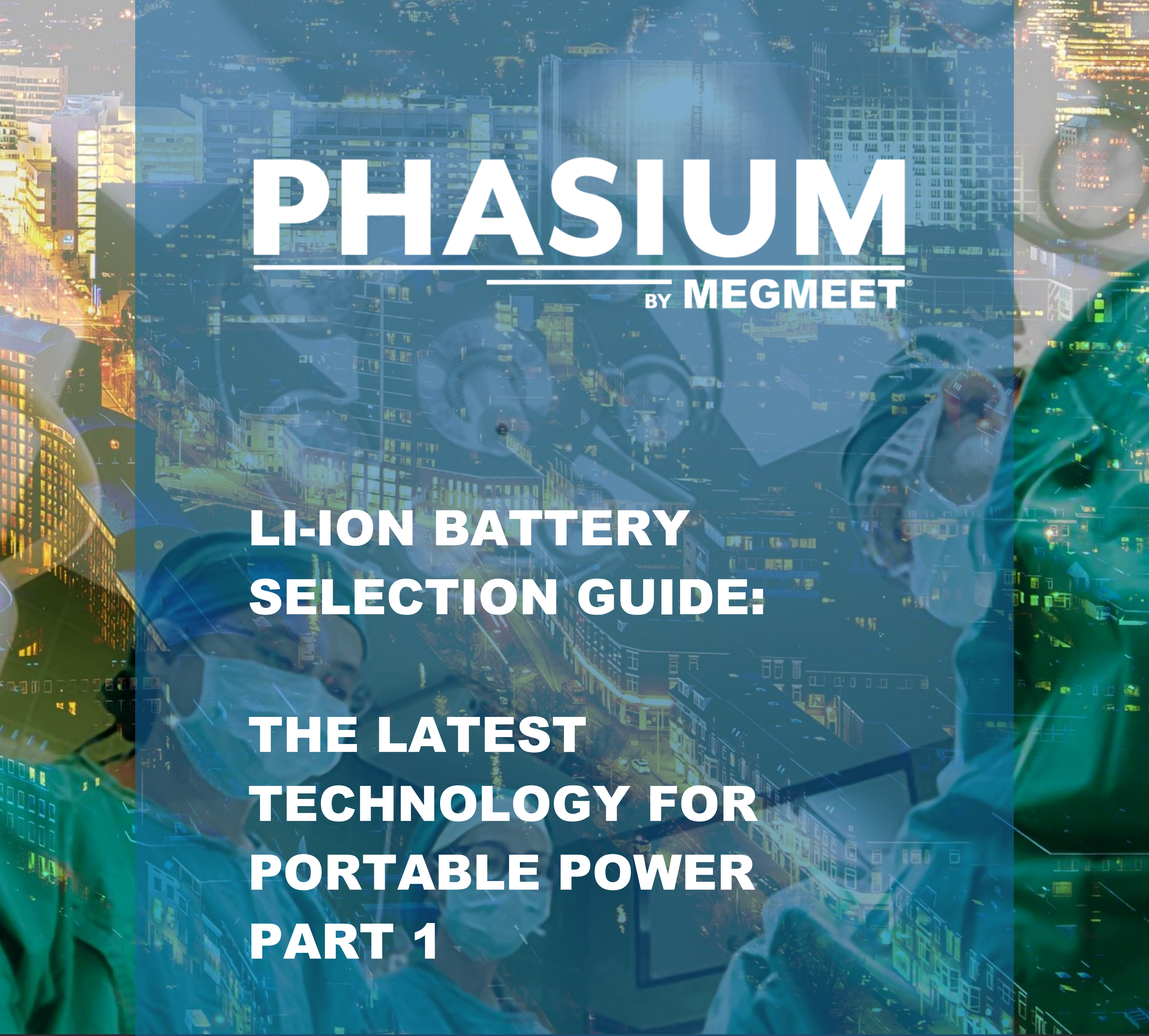

PHASIUM

BY MEGMEET

LI-ION BATTERY SELECTION GUIDE:

THE LATEST TECHNOLOGY FOR PORTABLE POWER PART 1

Industry update, battery choices, availability and their practical use and implementation

WHITEPAPER

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LI-ION BATTERY SELECTION GUIDE: THE LATEST TECHNOLOGY FOR PORTABLE POWER, PART 1

Industry update, battery choices, availability and their practical use and implementation

ABSTRACT

The Li-ion battery industry is rapidly expanding and with the industry growth, there is an improved variety in the chemistries and formfactors available and this is enabling the implementation of battery technology in a wider range of devices. Portable and mobile applications, from medical devices to lawn and garden equipment, can benefit from increased run-time, decreased weight, higher power and improved safety. Engineers will benefit from learning about the latest technology and how to use it to differentiate their new products. In this white paper, Phasium outlines battery chemistry and formfactor choices and their practical use and implementation. The second white paper in this series will outline advancements in safety, battery management electronics and regulatory issues.

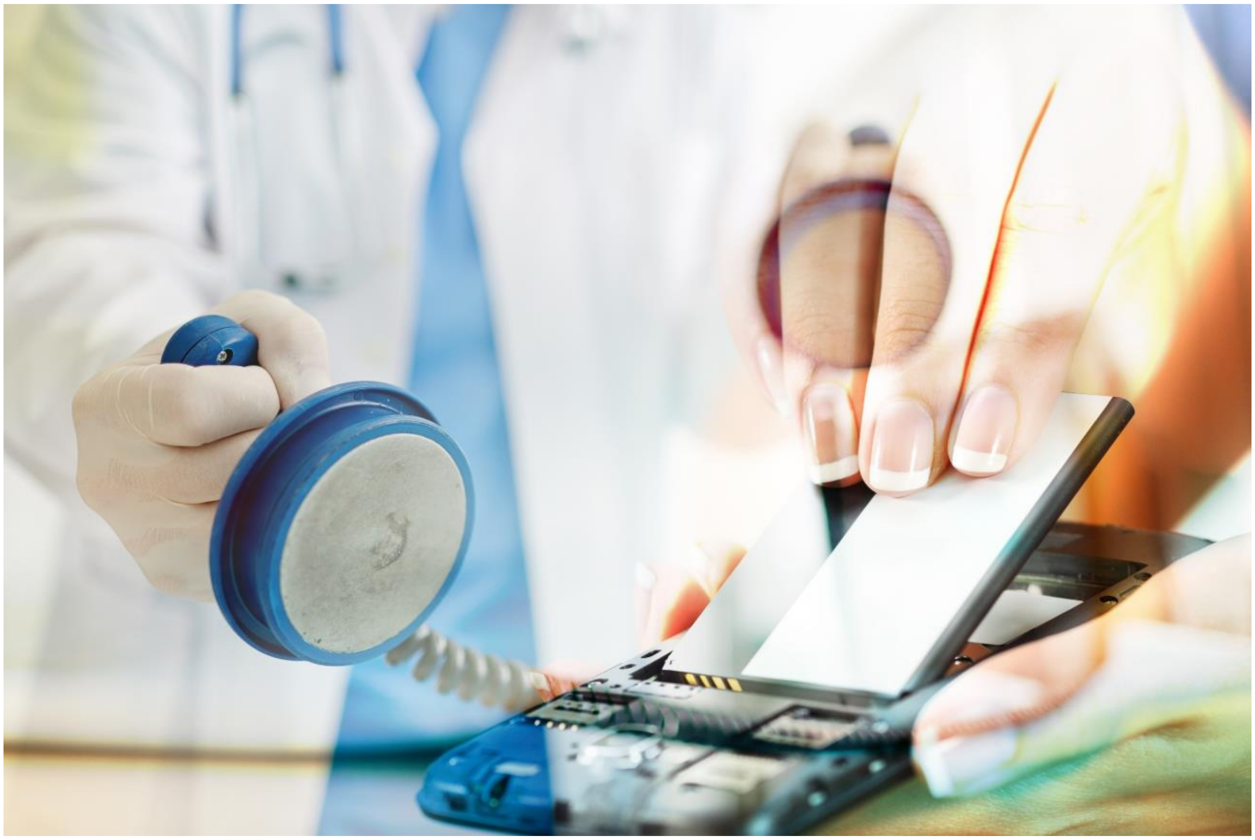
BACKGROUND

The markets and applications for batteries, especially those based on Lithium-ion (Li-ion) technology, is experiencing rapid growth and this is expected to continue beyond 2019. Li-ion batteries are finding new applications in markets where they are replacing older lead-acid technology and there is a drive to convert products that previously used internal combustion engines (ICE) to electric power. Rechargeable Li-ion batteries alleviate environmental concerns and improve performance and functionality for applications large and small.

> RECHARGEABLE BATTERIES ARE NOW BEING ADOPTED BY MARKETS WITH LARGE STATIONARY APPLICATIONS. GROWTH IS COMING FROM THE USE OF LI-ION BATTERIES AS REPLACEMENTS FOR ALREADY EXISTING BATTERY TECHNOLOGIES PARTICULARLY LEAD ACID, IN ADDITION TO THE RAPID GROWTH SEEN IN PORTABLE ELECTRONICS AND MOTIVE APPLICATIONS SUCH AS VEHICLES, E-BIKES, SCOOTERS AND BUSES.

Growth has been especially notable in the medium-to-large format area with larger systems becoming even more prevalent than traditional applications like mobile computing. Rechargeable batteries are now being adopted by markets with large stationary applications. Growth is coming from the use of li-ion batteries as replacements for already existing battery technologies, particularly lead acid, in addition to the rapid growth seen in portable electronics and motive applications such as vehicles, e-bikes, scooters and buses.

The rapid evolution of the market is driving innovation and variety, and the innovation, in turn, is enabling more applications. While the increase in options for form factors and specific chemical formulations provides an exciting opportunity for differentiation, it also brings a lack of stability for supply in terms of longevity and cost. The risks associated with being single sourced for a marginal chemistry variant have gone up in recent years and the market fundamentals of the raw materials used for rechargeable Li-ion cells, and the sourcing of these materials continue to be issues.



MARKET CHANGES AND INDUSTRY DRIVERS

Li-ion batteries first gained acceptance as an alternative to NiCd and NiMH that provided longer run-time and lighter weight for the portable computing industry, eventually becoming the de facto standard for consumer electronics and supporting the birth of small mobile devices from cell phones to watches and hearing aids. Smaller, mobile industrial devices, like bar-code scanners and portable ultrasound had requirements in common with consumer applications, so they also utilized the more modern technology. However, only recently has Li-ion technology been adapted and modified for transportation applications from e-bikes to buses. Battery-based designs are replacing small internal combustion engines for lawn mowers and yard equipment in both commercial and consumer products. New Li-ion technology is replacing lead-acid in back-up stationary applications such as hospital equipment and servers and motive applications like fork-lifts and other material handling equipment. Enabling electric power brings benefits such as elimination of polluting emissions, reduced noise, and lower maintenance needs. Self-contained backup power systems for residential and commercial sites are benefiting from battery-based designs which eliminate the issues associated with on-site hydrocarbon-based fuel storage. As seen in the figure below, starting, lighting and ignition (SLI), portable/cosumer devices, and EV application greatly dominate the $75 B dollar battery industry, but beyond that there are a wide variety of technical requirements for varied applicaitons. Lead-acid technology still holds the lead in these, but Li-ion has about a third of the market and is growing rapidly. In the large format applications, CAGRs are estimated at almost 25%.

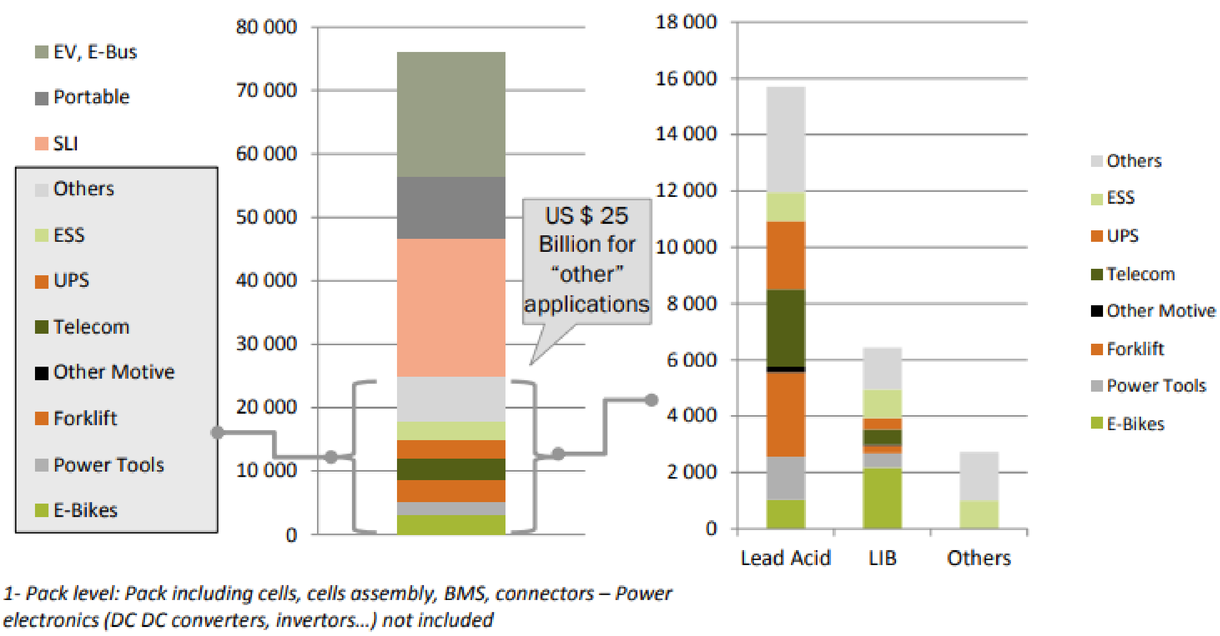


Figure 1: Worldwide battery market 2017: $75B USD (source Avicenne)

Implementing Li-ion in the design of a system requires understanding the specific ways in which the chemistry has been tailored for this newly huge variety of applications. The industry can expect the variety to continue to rapidly evolve and expand rather than consolidate as more applications and markets convert.

LI-ION TECHNOLOGY

There are several areas where Li-ion rechargeable-batteries are seeing technical changes and advances. The increase in cells designed for a specific purpose, with new form factors and higher performance, the use of enhanced chemistries and materials and supplier market shares in each will be discussed below after outlining some basic vocabulary, terminology and design strategies.

BASICS, TERMINOLOGY AND BUILDING BLOCKS

Li-ion cell: the building block for a battery pack. Figure 2 captures an overall comparison of Li-ion advantages versus older technologies. When replacing an older technology, it is helpful to understand what features were necessary and this will help inform the choice of Li-ion variant required in a new design.

- A Li-ion cell cannot be used individually
- Requires protection circuitry to prevent thermal runaway at a minimum
- Nominal average voltage: 3.6-3.7V
- Maximum voltage: typically 4.2V

Advantage of … / …On	Lead Acid	Nickel Cadmium NiCd	Nickel Metal Hydride NiMH	Lithium-Ion	
				Conventional	Laminate
Lead Acid		• energy density • Operating temperature • Self discharge rate • Reliability (progressive extinction)	• Gravimetric energy density • Volumetric energy density • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Design characteristics
Nickel Cadmium NiCd	• Higher cyclability • Voltage output • Price		• Gravimetric energy density • Volumetric energy density	• Gravimetric energy density • Volumetric energy density • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Design characteristics
Nickel Metal Hydride NiMH	• Higher cyclability • Voltage output • Price	• Operating temperature range • Higher cyclability • Self discharge rate • Price		• energy density • Operating temperature • Higher cyclability • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Operating temperature • Self discharge rate • Design characteristics
Lithium-Ion Conventional	• Higher cyclability • Price • Safety • Recyclability	• Operating temperature range • Higher cyclability • Price • Safety • Recyclability	• Price • Safety • Discharge rate • Recyclability		• Gravimetric energy density • Volumetric energy density • Design characteristics • Safety • Price
Lithium-Ion Laminate	• Higher cyclability • Price	• Operating temperature range • Higher cyclability • Price	• Volumetric energy density • Higher cyclability • Price	• Operating temperature range • Higher cyclability	
Absolute advantages	• Higher cyclability • Price	• Operating temperature range • Price	• Volumetric energy density	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Voltage output	• energy density • Self discharge rate • Voltage output • Design characteristics

Figure 2: Cell chemistry comparison

Li-ion battery pack (illustrated in Figure 3):

- A connection (circuit) of one or more cells and the appropriate protection circuit
- Cells could be connected in series or parallel or a combination of both
- Series connection increases pack voltage
- Parallel connection increases pack capacity

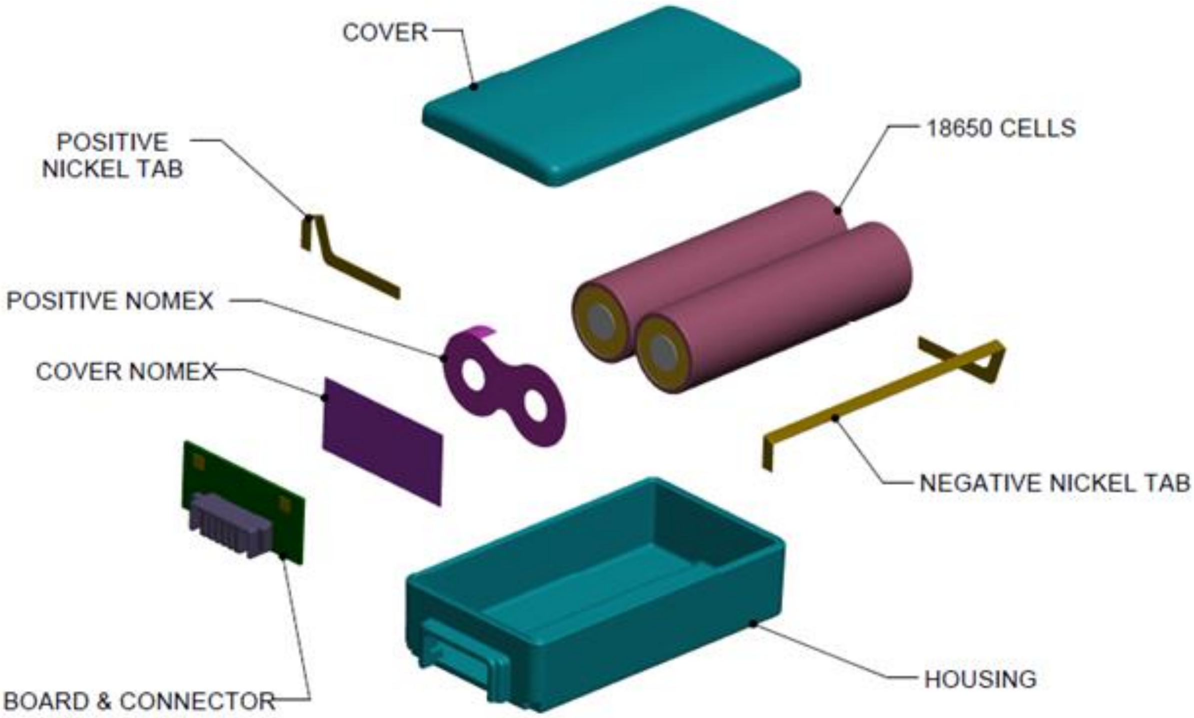


Figure 3: Battery pack construction

Useful definitions for requirements and specifications**:**

Cell Voltage – [V]

- Open Circuit Voltage (OCV) – the cell voltage under no load
- Nominal Voltage – the voltage under load

Resistance – [Ω]; usually measured in [mΩ] – opposition to flow of electrical current

- Cell internal resistance – resistance of a single cell
- Total pack resistance – sum of resistance for all cells, interconnects, wires & components in series path

Capacity – [Ah] (Current [A] x Time [hours]) - total stored electrical charge

- Nominal Capacity – the rated capacity of a cell given by the manufacturer
- C rate – proportional rate of charge or discharge related to rated capacity, “C” defined as discharge current divided by theoretical current draw under which the battery would deliver its nominal rated capacity in one hour. 1C discharge rate would deliver battery's rated capacity in 1 hour, 2C discharge rate means it will discharge twice as fast (30 minutes)
- 1C capacity – the capacity of a cell when discharged in 1 hour, usually at 25°C
- Capacity is rate and temperature dependent

Efficiency, [%]

- Capacity efficiency (Coulombic) – Ah(out)/Ah(in); around 99.5% for Li-ion
- Energy efficiency – Wh(out)/Wh(in); ~ 95% for Li-ion. The higher the rate of charge and discharge the lower the efficiency due to energy lost in heat

State-of-Charge (SOC) - %, SOC is a measure of the energy content in the battery

Depth-of-Discharge (DOD) - % DOD is measure of energy amount taken out of battery

Life

- Cycle life, [cycles] – USAGE, depends on rate, DOD, SOC and temperature
- Calendar life, [years] – STORAGE, depends on SOC and temperature

Self-discharge – [mV/day] – LEAKAGE, reversible loss of capacity over time

LI-ION CELL FORMFACTORS AND CHEMISTRY VARIANTS

The performance of a Li-ion cell is determined by a balance of competing and subtle trade-offs that depend on its major components: the cathode, anode, electrolyte, internal cell design and external cell size. The interplay of physical and chemical variables makes it difficult to make a direct or linear correlation between design and performance. When designating requirements, it is often best to specify a range of parameters and a pareto of performance priorities and find one or two cells that are a best fit.

Formfactors:

Li-ion cells are available in three main mechanical configurations pictured below: cylindrical, prismatic and polymer (also called pouch or laminate). These are designated by their physical dimensions- diameter by length for cylindrical and thickness by width by length for prismatic and polymer. These are all the same basic chemistry and fundamentally work the same way; the physical construction is different and mechanical design guidelines therefore vary.

Figure 4: Li-ion formfactors

Until recently, cylindrical cells were used most widely in consumer electronics- lap-top computers in particular. Prismatic cells were used in more niche products like camcorders and early cell phones, but as polymer production became more robust and quality became more reliable consumer products like notebooks, tablets, e-readers and mobile phones almost universally adopted that technology because of the extremely thin sizes and better gravimetric energy density. Some industry experts predicted an eventual decline in the use of cylindrical cells, also, but then the motive and high power applications took off, causing a steep increase in demand for larger sizes and higher power. The effect of these forces on market consumption are shown in the figure below.

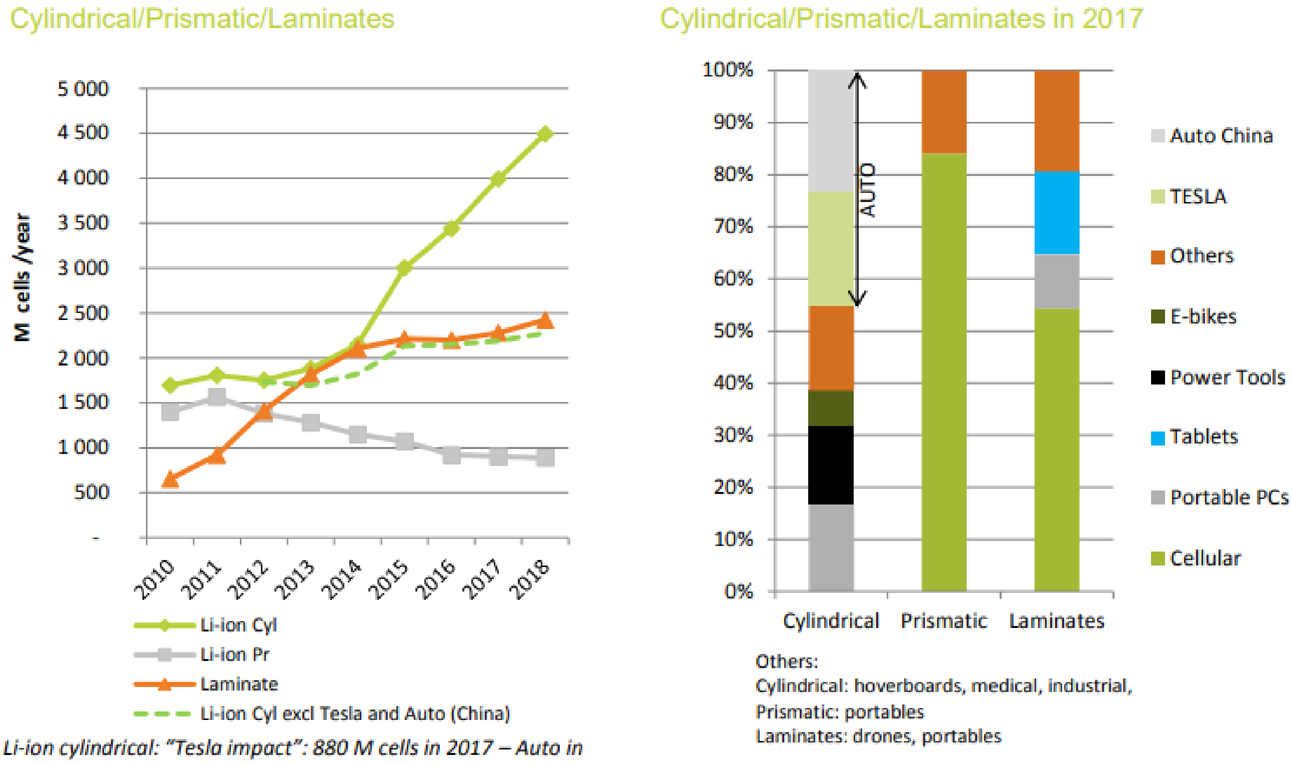


Figure 5: Li-ion market size and application by cell type (source Avicenne)

Newer cylindrical sizes are being introduced because of the widespread adoption of Li-ion cells in electric vehicles, electric-bikes and larger power tools particularly for lawn and garden equipment. The widely used 18650 cylindrical cells (18mm diameter × 65mm long) are being supplemented in the market by 21700 cells (21mm diameter × 70mm long) which provide both higher capacity (5.0Ah) and power (35-40 Amp) in a (larger) cylindrical form factor.

These new form factors are enabling battery pack manufacturers to optimally match cells to user priorities with respect to voltage, discharge power, operating temperature range, in order to better meet the increasing longer service life requirements.

Refer to the note on C rate above for the interplay between size, capacity and rate capability.

Chemistry:

Figure 9 gives an overview of the common cathode materials used today. $LiCoO_2$ (LCO) cathodes have been used from the introduction of Li-ion. “Mixed metal” oxides replace some of the cobalt content with Nickel, Manganese or Aluminum (NCA, NMC) in order to adjust safety, capacity and rate capability. Lithium iron-phosphate (LFP) is the most recent addition to the options. A divide has occurred in recent years with LCO still being dominant cathode in polymer/pouch cells used in consumer electronics and NMC/NCA now being the cathode of choice for cylindrical (18650/21700) and larger format EV cells. This is due to the different performance priorities and the trade-offs those applications require. Generally, consumer electronics differentiate with long run-time from high capacity or energy density and faster charge rates, but cycle/calendar life is a lower priority. This focus on higher energy density has led the consumer electronics to push the charge voltages up to 4.5V today largely using only LCO cathodes, knowing this will be a detriment to cycle life.

The cylindrical 18650/21700 and larger format cells have moved to NMC and NCA cathodes. At the lower charge voltages these materials provide good energy density with improved cycle and calendar life prioritized by the applications like electrical vehicles and energy storage. There is also a concerted effort to reduce the very expensive and toxic cobalt used going to higher and higher concentrations of nickel because these applications use so much raw material. NMC for example has gone from an even ratio of Ni, Co, Mn (each in equal 1/3 proportions) to the “high Nickel content” cathodes which are as high as 80% Ni with remaining roughly 10% each of Mn and Co (a.k.a. 811 NMC).

	Li-Co	Li-NMC or NCA	LFP
Common Name	Li-Cobalt	"mixed metal"	Li-Iron Phosphate
Capacity	2.6 - >3.0AH	2.2 – 2.8AH	1.3 – 3.0AH
Voltage	3.7 V	3.6V - 3.7V	3.3V
Internal Resistance	Low	Low	Lowest
Energy Density	Highest	High/highest	Lower
Max Discharge	1-2C typical	2C-10C	10C typical
Max Charge	0.7 C	0.3-0.7C	2C - 4C
Self Discharge	Low	Low	Lowest
Cycle Life	300-750 cycles	300 - 750 cycles	2-5k cycles
Safety	+	++	+++
Primary Application	PC Notebook, Mobile phones (mostly polymer going forward)	Mid-high rate cylindrical (E-bikes, power tools)	Power tool/ESS
Key Suppliers	Sanyo, Panasonic, LG, ATL (polymer)	Panasonic, Samsung, LG, Sony	A123, Sony, K2, BAK

Figure 6: Li-ion cathode chemistry comparison

LFP cells continue to grow slowly and steadily. The stability of the LFP cathode provides very long cycle and calendar life with improved safety making it attractive for markets where total cost of ownership is a priority. LFP is gaining traction replacing Lead Acid in UPS, Material Handling, Medical, and Industrial markets. LFP is a good match helping to ease the transition from the legacy Lead Acid infrastructure because it's voltage is a more even match, it can tolerate high intermittent loads and tolerates a somewhat less strict charge regimen that the other cells. In applications where a lead acid battery needs to be replaced frequently, it can make good economic sense to transition to LFP.

Rate Capability:

Another change taking place in the market relates to rate capability of cells and their adoption into new applications. High capacity and lower (1C) rate capable 18650 cells traditionally used in consumer electronics products are being replaced by polymer. Mid-rate cells were introduced initially for e-bikes but are making their way into applications such as material handling, telecom, and light electric vehicle. High-rate cells, which were originally designed specifically for power tools, are now being used in lawn and garden/outdoor power equipment as well as UPS and server applications requiring high discharge rates

The figure below shows a generalization of the industry roadmap, attempting to consolidate capacity, rate capability and size in one picture.

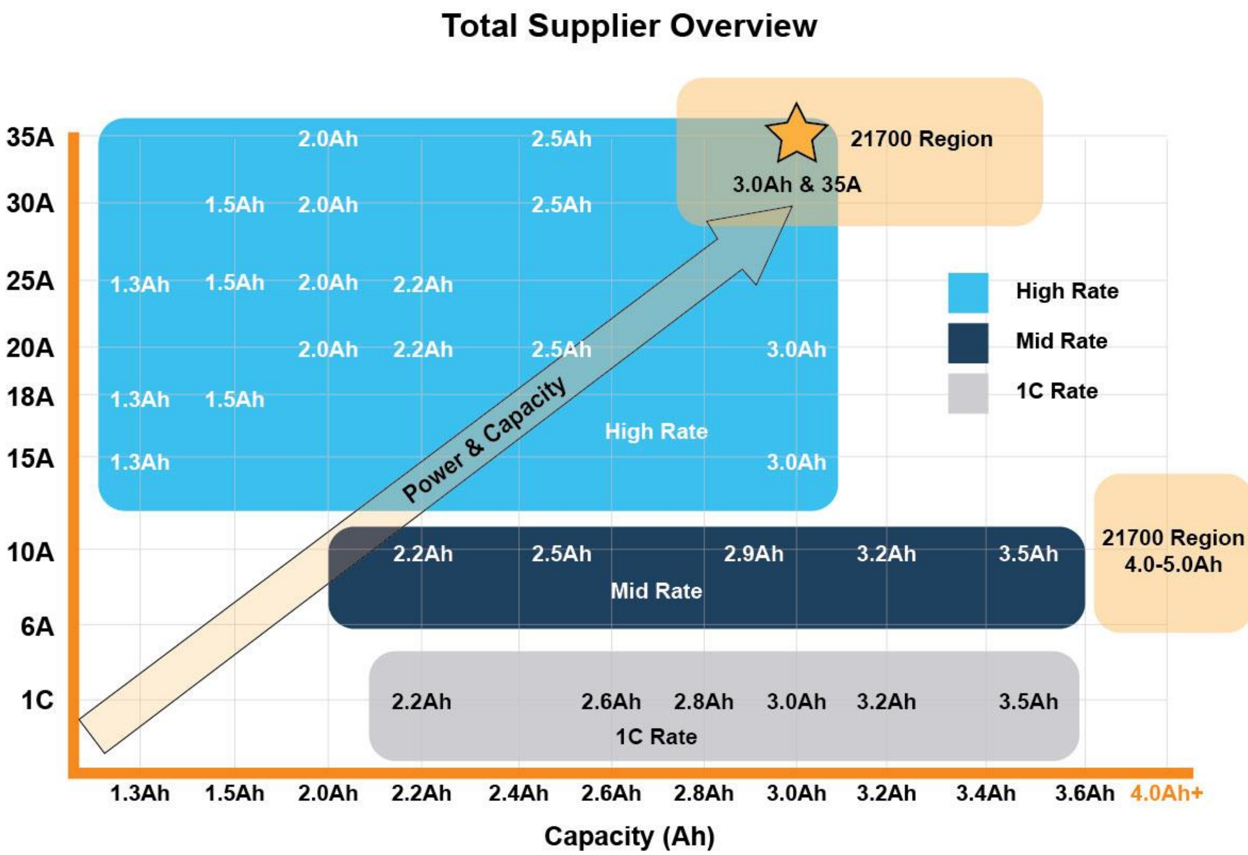


Figure 7: Cylindrical cell supplier roadmap

LI-ION CELL SUPPLIERS MARKET SHARES

The following three charts show the market share percentage for cell manufacturers of each of the three major form factors. For the cylindrical market there has been considerable consolidation within the traditional top tier manufacturers, so much so that automotive makes up roughly half the product consumption. Given this situation, it is difficult to find a source for small and mid-products, so a supplier with the resources to qualify and monitor the quality of a lesser known cell supplier is crucial.

As discussed above, prismatic cells are on the decline and are largely being replaced by polymer cells. Polymer cell volumes are being driven by consumer electronics and because of the manufacturing methods used have the advantage of being customizable for high volume, but the disadvantage of few standard products and set up costs that are too high for small and medium volume products. Managing these competing requirements is a careful balancing act in the selection of a supplier.

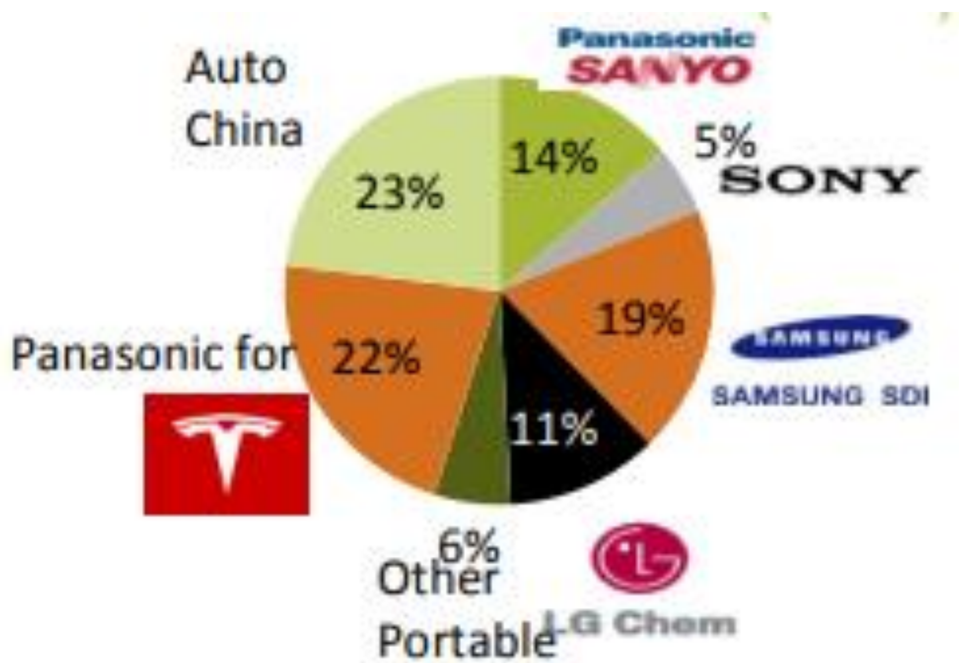


Figure 8: Cylindrical cell market share (source: Avicenne)

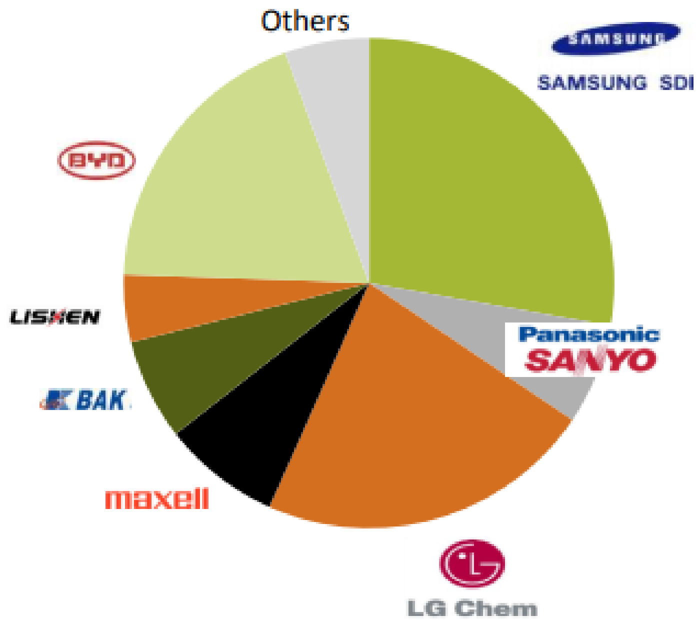


Figure 9: Prismatic cell market share (source: Avicenne)

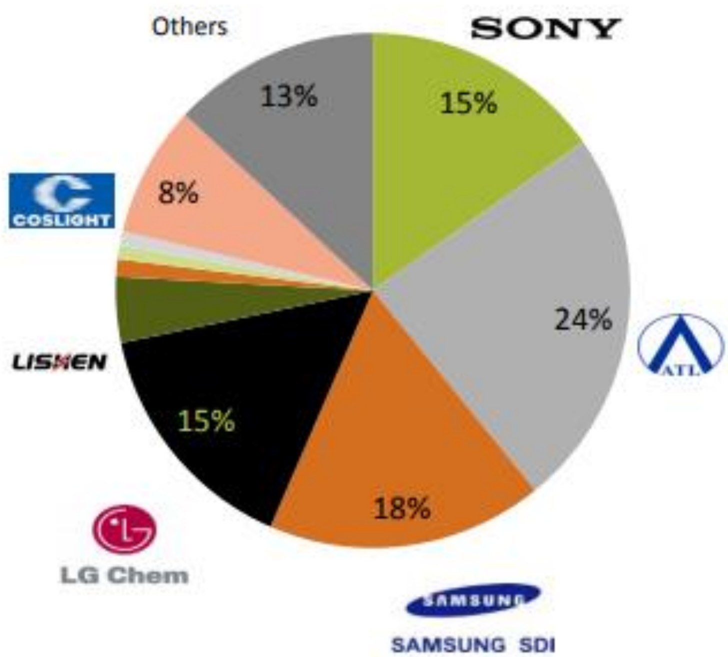


Figure 10: Polymer cell market share (source: Avicenne)

CONCLUSIONS

The rapid evolution of the battery market is driving innovation and variety and the innovation, in turn, is enabling more applications.

The increase in options for formfactors and specific chemical formulations provides an exciting opportunity for differentiation, it also brings a lack of stability for both supply and cost.

Growth has been especially notable in the medium-to-large format area with larger systems becoming even more prevalent than traditional applications like mobile computing.

The widely used 18650 cylindrical cells are being supplemented by 21700 cells which provide both higher capacity and power in a cylindrical form.

Cells are now available with low, mid and high rate capabilities for higher power applications.

A divide has occurred in recent years with LCO still being dominant cathode in polymer/pouch cells used in consumer electronics and NMC/NCA now being the cathode of choice for cylindrical and larger format EV cells.

LFP cathodes continue to grow steadily. The stability of the LFP cathode provides very long cycle and calendar life with improved safety making it attractive for certain markets.

Lithium-ion anodes have traditionally been Carbon (graphite) based but, in the last few years, Silicon has been added in relatively small increments to the graphite.

Phasium designs and manufactures high-efficiency, smart, power products and assemblies for medical and industrial markets. Using advanced conversion techniques, resourceful mechanical design, and conservative design rules, the company's competitively priced products include standard and custom adapters, power supplies, battery packs, chargers, and docking stations. With an ISO 13485 facility, Phasium is the premier power brand of Megmeet.

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