August 2020

Cobalt Substitution and Future Battery Material Requirements

Large scale utilization of renewable energy sources and electric mobility will rely on the development of high density and efficient storage solutions. To date, the ubiquitous chemical battery technologies have included alkaline, lead-acid, nickel based, and various types of lithium ion chemistries. However, in deep cycle applications, lead-acid batteries quickly experience capacity degradations due to grid corrosion of the positive electrode and positive plate expansion.[i] Nickel-cadmium (NiCd) and nickel-metal-hydride (NiMH) drawbacks include high self-discharge rates and relatively low Coulombic efficiency. Thus, lithium ion chemistries including lithium-cobalt oxide (LCO), lithium-nickel-cobalt-aluminum oxide (NCA), lithium-nickel-manganese-cobalt oxide (NMC), and lithium-iron phosphate (LFP) exhibit the characteristics best suited to address the demands of expanding renewable energy consumption.

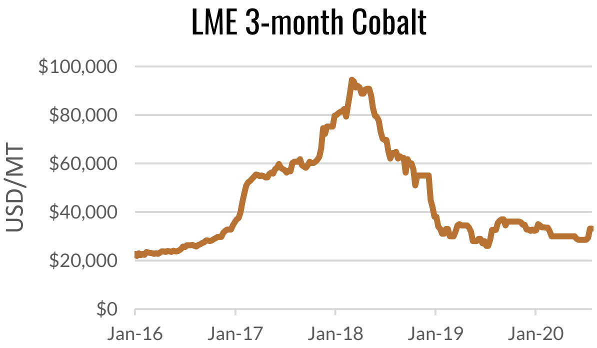


Figure 1: Source: Bloomberg

Lithium ion battery (LIB) technologies are not without drawbacks. Despite their higher energy density and low maintenance requirements, lithium ion batteries are higher cost and more fragile than other technologies and require a protection circuit to maintain safe operations. Additionally, concerns have arisen over the use of cobalt anodes in most LIB applications. Over 60% of global cobalt supply comes from environmentally damaging, child labor utilizing mines in the Democratic Republic of the Congo.[ii] These practices are antithetical to the ideals surrounding the push for renewable energy technologies. This, combined with the cobalt price spike from 2017 – 2018 (Figure 1) and various automotive safety regulations, have led battery manufactures to pursue zero-cobalt cathodes. As a result, there have been rapid advances in cathode chemistries that may materially alter the future raw material needs of the battery industry. Furthermore, electrolyte and anode chemistries will likely have to evolve alongside the cathodes. Thus, evolving battery chemistries must be closely monitored to ensure that the appropriate raw materials are available to enable the expansion of renewable energy generation and use.

Despite exhibiting a lower massic energy than other lithium ion chemistries, lithium-iron phosphate (LFP) battery production has surged in China in 2020. Tesla, BYD and VW have all chosen to utilize LFP batteries in some of their EVs in the Chinese market. In May 2020, China's Ministry of Industry and Information Technology (MIIT) approved EV safety regulations which require EVs to inhibit any fire or explosion caused by thermal runaway within five minutes. Unlike other lithium-ion chemistries, nano-scale phosphate cathodes, the only commercial cathodes that are olivine, allow LFP batteries to naturally conform to these standards. NCM and NMC batteries would require mitigation systems such as fire-proof mica plating to meet these requirements. While there have been significant advances in LFP technologies, the global EV market is still likely to be dominated by high nickel loading chemistries. LFP batteries' comparatively low specific energy (50% - 60% capacity of NMC and NCA technologies)[iii] restricts their application to low range and compact vehicle applications. Furthermore, the consortium managing LFP intellectual property rights allows license free manufacturing of LFP only in mainland China. Thus, LFP battery deployment in these applications will be relegated to China's domestic market at least until these IP protections begin to expire in 2022.

Though NCA, LCO, and NMC batteries will likely dominate the EV market (Figure 2), China's reversion to LFP batteries to meet safety standards highlights one of the many ancillary effects of removing cobalt from cathode materials: as batteries utilize higher percentages of nickel, the nickel ions tend to intermix with lithium ions, leading to thermal instability. This instability is due to the fact that nickel has a relatively strong magnetic moment and any trinity of nickel cations will have two opposing magnetic moments.[iv] Without cobalt, the lithium ions, which have no magnetic moment, will preferentially exchange with the nickel ions, thereby deteriorating battery performance. When cobalt is introduced, this lithium-nickel mixing is mitigated.

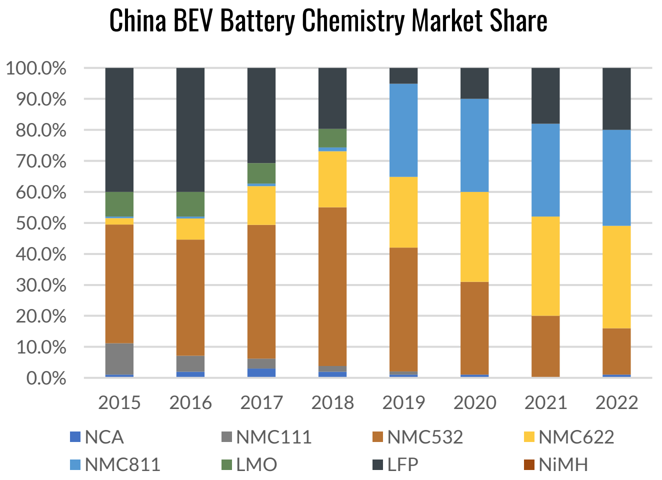


Figure 2: Source: CRU

Despite its beneficial electrochemical properties, battery manufacturers are focusing their efforts on reducing cobalt loadings due to the previously described supply practices. These efforts have yielded significant results. NMC chemistries were introduced with 111 ratios, with each number representing the mass of nickel, manganese and cobalt, respectively, utilized in the cathode. Technological advances progressively led to the introduction of 532, 622 and 811 chemistries, though, generally, each reduction in relative cobalt loading led to a concomitant decrease in cycle stability and safety.[v] Panasonic has already achieved under 5% cobalt content in the cathode materials of their NCA batteries, which are utilized by Tesla. Substituting cobalt with other transition metals such as titanium and manganese has been shown to outperform the cobalt containing equivalent, but only in ratios that would not be considered commercially viable.[vi] Furthermore, while manganese and aluminum may increase cathode thermal stability and reduce reactivity with the electrolyte compared to cobalt, this comes at the cost of specific capacity.[vii,viii] Regardless of the stabilizing constituents, Dahn et. al. (2019)[ix] found that all high nickel cathodes exhibit reduced specific capacity and premature cell failure, implying that there may be a ceiling to relative nickel loadings.

The above observations call into question the seemingly ubiquitous assumption that NCM 811 will come to dominate the EV market (Figure 3). NCM 811 chemistries have seen rapid increases in energy density and thermal stability, but lithium ion decoupling issues remain. Furthermore, NCM 811 batteries may have trouble meeting EV safety standards without modulators and fireproof plating, each of which increase the weight and cost of the vehicle. NCM 622 do not exhibit the same issues as NCM 811 batteries while still achieving specific capacities of 350Wh/kg or more. Thus, while forecasts broadly assume that market share will be determined simply by the highest nickel content and therefore highest energy density, actual market share of each chemistry will likely be determined rather by the market share of the appropriate end use: NCM 811 for luxury or high performance vehicles, NCM 622 for mid-size passenger vehicles and LFP batteries for low range, city vehicles. The viability of each of these will further be dictated by factors such as population density and available EV charging infrastructure (Figure 4).

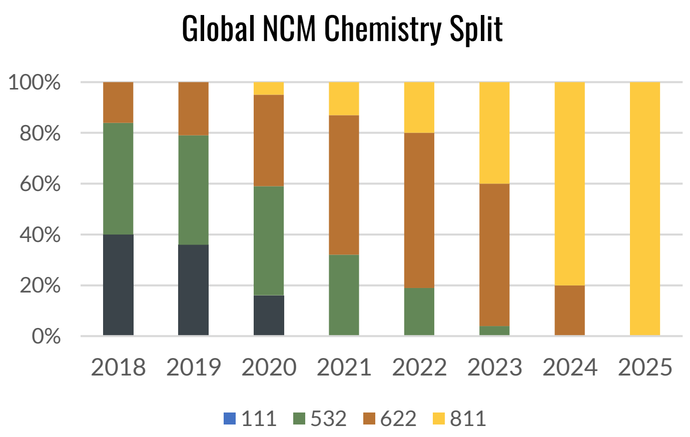


Figure 3: Source: Wood Mackenzie

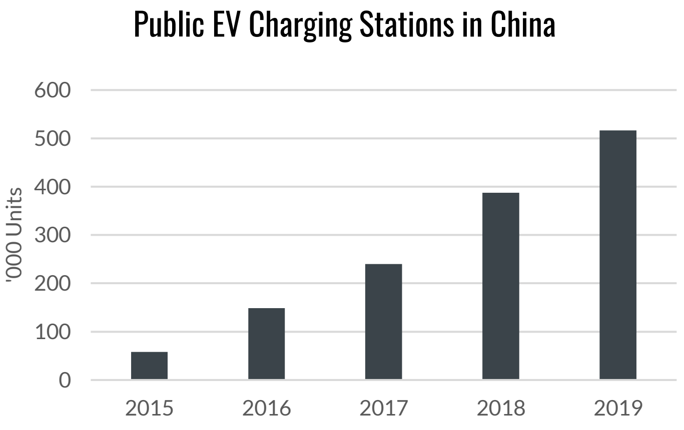


Figure 4: Source: SAE China

While tailoring a battery's chemistry to its end use may seem like an effective way to achieve cost efficiency gains, myriad factors contribute to the overall cost of the application in practice. Firstly, as with any manufacturing, unit cost reductions are achieved by increasing plant utilization rates. However, battery production facilities are tailored to specific chemistries and retooling these facilities is time consuming and expensive. Thus, manufacturers and consumers will be reluctant to quickly adopt a new chemistry. Second, as described above, additional safety components may be needed for specific battery chemistries. In some instances, these additional components may completely negate the higher specific energy or lower cost of a given battery chemistry. Last, in the case of EVs, different battery chemistries may be better suited for different types of motors. For instance, variations in battery costs must be assessed alongside the relative efficiencies of permanent magnet motors versus induction motors when calculating an EV's lifecycle cost (Figure 5). Given the above,

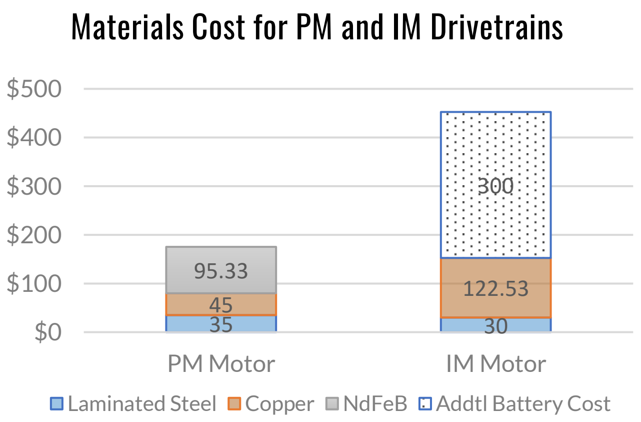
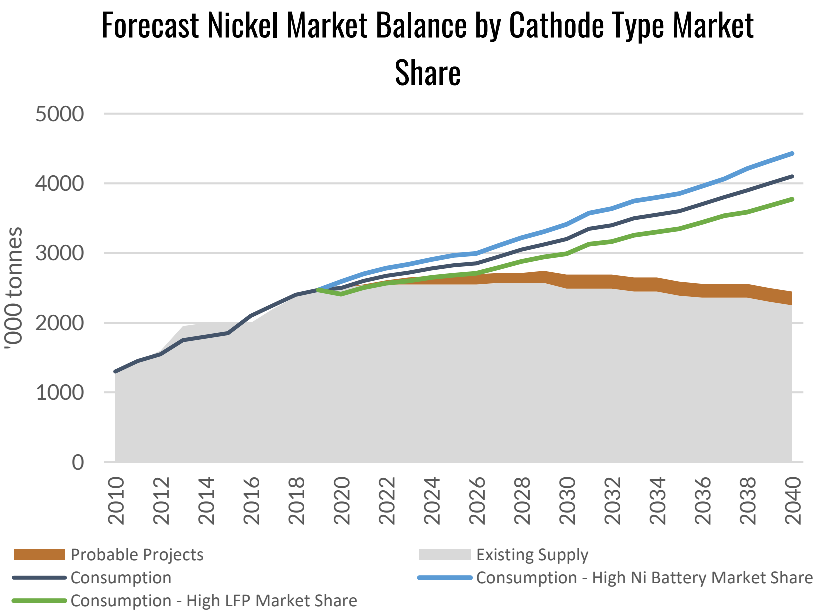


Figure 5: Source: Adamas Research. PM: Permanent Magnet; IM: Induction Motor

myopically focusing on battery production costs may not be completely effective in reducing battery powered consumer products, particularly EVs.

The importance of developing efficient battery chemistry extends beyond electric mobility. Large scale utilization of renewable energy sources will rely on the development of high density and capacity storage solutions. A study commissioned by California’s largest utilities found that that the effective load carrying capability (ELCC) of solar generation facilities ranged from 4 – 5.8%.[x] ELCC conveys the reliability of a resource to provide electricity at a given time. In this case, assuming a 6% ELCC, a 100MW solar plant would only be expected to provide 6MW during periods of peak demand. Wind generation was found to have an ELCC of 30%. However, with the addition of a four-hour battery storage solution, solar and wind ELCCs jump to 99% and 62%, respectively. Furthermore, these storage solutions can be quickly integrated with existing renewable generation facilities to replace a portion of fossil fuel powered peaking plants.

Cathode material needs will be constantly evolving and analyzing one component of any battery powered end product in isolation may produce erroneous overall cost estimates. This will be especially true as cathode efficiency is improved to the point where graphite anodes and liquid electrolytes become the limiting factor for increasing specific energy. Solid state electrolyte batteries are believed to be the only viable solution for achieving EV cost parity with internal combustion engines, and the introduction of a viable solid electrolyte, such as Aionics’ lithium-boron-sulfur system, will again significantly impact the raw material needs.[xi] For materials such as nickel, the demand variations due to LFP or other nickel-free cathode solutions’ market share will impact the magnitude of future deficits, but will likely be unable to alleviate these market imbalances altogether (Figure 6). In contrast, battery related demand variations of materials such as cobalt or titanium may be significantly impacted by breakthroughs in cathode technology, consumer preferences, safety standards or other government regulations. Thus, forecasting future battery material needs must look beyond solely the battery components and integrate charging infrastructure, grid storage needs, demand by applications, and myriad other factors to accurately provide a comprehensive picture of future needs.



Endnotes

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[i] www.batteryuniversity.com

[ii] https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

[iii] https://www.reuters.com/article/us-panasonic-tesla-exclusive/exclusive-panasonic-aims-to-boost-energy-density-in-tesla-batteries-by-20-executive-idUSKCN24V1GB

[iv] 2. J. Zheng et al., J. Phys. Chem. Lett. 8, 5537 (2017).

[v] T. Li *et al.*, *Electrochem. Energy Rev.* 2019, 1 (2019)

[vi] Cobalt in Lithium-ion batteries

[vii] BMO Capital Markets. Accelerating Quest for Zero Cobalt Cathode has Hit a Speed Bump. August 13,2020

[viii] Li, H., Cormier, M., Zhang, N., Inglis, J., Li, J. and Dahn, J. (2019). Is Cobalt Needed in Ni-Rich Positive Electrode Materials for Lithium Ion Batteries? Journal of the Electrochemical Society; 166(4):A429-A439.

[ix] Li, H., Liu, A., Zhang, N., Wang, Y., Yin, S., Wu, H. and Dahn, J. (2019). An Unavoidable Challenge for Ni-Rich Positive Electrode Materials for Lithium-Ion Batteries. Chemical Materials, 31(18):7574-7583.

[x] https://library.sce.com/content/dam/sce-doclib/public/regulatory/filings/pending/electric/ELECTRIC_4243-E.pdf

[xi] Sendek, A., Antoniuk, E., Cubuk, E., Ransom, B., Francisco, B., Buettner-Garrett, H., Cui, Y. and Reed, E. (2020). Combining superionic conduction and favorable decomposition products in the crystalline lithium-boron-sulfur system: a new mechanism for stabilizing solid Li-ion electrolytes. ACS Applied Materials & Interfaces; doi.org/10.1021/acsami.9b19091