Lithium-ion Battery High-energy Cathode Innovation & Patent Review

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About the Author

Pirmin Ulmann obtained a diploma in chemistry from ETH Zurich (Switzerland) in 2004 and a PhD from Northwestern University (USA) in 2009. Thereafter, he was a JSPS Foreign Fellow in an ERATO academic-industrial project at the University of Tokyo (Japan). From 2010 to 2016, while working at a major battery materials manufacturer in Switzerland, he was a co-inventor of 7 patent families related to lithium-ion batteries. He was also in charge of a collaboration with the Paul Scherrer Institute, evaluated outside technologies for corporate strategy, and made customer visits to battery manufacturers in East Asia, North America & Europe. He holds the credential Stanford Certified Project Manager (SCPM) and has co-authored scientific articles with more than 1,800 citations.

Balancing Raw Materials Costs – Ni / Mn-containing vs. Fe / Mn-containing Active Materials

Ni / Mn-containing positive electrode (cathode) active materials (such as NMC, NMCA, Co-free NMx) typically account for >50% of overall Li-ion battery cell materials costs. For this reason, Li-ion battery cell manufacturers are continuously evaluating if a replacement with lower cost positive electrode active materials is feasible:

- by relying on lower-cost raw materials, such as Fe & Mn (price information Ni / Li / Co / Mn / Fe),
- or through reduced manufacturing process costs (see below).

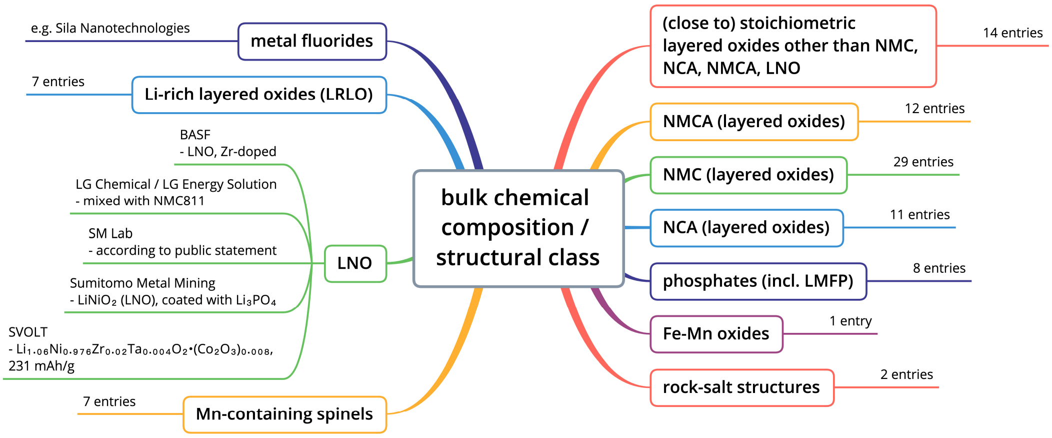
Recent developments (within the frame of liquid electrolyte Li-ion battery cells) suggest that two positive electrode material technology tracks will split up most electrified transport applications between them:

- cells with **Ni-dominant positive electrode active materials,** 90 to >99 mass% Ni (in relation to the total transition metal content), theoretical limit for LNO ($LiNiO_2$): 275 mAh/g reversible capacity, 3.8 V vs. Li^+/Li average potential.
- cells with **iron-based LFP ($LiFePO_4$) positive electrode active materials,** theoretical limit: 170 mAh/g, 3.43 V vs. Li^+/Li average potential. These materials will evolve towards **iron / manganese-based LMFP with increasing Mn content,** theoretical limit for LMP ($LiMnPO_4$): 170 mAh/g, 4.1 V vs. Li^+/Li.

Decision Tree for High-energy Cathodes

In Figures 2-7, R&D decisions by various companies are plotted, as reflected in the patent literature. The emphasis is on illustrating the commercially most relevant and promising options, without claiming comprehensiveness as to capturing all applicants active in a certain area. With few exceptions, only new patent families published since 2019 have been included (focus: new patent families published since 2021). It is therefore possible that earlier patents that constitute 'foundational IP' are not shown.

Figure 4: decision tree - bulk chemical composition / structural class (full review contains all entries)



- **LNO (stoichiometric, layered $LiNiO_2$):** LNO has very quickly expanded from the academic domain to being a very hot topic of commercially oriented product development. Doping (BASF - Zr, SVOLT - Zr / Ta / Co), coating (Sumitomo Metal Mining - Li_3PO_4), mixing with NMC (LG Chemical / LG Energy Solution) are strategies pursued to stabilize LNO towards sufficient cycling stability and 1st cycle efficiency. SM Lab's approach to LNO has not yet been published in the patent literature.
  Because the theoretical energy density limits of LNO are very favorable (275 mAh/g reversible capacity, 3.8 V vs. Li^+/Li average potential) without the need for overlithiation (risk of gassing, accelerated aging at high voltages as described above for LRLO), LNO will continue to represent a highly attractive product development target for current manufacturers of stoichiometric layered oxides and other players that wish to develop positive electrode active materials that can be deployed in liquid, semi-solid and solid Li-ion battery cells (i.e., unlike overlithiated LRLO and Mn-rich spinels, the market success of LNO likely does not hinge on the successful establishment of solid catholyte / solid electrolyte supply chains).

AI-based Identification of Commercially Relevant Patents

b-science.net has developed a supervised AI methodology to assess the commercial relevance of patents, combined with an automatic translation framework that makes sure Non-English patents are also identified. The methodology was validated as shown in the Appendix. With this approach, we have comprehensively identified & classified patents by companies active in commercial R&D on high-energy Li-ion battery positive electrodes.

Focus of This Review

This review focuses on the global innovation & patenting activity by companies in Li-ion battery high-energy positive electrode active materials for large scale, high-energy applications (key application: EVs). Patent families were classified into 5 categories: **A)** bulk properties; **B)** particle microstructure, composites, gradients; **C)** surfaces; **D)** manufacturing, reliability & safety; **E)** positive electrodes; **F)** active materials produced through recycling.

Each listed patent family has been labeled according to its active material category: Li-rich layered oxides - (LRLO, 10% or more overlithiation), Mn-containing spinels, LNO, (close to) stoichiometric layered oxides other than NMC, NCA, NMCA, LNO (up to 10% overlithiation), NMCA, NCA, NMC, phosphates, Fe-Mn oxides, rock-salt structures. If applicable, listed patent families are flagged with 'possible use for commercial products' (if an elevated likelihood is seen by the author towards commercialization). The goal is that the reader understands which product development topics are of highest commercial interest to the industry, and how the high-energy positive electrode active materials supply chain will prospectively evolve in the coming years.

Patent Analysis AI Methodology & Validation

The patent information source for this review is the European Patent Office (EPO), which covers patent filings from more than 100 patent offices around the world. >2.4M patent documents are included in the b-science.net database that were published since 1980, which either contain the words 'battery' or 'batteries' in the title or abstract, or were assigned to one of the energy storage-related CPC (cooperative patent classification) or IPC (international patent classification) codes: H01M (batteries & fuel cells) or H01G (capacitors). An AI model was defined for commercially relevant high-energy positive electrodes of Li-ion batteries. Patent documents were grouped into patent families and scored with the AI model. An AI relevancy score cutoff value of 40 was applied (100: very relevant, 0: not relevant).

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