**The Iron Age of Automotive Batteries:
Techno-economic assessment of batteries with
lithium metal anodes paired with iron phosphate
cathodes**

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Abstract: There are two major recent trends in batteries, (i) the resurgence of lithium iron phosphate (LFP) as the cathode material of choice for EV applications and (ii) lithium metal anode batteries either with a Li-foil or in an anode-free configuration emerging as competitive options over the conventional Li-ion anodes. In this study, we perform a techno-economic assessment of pairing LFP with Li metal anode (LFP|Li). Based on this analysis, we find that the combination of Li|LFP provides a 20-25% increase in specific energy and over 35% increase in energy density with an anode-free configuration using an oxidic solid-state separator while a thin thin Li-foil provides a specific energy increase of about 30%. We find that Li|LFP in an anode-free configuration provides significant cost reductions over cells with a graphitic anode. The cost of Li|LFP is most sensitive to the cost of a solid separator in the anode-free configuration and the cost of lithium foil in the Li-foil configuration.

Electrification of transportation is well underway but further cost declines are needed to enable more widespread mass-market adoption.¹ In an earlier article,² we highlighted two noteworthy developments: announcements by *Volkswagen AG* and *Tesla Inc.* of their intention to employ lithium-iron-phosphate (LFP) for a large fraction of the anticipated production,³ and an announcement by stationary storage battery manufacturer *Form Energy Inc.* of the development of iron-air batteries for long-duration energy storage.^{4,5}

Alongside, there are massive investments related to anode development, most notably related to lithium metal anodes.^{6,7} Li metal anodes provide a much higher specific energy than graphite⁸ but have been plagued by low cycle life, resulting in cells which are not commercially viable. However, a slew of recent innovations have rendered cells that can potentially satisfy the challenging automotive requirements simultaneously.

Pairing lithium metal anodes with LFP cathodes is at first counter-intuitive, since LFP has lower performance metrics (energy density, specific energy) than nickel-rich cathode materials such as Nickel-Cobalt-Aluminum oxide (NCA) or Nickel-Manganese-Cobalt oxide (NMC).⁹ But, pairing LFP with a metal anode may be able to offset the disadvantage relative to a nickel-based layered oxide/graphite cell, enabling higher energy efficiency from batteries using these chemistries.¹⁰ In addition, LFP offers improved thermal safety,¹¹ avoids nickel and cobalt supply chain challenges,^{12,13} and, as will be shown in this analysis, provides a lower cost compared to nickel-rich materials.

In this work, we augment our previous analysis² by comparing various configurations of LFP cathodes with Li-foil anode and anode-free configurations as well. We find that anode-free cells with an LFP cathode present a strong opportunity to enhance EV adoption by providing a specific energy and energy density comparable to that of NMC-graphite, but costing up to 25% less. The cost reduction for anode-free configuration with a solid-state separator is realized only if the cost of the solid-state separator approaches the cost of polymeric separators used today. Li-foil cost plays a significant role in determining the feasibility of pairing Li-foil with LFP.

Techno-economic assessment

The manufacturing cost of Li-ion batteries has seen a remarkable drop in the last decade.¹⁴ The reported cost of Li-ion cells was around lower than US\$100/kWh across all commonly used chemistries for the last two years.¹⁵ Li-ion cells with LFP cathodes were reported to have achieved a cost of about US\$80/kWh^{15,16} while NMC and NCA-based cells were at about US\$100/kWh.^{15,16} It is worth highlighting that in the year 2021, there has been a considerable spike in prices of required commodities for manufacturing Li-ion cathode active materials including a sharp increase in the price of raw materials^{17–19} including lithium carbonate, lithium hydroxide, nickel sulfate, and other materials. This has led to an increase in the price of active materials to pre-2020 levels.¹⁹ In this analysis, we use the recent¹ active materials prices as inputs to our cost model, however, note that in 2021, there has been a deviation in the expected trend in the historical price of commodities required for manufacturing Li-ion batteries.¹⁷ Further, due to the volatility in active material prices, we limit our analysis to the use of NMC-811 and LFP as the cathode materials of choice, given their relevance to the EV market, and due to the availability of multiples sources and price indices for the two cathode materials.

The active material cost for 2021 used within the cost modeling framework for LFP is US\$7/kg (compared to <US\$5/kg reported for 2020¹⁵ and current price of around US\$10/kg¹⁹). For NMC-811 we use an active material input cost of US\$22.7/kg (compared to about US\$16/kg reported for 2020¹⁵ and current price of around US\$35/kg¹⁹). The price of other components can be found in the model file from the Github repository.

The broad goal of the techno-economic assessment is to first quantify the relative change in specific energy and energy density when current graphite anodes are replaced with Li-metal foil as well as anode-free designs enabled by solid-state electrolytes and further compare the cell manufacturing cost for the same via a process based cost model (PBCM). These comparisons are performed for an LFP based cathode, given the context discussed earlier.

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¹'Recent prices' are reflective of the price across the last quarter of 2020 and the year 2021^{15,16,18} while 'current price' refers to the publicly available prices as of September 9, 2021.¹⁹

We also model the cell performance metrics and manufacturing cost of an NMC-811|graphite cell which is considered to be representative of the state-of-the-art Li-ion battery. We assume oxidic and sulfidic solid electrolytes for our analysis of anode-free cell designs. The cells considered for analysis here are all housed in large format prismatic form factor, which is both suitable for EVs as well as currently expected cells designs incorporating solid state electrolytes.^{20,21}

Figure 1: A comparison of the cell-level specific energy and energy density of various prismatic cells designed for EV applications. The cells designed such that the power-to-energy ratio and other performance metrics of each cell is held constant to provide a reasonable basis for comparison. Other details of the cell design can be found in the Supplementary Material. Gr indicates graphite anodes, LE indicates liquid electrolytes, SE is solid electrolytes, and AF stands for anode-free configuration.

A comparison of the specific energy for various cells designed for EV applications, is shown in Figure 1. Given the lower specific energy of LFP cathodes, we observe in Figure 1a that none of the cell designs with LFP match the specific energy of the NMC|Gr cell. The LFP|Li-foil cell where the graphite anode is swapped with a Li-foil between $20\mu\text{m}$ and $100\mu\text{m}$, with all other components retained has a over 30% higher specific energy than the LFP|Gr cell given the high specific capacity of lithium. The anode-free cell design depending on the density of the solid state separator has a marginally lower specific energy averaging at about 250

Wh/kg for oxidic separators and about 260 Wh/kg for sulfidic separators. For a conventional polypropylene-based separator using LFP|Li-foil cell has a specific energy of 270Wh/kg. This is due to the difference in density of the solid state electrolyte relative to a lithium foil. On examining Figure 1b, we find that in terms of energy density (Wh/L), the improvements for LFP|Li-foil are marginal compared to LFP|Gr because of the low density of the lithium foil. However, there is considerable uncertainty in the Li-foil case given the thickness of the foil can vary significantly resulting in energy density bounds of ~ 495 Wh/L and ~ 590 Wh/L. With the LFP|Li-AF case where the cell does not have a Li-foil, the energy density is seen to improve considerably to over 600 Wh/L which represents a 30% increase in the energy density from LFP|Gr. The uncertainty in energy density for the LFP|Li-AF case is from the thickness of the solid electrolyte separator which was considered to be bounded between $10\mu\text{m}$ and $20\mu\text{m}$. The volumetric energy density of a sulfidic solid electrolyte would be similar to the oxidic one at the same separator thickness.

Each of the cell designs discussed in Figure 1 are analyzed for the manufacturing cost via a process-based cost model based on BatPaC-2019.^{22,23} The summary of the cell-level manufacturing cost estimates are shown in Figure 2. The cost of current Li-ion batteries using LFP and NMC-811 cathodes with graphite are estimated to be about US\$90/kWh and US\$95/kWh respectively. Given the considerable uncertainty in the cost of battery grade lithium foil^{20,21} the cost of LFP|Li-foil could cost up to $\sim$ US\$160/kWh from about US\$90/kWh in the optimistic scenario. Similarly, for the LFP|SE|Li-AF case, in the optimistic scenario of the solid electrolyte costing about US\$1.5/m², the cell manufacturing cost could be about US\$70/kWh. A cost of US\$10/m²²⁴ which is the upper bound considered in this study, the cell manufacturing could be about $\sim$ US\$165/kWh. In the optimistic scenario for the Li-metal anode coupled with LFP cathodes with considered here, the specific energy and energy density advantages lead to reduced use of inactive materials per cell and result in a manufacturing cost that could be much lower than an equivalent Li-ion battery.

PBCM's enable analysis of the effects of and sensitivity to changes in cell inputs, such

Figure 2: A comparison of the cost the four cell designs considered in this analysis. We observe that the specific energy and energy density improvements from moving to lithium-metal anodes provides a considerable advantage and a route to reducing the manufacturing costs, however, there is considerable uncertainty in the price of Li-foil and the price of (oxidic) solid electrolytes which is also shown in the figure. Under an optimistic scenario where the cost of solid electrolyte separator is about US\$1.5/m², the cost of the LFP|SE|Li-AF cell can be as low as ~US\$70/kWh, while higher separator costs of US\$10/m² can drive the manufacturing costs up to ~US\$160/kWh.

as material costs, manufacturing processes, and capital expenditures required to build batteries by incorporating simple models of each process. To analyze lithium-metal anode-free cells, BatPaC²² and BatteryCost.jl²³ are suitably modified to incorporate only a cathode and a lithium foil if required along with the required modifications to the manufacturing process. The required changes to the cell design routine to incorporate varying thickness and density of the separator for solid electrolytes is also implemented within the model. Other details can be found in the Supplementary Material. The processes considered in a typical PBCM include receiving, material preparation, coating, calendaring, binder and solvent recovery, slitting, vacuum drying, stacking, welding, inserting the cell into the container, electrolyte filling, formation cycling, sealing, shipping, and quality control. These processes are modeled using scaling relations which take a baseline cost for each process, scale it based on volume, and result in a final price. The baseline plant assumed for this study produces 5 GWh of batteries annually, this is equivalent to the default assumption in BatPaC of 100,000 battery packs manufactured every year.

Packing Considerations

The enhanced safety of LFP presents opportunities to lower the packing factor of cells as opposed to cells based on nickel-rich cathodes, this can be further exploited in innovations such as structural battery packs. In particular, LFP brings greater thermal stability compared to NMC or NCA. This allows for development of large format cells, such as those proposed by BYD.²⁵ This has led to a cell-to-pack integration efficiency that is 40% higher,¹¹ bringing further increases in specific energy, and thus bolstering the case for LFP. Due to high volumetric cell-to-pack integration efficiency, BYD LFP battery has among the highest pack-level energy density.¹¹

Conclusion

Based on a detailed techno-economic analysis, we find that pairing Li metal with an LFP cathode in an anode-free configuration can close the specific energy and energy density gap to graphite/layered oxide cathodes while simultaneously offering a path towards cost-reduction beyond graphite/layered oxide cathodes. Beyond the cell level, there is a significant potential around achieving a greater cell-to-pack efficiency with LFP, along with possibility of structural battery packs. These two factors along with the chemistry improvements enabled by pairing Li metal with LFP could potentially be an attractive candidate for long-range mass-market EVs.

Data and Model Availability: The `.xlsx` model file and other files are hosted at <https://github.com/BattModels/li-lfp> and at <https://github.com/BattModels/BatteryCost/tree/metal>

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Competing Interests: V.V. is a technical consultant and Scientific Advisory Board member at QuantumScape Corporation, Chief Scientist at Aionics, and technical consultant to Form Energy. All analysis carried out in this work is independent work of the authors.

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