

Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries

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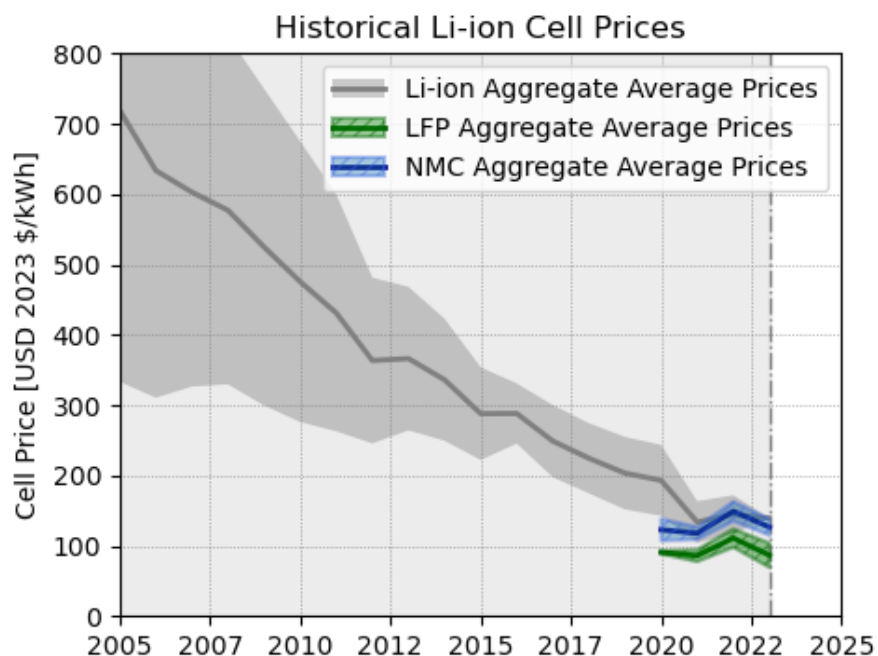
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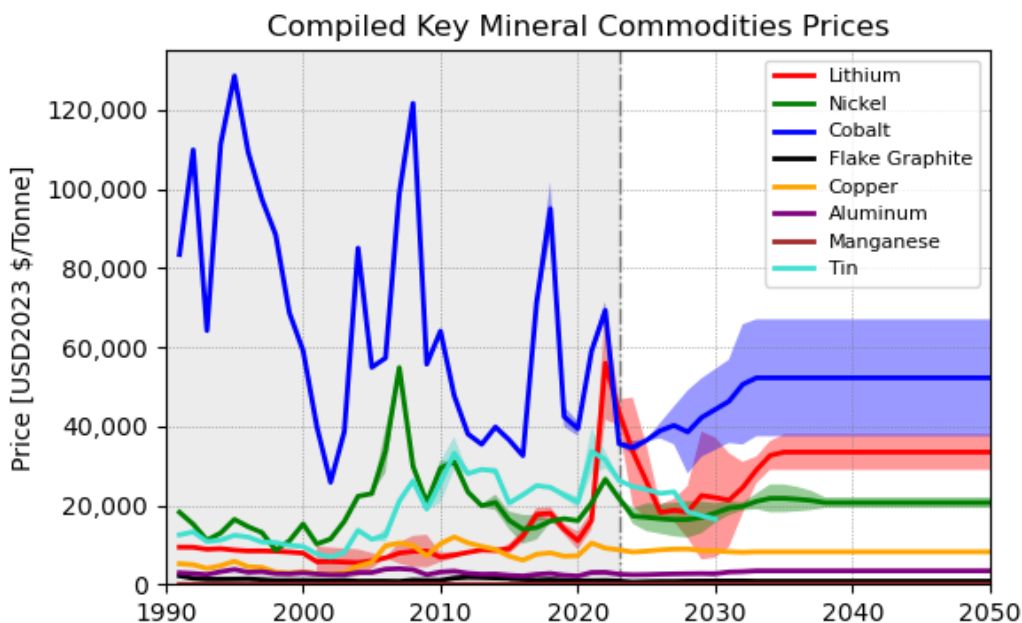
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SUPPLEMENTARY FIGURES



Supplementary Figure 1: Aggregated historical average Li-ion cell prices

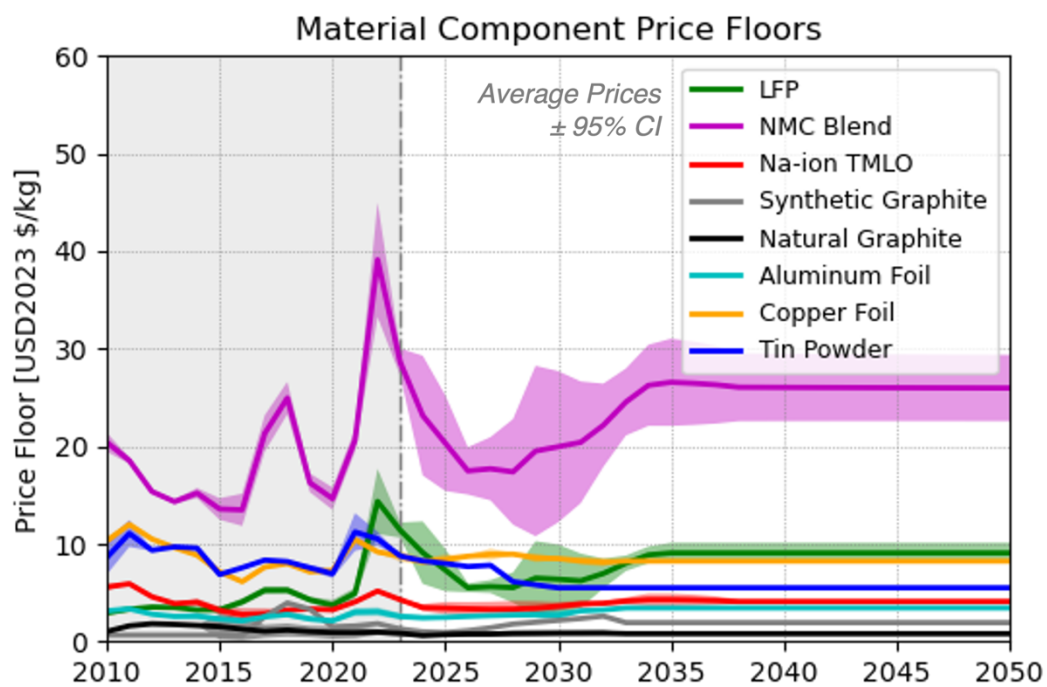
Aggregate average Li-ion cell prices have been well-documented in literature and market intelligence reports¹⁻⁴. In recent years, two dominant families of Li-ion cathode material chemistries have emerged to capture most of the Li-ion market share—NMC-type (nickel-manganese-cobalt oxide) and LFP-type (lithium iron phosphate) cathodes. Due to their diverging price trajectories resulting from differing minerals makeup, market intelligence firms have begun distinguishing chemistry-specific cell prices of NMC and LFP circa 2019. This is reflected in the historic NMC and LFP cell prices shown above aggregated from the industry data contributors to this work with 95% confidence intervals^{1,2,5,6}. As NMC and LFP will approach different price floors, we find it important to resolve the price differences in our modeling.



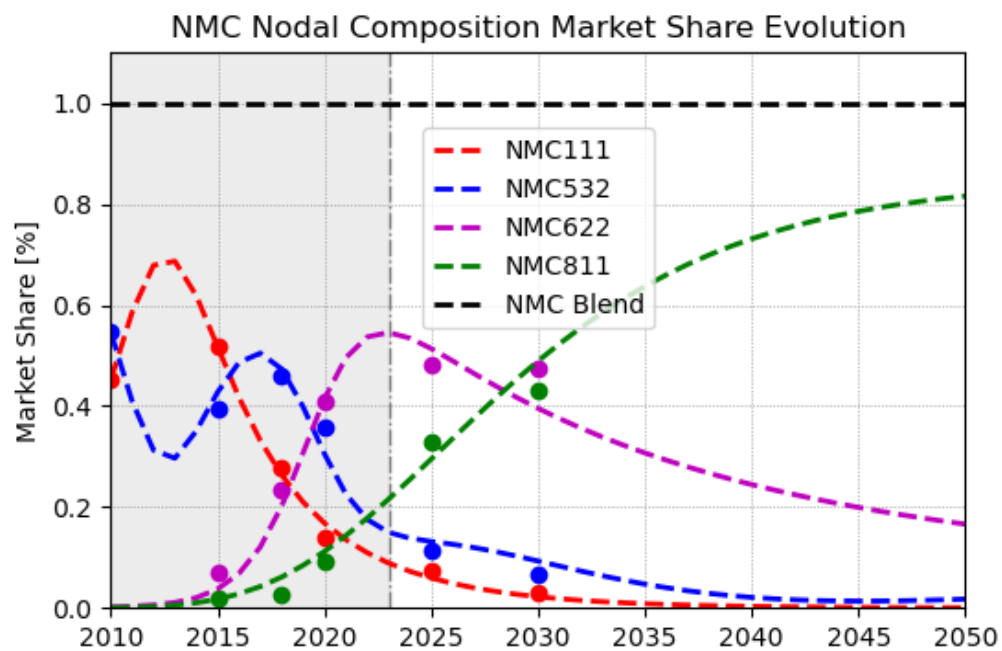
Supplementary Figure 2: Compiled historical and forecasted prices for key minerals.

In this work, we collect historical and forecasted prices for minerals from industry data contributors, such as Benchmark Mineral Intelligence, Wood Mackenzie, S&P Global, and additionally include historical prices from the United States Geological Survey (USGS) dating back to 1991. Aggregated price trends of key minerals are shown with averages and 95% confidence intervals to protect the proprietary nature of price forecasts from individual data sources.

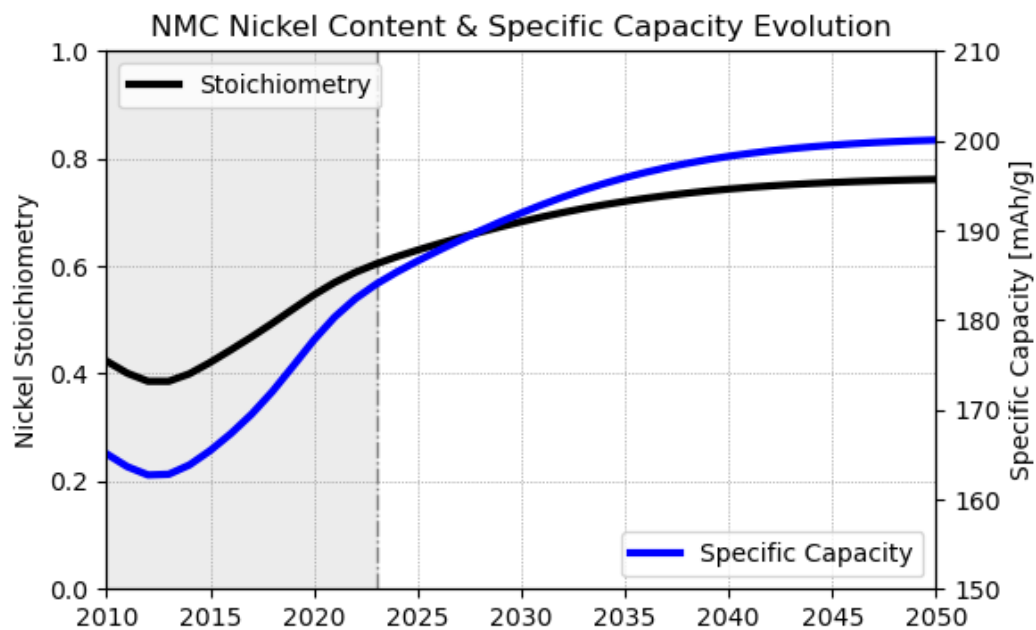
A summary of the tabulated minerals and commodities along with their data sources are detailed in Supplementary Table 1. All prices were inflation-adjusted to USD2023. For all minerals/commodities price data sets that are incomplete, the first price figure in the time-series is extended backwards to 1991, and the last price figure in the time-series is extended forwards to 2050.



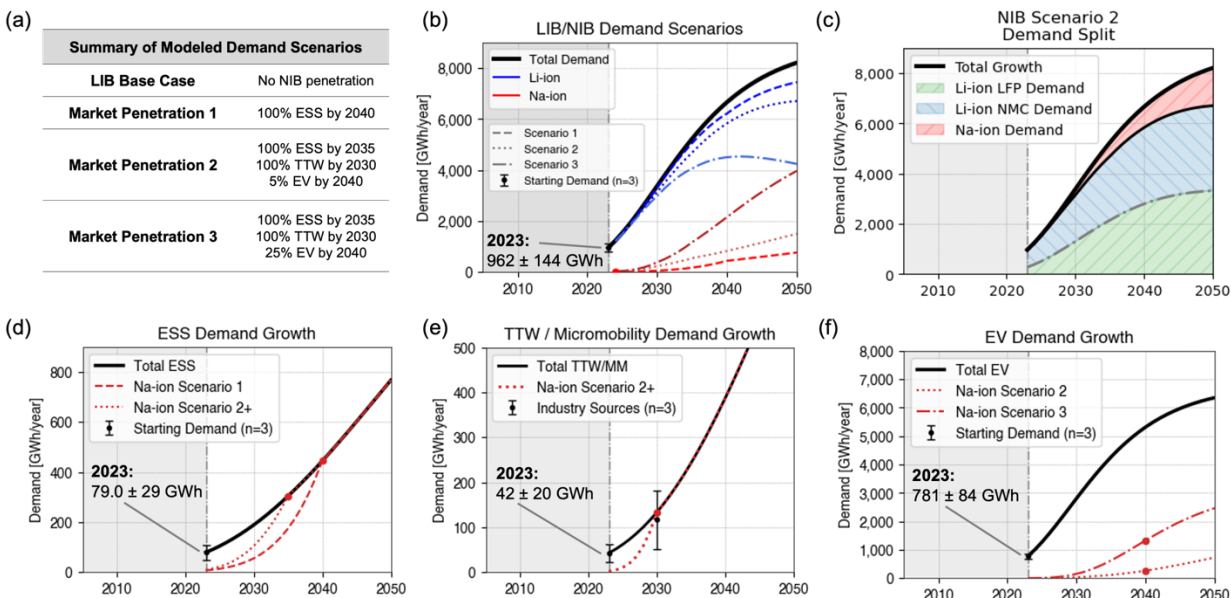
Supplementary Figure 3: Material component price floors for key components.



Supplementary Figure 4: Fitted NMC nodal composition market penetration curves.

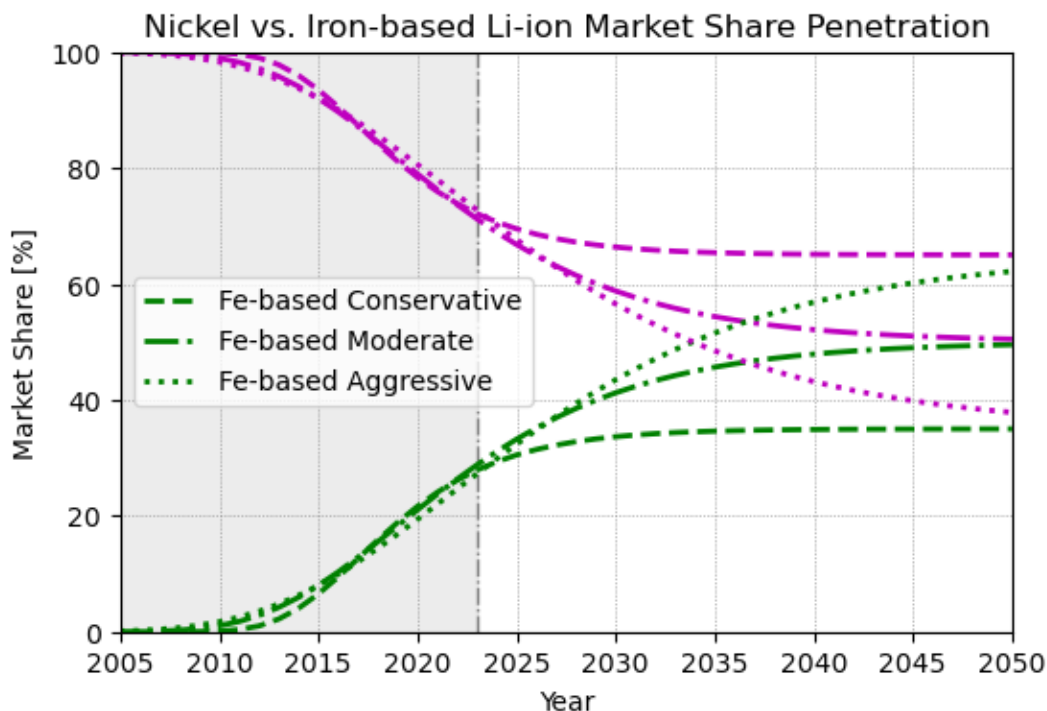


Supplementary Figure 5: NMC volume-weighted nickel content and specific capacity.



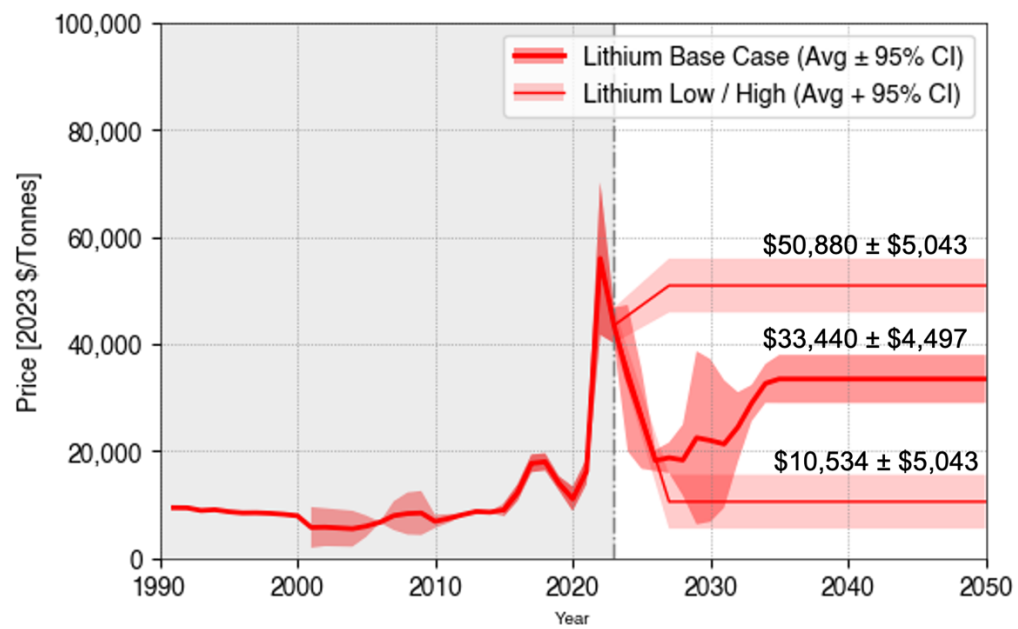
Supplementary Figure 6: Modeled market growth rates.

(a) Modeled market demand scenarios. (b) Overall demand curves for Li-ion and Na-ion based upon the three modeled market penetration scenarios that each cannibalize Li-ion market share but do not change the overall market demand for batteries. (c) Demand split between NMC, LFP, and a hypothetical Na-ion chemistry based upon scenario “Market Penetration 2”. (d-f) Modeled market growth curves for the ESS, TTW/MM, and EV markets showing various degrees of Na-ion penetration. Industry average and 95% CI for current market sizes are shown with generally good agreement between independent sources, with the exception of TTW/MM where a larger variance in forecasts is shown in 2030. Reasonable agreement was found between three independent sources^{1,2,5} on market growth trajectories to 2050 for the total battery market, EV segment, and stationary ESS segment. There was noticeably more variance in predicted sizes and growth rates of emerging markets, such as two/three-wheelers & micromobility (TTW/MM). Note, however, that emerging markets are dwarfed by EV demand.

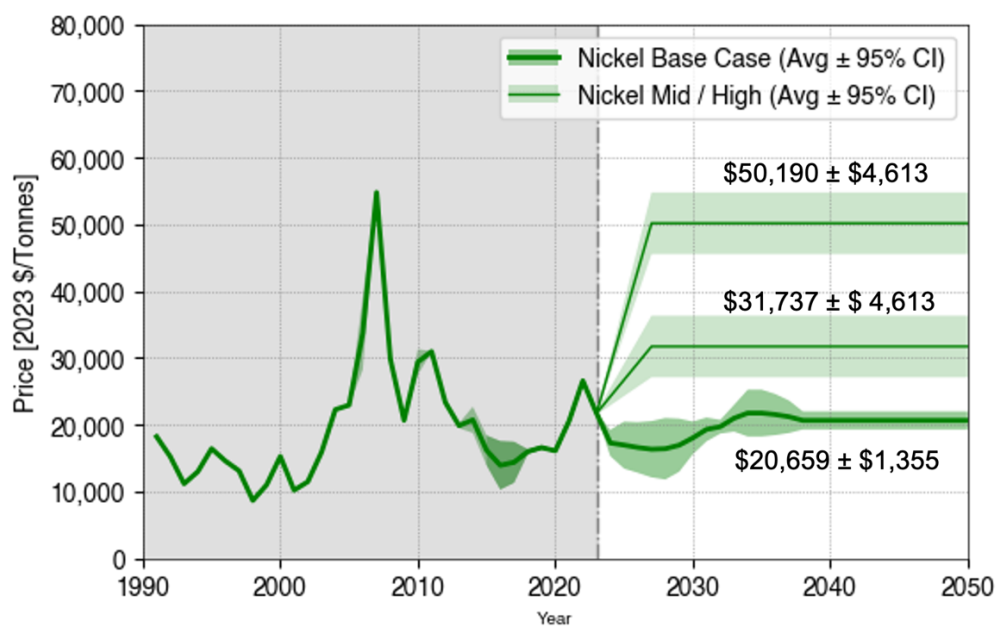


Supplementary Figure 7: Market penetration scenarios for Fe-based chemistries.

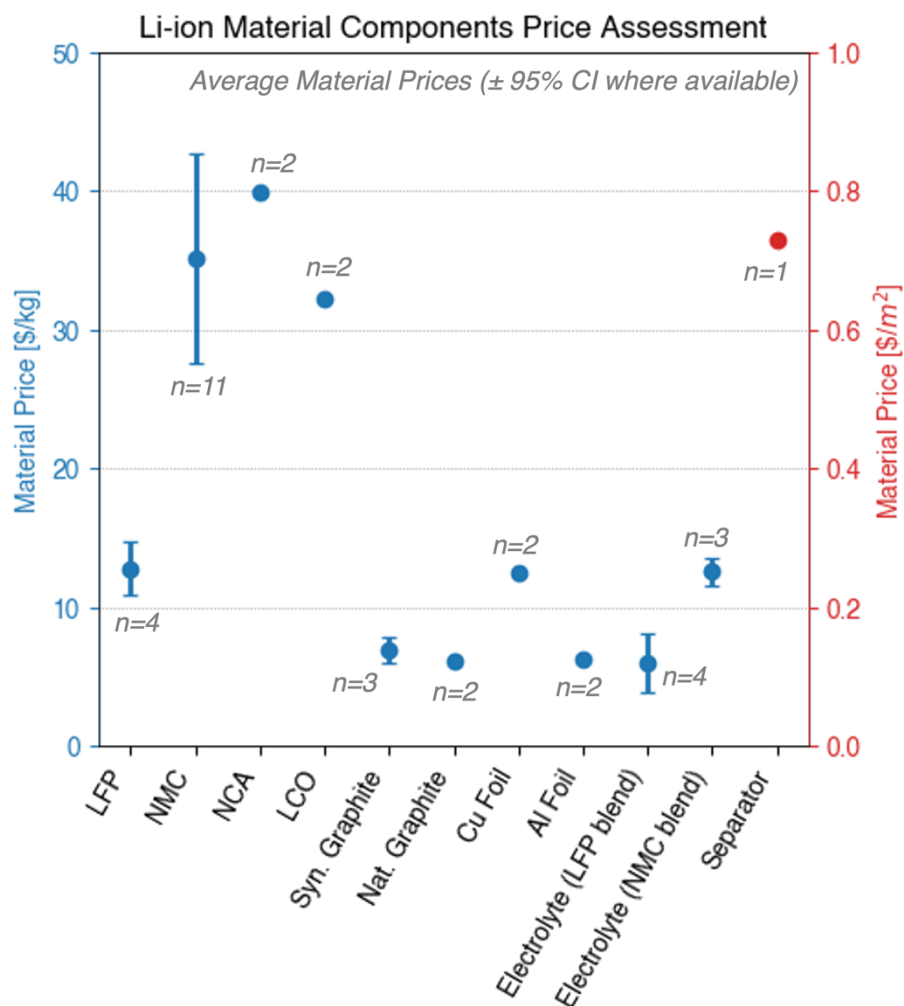
NMC- and LFP-type Li-ion cells, more broadly referred to as nickel- and iron-based chemistries to capture future evolution, are the two competing sub-classes of Li-ion that capture the majority of the Li-ion market share^{5,7}. How they evolve with respect to each other, however, is still unclear. With the lower cost, improved safety, and more stable cycling performance of LFP, predictions of LFP market share continue to be revised^{8,9}. As the market share of LFP is directly related to its cumulative demand and hence learning curve, we want to accurately capture the market segmentation between nickel- and iron-based chemistries within Li-ion. Above are three different market penetration scenarios for iron (Fe)-based chemistries. The “Conservative” case is aligned with industry estimates of LFP penetration. The “Moderate” case assumes ~50% saturation by 2050, and the “Aggressive” case assumes ~65% saturation by 2050.



Supplementary Figure 8: Modeled lithium price scenarios.



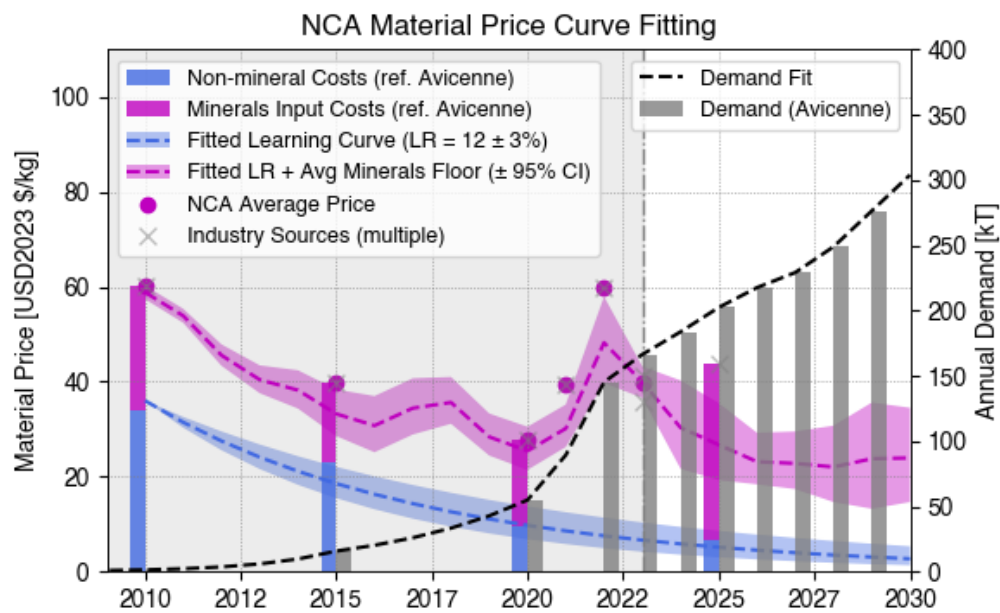
Supplementary Figure 9: Modeled nickel price scenarios.



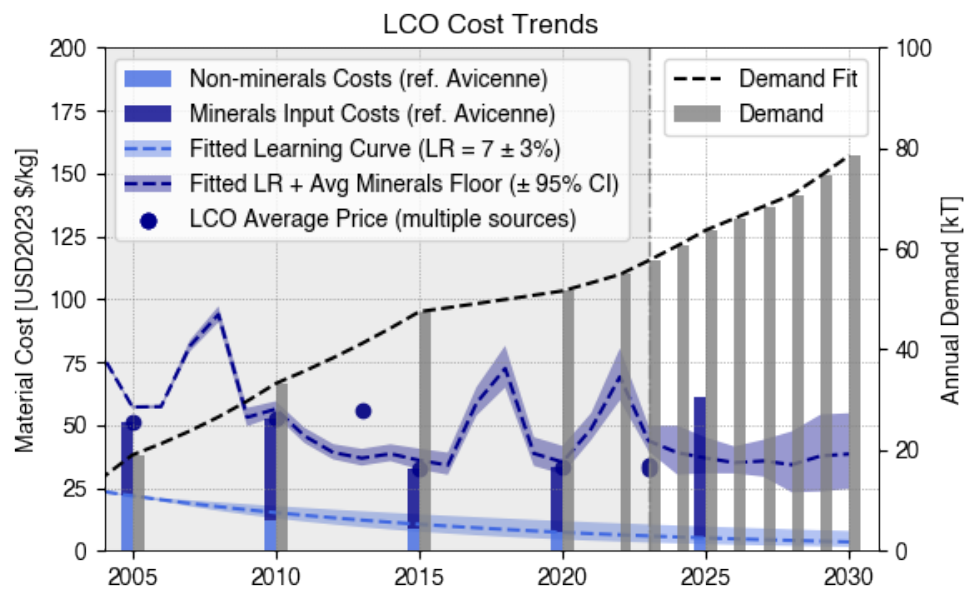
Supplementary Figure 10: Present-day price assessments of key Li-ion material components.

Note the relatively tight spread in materials prices for most components except for NMC and NCA. The higher variance for these materials is attributed to (1) their nickel content, which is currently experiencing more market volatility, and (2) the multiple commercially available stoichiometries categorized within their respectively broad family labels.

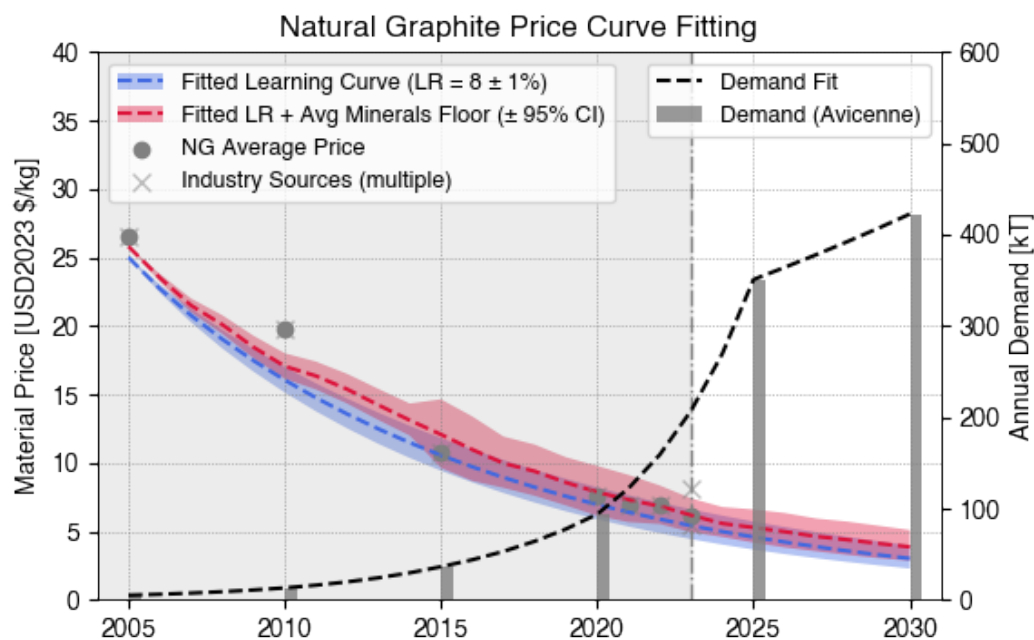
LFP=Lithium iron phosphate polyanion cathodes. NMC=Nickel-manganese-cobalt layered oxide cathodes. NCA=Nickel-cobalt-aluminum layered oxide cathodes. LCO=Lithium cobalt oxide layered cathodes. Syn. Graphite=Synthetic Graphite. Nat. Graphite=Natural Graphite.



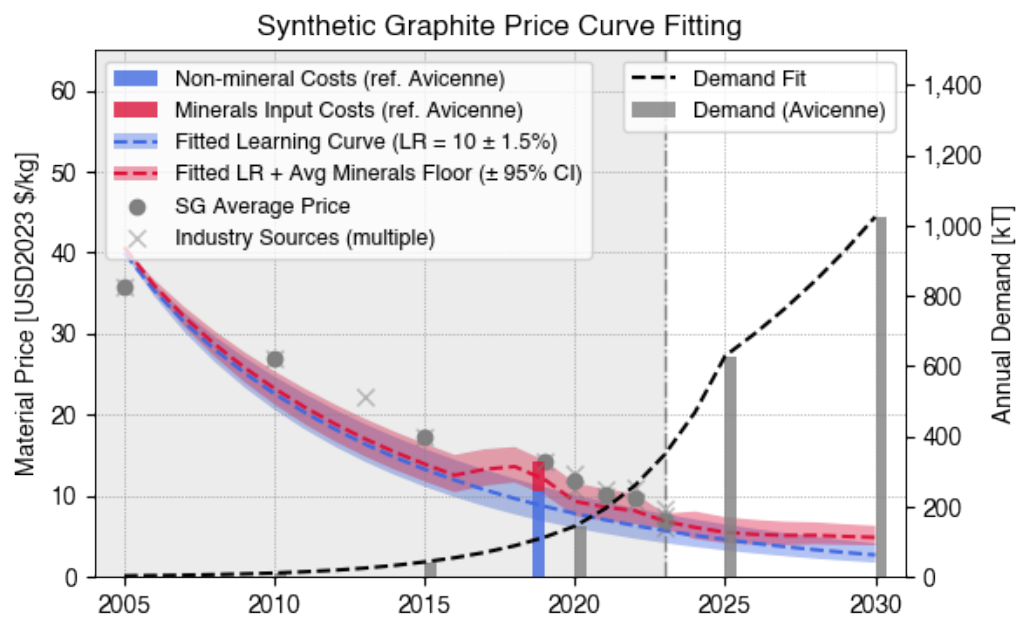
Supplementary Figure 11: NCA component price forecasts.



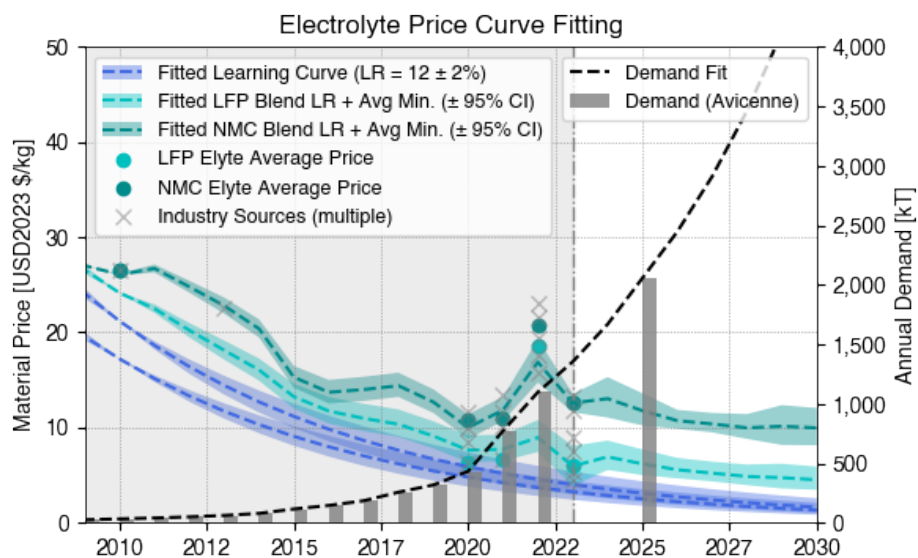
Supplementary Figure 12: LCO component price forecasts.



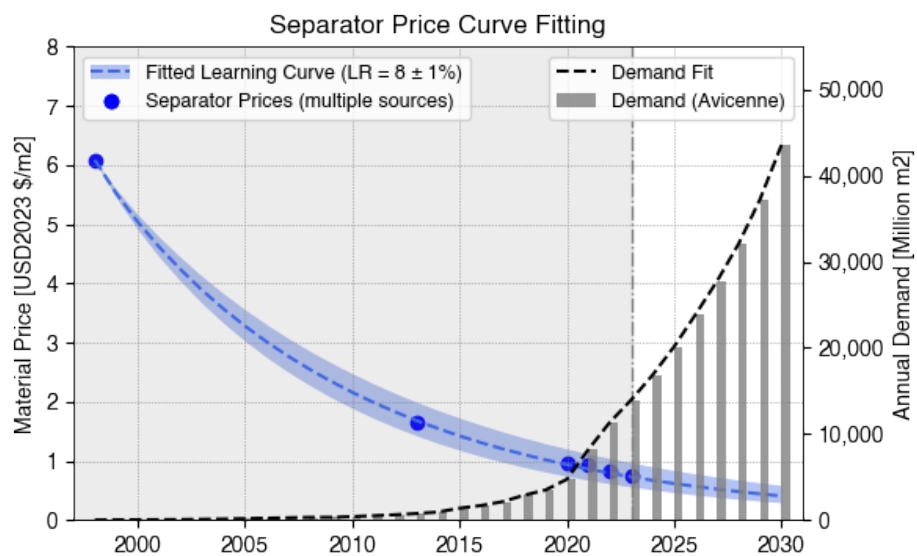
Supplementary Figure 13: Natural graphite component price forecasts.



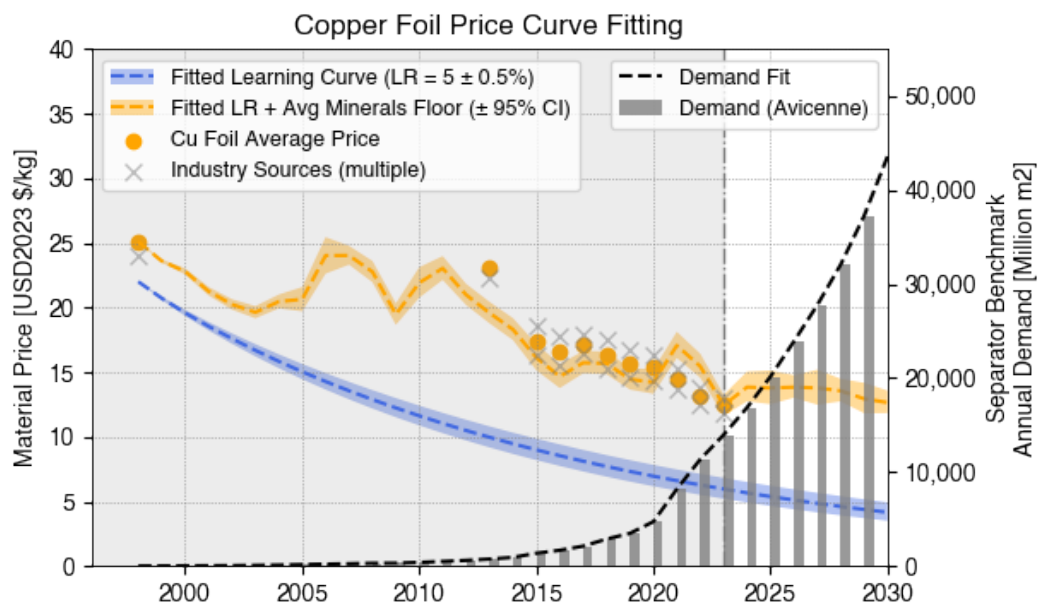
Supplementary Figure 14: Synthetic graphite component price forecasts.



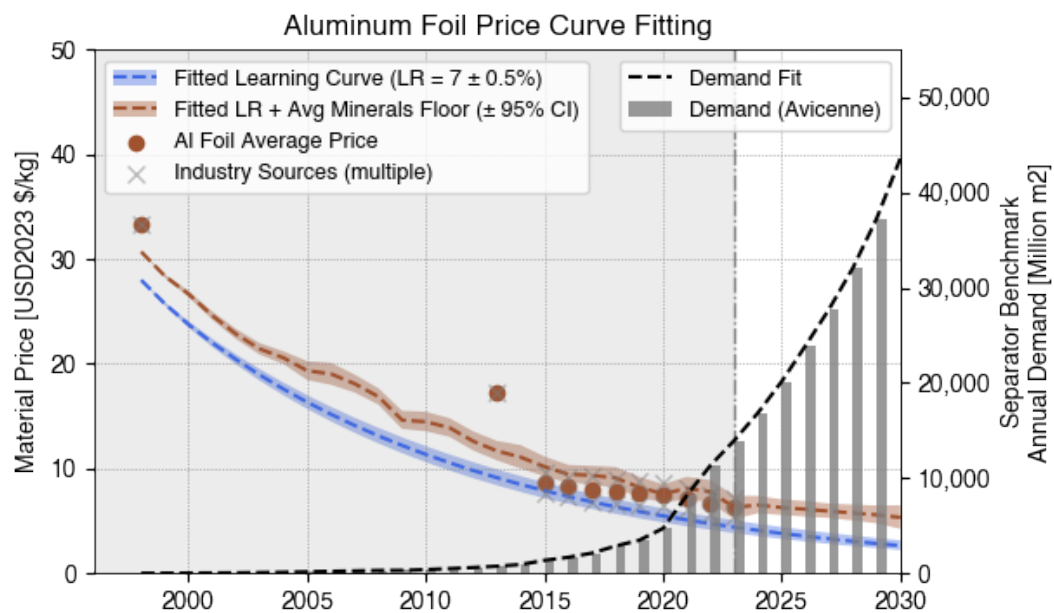
Supplementary Figure 15: Electrolyte component price forecasts.



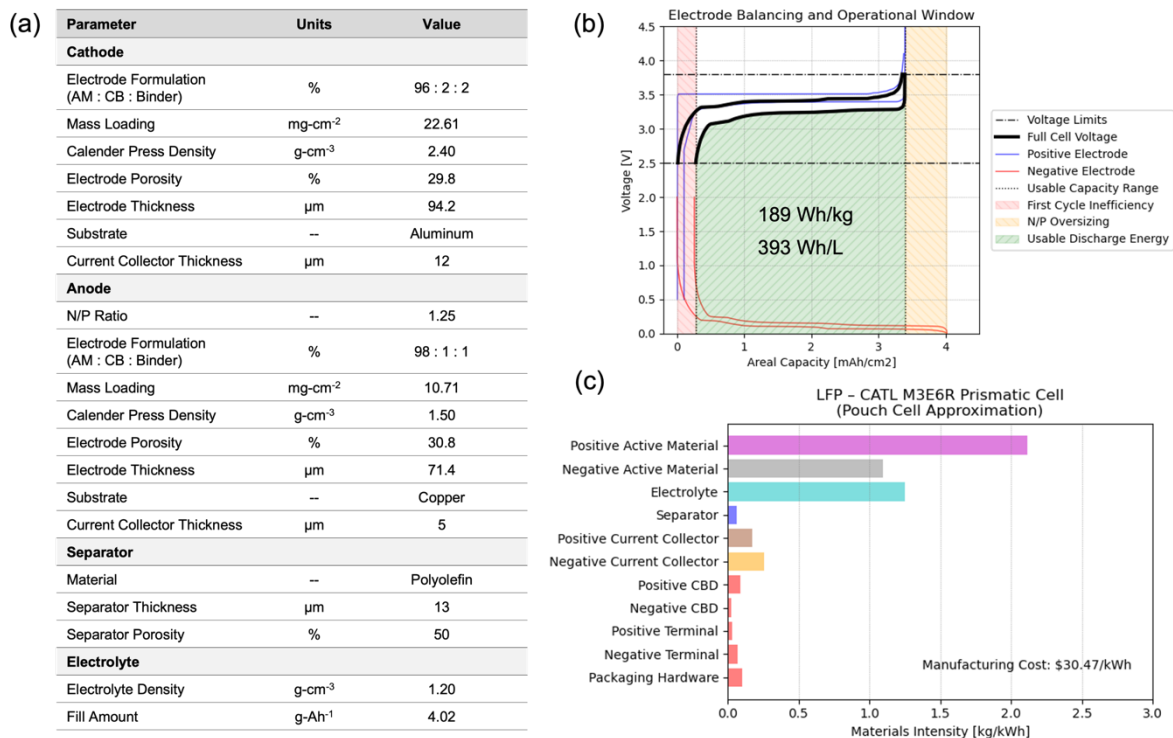
Supplementary Figure 16: Separator component price forecasts.



Supplementary Figure 17: Copper foil component price forecasts.



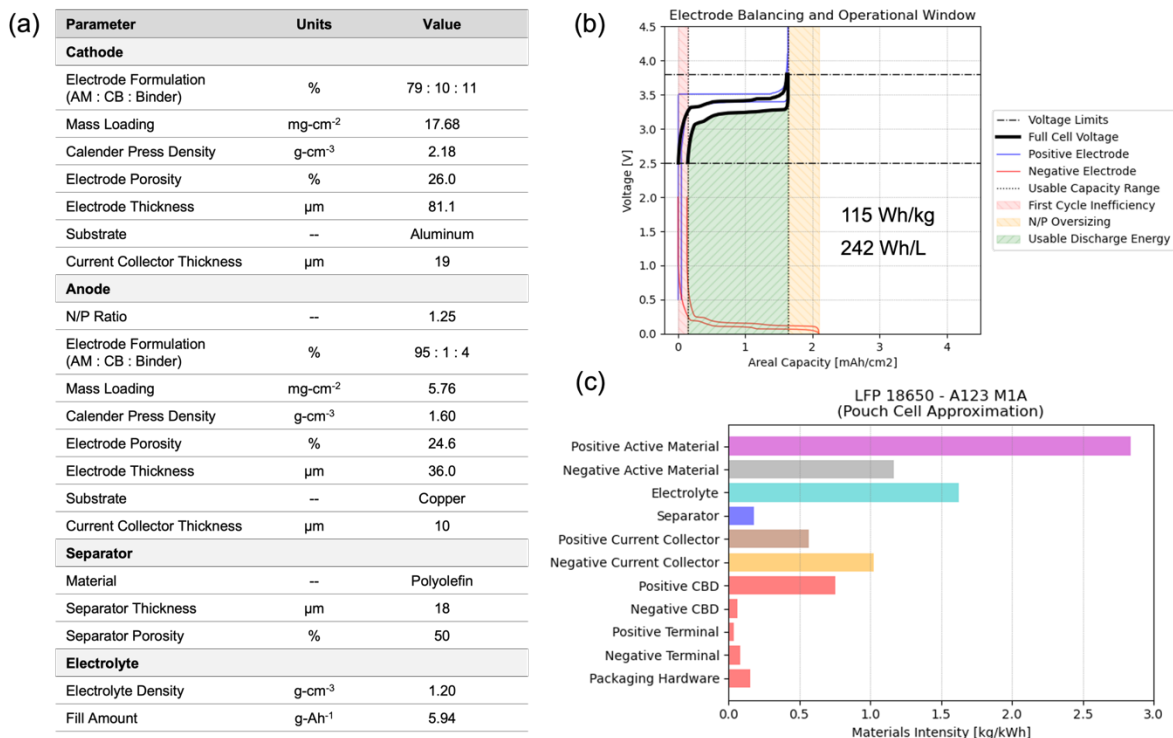
Supplementary Figure 18: Aluminum foil component price forecasts.



Supplementary Figure 19: Modeled Li-ion LFP CATL Prismatic Cell.

The prismatic LFP cell used in the Tesla Model 3 Standard Range model is manufactured by CATL (Contemporary Amperex Technology Limited) starting in 2020, and a detailed cell teardown is referenced in literature¹¹. Based on the parameters obtained from the literature, a pouch cell representative of the same unit cell design was constructed in BatPaC, and exact cell design construction details were obtained (e.g. electrode areas, dimensions, bilayer count, etc.).

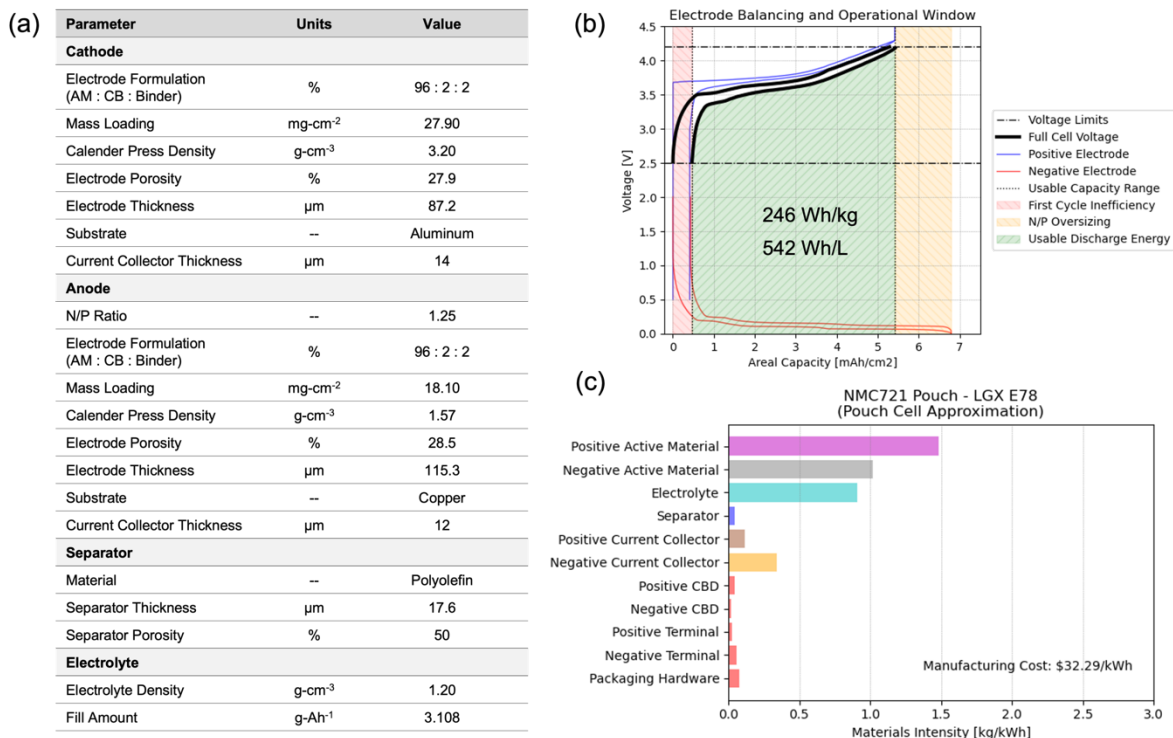
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 20: Modeled Li-ion LFP A123 18650 Cylindrical Cell.

A cylindrical LFP 18650 power cell manufactured by A123 in 2009 for power tool applications is modeled here based upon a cell teardown from literature¹². Based on the parameters obtained from the literature, a pouch cell representative of the same unit cell design was constructed in BatPaC, and exact cell design construction details were obtained (e.g. electrode areas, dimensions, bilayer count, etc.).

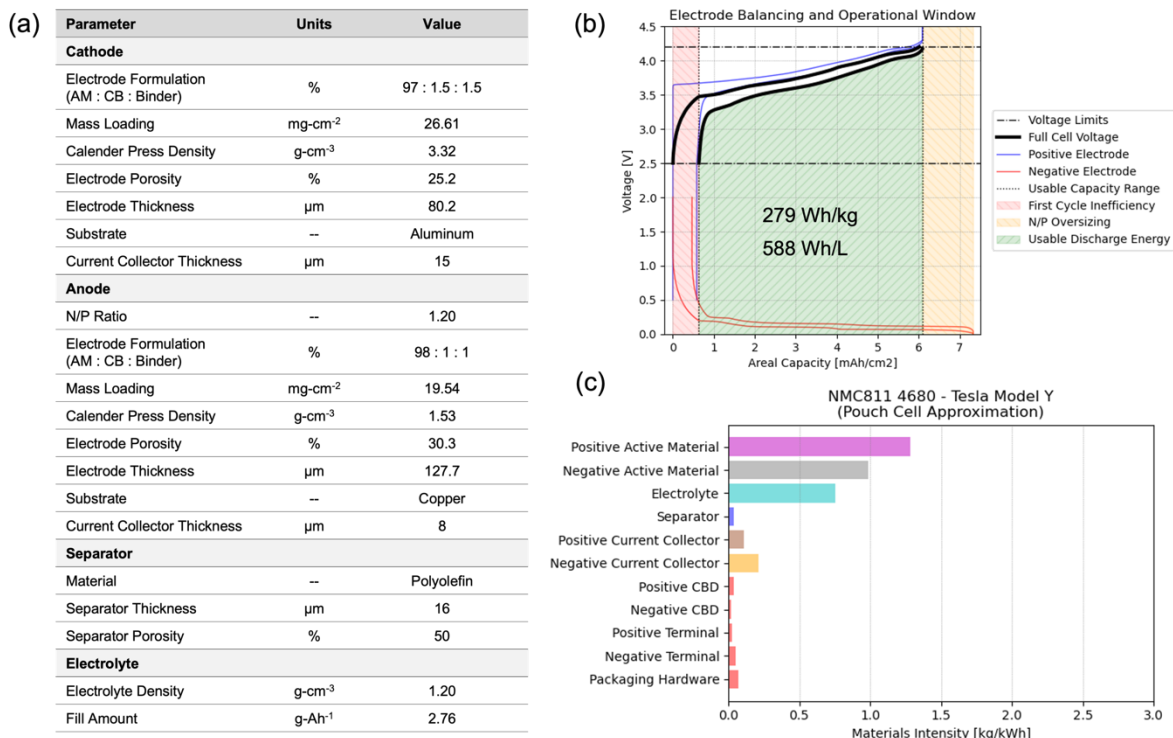
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 21: Modeled Li-ion NMC LGX E78 Pouch Cell.

The pouch NMC cell used in the Volkswagen ID.3, Audi Q4 e-tron, and other vehicle models is manufactured by LG Energy Solutions, and a detailed cell teardown is referenced in literature¹³. Unlike the previous examples, this cell is already a large-format pouch cell, so we first model the actual design produced by LG Energy Solutions before converting it to a BatPaC-generated cell design. We obtain good agreement with the commercial cell but note that the total electrolyte overfill amount in addition to the actual calculated pore volume is closer to 10-20% as opposed to our assumed 80%. This makes sense as pouch cells are generally more electrolyte-starved cell designs compared to that of hard-case cells like prismatic or cylindrical formats. Then, based on the parameters that are in good agreement with the commercial cell, a pouch cell representative of the same unit cell design was constructed in BatPaC, and exact cell design construction details were obtained.

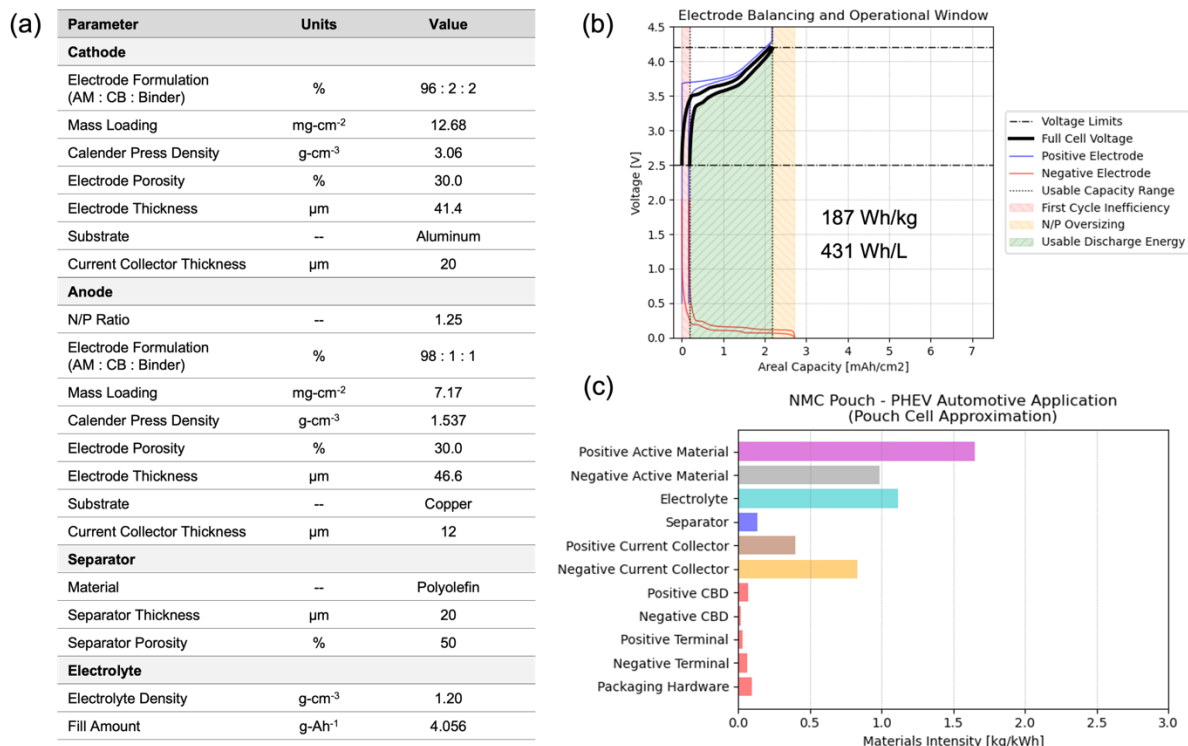
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 22: Modeled Li-ion NMC Tesla 4680 Cylindrical Cell.

The cylindrical NMC cell used in the Tesla Model Y and manufactured by Tesla and a detailed cell teardown is referenced in literature¹⁴. Based on the parameters obtained from the literature, a pouch cell representative of the same unit cell design was constructed in BatPaC, and exact cell design construction details were obtained (e.g. electrode areas, dimensions, bilayer count, etc.). We note here, in agreement with the authors of the cell teardown study¹⁴, that this cell design appears to be more conservative, with a larger N/P ratio and lower calender densities than one may expect. These design decisions, however, may be more conservative considering the novelty of the 4680 cell format, and future engineering optimization can likely be rapidly implemented to increase cell-level energy densities.

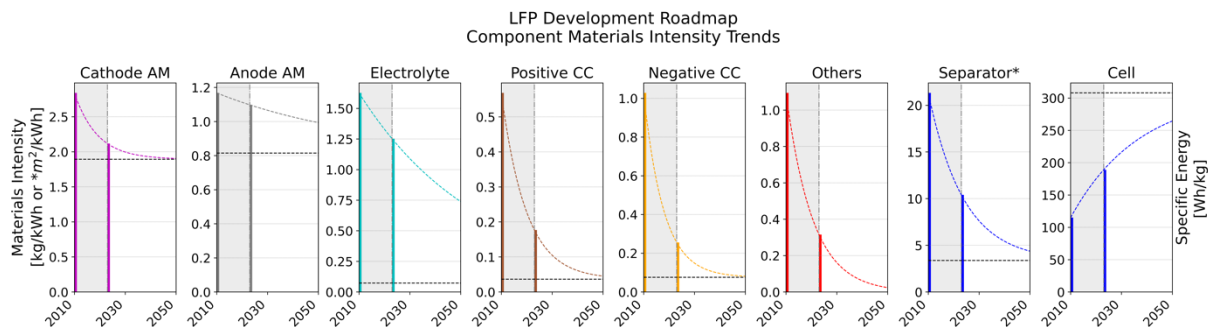
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 23: Modeled Li-ion NMC – PHEV Pouch Cell.

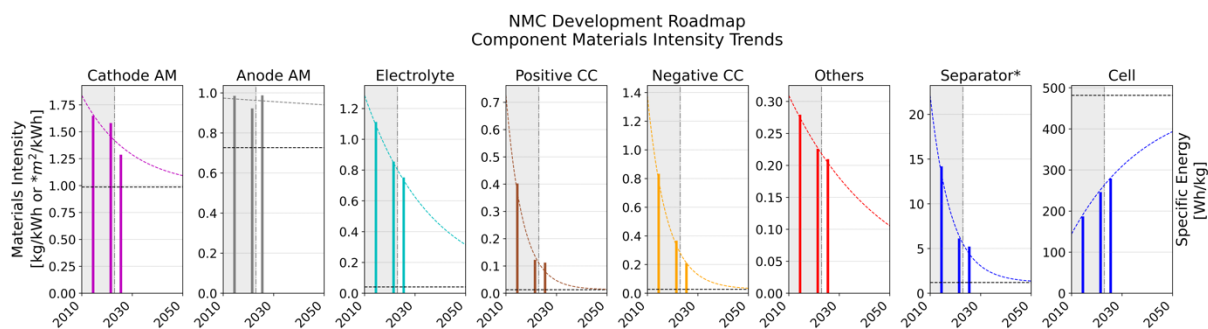
A Li-ion pouch cell representing state-of-art cells in 2014 is modeled after documents and literature gathered from around that time^{15,16}. With the launch of the PHEV Chevrolet Volt circa 2011, NMC-type cells at the time tended to be power cell designs as opposed to the energy cells commonly used in BEVs today. Consistent with power cell designs, these cells had low areal loadings ~ 2.0 mAh-cm⁻², higher electrode porosities, and thicker current collectors and separators.

(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



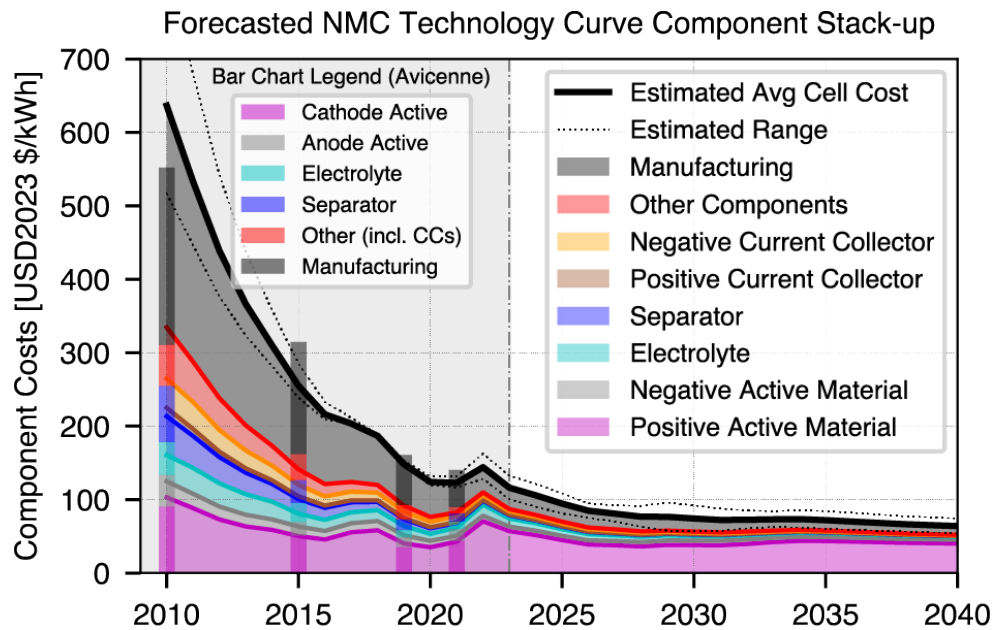
Supplementary Figure 24: Li-ion LFP Development Roadmap

We assign the CATL prismatic LFP cell and the A123 cylindrical LFP cell to the years 2023 and 2010, respectively, approximating when they were each considered to be state-of-art. The resulting LFP development roadmap is shown, where the materials intensities of each component decreases through time and eventually plateaus at the specified engineering limits.



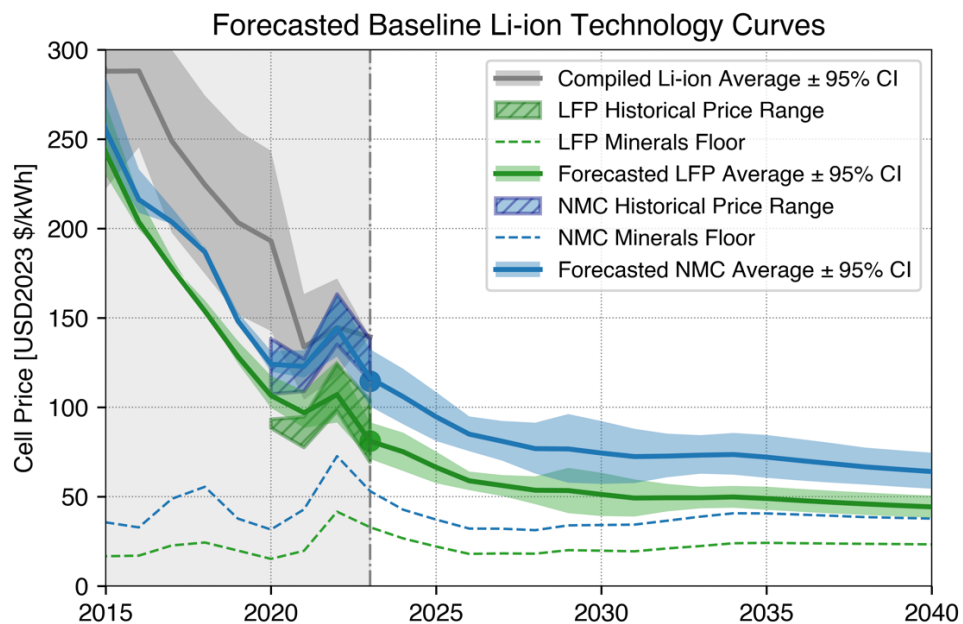
Supplementary Figure 25: Li-ion NMC Development Roadmap

For NMC, we assign the NMC PHEV pouch cell, the LGX E78 NMC721 pouch cell, and the Tesla 4680 NMC811 cylindrical cell to the years 2014, 2021, and 2025. The resulting NMC development roadmap is shown.



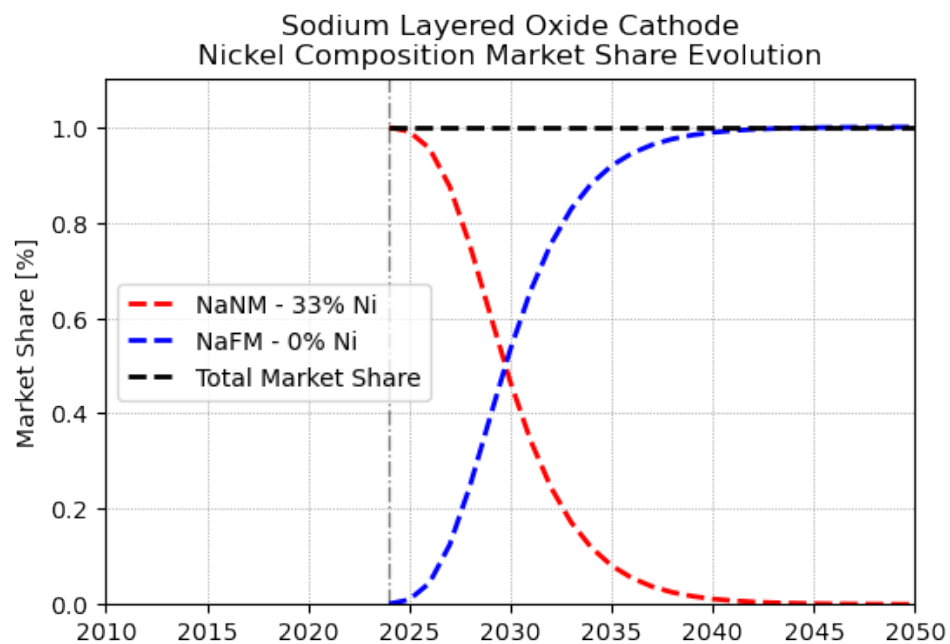
Supplementary Figure 26: Component curve stack-up for NMC-type cells.

The component curve stack-up for the NMC Li-ion baseline shows reasonable agreement with historical component price breakdowns (bar charts^{1,7}). Bar charts show cell price breakdown by component in previous years provided by Avicenne.



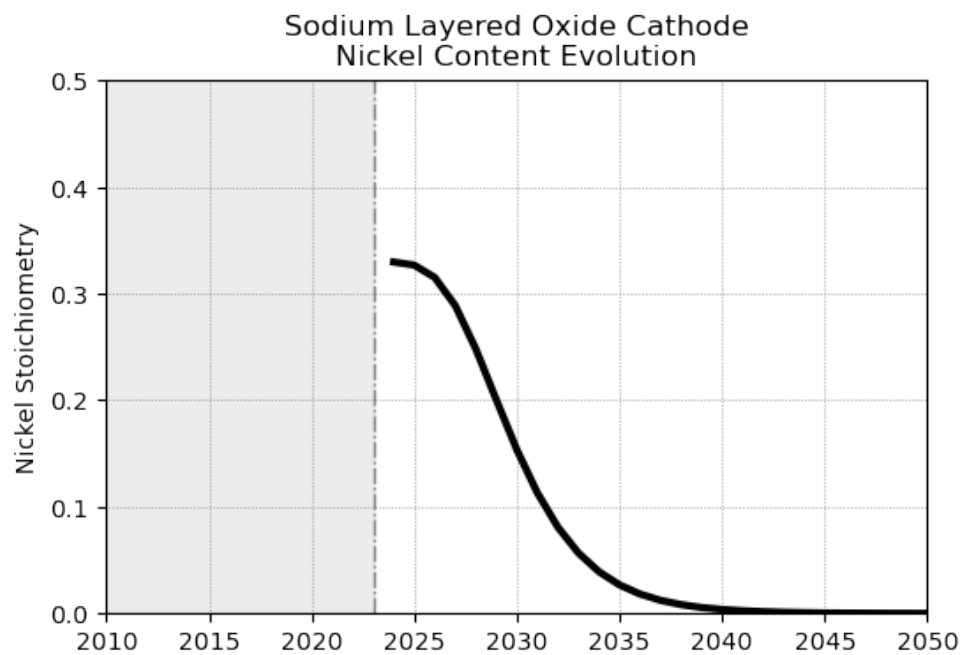
Supplementary Figure 27: Forecasted LFP and NMC Li-ion technology curves

This assumes the baseline minerals forecasts shown in Supplementary Figure 2, showing good agreement with historical averages obtained from industry data contributors.



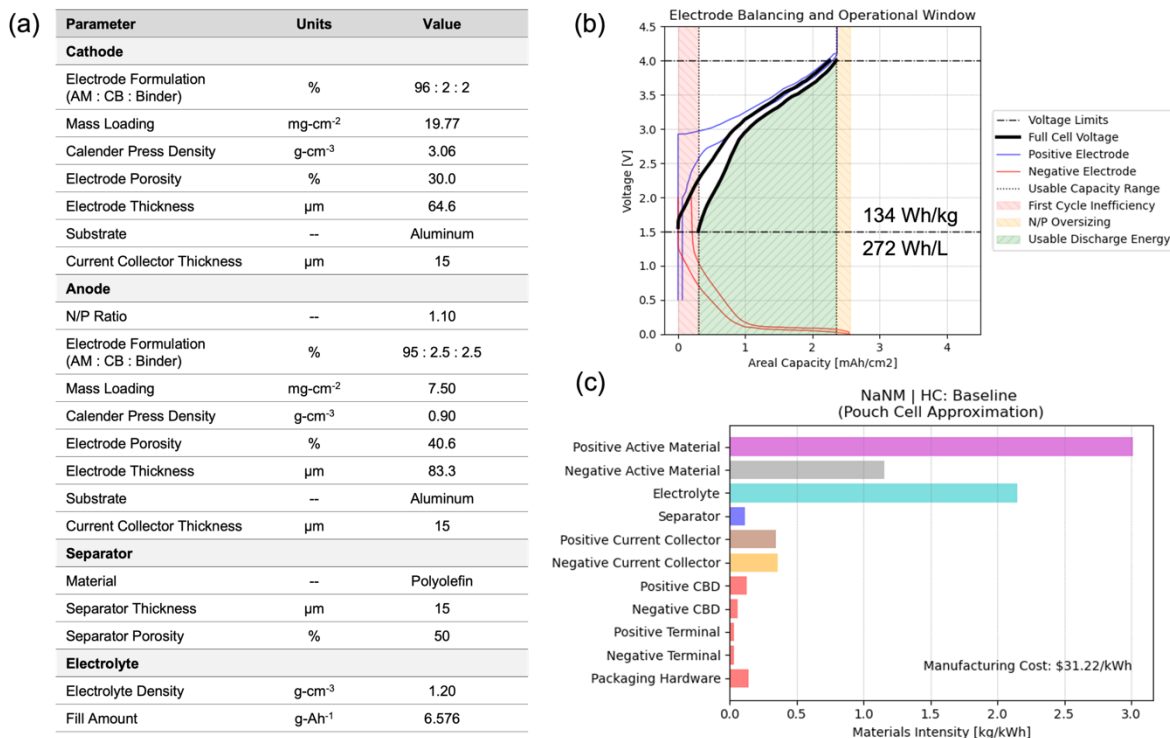
Supplementary Figure 28: Market penetration of nickel-containing sodium layered oxide cathodes.

Modeled market penetration curves for nickel-containing (33%) and nickel-free sodium layered oxide cathodes



Supplementary Figure 29: Nickel content evolution in sodium layered oxide cathodes.

Modeled volume-weighted nickel content evolution in sodium layered oxide cathodes.



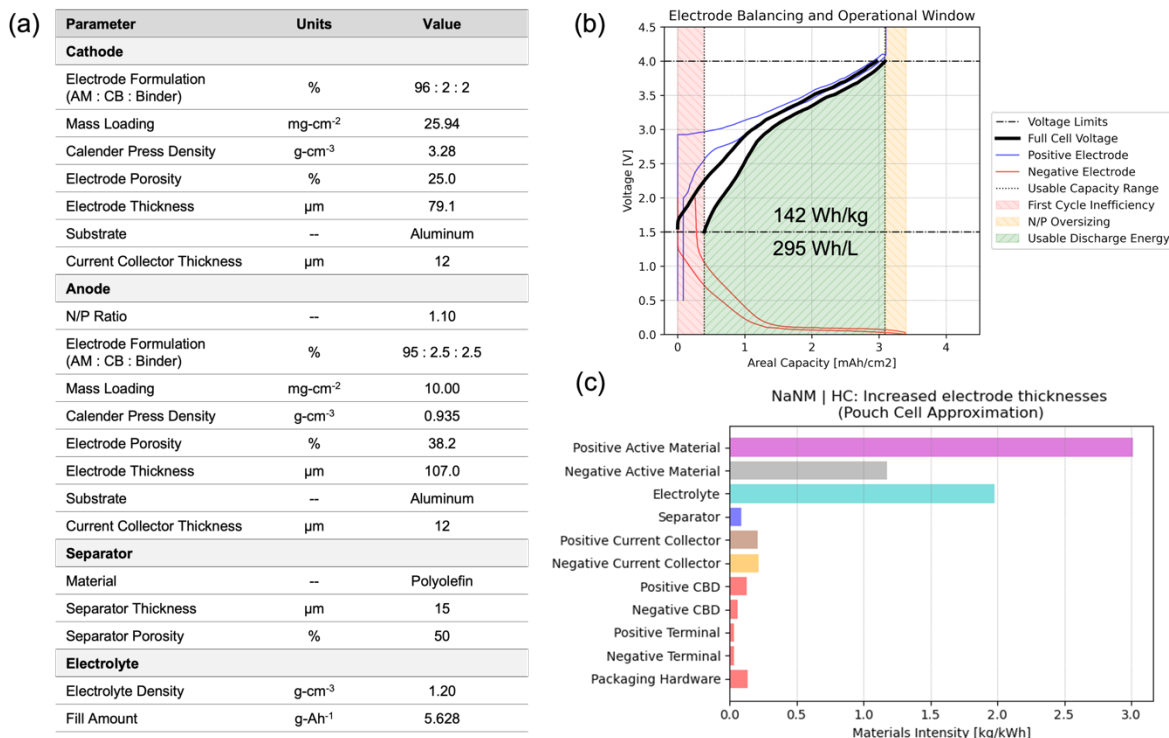
Supplementary Figure 30: Modeled Na-ion NaNM | HC – Baseline.

As rapid progress is being made within Na-ion commercialization efforts, we create an anticipated Na-ion baseline cell design to represent state-of-art in 2024. This design is based upon the Faradion 12Ah cell discussed in but with more aggressive design parameters. Namely, this includes increased electrode loadings and active mass fractions within electrodes. This also assumes a lower cost aqueous-based binder system using carboxymethyl cellulose (CMC) and styrene-butadiene rubber (SBR) for the hard carbon (HC) anode (as is predominantly used for graphite anodes in Li-ion batteries) instead of the polyvinylidene (PVDF) based system used in Faradion’s formulations found within literature¹⁷. We also limit the upper voltage cutoff to 4.0V. As previously discussed in Supplementary Note 10:, a derated upper voltage cutoff minimizes degradation reactions that have been empirically shown to increase cycle life. However, another key reason to derate voltages is to enable compatibility with state-of-art power electronics, according to feedback from several experts on our panel of industry consultants¹⁸. Whereas a NaNM | HC system may exhibit a cell voltage between 1.0 – 4.2V, most power conversion systems cannot handle such a wide voltage range and may be limited to $V_{\min} \geq \frac{1}{2} V_{\max}$ ¹⁸. Furthermore, for constant power system requirements, the current draw requirement at low states-of-charge (SOC) will substantially increase as voltage drops precipitously. We note that this is a topic that may be underappreciated and deserves much greater scrutiny. Here, we limit the voltage range of a baseline NaNM | HC system between 1.5 – 4.0V.

Compared to the Faradion 12Ah baseline cell discussed in Supplementary Note 10:, we increase active mass fractions of both the cathode and anode electrode formulations from 89% and 88% to 96% and 95%, respectively. We further increase cathode and anode mass loadings from 14.90 mg-cm⁻² and 7.14 mg-cm⁻² to 19.77 mg-cm⁻² and 7.50 mg-cm⁻², respectively, while also reducing the electrode porosity and hence increasing the calender density of the cathode. We note that these elevated calender densities are aggressive values based on the challenging morphology of state-of-art co-precipitated NaNM-type cathode particles¹⁸, but we prefer to err on the side of presenting a best-case scenario for Na-ion. Additionally, we drop the N/P ratio to 1.10 balanced at 4.0V to maximize material utilization. This combination of improvements increases the cell-level areal capacity by ~50% versus the Faradion 4.0V baseline. Here, we maintain the same

capacity and first cycle efficiencies (FCEs) of the Faradion Gen 2 NaNM cathode and HC anode materials, as they represent state-of-art performance within their class.

(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.

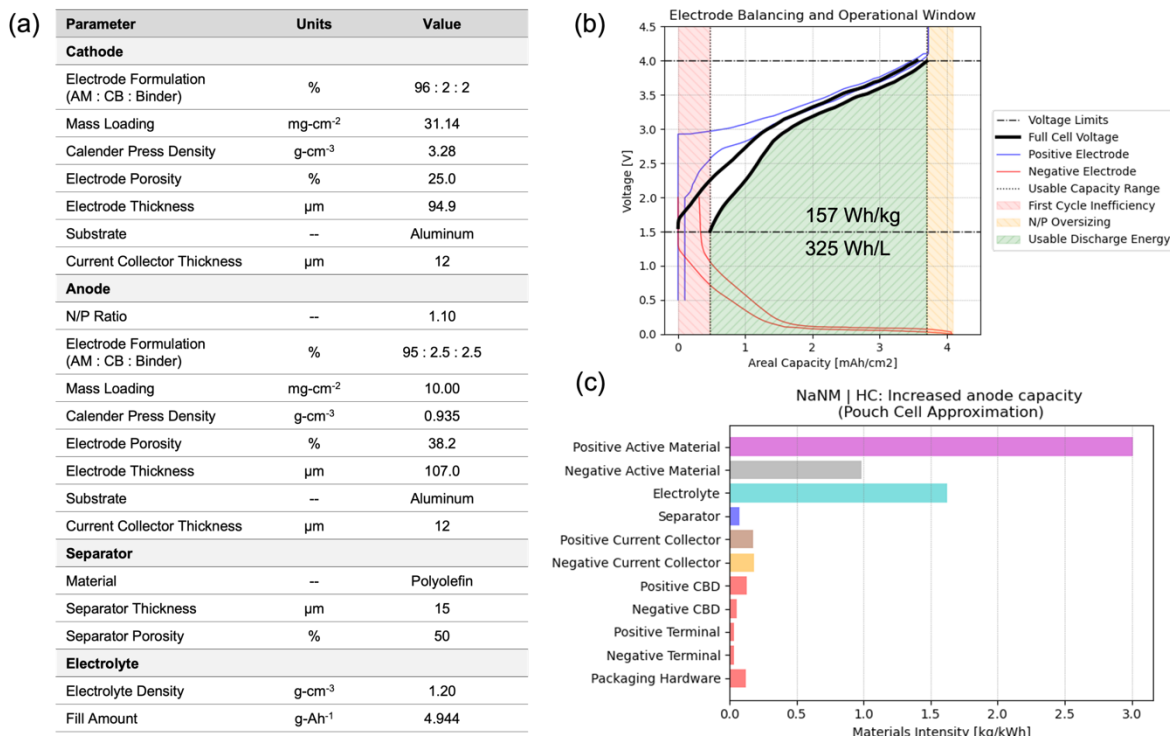


Supplementary Figure 31: Modeled Na-ion NaNM | HC – Increased electrode thicknesses.

One of the most common ways to increase cell-level energy densities and reduce costs is to increase the thickness of electrodes—thereby minimizing the quantity of inactive materials. Of course, this will have a tradeoff with power density as thicker electrodes require longer distances for ion mass transport in the electrolyte phase. Therefore, there are practical limits to increasing electrode thicknesses prior to the onset of significant concentration polarization—which may result in unwanted phenomena such as sodium plating upon charging¹⁷, not to mention challenges from a manufacturability perspective of drying thick electrodes after coating¹⁸. Increasing the practically attainable thickness of hard carbon anodes will result in energy density increases and cost decreases assuming rate performance is not hindered for the applications considered.

In this first baseline-improved scenario, we increase the realizable electrode mass loadings for the hard carbon anode to 10.00 mg-cm⁻², which was communicated as a realistic but challenging target by industry experts¹⁸. We additionally increase calender densities. Typical maximum calender densities for a hard carbon anode are below 0.9 g-cm⁻³ which corresponds to ~40% porosity, but here we increase the density to 0.938 g-cm⁻³ to achieve a realistically attainable 38% porosity^{17–19}. This results in a single-sided anode thickness of 107 μm. We also assume thinner current collectors—which are yet additional common strategies associated with electrode optimization.

(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.

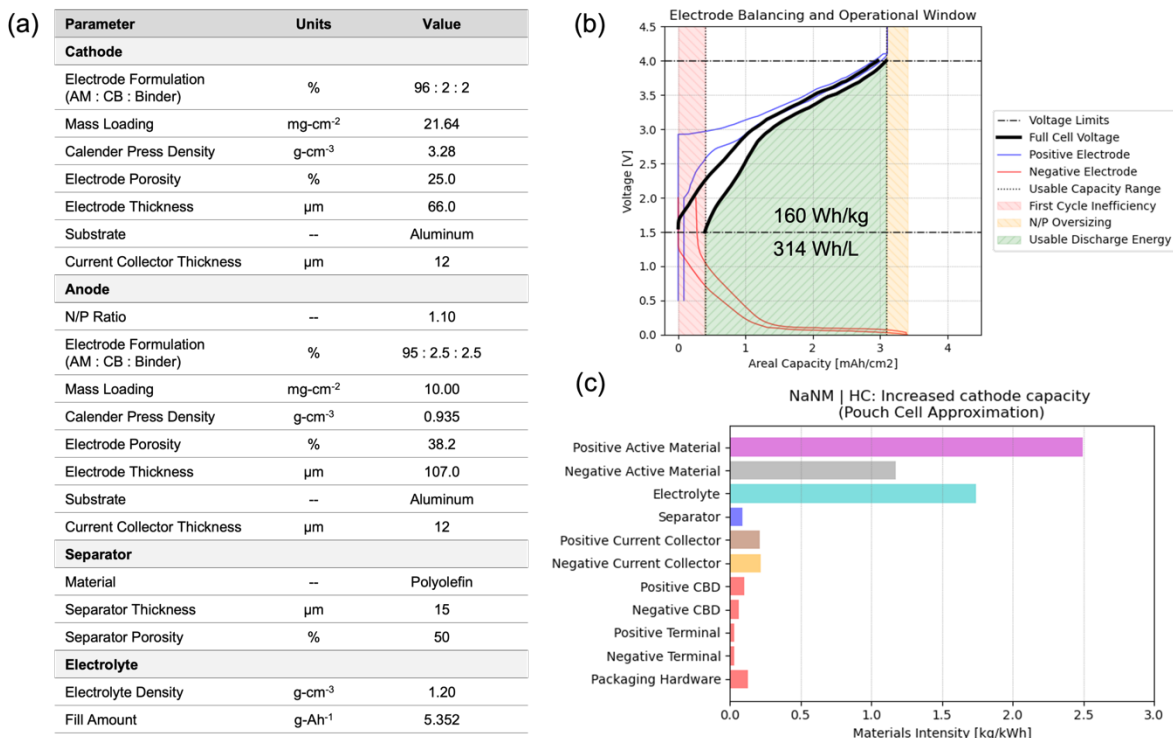


Supplementary Figure 32: Modeled Na-ion NaNM | HC – Increased anode specific capacity.

Hard carbons are non-graphitizable disordered materials consisting graphene nanosheets, and a mechanistic understanding of their sodium storing capability is still not widely agreed upon^{19–22}. Broadly, however, hard carbons are universally observed to exhibit a first slopy region in the voltage profile upon sodiation and a second flat region just above 0V vs. Na/Na⁺, with each contributing approximately half of the overall useable capacity of the anode^{19,20}. Furthermore, there appears to be general agreement attributing sodium storage via interactions with the graphene nanosheets (either intercalation between sheets or localization around defects) to the slopy region, and sodium cluster formation within micropores to the flat region^{19,20}. Both phenomena appear highly dependent on the hard carbon precursor type (phenolic resin, biomass, anthracite, etc.) and synthesis conditions. Due to an inherently amorphous structure without clearly defined stoichiometry (such as LiC₆ for graphite), the limits to sodium storage capacities of hard carbons are not well-understood, and there is significant variability in reported values, ranging from 200–500 mAh-g⁻¹²³.

In this scenario, we assume 400 mAh-g⁻¹ as a reach goal for useable, reversible specific capacity based upon expert opinion¹⁸. Given the importance of internal microporosity to the storage mechanism of hard carbons, we do not assume significant improvements to material, tap, or calender densities beyond what was discussed in the previous section to be practically realizable. We do, however, increase the calender densities on the cathode, assume thinner current collectors, and further increase the realizable electrode mass loadings for the hard carbon anode to 10.00 mg-cm⁻², which was communicated as a realistic but challenging target by industry experts¹⁸. This results in a single-sided anode thickness of 107 μm. Additionally, we assume the precursor for a high-capacity hard carbon material is phenolic resin-based (which has implications on assumed starting costs, see Main Text Figure 2c). This is based upon feedback regarding the variability in quality and composition for biomass precursors, and the inflexibility to micropore engineering in anthracite precursors¹⁸.

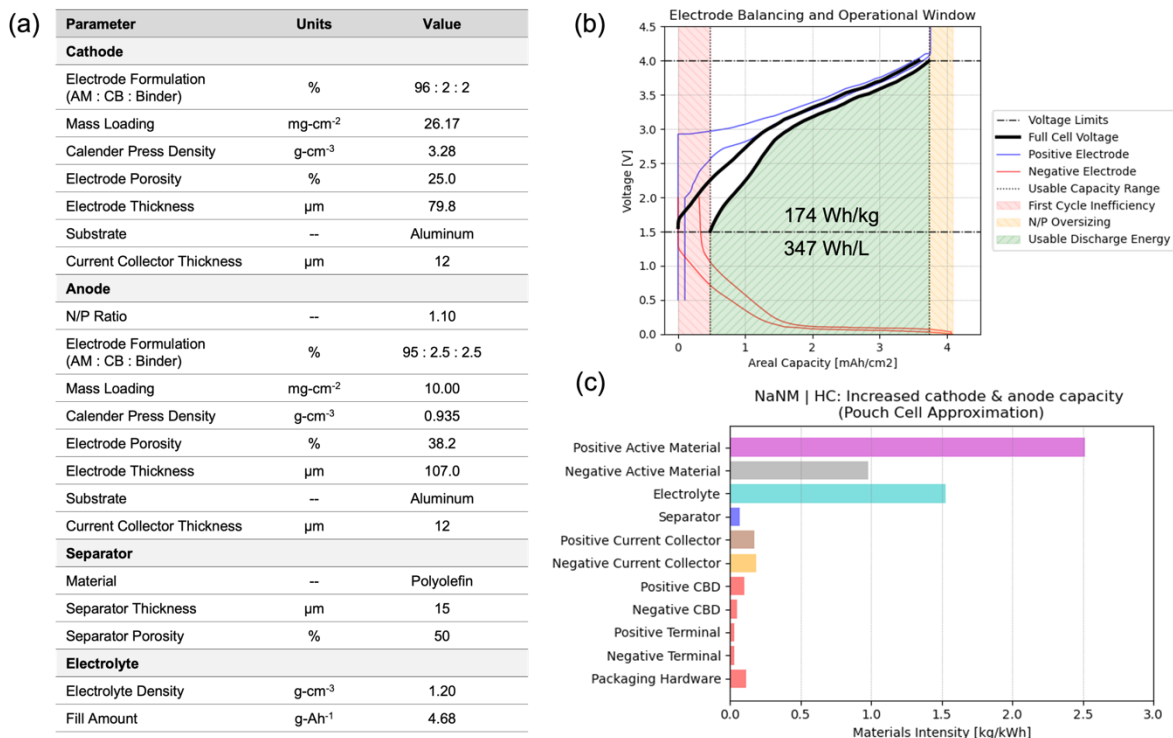
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 33: Modeled Na-ion NaNM | HC – Increased cathode specific capacity.

Yet another way to boost areal capacities is to increase the specific capacity of the layered oxide cathode, ideally keeping most of the capacity increase under a 4.0V upper cutoff voltage for reasons discussed above. Here, we simply evaluate a hypothetical 20% increase to realizable specific capacity in the cathode as a scenario analysis, which entails mathematically scaling the half-cell voltage curve obtained from Faradion's Gen 2 cathode. We note that actual increases to specific capacity via potential use of different transition metal redox centers, for example, will likely alter the shape of the voltage profile compared to the current NaNM representative. However, this approach will provide a reasonable estimate of the technoeconomic impact of such a development roadmap assuming the materials starting costs and learning rates will follow that of the layered oxide class of materials. Similarly to the previous scenario, we also assume increased cathode calender densities, thinner current collectors, and increased anode mass loadings.

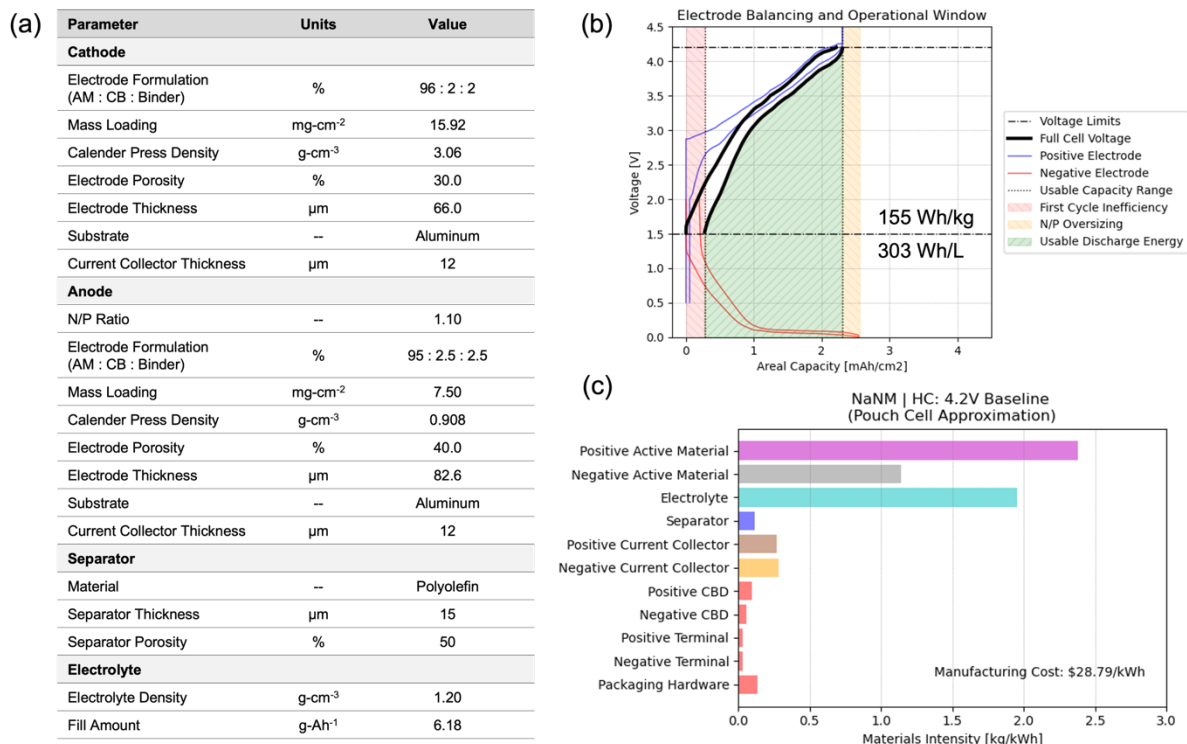
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 34: Modeled Na-ion NaNM | HC – Increased cathode & anode specific capacities.

Assuming improvements to the hard carbon and NaNM cathode specific capacities can occur in parallel, we combine their contributions in this scenario.

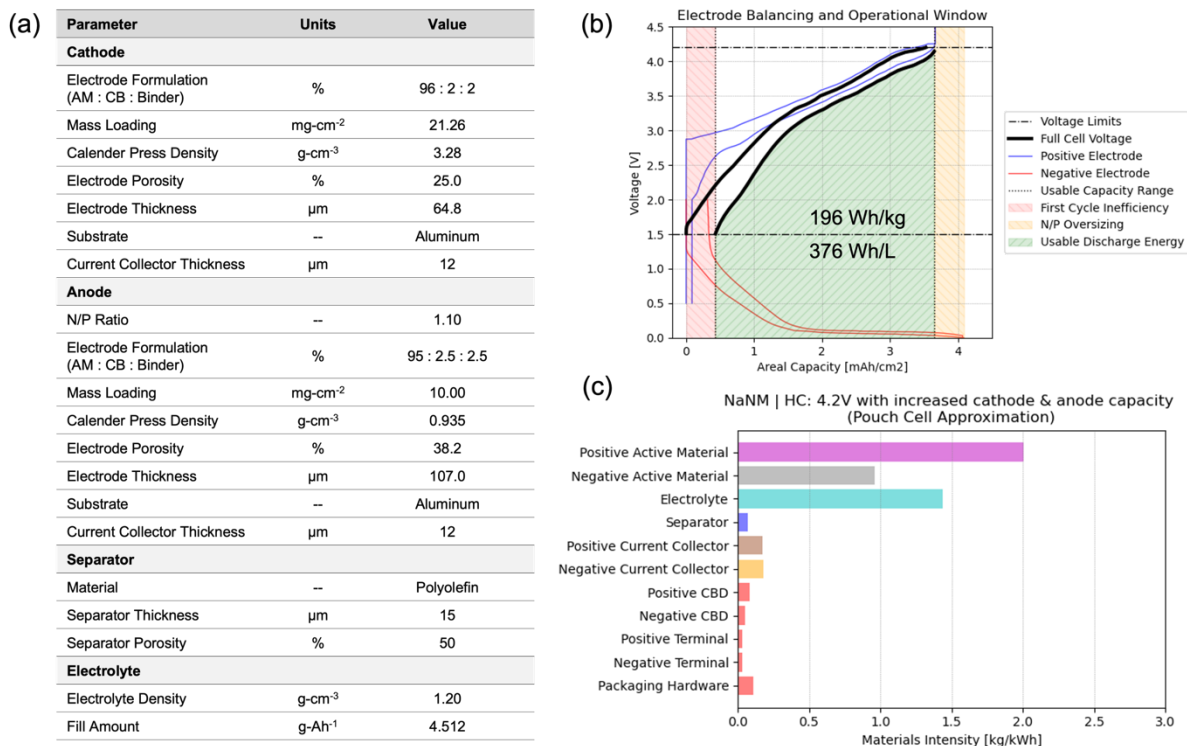
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 35: Modeled Na-ion NaNM | HC – 4.2V Baseline.

Assuming a wider cell voltage range is tolerable to cycle life implications and power conversion electronics, we augment the Baseline scenario from Supplementary Figure 30 by increasing the cathode voltage while still balancing the cell to a 1.10 N/P ratio.

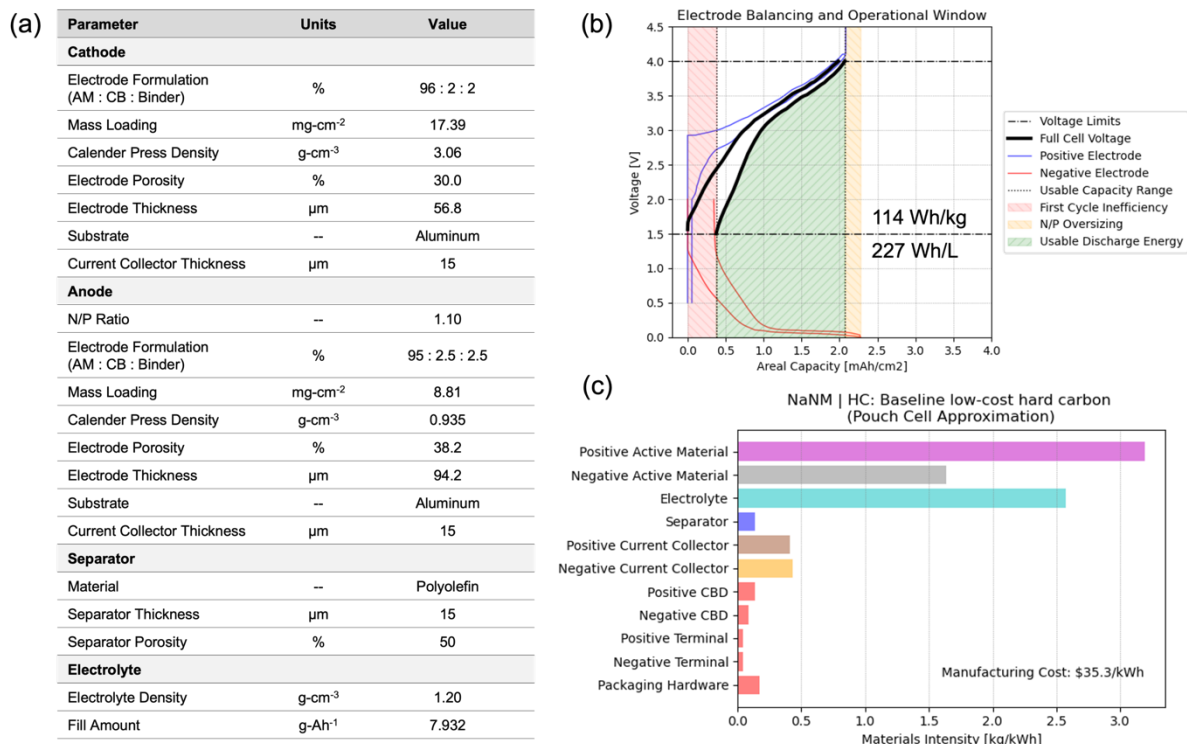
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 36: Modeled Na-ion NaNM | HC – 4.2V; increased cathode & anode specific capacities.

Combining the increased hard carbon specific capacity of 400 mAh-g⁻¹ and the 20% increase to NaNM cathode specific capacity while operating at 4.2V, we evaluate the highest energy density cell design scenario using layered oxide cathodes and hard carbons.

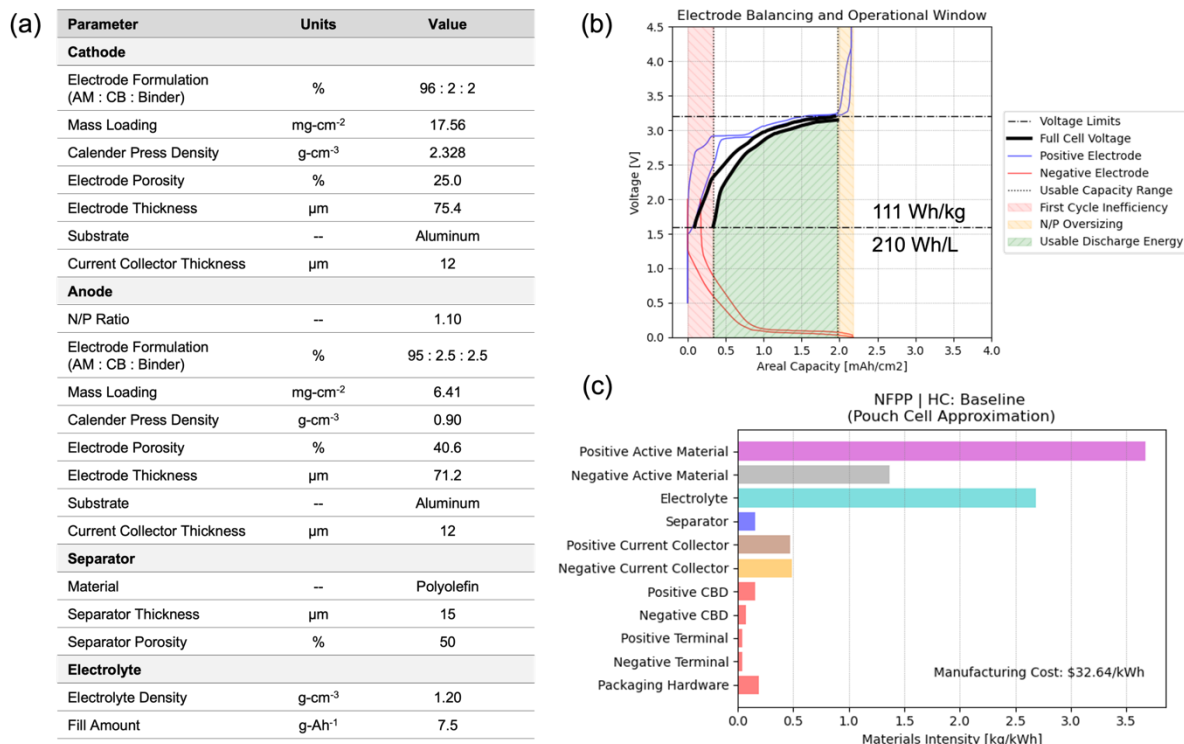
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 37: Modeled Na-ion NaNM | HC – Baseline with low-cost hard carbon.

As discussed earlier in Supplementary Figure 32, hard carbons can be synthesized from various precursors and can have significantly differing performance characteristics as sodium storage is highly dependent on hard carbon microstructure. It is widely understood that the best performing hard carbons in terms of specific capacity are derived from phenolic resin, but they are typically more expensive due to additional costs of chemical feedstock and processing¹⁸. Alternatives to phenolic resin-based hard carbons are those derived from biomass precursors such as coconut shells or fossil fuel precursors such as anthracite, the latter of which have significantly lower costs as detailed in Main Text Figure 2c. However, as these carbon precursors are already in their disordered state, minimal microstructural restructuring can be performed with further processing, and thus little performance gain can be engineered and realized¹⁸. Anthracite-based hard carbons are thus known to be low-cost options with low specific capacity, approximately 250 mAh-g⁻¹^{1,23}. Here, we model cells that may use such a material, forgoing specific capacity performance to use low-cost hard carbons. Note that there are additional knock-on effects to this design decision. Not only is the anode active material intensity (in kg-kWh⁻¹) increased due to lower capacity, but the increased total pore volume resulting from the thicker hard carbon anode will require substantially more electrolyte, which also represents a non-trivial fraction of overall cell costs.

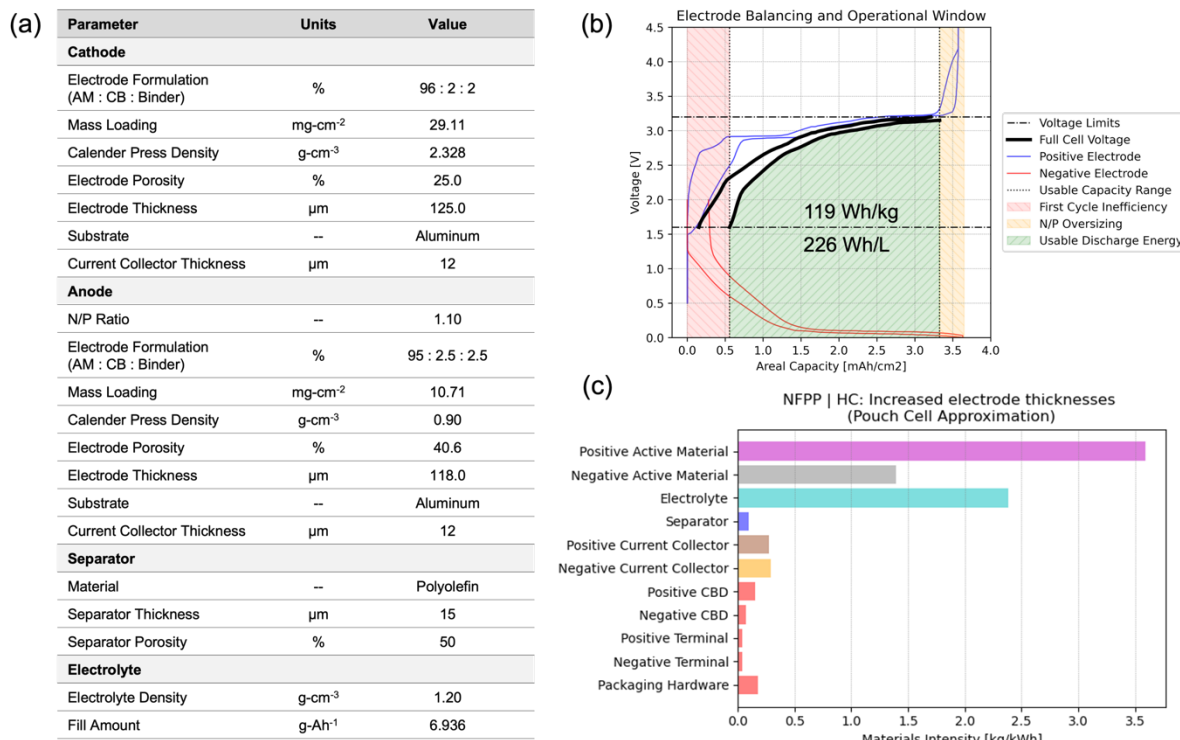
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 38: Modeled Na-ion NFPP | HC – Baseline.

Another class of cathodes that have gained significant attention are polyanionic materials. Specifically, within polyanionic materials, $\text{Na}_4\text{Fe}_3(\text{PO}_4)_2(\text{P}_2\text{O}_7)$ or NFPP is a vanadium-free mixed phosphate cathode that has gained recent popularity as a stable-cycling and low-cost material. However, with a relatively low specific capacity and tap density compared to layered oxide materials, the NFPP cathode becomes the limiting electrode as opposed to the hard carbon anode¹⁸. Similar to the NaNM baseline examples discussed in Supplementary Figure 30, we model a NFPP | HC baseline cell design here.

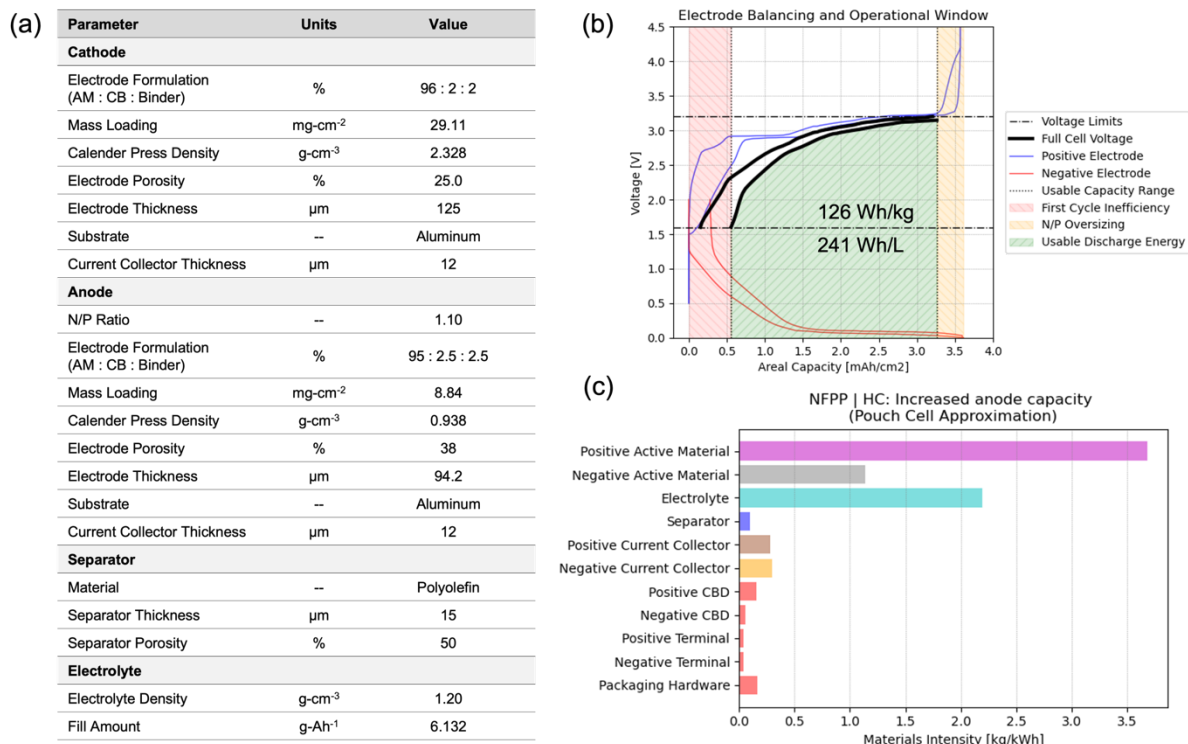
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 39: Modeled Na-ion NFPP | HC – Increased electrode thicknesses.

As discussed in Supplementary Figure 31, increasing electrode thicknesses is a common strategy to increase energy densities and reduce costs. However, as NFPP cathodes are low in specific capacity and tap density, they become the limiting electrode in a NFPP | HC electrochemical couple in terms of thickness, and a post-calendered thickness of $>100\ \mu\text{m}$ would be required. This is substantially thicker than what state-of-art wet slurry-coated electrodes can typically achieve, and there is consensus that dry-electrode coating technology must be utilized to achieve such thicknesses for NFPP¹⁸. In this example, we model an NFPP thickness of $125\ \mu\text{m}$.

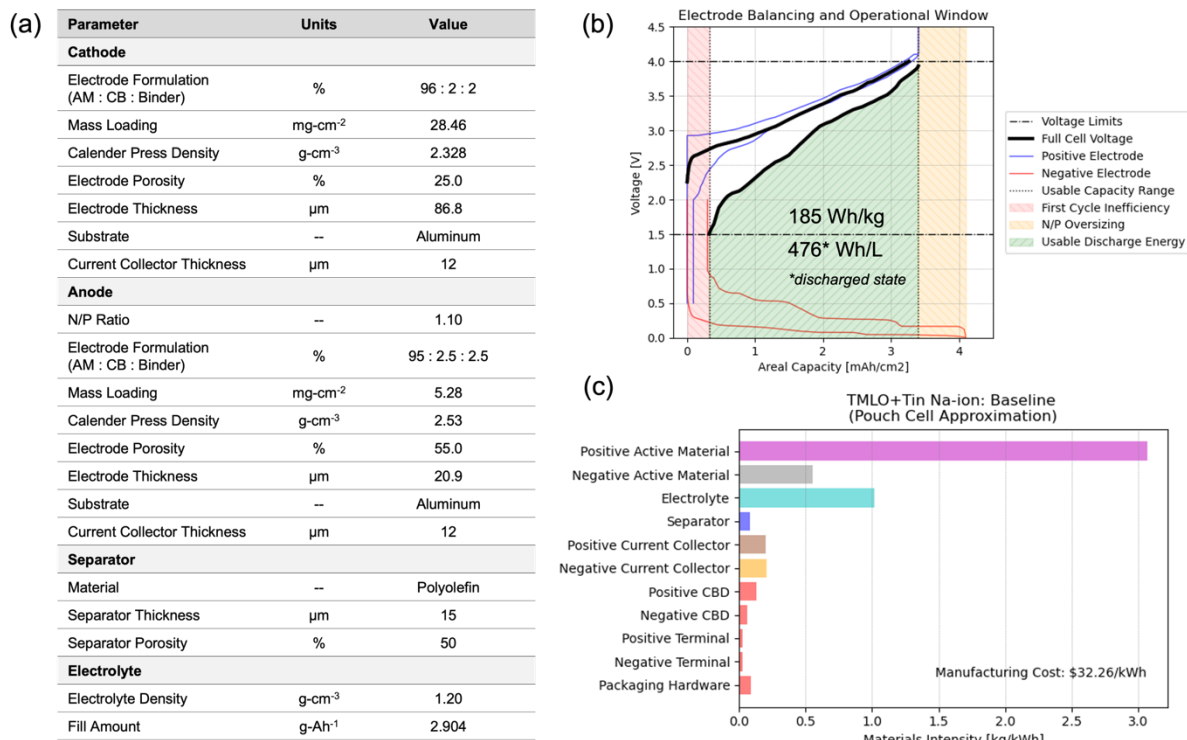
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 40: Modeled Na-ion NFPP | HC – Increased anode specific capacity.

As in Supplementary Figure 32, we similarly model an increase in the hard carbon anode specific capacity. As the assumed NFPP capacity of 128 mAh-g⁻¹ is approximately the theoretical maximum for this material with three sodium ions transferred, improvements to the anode capacity may be the only available route for increased material-level performance.

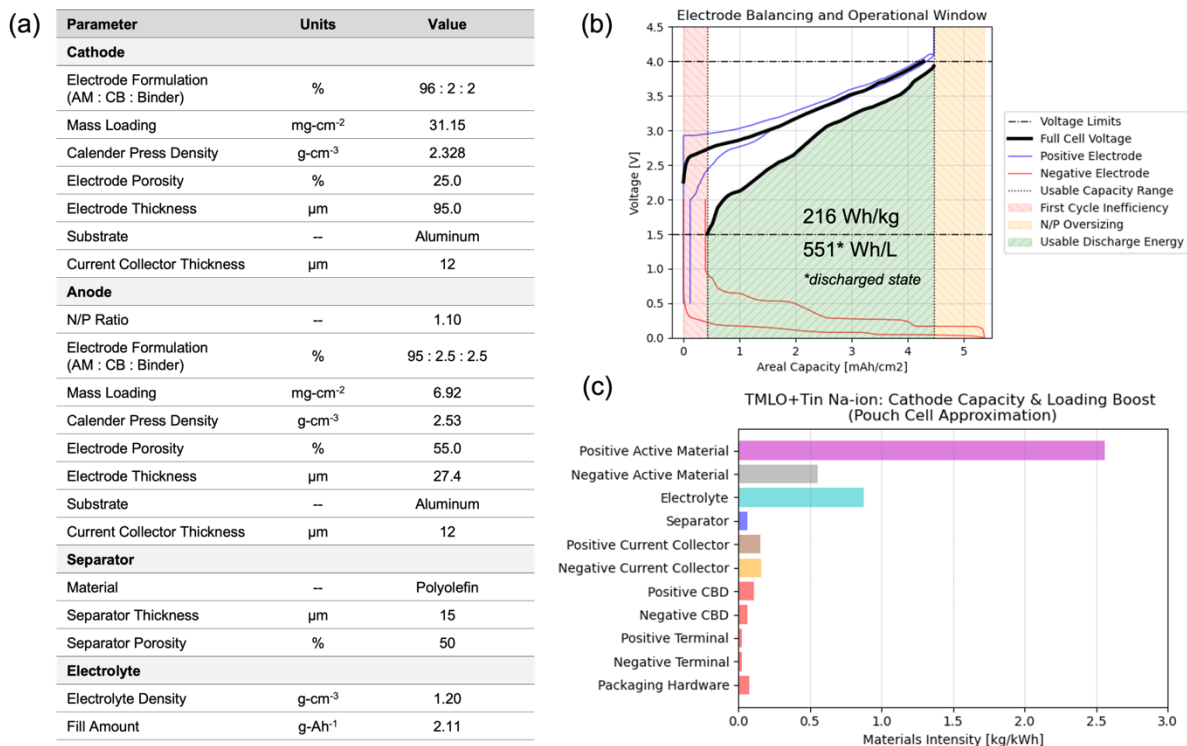
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 41: Modeled Na-ion NaNM | Sn – Baseline.

One potential alternative to using hard carbons as an anode material is to use micron-sized metallic tin (Sn) powder instead. Tin, like antimony (Sb) and lead (Pb) is a metal that alloys with sodium upon sodiation, but is considered the most viable candidate of the three due to its low-toxicity and relative crustal abundance²⁴. As the sodium storage mechanism occurs through an alloying process versus a typical intercalation process, the specific capacity tends to be significantly higher, with a theoretical capacity of 847 mAh-g⁻¹ correlating with an alloy stoichiometry of Na₁₅Sn₄²⁴. In addition to having ultra-high density (~7.31 g-cc⁻³), tin presents an interesting alternative to hard carbon capable of enabling high energy densities. However, large volumetric expansion is commonly observed with alloying reactions, and tin is known to expand by ~420% upon sodiation²⁴. With repeated expansion and contraction upon cycling, the repeated formation/breakage of SEI films can often result in poor cycle life. While somewhat analogous to silicon as a candidate high-capacity anode in Li-ion batteries, tin is unlike silicon in that it is metallic and malleable, which helps mitigate some challenges associated with loss of electrical contact often experienced by silicon. Recent research²⁴ and commercialization efforts¹⁸ point to the ability to form stable SEI using glyme-based electrolytes that enable substantially improved cycle lives, though their stability at higher voltages need to be improved. Using the same principles detailed above, we model a theoretical layered oxide NaNM cathode | Sn anode baseline cell design, drawing from feedback on practical tin electrode designs from industry sources commercializing the technology¹⁸. Here, we assume 800 mAh-g⁻¹ of reversible capacity, and we increase the N/P ratio to 1.20 to minimize material pulverization. Given the high density and specific capacity of tin, the anode in such a system is no longer the limiting electrode in terms of thickness and a balanced anode can be quite thin. In fact, too thin of an electrode coating becomes challenging to manufacture with high uniformity in a slurry-based coating process, and thus a baseline NaNM | Sn design requires >3 mAh-cm⁻² capacity loading¹⁸. Here, we model a baseline cell design with an effective capacity loading of 3.1 mAh-cm⁻² which correlates to single-sided anode composite thickness of 20.9 μm thickness at an assumed porosity of 55% (to accommodate material swelling¹⁸).

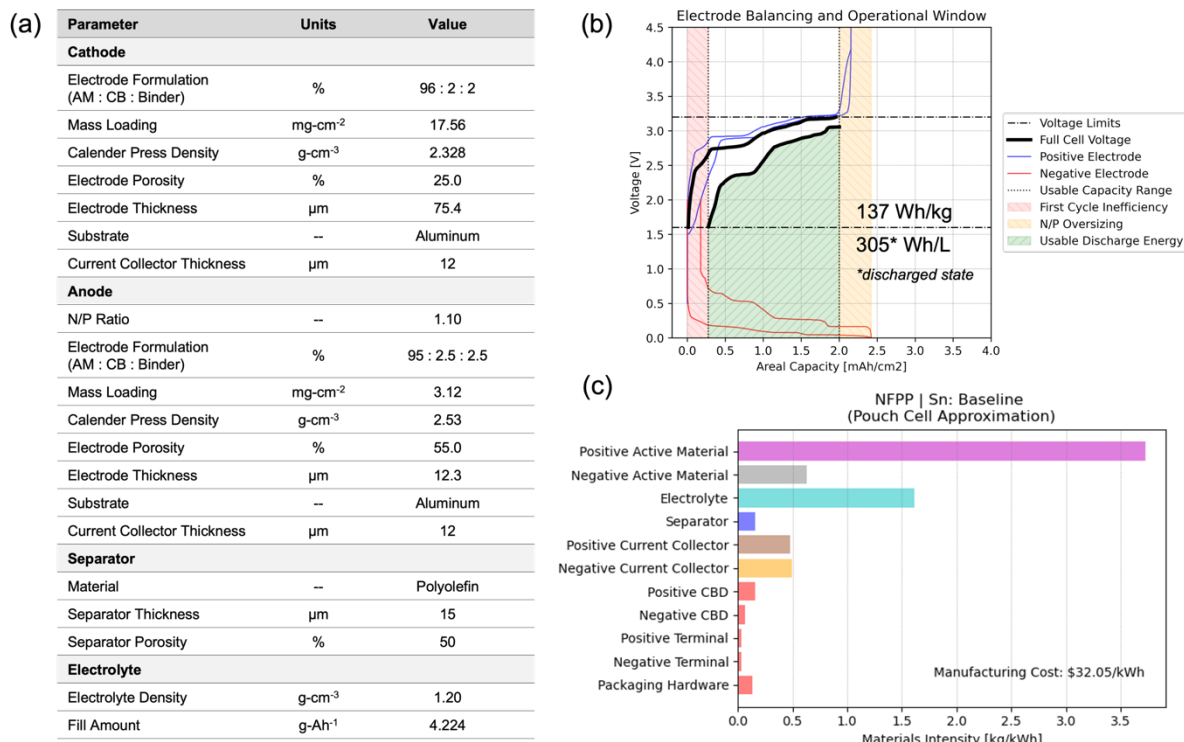
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 42: Modeled Na-ion NaNM | Sn – Cathode Capacity Boost.

Similar to prior examples, we model an increase in NaNM specific capacity by 20% while still being limited to a 4.0V full cell system. We note that since the assumed 800 mAh-g⁻¹ specific capacity in the baseline example is ~95% of tin's theoretical capacity, we do not include additional increases to the anode capacity. We however do increase the electrode loading of the cathode. As the cathode is now the limiting electrode, we assume a maximum thickness of 95 μm considering practical manufacturability and liquid-phase mass transport limitations.

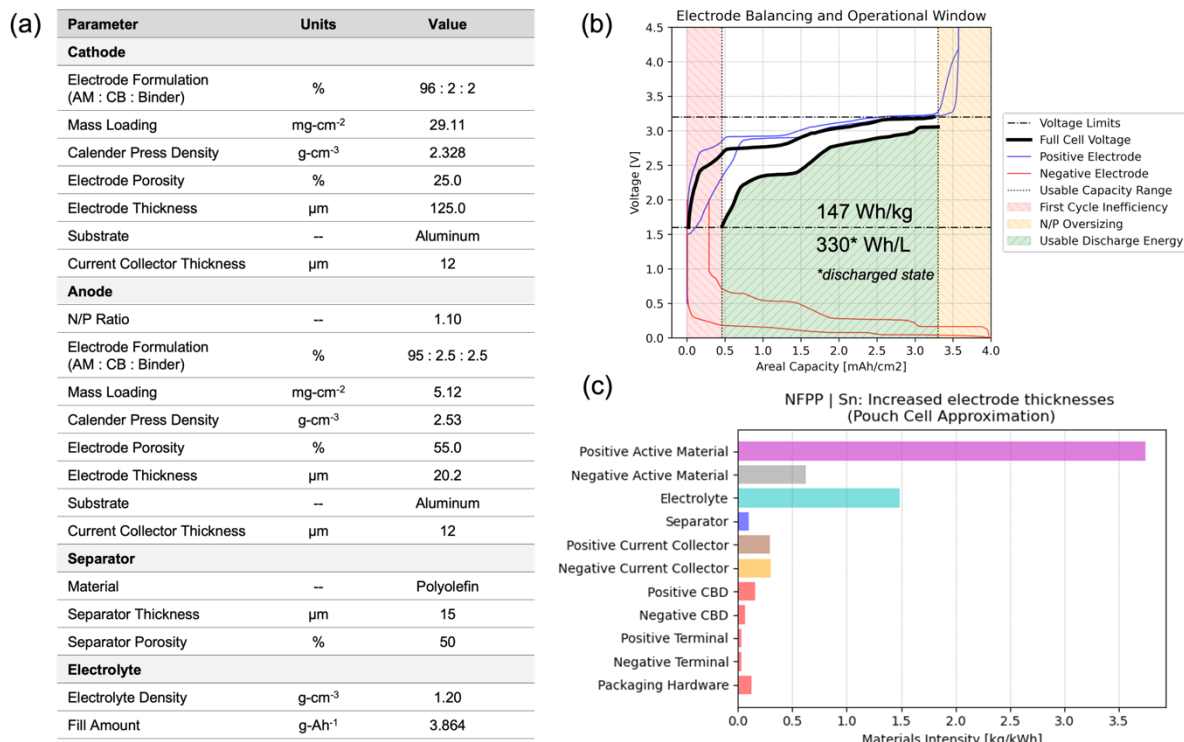
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 43: Modeled Na-ion NFPP | Sn – Baseline

Similarly, we model a Sn anode paired against a NFPP cathode as yet another strategy to increase energy densities. We first model a cell with the same NFPP cathode thickness as the NFPP | HC baseline. Note however that the resulting Sn anode is very thin due to the low areal capacity of the cathode.

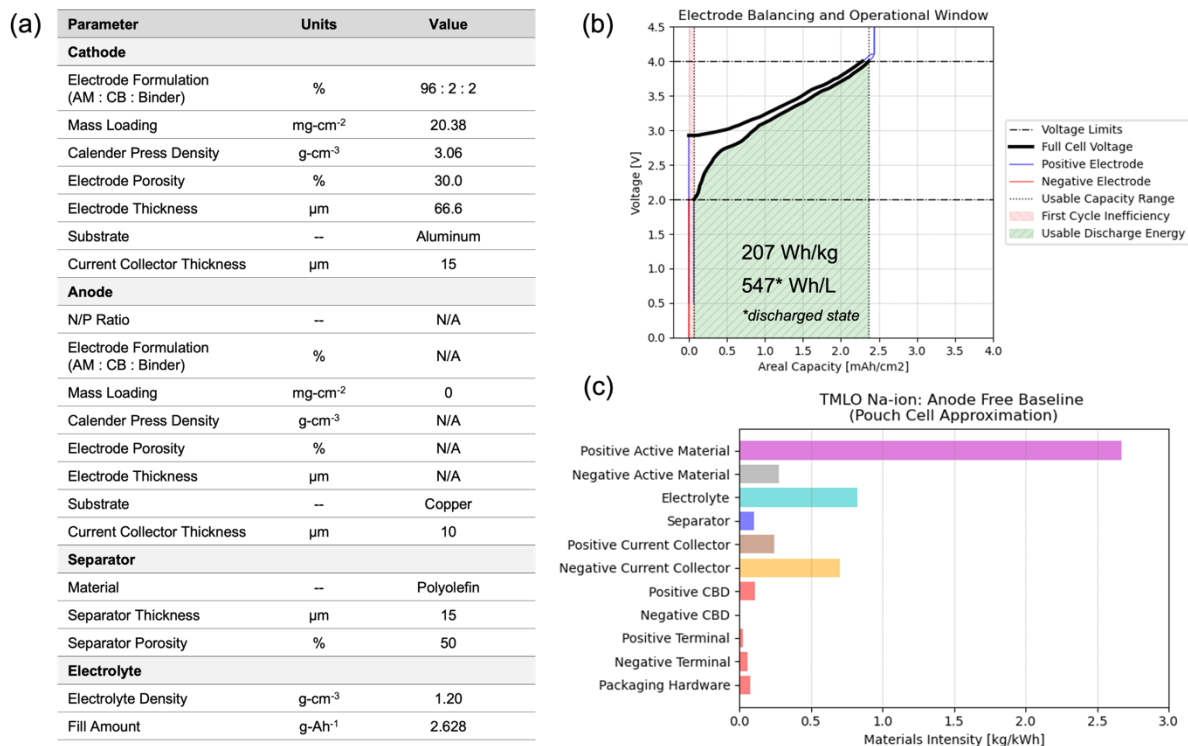
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 44: Modeled Na-ion NFPP | Sn – Increased electrode thicknesses.

We again assume dry-coated NFPP cathodes can enable thick cathodes of 125 μm. This increases the Sn anode back to ~20 μm.

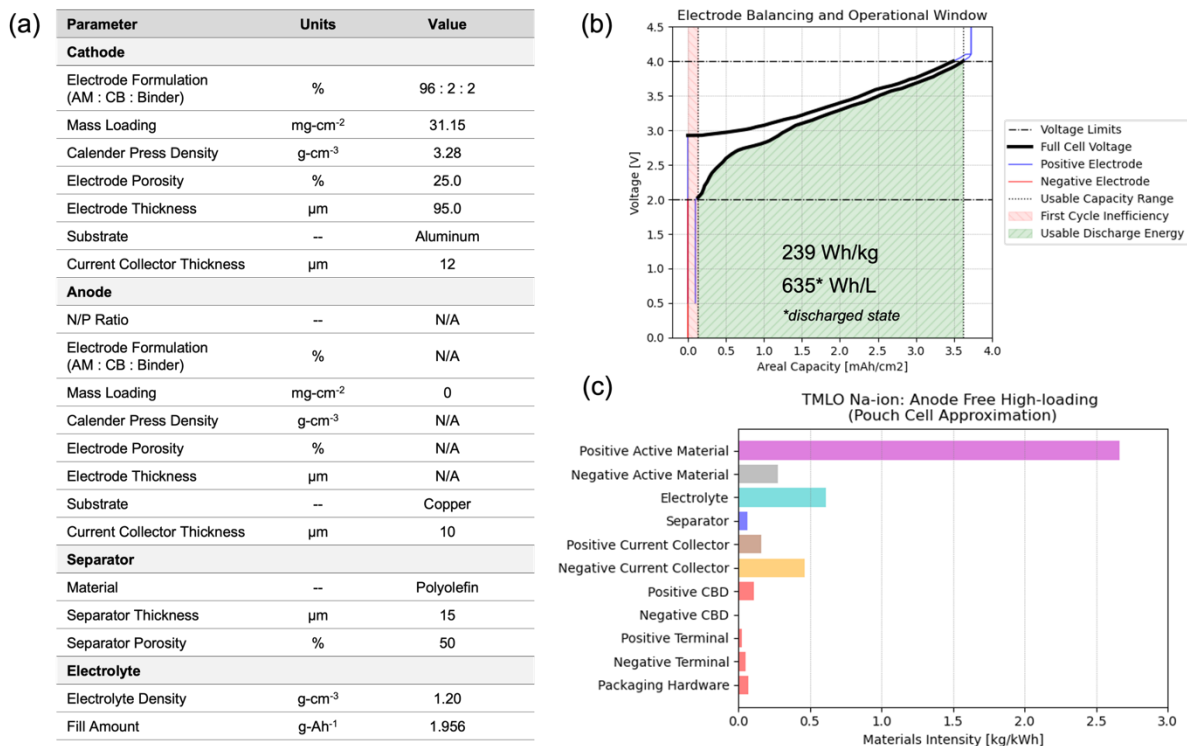
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 45: Modeled Na-ion NaNM | Anode-free – Baseline

The ultimate replacement anode material is to not have an anode material at all, and instead directly electrodeposit/strip sodium metal upon a bare substrate current collector, termed “anode-free”. This is also notably different from a design using metallic lithium or sodium (alloy) foils, as the processing costs to handle alkali metals and the minimum attainable foil thicknesses present additional unique challenges. Therefore, in the anode-free cell configuration, the cell is assembled in the discharged state with all the working ion inventory (lithium or sodium) in the cathode active material, which are subsequently electrodeposited *in-situ* onto a bare (or treated) negative current collector upon charging and completely stripped upon discharging again. Common challenges to overcome in this configuration include mitigating excessive SEI growth on newly formed metal-electrolyte interfaces with every charge/discharge cycle, ensuring no loss of active sodium upon cycling, and suppression of dendrite growth that may eventually short-circuit through the separator. There is some preliminary evidence that electroplating sodium metal may be performed with higher Coulombic efficiency than lithium, but this is still an area of early research. What appears to be known, however, is that an anode-free Na-ion cell design will most likely require (i) a copper anode current collector due to the lower nucleation barrier overpotentials or an advanced 3D current collector to mitigate excessive swelling, (ii) an advanced electrolyte system with high cathodic stability to form stable SEI, such as a glyme-based solvent system with engineered salts and additives, and (iii) a modified separator to prevent dendrite penetration. Assuming sodium metal can be electrodeposited as a dense film with near 0% porosity, one of the ancillary benefits of an anode-free Na-ion cell is the lack of a porous composite hard carbon anode that requires substantial electrolyte volume to saturate. Therefore, an anode-free cell design reduces the bill-of-materials significantly by eliminating the anode electrode composite and electrolyte volume but must balance those savings with the cost of advanced electrolytes, separators, and current collectors. Finally, we note that there may be additional cost savings in the manufacturing of anode-free cells if formation processes can be simplified. However, lacking a mature commercial anode-free Na-ion process today, we do not make such assumptions.

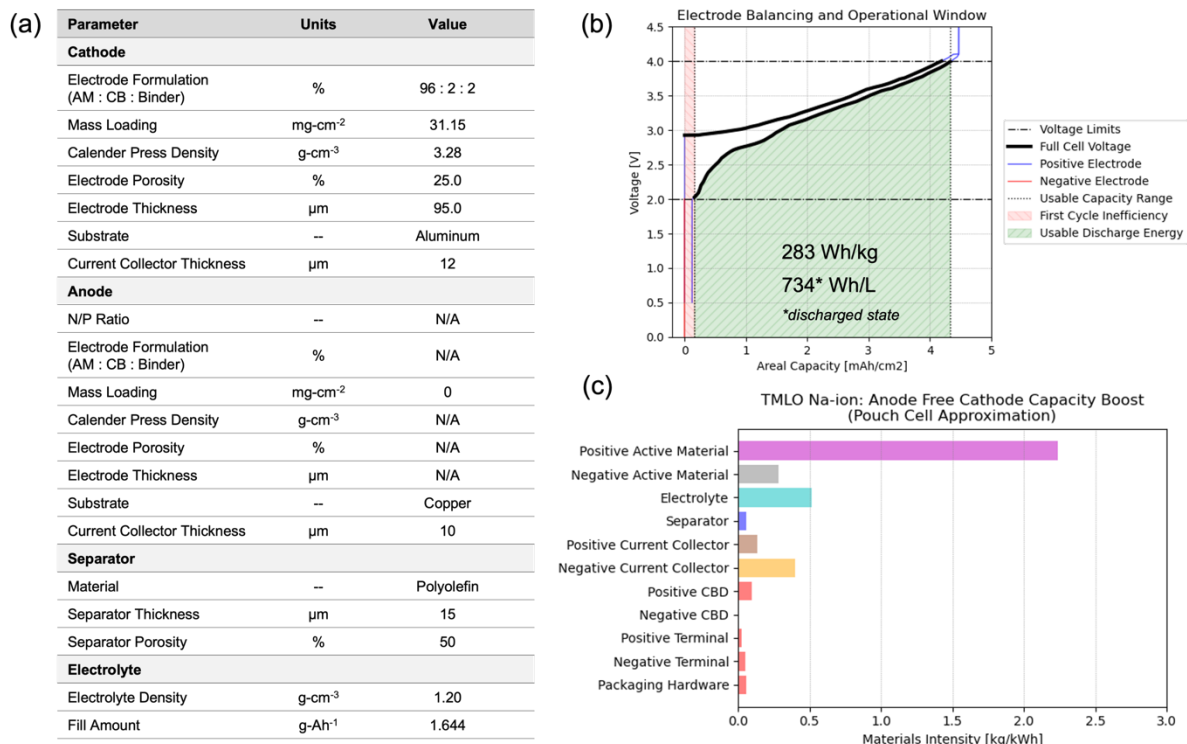
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



Supplementary Figure 46: Modeled Na-ion NaNM | Anode-free – Cathode Loading Boost.

We further model an anode-free Na-ion cell where the cathode electrode calender density is increased along with coated mass loadings. Here, we assume the same maximum cathode electrode thickness as in Supplementary Figure 31.

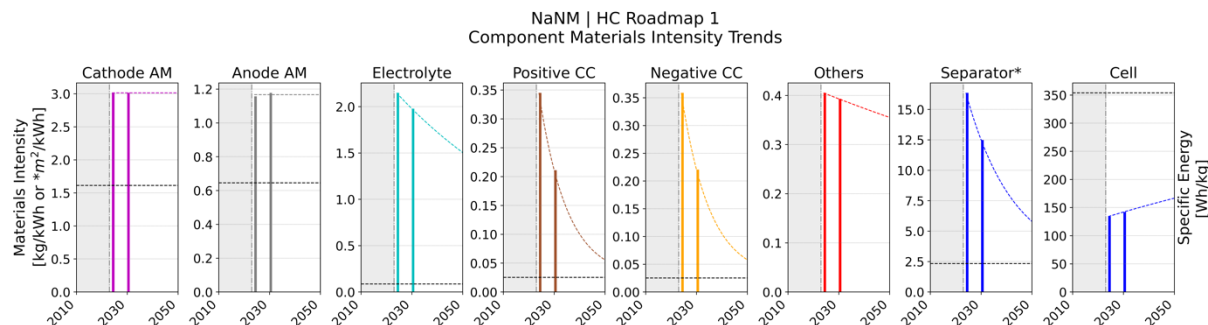
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



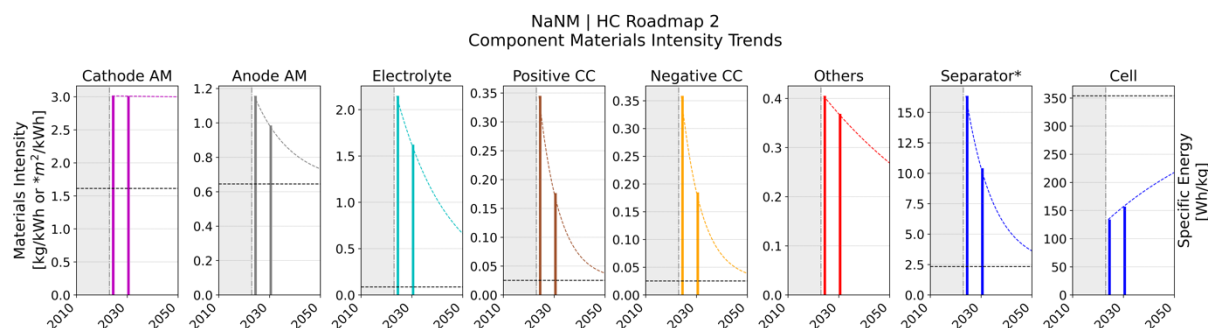
Supplementary Figure 47: Modeled Na-ion NaNM | Anode-free – Cathode Capacity Boost.

Finally, we model an anode-free Na-ion cell design where the cathode active material experiences a 20% increase in specific capacity while still maintaining an operating voltage range between 2.0V and 4.0V. We note that this is the highest specific energy Na-ion cell design evaluated in this entire study and would outperform the performance boundaries of LFP | graphite Li-ion cell designs.

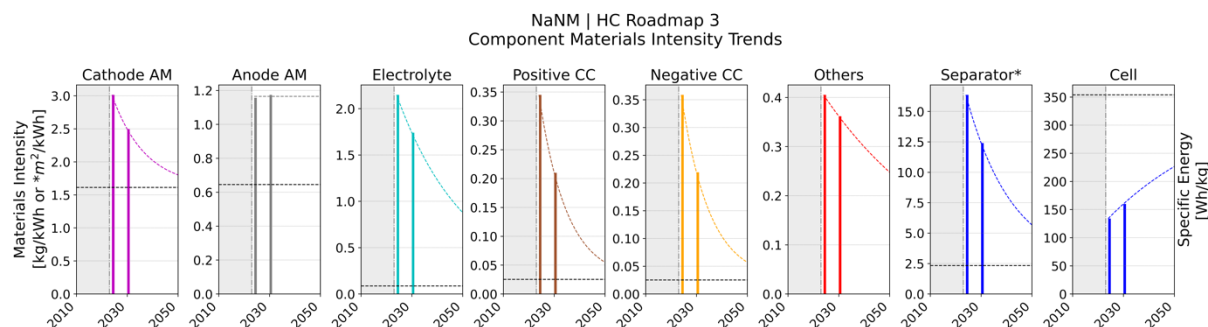
(a) Unit cell design parameters. (b) Electrode balancing in BatPaC-designed pouch cell representative. (c) Calculated materials intensity for BatPaC-designed pouch cell representative.



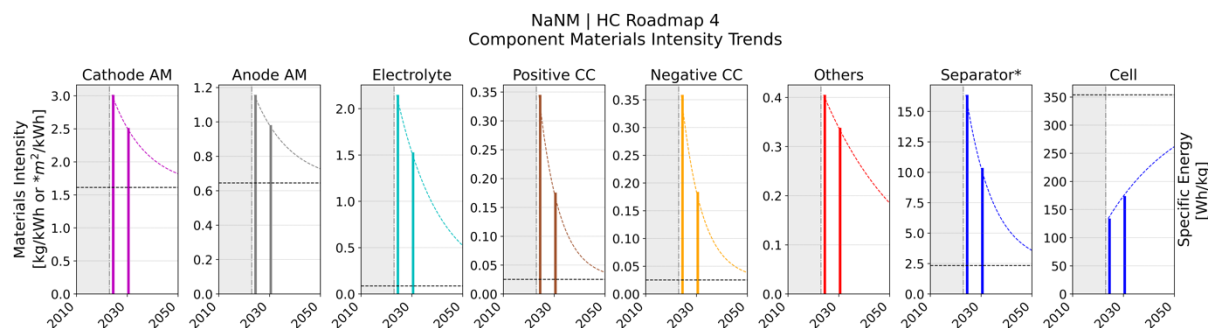
Supplementary Figure 48: NaNM | HC Roadmap 1.



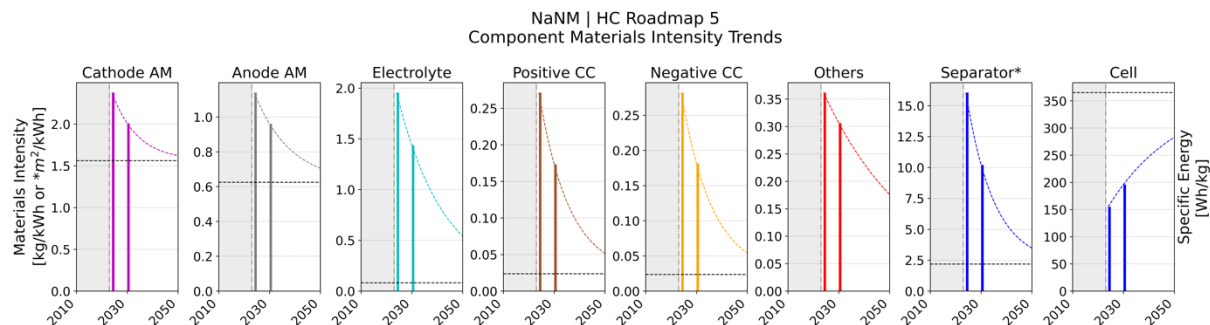
Supplementary Figure 49: NaNM | HC Roadmap 2.



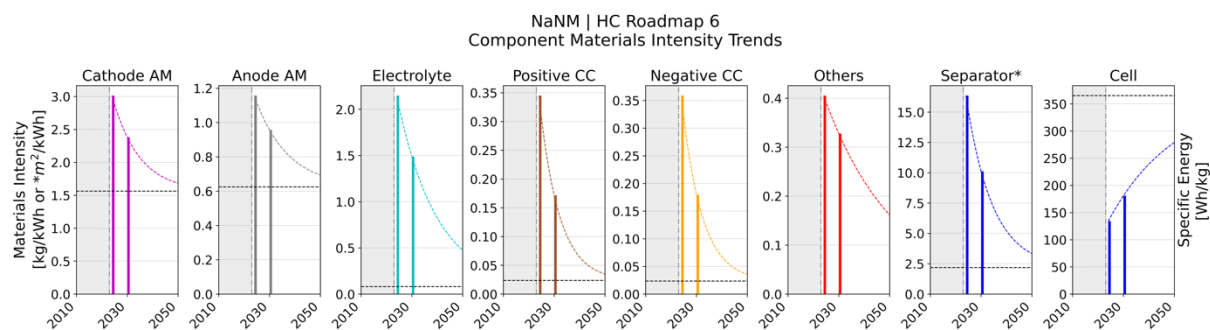
Supplementary Figure 50: NaNM | HC Roadmap 3.



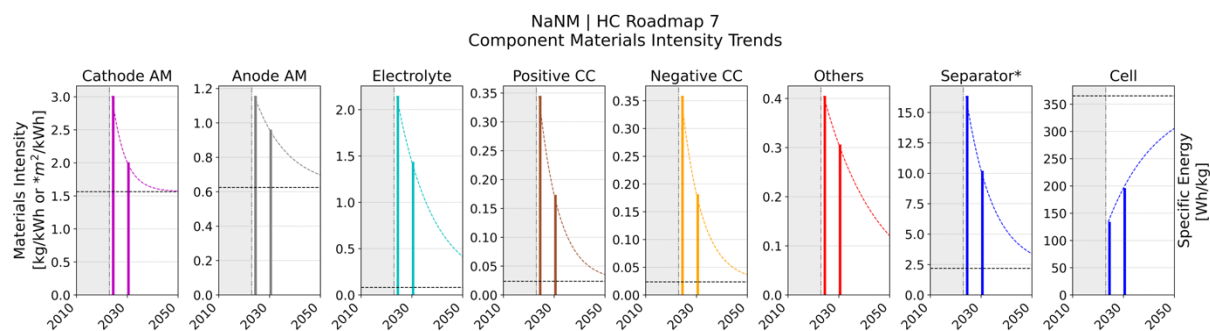
Supplementary Figure 51: NaNM | HC Roadmap 4.



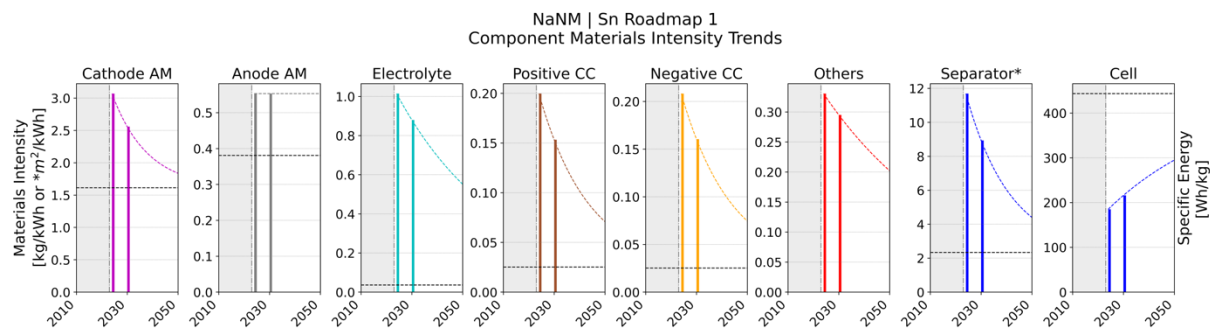
Supplementary Figure 52: NaNM | HC Roadmap 5



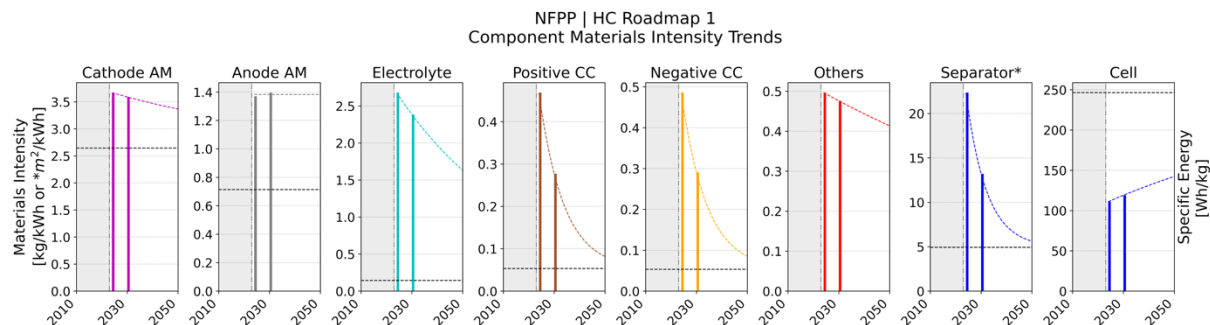
Supplementary Figure 53: NaNM | HC Roadmap 6.



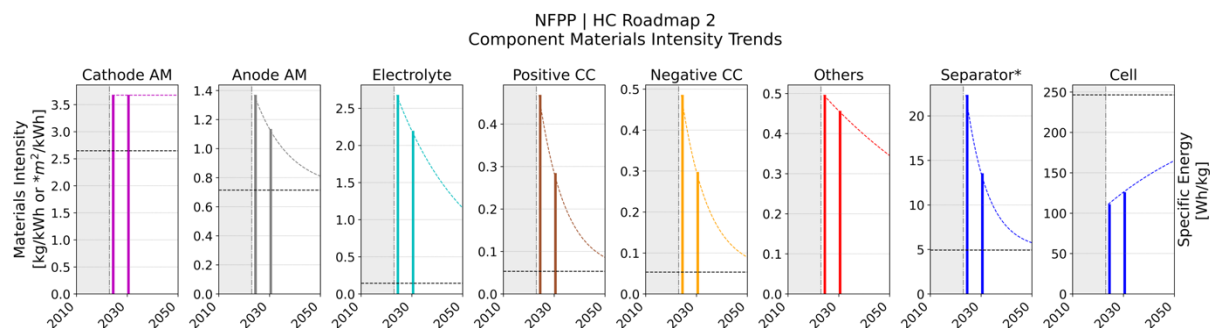
Supplementary Figure 54: NaNM | HC Roadmap 7.



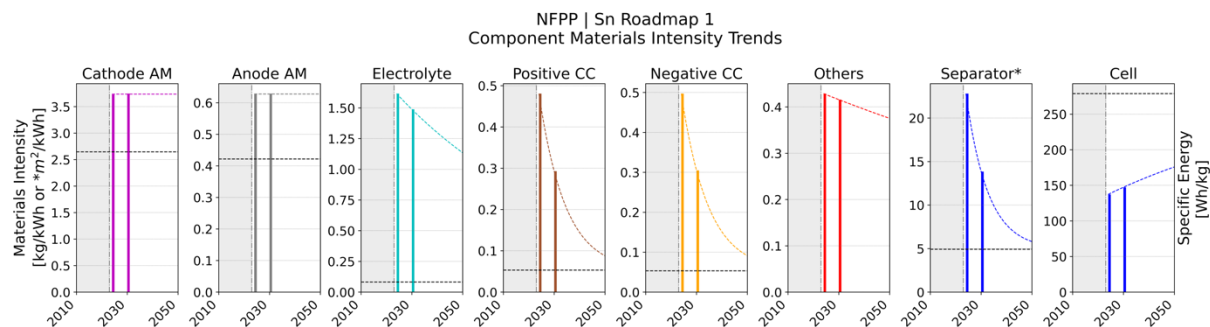
Supplementary Figure 55: NaNM | Sn Roadmap 1.



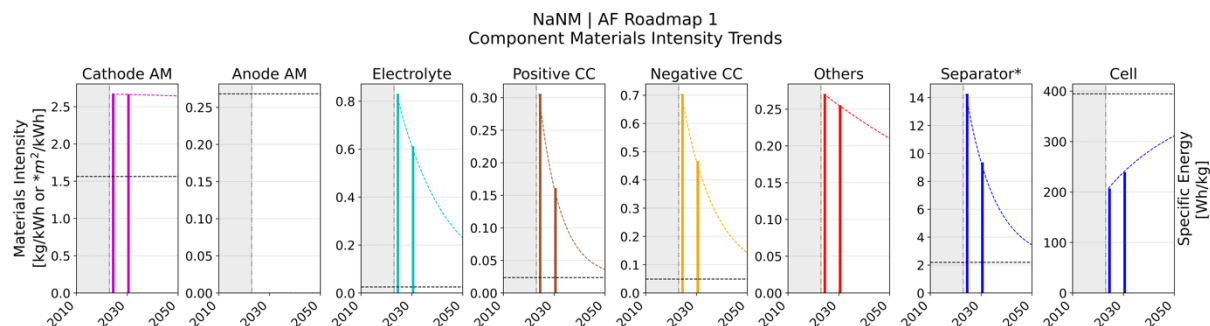
Supplementary Figure 56: NFPP | HC Roadmap 1.



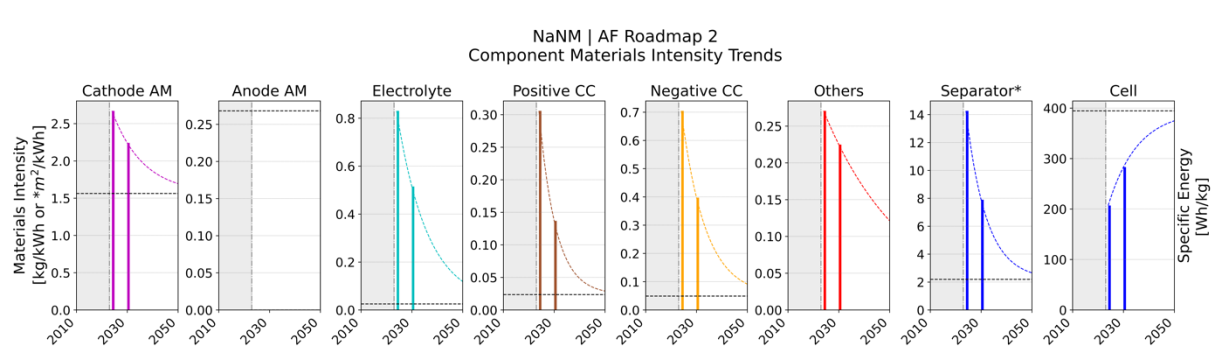
Supplementary Figure 57: NFPP | HC Roadmap 2.



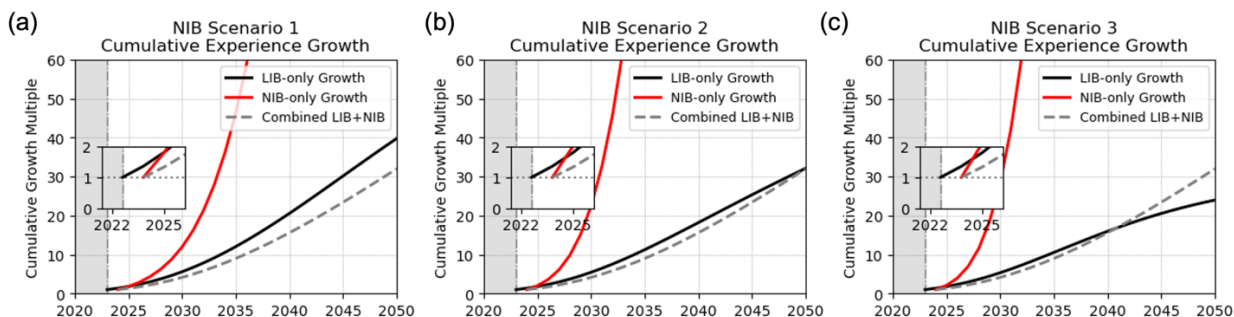
Supplementary Figure 58: NFPP | Sn Roadmap 1.



Supplementary Figure 59: NaNM | AF Roadmap 1.

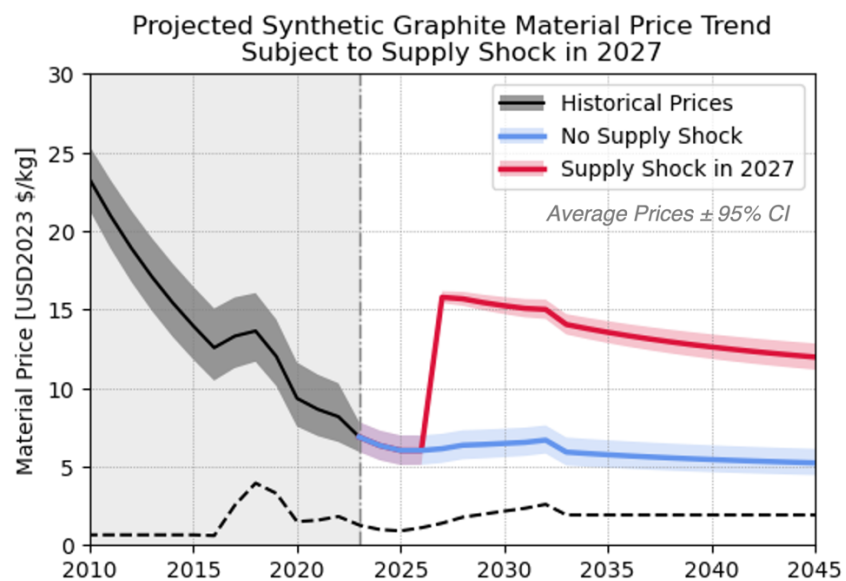


Supplementary Figure 60: NaNM | AF Roadmap 2.



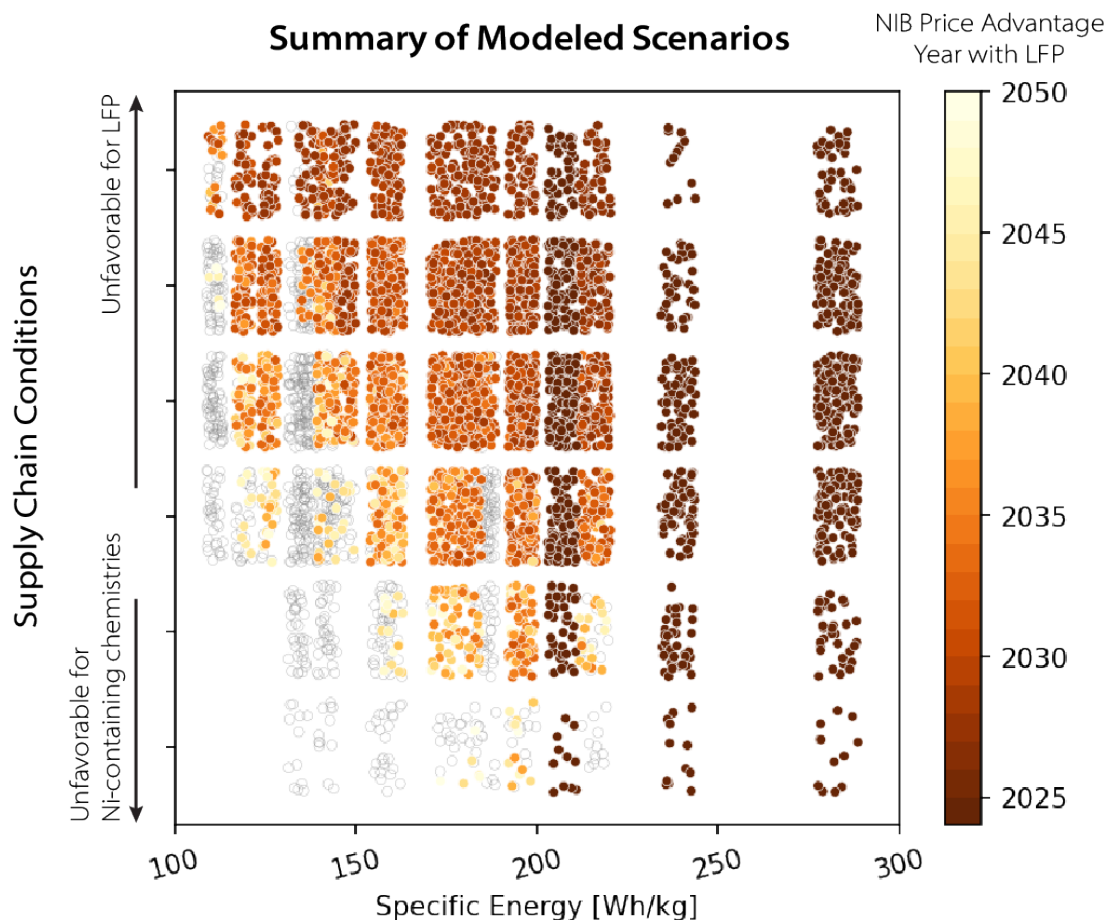
Supplementary Figure 61: Cumulative experience growth curves for modeled scenarios

Cumulative experience growth curves for each of the Na-ion market penetration scenarios discussed in Supplementary Note 7:. Note that the cumulative experience growth of Li-ion-specific components is more modest due to the large cumulative deployed capacity to-date in comparison to an emerging technology like Na-ion.



Supplementary Figure 62: Synthetic graphite prices modeling hypothetical supply shock scenario.

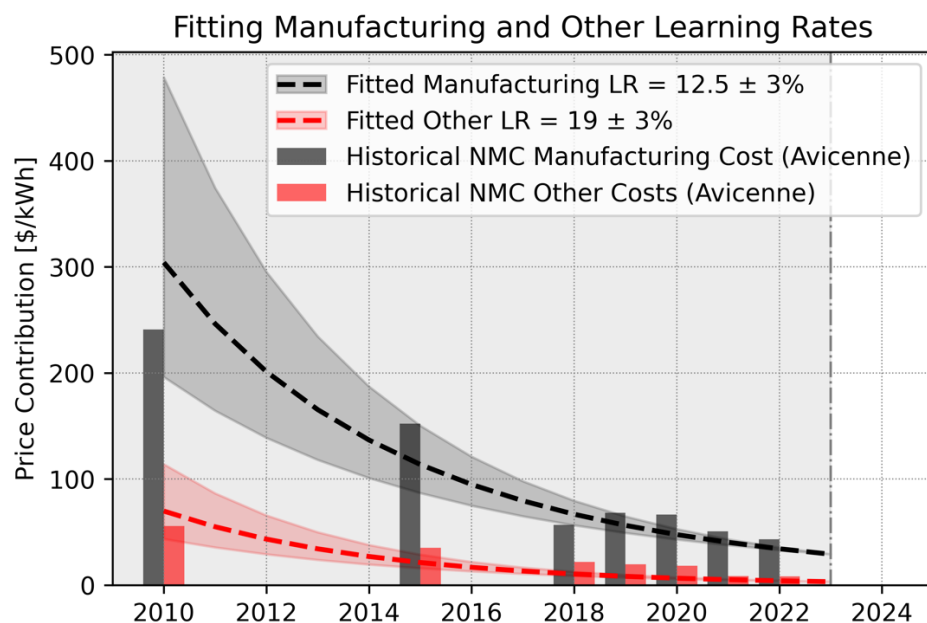
Synthetic graphite prices with and without hypothetical supply shock scenario.



Supplementary Figure 63: Na-ion Price Parity Summary

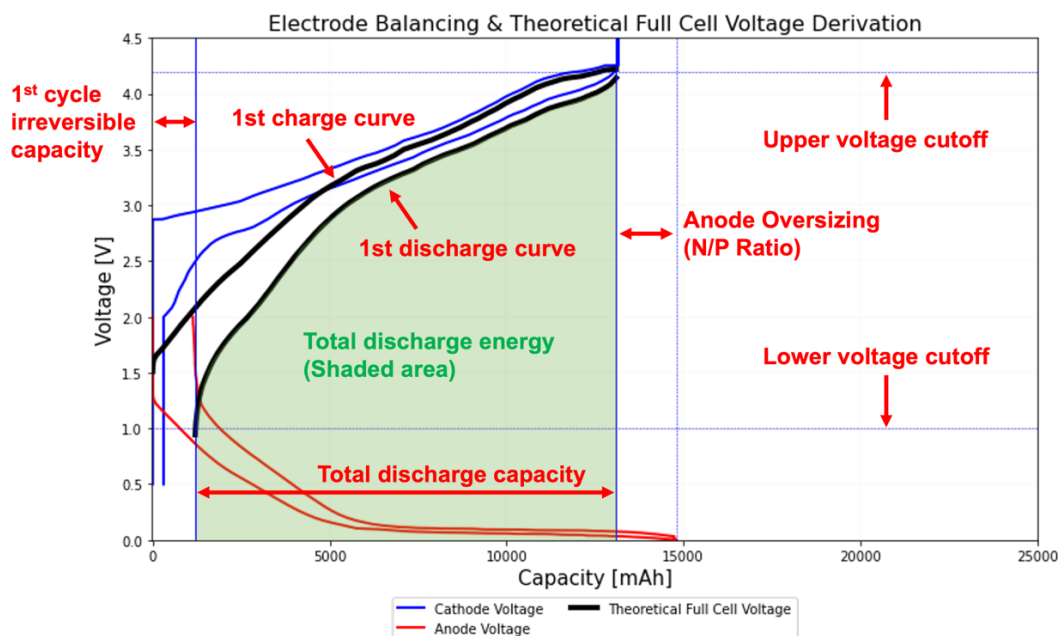
Heatmap showing timelines to price parity. Supply chain conditions ranked categorically here via summation of integer increments/decrements of lithium, graphite, and nickel supply chain conditions according to Na-ion favorability—with increased nickel commodity pricing being unfavorable to only nickel-containing Na-ion layered oxide cathodes. For example, a high lithium price scenario (+1) coinciding with a graphite supply shock (+1) will produce a supply chain score of +2. The x-axis is ranked by the specific energy density targets achieved by 2030 in the various roadmaps.

Despite many scenarios modeled showing long timelines to Price Advantage, or even no Price Advantage condition at all (Main Text, Figure 5), it does not mean Na-ion is not competitive against LFP. This figure shows a complementary plot to Main Text, Figure 5 by illustrating the timelines to Price Parity. As depicted via the noticeably higher density of darker colored markers which correspond to a nearer term time frame, almost all Na-ion development roadmaps lead to a price competitive scenario by the mid 2030s.



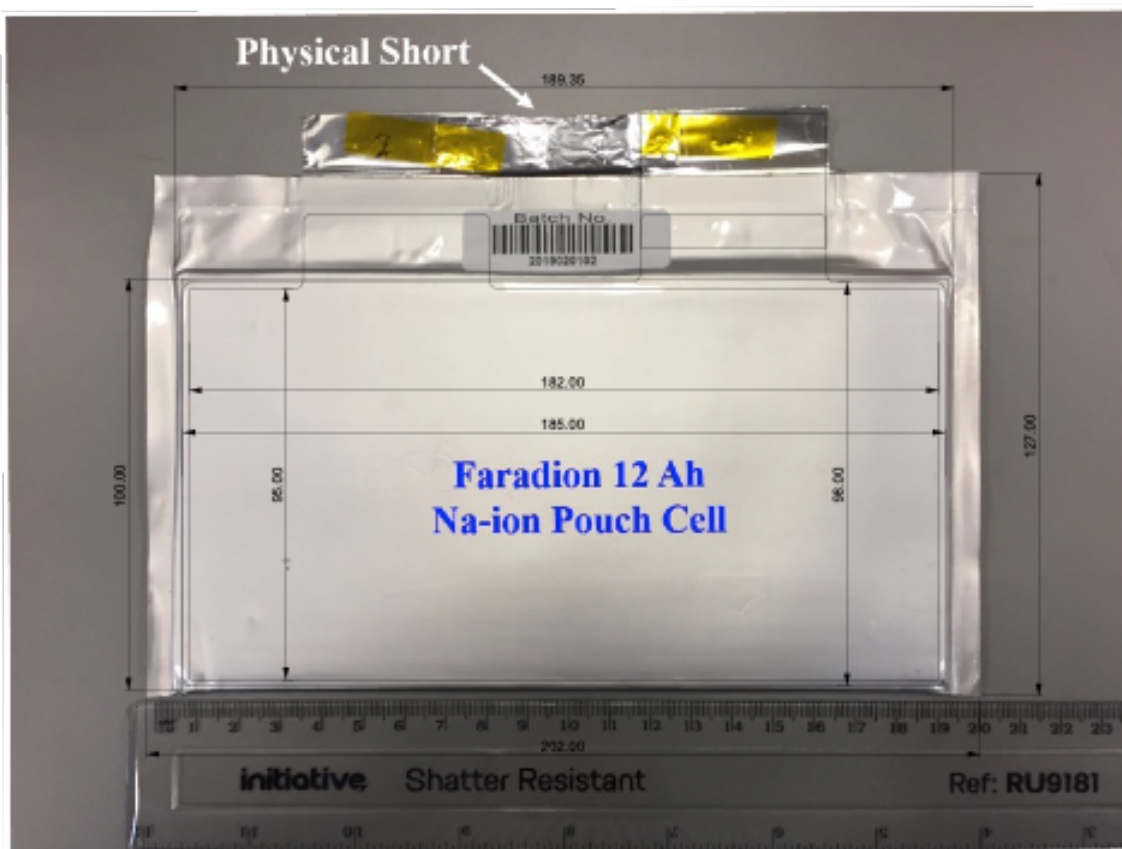
Supplementary Figure 64: Fitting Manufacturing and Other learning rates.

To fit the learning rates of Manufacturing and Other components, historical component price breakdowns for the two categories were obtained from Avicenne Energy tracking the price evolution of NMC-type cells^{1,7}. Unconstrained learning curves were then backcast and fitted with known starting cost contributions from the bill-of-materials (for the Others component) and BatPaC cost calculations (for the Manufacturing component). For the Others component, the materials intensity trends established in Supplementary Figure 25 were used as a multiplier to capture the reduction in the Others component due to improvements in cell design efficiency. Similarly, the evolution of increasing cell-level gravimetric energy densities over time (also established in Supplementary Figure 25) is factored to ensure the Manufacturing cost component falls as a function of increasing energy densities. Both of these measures enable deconvolution of improvements due to learning-by-doing versus cell design efficiency. We assume the learning rates fitted for NMC-type Li-ion are transferrable to LFP-type Li-ion as well as Na-ion batteries.



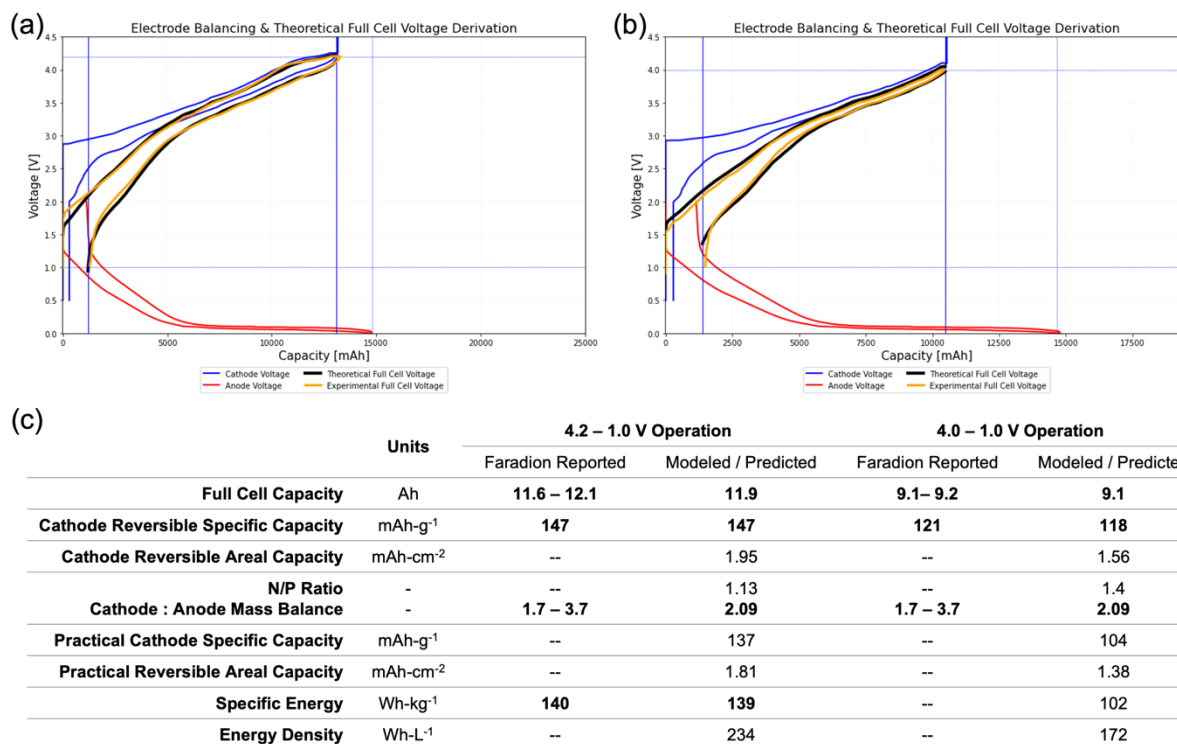
Supplementary Figure 65: Cell modeling procedure and energy determination.

Representative figure showing cathode (blue) and anode (red) curves scaled from extracted half-cell data, producing a theoretical full cell curve from their difference. Other cell design parameters labeled in red. Note the green shaded region representing the total available discharge energy is substantially less than what the cathode can provide.



Supplementary Figure 66: Dimensional analysis of Faradion's 12Ah pouch cell platform.

Dimensional analysis of Faradion's 12Ah pouch cell platform obtained from ref.¹⁰ with estimated electrode footprint design.



Supplementary Figure 67: Summary of modeling results compared with Faradion data.

(a) Modeling Faradion 12Ah pouch cell from 4.2 – 1.0V. Blue and red curves produced via mathematical scaling of extracted half-cell data published by Faradion. Black curve predicted based upon cell balancing exercise. Orange curve overlay shows actual extracted voltage curves from Faradion full cells, showing good agreement with our model. (b) Same cell design but derated to 4.0 – 1.0V operation. Resulting cell voltage and capacity matches Faradion reported results. (c) Table of key cell parameters obtained via modeling and compared against Faradion reported figures. Good agreement is found for all publicly reported values from Faradion, shown in bold.

SUPPLEMENTARY TABLES

Supplementary Table 1: Summary of tabulated minerals/commodities and data sources

Mineral / Commodity	Source(s)
Lithium Carbonate Equivalents (LCE), Lithium Carbonate, Lithium Hydroxide	Benchmark Mineral Intelligence Wood Mackenzie S&P Global Avicenne Energy United States Geological Survey
Nickel, Nickel Sulfate	Benchmark Mineral Intelligence Wood Mackenzie S&P Global United States Geological Survey
Cobalt, Cobalt Sulfate	Benchmark Mineral Intelligence Wood Mackenzie S&P Global United States Geological Survey
Flake Graphite, Spherical Graphite, Needle Coke	Benchmark Mineral Intelligence Wood Mackenzie United States Geological Survey
Manganese, Manganese Sulfate	Wood Mackenzie United States Geological Survey
Copper	Wood Mackenzie S&P Global United States Geological Survey
Aluminum	Wood Mackenzie S&P Global United States Geological Survey
Phosphate Rock	United States Geological Survey
Fluorspar	United States Geological Survey
Soda Ash	United States Geological Survey
Tin	S&P Global United States Geological Survey
Iron Ore	Wood Mackenzie

Supplementary Table 2: Summary of mineral and elemental compositions of material components

Material	Mineral / Commodity	Useful Molar Fraction [%]	Percent Mass of Material [%]
NMC111, $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$	Lithium Carbonate Equivalent	18.79	7.20
	Nickel	100.00	20.27
	Manganese	100.00	18.98
	Cobalt	100.00	20.36
NMC532, $\text{LiNi}_{0.50}\text{Mn}_{0.30}\text{Co}_{0.20}\text{O}_2$	Lithium Carbonate Equivalent	18.79	7.19
	Nickel	100.00	30.39
	Manganese	100.00	17.07
	Cobalt	100.00	12.21
NMC622, $\text{LiNi}_{0.60}\text{Mn}_{0.20}\text{Co}_{0.20}\text{O}_2$	Lithium Carbonate Equivalent	18.79	7.16
	Nickel	100.00	36.33
	Manganese	100.00	11.34
	Cobalt	100.00	12.16
NMC811, $\text{LiNi}_{0.80}\text{Mn}_{0.10}\text{Co}_{0.10}\text{O}_2$	Lithium Carbonate Equivalent	18.79	7.14
	Nickel	100.00	48.27
	Manganese	100.00	5.65
	Cobalt	100.00	6.06
NCA, $\text{LiNi}_{0.82}\text{Co}_{0.14}\text{Al}_{0.04}\text{O}_2$	Lithium Carbonate Equivalent	18.79	7.20
	Nickel	100.00	49.93
	Cobalt	100.00	8.56
	Aluminum	100.00	1.12
LFP, LiFePO_4	Lithium Carbonate Equivalent	18.79	4.40
	Iron Ore	55.00	35.40
	Phosphate Rock	5.00	60.20
LCO, LiCoO_2	Lithium Carbonate Equivalent	18.79	7.09
	Cobalt	100.00	60.21
NaNM (Faradion O3-type Gen2), $\text{NaNi}_{0.30}\text{Mn}_{0.30}\text{Mg}_{0.17}\text{Ti}_{0.17}\text{O}_2$	Soda Ash	43.38	21.92
	Nickel	100.00	18.64
	Manganese	100.00	17.44
	Magnesium Hydroxide	41.67	3.87
	Titanium Dioxide	59.93	7.62
NaNM (Faradion P2-type Gen2)	Soda Ash	43.38	15.05
	Nickel	100.00	17.28
	Manganese	100.00	32.34
	Magnesium Hydroxide	41.67	0.79
	Titanium Dioxide	59.93	3.15
NaNM (Faradion 0.67-0.33 O3-P2 Composite Blend Gen2)	Soda Ash	43.38	19.65
	Nickel	100.00	18.19
	Manganese	100.00	22.36
	Magnesium Hydroxide	41.67	6.15
	Titanium Dioxide	59.93	2.85
NaFM, $\text{Na}_{0.67}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{O}_2$	Soda Ash	43.38	14.92
	Iron Ore	55.00	27.18
	Manganese	100.00	26.74
NFPP, $\text{Na}_4\text{Fe}_3(\text{PO}_4)_2(\text{P}_2\text{O}_7)$	Soda Ash	43.38	15.11
	Iron Ore	55.00	25.11
	Phosphate Rock	5.00	31.21
Synthetic Graphite	Needle Coke	100.00	100.00
Natural Graphite	Flake Graphite	100.00	100.00
1M LiPF_6 in Carbonate Solvent	Lithium Carbonate Equivalent	18.79	0.55
	Fluorspar	49.00	9.01

1M NaPF ₆ in Carbonate Solvent	Soda Ash	43.38	1.64
	Fluorspar	49.00	8.14
Copper Foil	Copper	100.00	100.00
Aluminum Foil	Aluminum	100.00	100.00
Tin Powder	Tin	100.00	100.00

Supplementary Table 3: Summary of modeled scenarios

Parameter	Scenarios	Count
Technical Scenario (Roadmap)	Technical Roadmaps detailed in Table 1 of Main Text	28
Na-ion Market Penetration	- NIB Market Penetration 1 - NIB Market Penetration 2 - NIB Market Penetration 3	3
Lithium Minerals Pricing	- Lithium High - Lithium Baseline (Aggregated forecasts) - Lithium Low	3
Nickel Minerals Pricing	- Nickel High - Nickel Mid - Nickel Baseline (Aggregated forecasts)	3
Graphite Supply Shock	- No Supply Shock - Supply shock in 2027	2
Cumulative Experience Scenarios	- Novel growth for Anode only - Novel growth for Anode & Cathode	2
Na-ion Learning Rates	- Normal LRs – based on Li-ion analogues - Aggressive LRs for Na-ion cathode, anode, and electrolyte	2
Total Count of Scenario Combinations		6,048

Supplementary Table 4: Engineering limits for development roadmaps

	Units	LFP Graphite	NMC Graphite	NaN(F)M HC	NFPP HC	NaN(F)M Sn	NFPP Sn	NaN(F)M Anode-free
Nominal System Voltage	V	3.3	3.7	3.1	2.8	3.1	2.8	3.1
Cathode Max Specific Capacity	mAh-g ⁻¹	160	274	200	135	200	135	200
Cathode Material / Crystal Density	g-cm ⁻³	3.55	4.65	4.65	3.20	4.65	3.20	4.65
Cathode Min Porosity	%	20	20	20	20	20	20	20
Cathode Max Thickness	μm	120	120	120	150	120	150	150
Anode Max Specific Capacity	mAh-g ⁻¹	372	372	500	500	847	847	1166
Anode Material / Crystal Density	g-cm ⁻³	2.24	2.24	1.5	1.5	7.31	7.31	0.97
Anode Min Porosity	%	25	25	35	35	45	45	0
Anode Max Thickness	μm	120	120	120	150	50	50	20
Min N/P Ratio	--	1.02	1.02	1.02	1.02	1.02	1.02	1.00
Electrolyte Density	g-cm ⁻³	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Positive CC Density	g-cm ⁻³	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Positive CC Min Thickness	μm	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Negative CC Density	g-cm ⁻³	8.96	8.96	2.7	2.7	2.7	2.7	2.7
Negative CC Min Thickness	μm	5.0	5.0	8.0	8.0	8.0	8.0	8.0
Separator Min Thickness	μm	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Separator Max Porosity	%	50	50	50	50	50	50	50
Separator Material Density	g-cm ⁻³	1.2	1.2	1.2	1.2	1.2	1.2	1.2

The engineering limits for the various chemistries are used to calculate each of the M_{min} parameters representing minimum materials intensity and SE_{max} values representing maximum theoretical (engineering) limits on specific energy.

Supplementary Table 5: Summary of unit cell design parameters for Faradion 12Ah cell modeling.

Parameter	Units	Value	Ref.
Cathode			
Electrode Formulation (AM : CB : Binder)	%	89 : 5 : 6	17
Mass Loading	mg-cm ⁻²	14.90	
Calender Press Density	g-cm ⁻³	2.77	18
Electrode Porosity	%	30.0	18
Electrode Thickness	μm	53.8	
Substrate	--	Aluminum	
Current Collector Thickness	μm	15	
Anode			
Electrode Formulation (AM : CB : Binder)	%	88 : 3 : 9	17
Mass Loading	mg-cm ⁻²	7.14	17
Calender Press Density	g-cm ⁻³	0.95	19
Electrode Porosity	%	38.0	17,18
Electrode Thickness	μm	75.2	
Substrate	--	Aluminum	
Current Collector Thickness	μm	15	
Separator			
Material	--	Polypropylene / polyolefin	19
Separator Thickness	μm	15	
Separator Porosity	%	47	
Electrolyte			
Electrolyte Density	g-cm ⁻³	1.20	
Fill amount	g-Ah ⁻¹	6.0	19

SUPPLEMENTARY NOTES

Supplementary Note 1: Establishing material component price floors

Each material component used in a Li-ion or Na-ion battery is synthesized from certain underlying minerals and commodities. The material component price floor can thus be calculated based on the useful molar mass fraction of the mineral/commodity contributing to the molar mass fraction of the material composition.

Taking NMC532 as an example, the key underlying minerals/commodities include lithium hydroxide (which is captured within the Lithium Carbonate Equivalent, LCE, commodity), nickel, manganese, and cobalt. Oxygen is ignored here due to abundance. The lithium content within lithium carbonate is 18.79%, which represents its useful molar fraction. In contrast, nickel, manganese, and cobalt are largely traded based on the metal itself, and therefore have useful molar fractions of 100% for the sake of pricing. Within NMC532, the stoichiometric molar mass fractions of lithium, nickel, manganese, and cobalt are 7.19%, 30.39%, 17.07%, and 12.21%, respectively, with oxygen comprising the remainder. Thus, by multiplying the underlying commodity prices of each mineral by its useful molar fraction and its mass fraction within a given material component, the mineral's contribution to the material component's price floor can be obtained. The total price floor of a material component is then obtained by summing all contributions from its key minerals. The useful molar fraction of minerals/commodities along with their mass fraction within material components are tabulated in Supplementary Table 2.

A representative set of material component price floors are shown in Supplementary Figure 3, dynamically varying within the time frame from 2010 to 2050. Due to global supply chain shocks resulting from the COVID-19 pandemic exacerbated by record electric vehicle demand, the prices of many key material components saw dramatic spikes in the year 2022. The biggest contributor by far in these price spikes is the cost of lithium, which rose 1,000% between 2021 and 2022 exceeding \$80,000 tonne⁻¹ at its peak in certain markets²⁸. A noticeable, albeit smaller lithium price spike is also observed circa 2018. An “NMC Blend” material is shown as a representative NMC-type cathode in Supplementary Figure 3 (see Supplementary Note 2: for discussion on a volume-weighted NMC average), and it shows a substantially higher price spike relative to LFP in 2022. This is because NMC also suffered from the coinciding price spikes within the nickel market upon the Russian invasion of Ukraine in 2022, as Russia accounts for 17% of the world's production of high-purity nickel²⁹ to which LFP is immune. This nickel spike is also manifested in the price floor of Na-ion nickel-containing layered oxide cathodes, NaNM, (comprising primarily sodium, nickel and manganese and abbreviated NNM), though to a much lesser degree due to a lower overall nickel content.

Supplementary Note 2: Capturing evolution of NMC

NMC-type cathodes are a family of transition metal layered oxides that primarily comprise lithium, nickel, manganese, and cobalt. Throughout the years, the stoichiometry of NMC has evolved, following the trend of increasing nickel content to maximize specific capacity ($\text{mAh}\cdot\text{g}^{-1}$) and reducing cobalt content to minimize reliance on an expensive, volatile mineral with ethical sourcing concerns. While the exact stoichiometry varies between cathode material component manufacturers, the evolution of NMC can be mapped to technology “nodes” with rough estimates on composition. Starting with equal-parts nickel, manganese, and cobalt in $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$ (NMC333—but more traditionally referred to as NMC111), the stoichiometry continued to evolve through $\text{LiNi}_{0.50}\text{Mn}_{0.30}\text{Co}_{0.20}\text{O}_2$ (NMC532), $\text{LiNi}_{0.60}\text{Mn}_{0.20}\text{Co}_{0.20}\text{O}_2$ (NMC622), and $\text{LiNi}_{0.80}\text{Mn}_{0.10}\text{Co}_{0.10}\text{O}_2$ (NMC811). Intermediate stoichiometries also exist between nodes (e.g. NMC433 and NMC721) and cathode chemistries with Ni_x , $x > 0.90$ continues to be developed and commercialized, but the above are generally considered primary.

To accurately describe the prices of the NMC family using one metric, we calculate a volume-weighted average at each year from 2010 onwards based upon the individual minerals price floors (using methods described in Supplementary Note 1:) and historical price assessments of each nodal composition. Here, volume refers to total market share obtained from industry-specific reports with relative penetration of each NMC nodal composition¹. We fit continuous curves to match the data as closely as possible so that we can compute a volume-weighted average at each time step (see Supplementary Figure 4). Here, NMC811 is fitted with a Gompertz sigmoidal function to capture its gradual market share growth, whereas NMC111 and NMC622 are fitted with a piecewise function that has a logistic growth phase and an exponential decay phase smoothed via a sigmoid weighting function. This allows us to capture the sunrise and sunset phases characteristic of any technology as they gain and lose market share relative to incumbents and new entrants. Despite knowing higher-Ni materials are currently being developed, we do not sunset NMC811 here as we lack credible projections, and the ultimate impact on technoeconomics is likely to be trivial. Finally, the market share of NMC532 is taken to be the difference between 100% and the sum of the other three nodal compositions. Note that even though state-of-art (in 2023) corresponds to high-nickel NMC811 or greater, the market share of earlier nodal compositions is still substantial, bringing the volume-weighted average nickel stoichiometry closer to 0.6 in 2023 (Supplementary Figure 5). Mapping the nickel stoichiometry to realizable specific capacities³⁰, we also show the increasing trends in specific capacities throughout time (Supplementary Figure 5). The minor dip in nickel stoichiometry and hence specific capacity between 2010-2015 is believed to be an artifact of fitting the available dataset—which shows competition between NMC111 and NMC532 in that period—and not truly reflective of an anomaly in actual trends.

Supplementary Note 3: Material component learning curves & uncertainty

As described in the main text, we combine knowledge of historical demand (in kT or Mm²) and pricing for each material component (sometimes with knowledge of conversion costs) to fit individual learning curves. This enables a novel look at the actual learning rates of materials versus devices and informs anticipated learnings in emerging technologies, such as Na-ion. We show all the fitted learning curves in Supplementary Figures Supplementary Figure 11-Supplementary Figure 18. Given the scarcity in historical price assessments from which the above learning curves are fitted, it is worth discussing the potential sources of uncertainty in our modeling.

Data uncertainty – As evident in the data points shown in the above plots (Supplementary Figures Supplementary Figure 11-Supplementary Figure 18) and Main Text (Figures 1 and 2a), it is apparent that price assessments for each material is sporadic over many years. We have plotted the values of component pricing (unattributed) from multiple sources, and it is evident that many data points are obtained from a single source. Additionally, the historical annual demand (in kT or Mm²) of material components are sourced solely from Avicenne^{1,7}. This can thus be subject to biases inherent to the price assessment methodologies adopted by the data source, which may be regionally biased (e.g. China- or European-centric pricing) or simply inaccurate due to limited sampling. However, where multiple data sources are available above, the confidence intervals appear to be constrained within relatively tight spreads—suggesting the compiled dataset above to be a reasonably accurate representation of historical trends.

Structural uncertainty (model uncertainty) – Implicit in our floor-constrained learning curve modeling approach is the assumed Wright's Law relationship between prices and cumulative experience. Whereas prior literature has established this to be a reasonable descriptor for many different industries, including chemical and energy products³¹, it is not guaranteed all material components follow this trend. From the historical price assessments presented above, it is not immediately clear that all material components follow a power law. This of course is convoluted by the volatility in minerals pricing that we seek to deconvolute. Whereas our fitted floor-constrained learning curves above may appear to reasonably fit historical price assessments, it is still worth clarifying that our modeling approach is only an estimation of the price trends of each material component.

Supplementary Note 4: Fixed High/Mid/Low minerals price forecasts

Due to the inherent uncertainty associated with forecasting the prices of key minerals, we also evaluate scenarios where prices are fixed at a high/mid/low value. Specifically, we institute this for lithium and nickel, as they are the biggest contributors to the outcome of LFP-type Li-ion batteries and nickel-containing layered oxide cathode Na-ion batteries. We note that while the forecasted cobalt prices have significant variance between multiple sources and has historically been a metal subject to scrutiny, it only affects the pricing of NMC-type Li-ion batteries, which have also managed to significantly reduce cobalt intensity through the years. As the primary comparison of Na-ion batteries is against LFP, we ignore scenarios that may affect cobalt and NMC.

To calculate High/Mid/Low scenarios, we calculate the 90th, 50th, and 10th percentiles of the total range of historic pricing for lithium and nickel. We fix the prices starting in 2027 and implement a linear ramp from 2023 actual prices and include a confidence interval representing $\pm 10\%$ of the total historic range for each scenario. We then compare our High/Mid/Low scenarios with the Base Cases obtained from aggregating forecasts from data contributors and drop the scenarios that most resemble the Base Cases.

For lithium prices, we drop the Mid case and keep the High/Low scenarios as the Base Case settles around $\$33,440 \pm 4,497 \text{ tonne}^{-1}$. The High scenario is fixed from 2027 onwards at $\$50,880 \pm 5,043 \text{ tonne}^{-1}$, and the Low scenario at $\$10,534 \pm 5,043 \text{ tonne}^{-1}$. See Supplementary Figure 8.

For nickel prices, we drop the Low case and keep the High/Mid scenarios as the Base Case settles around $\$20,659 \pm 1,355 \text{ tonne}^{-1}$. The High scenario is fixed from 2027 onwards at $\$50,190 \pm 4,613 \text{ tonne}^{-1}$, and the Mid scenario at $\$31,737 \pm 4,613 \text{ tonne}^{-1}$. See Supplementary Figure 9.

For reference, at the time of this writing (1Q 2024), the spot price of lithium averages $\$10,000 - 15,000 \text{ tonne}^{-1}$, and the spot price of nickel averages near historic lows at less than $\$20,000 \text{ tonne}^{-1}$, both largely the result from oversupply of battery metals due to a slump in electric vehicle sales in the latter half of 2023²⁵⁻²⁷.

Supplementary Note 5: Patterns in observed learning rates

Based on the fitted learning rates (Main Text, Figure 1b), there appears to be an observable pattern when evaluating the color coding. In magenta are cathode active materials, in gray are anode active materials, in orange are metallic foils, and the electrolyte and separator are within their own categories. Among the material components, it appears that cathodes tend to exhibit a higher learning rate). On the opposite end of the spectrum, metallic foils have the lowest learning rates. Qualitatively envisioning a “degree of transformation” for the two categories, we can note that cathode synthesis exceeds foil production by far. We postulate that learning rates may be a function of manufacturing process complexity and such degree of transformation. Between these two extremes, graphite anode production seems to have an intermediate learning rate. Considering that the conversion of natural mined flake graphite into battery grade spherical graphite or the conversion of needle coke into synthetic graphite might appear to have an “intermediate” degree of transformation, the hypothesis holds true qualitatively. We note that fitted cell manufacturing learning rates are also high, on the same order as cathode learning rates. Considering the complex assembly of many components to produce a battery cell—a very high degree of transformation—the high manufacturing learning rate for cell production also makes sense.

Being able to predict characteristic learning rates for new industries would have profound implications. This would enable forecasts of emerging technologies that do not have as clear-cut analogues as does Na-ion with Li-ion. We highlight this as a subject of future studies.

Supplementary Note 6: Development of nickel-free layered oxide compositions

The first NMC Li-ion cathode stoichiometry that was commercialized was equal parts nickel, manganese, and cobalt with the formula $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$ and abbreviated as NMC333 but more commonly NMC111, as discussed in Supplementary Note 2:. Similarly, the sodium layered oxide cathode that is experiencing the most widespread initial adoption is NFM111, which refers to a stoichiometry that is equal parts nickel, iron, and manganese with the formula $\text{NaNi}_{0.33}\text{Fe}_{0.33}\text{Mn}_{0.33}\text{O}_2$ ¹⁸. Just as NMC saw the gradual stoichiometric evolution to minimize cobalt content to reduce costs and reliance on an ethically challenged mineral (while increasing nickel content to maximize energy densities), it is anticipated that future generations of Na-ion layered oxide cathodes can gradually reduce their nickel content in a similar fashion to enable a truly low-cost chemistry free of critical minerals. To model this, we introduce a nickel-free Na-ion cathode end member, $\text{Na}_{0.67}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{O}_2$ (NaFM) and gradually increase its market penetration from zero in 2024 to near complete cannibalization of its nickel-containing counterpart (NaNM) by 2040, as shown in Supplementary Figure 28. Here, we again assume that the complete substitution of nickel for an element like Fe (NaFM) can maintain our representative NaNM voltage-capacity profile, and we duplicate analysis of select roadmaps with the only difference of phasing out nickel from layered oxide cathode materials. Thus, in our NaFM | X modeled roadmap scenarios, we assume identical cell designs as their NaNM counterparts as detailed in the sections above. The only difference in the modeled roadmaps therefore lies in the minerals price floor of the cathode as nickel is gradually phased out. Based on a market volume-weighted average of the layered oxide cathodes, we can chart the gradual evolution of nickel stoichiometry in Na-ion layered cathodes, shown in Supplementary Figure 29. This evolution in nickel stoichiometry will manifest in a gradually reducing minerals price floor as illustrated in Figure 3 in the Main Text.

Supplementary Note 7: Defining “cumulative experience”

In forecasting componential learning curves for Na-ion, there is a critical nuance in the assumptions of experience that inform future price trends. For example, Na-ion’s drop-in compatibility with existing Li-ion manufacturing infrastructure is perceived as an advantage. While it may be impractical to substitute one for the other on the same production lines from a logistics, equipment uptime, yield, and contamination standpoint¹⁸, it is generally accepted that the same manufacturing processes and learnings from Li-ion apply to Na-ion as it is not a fundamentally new process. Therefore, the cumulative experience applied to the manufacturing cost component of Na-ion batteries should scale with the cumulative production experience of *both* Li-ion and Na-ion batteries. In contrast, for new Na-ion-specific material components such as hard carbons, the cumulative experience growth rate is expected to be much greater. This is because the total deployed quantity of hard carbons to-date is substantially lower and is therefore expected to see market doublings at a quicker pace, thereby seeing a greater rate of price reduction even if learning rate values are similar. Considering transition metal layered oxide cathodes that may predominantly be manufactured using the same co-precipitation process pioneered by Li-ion layered oxides, the expected pace of cumulative experience growth for cathode synthesis may therefore be more modest. In our subsequent scenarios modeling, we vary this assumption and toggle whether this applies to the anode material only or to the cathode material as well to test the sensitivity to outcomes. Assuming Na-ion batteries see large-scale commercialization this year (2024), the normalized cumulative experience growth curves are shown in Supplementary Figure 61 for the various Na-ion market penetration scenarios.

Supplementary Note 8: Simulating graphite supply shock

While there is substantial supply chain concentration within China for the mining, refining, processing, and manufacturing of many Li-ion components, few are as concentrated as the graphite supply chain. 92.6% of battery-grade graphite for Li-ion anodes came from China in 2023³³, including both synthetic and natural graphite. As the dominant anode material within Li-ion by far, graphite's concentrated supply chain poses a significant risk amongst rising geopolitical tensions. On December 1, 2023, China's Ministry of Commerce and the General Administration of Customs imposed export controls on graphite in order to protect the country's "security and interests"³³. While this move only requires additional permits and does not outright ban graphite exports, it is largely seen as a retaliatory response to the U.S. policy on restricting semiconductor technology exports to China³⁴, and may foreshadow actionable threats to cut off Western access to this critical mineral.

Given the recent policies and the vulnerability to this risk, we choose to model scenarios in which the graphite supply chain does in fact experience a supply shock. However, the means to model such a shock are notably different from the high fixed lithium price scenario discussed in Supplementary Note 1: where the underlying mineral experiences sustained high prices. Here, instead of affecting the minerals pricing, a graphite supply shock would more likely affect the conversion costs associated with graphite production. We specifically refer to synthetic graphite as it is the dominant form (accounting for 70% of anodes in 2023 versus just 25% for natural graphite³³), where the minerals derived from petroleum coke are relatively geographically widespread. As the graphitization process of carbon-rich precursors requires use of Acheson-type furnaces that can attain extremely high temperatures ($>2,800^{\circ}\text{C}$) for extended periods of time, the capital and operational expenditures associated with graphitization dominates the costs of conversion^{18,35}. In addition to the need to address sulfur emissions (SO_x) from graphitization, volatile organic compounds (VOCs) from calcination steps, and considering other factors such as labor safety, it is expected for the conversion costs of graphite production ex-China to be substantially higher¹⁸. Like any other process, the conversion costs are expected to fall due to learning rates, but such a graphite shock would manifest as a step-change in the price of graphite followed by the same characteristic price reduction trend. This would resemble a "sawtooth" pattern in the price curve.

Of course, we cannot predict if or when such a supply shock could occur, but we perform a scenario analysis on a hypothetical supply shock in 2027 where the conversion costs of graphite ex-China are three times higher. We note that in addition to the above operational cost disadvantages, the U.S. and Europe currently lack large-scale graphite production and would need to incur substantial capital expense to stand up production. The resulting graphite price curve subject to these scenarios are illustrated in Supplementary Figure 62.

Supplementary Note 9: Modeling cells

Accurately modeling the technoeconomic performance of battery technologies requires detailed modeling of commercial cell designs. To do this, it is most important to capture the unit cell stack design. This includes electrode design parameters for the cathode and anode, their relative balancing, and the resulting voltage profiles they generate after accounting for first cycle Coulombic efficiencies (assuming the majority of solid electrolyte interphase (SEI) side reactions have been formed by then). To do this, we mathematically scale voltage curves obtained from half-cells measured against Li/Li^+ for Li-ion materials and Na/Na^+ for Na-ion materials. We obtain the first two half-cycles (e.g. one (de)lithiation cycle or (de)sodiation cycle) measured as a function of active material specific capacity ($\text{mAh}\cdot\text{g}^{-1}$) for a positive (cathode) and negative (anode) electrode couple obtained at sufficiently low rates to avoid excessive polarization (e.g. $C/20$), multiply by their respective active mass fractions corresponding to their formulation within realistic electrode composite designs, and then multiply by their areal mass loadings ($\text{mg}\cdot\text{cm}^{-2}$) to obtain areal capacity loadings ($\text{mAh}\cdot\text{cm}^{-2}$). Based upon known total cathode and anode electrode footprints (in cm^2) derived from large-format cell designs generated by the industry-validated Battery Performance and Cost (BatPaC) model developed by Argonne National Lab³², we obtain true cathode and anode capacities within a cell. Calculation for the electrode capacity is given in Equation (1).

$$Q_{\text{electrode}} [\text{Ah}] = q_{\text{active material}} \left[\frac{\text{mAh}}{\text{g}} \right] * x_{\text{fraction}} [\%] * m_{\text{electrode}} \left[\frac{\text{mg}}{\text{cm}^2} \right] * A_{\text{electrode}} [\text{cm}^2] \quad (1)$$

Anode capacities are oversized according to realistic N/P ratios based on areal capacity (in addition to being dimensionally oversized with an electrode “overhang”), and electrode calender press densities (in $\text{g}\cdot\text{cm}^{-3}$) are also modeled based upon industry expert opinion to obtain practical electrode thicknesses and hence porosities¹⁸. Finally, the difference between the cathode and anode half-cell voltage curves are obtained via curve interpolation to derive a theoretical full cell voltage profile. The electrode parameters are iteratively tweaked to obtain the desired capacity between the operating voltage limits defined by the lower- and upper-voltage cutoffs. The true energy contained within a cell is calculated based upon the integrated area under the first discharge (second half cycle) full-cell voltage curve bounded by the window of operation (top/bottom defined by voltage limits, left/right defined by irreversible capacity loss and cell capacity). This approach ensures an accurate calculation of energy density, as the characteristically sloped voltage curves of some material chemistries (e.g. Na-ion layered oxide cathodes and hard carbon anodes) can have substantially lower expected energy within a balanced full-cell than their individual specific capacities suggest. See Supplementary Figure 65 for representative considerations for full cell voltage curve derivation. Since the N/P ratio can be defined in various ways, here we clarify the N/P ratio is defined within this work as the ratio of the *irreversible* areal capacity loadings of the negative versus the positive electrode, as shown in Supplementary Figure 65.

To calculate relevant electrolyte quantities, we calculate the total pore volume within the cathode, the anode, and the separator and add an additional overhead of 80% electrolyte fill to account for additional “dead” volume to arrive at practical $\text{mL}\cdot\text{Ah}^{-1}$ values. While an 80% overhead amount may be considered a more generous amount specifically for pouch cells that tend to be electrolyte starved systems, a higher fill quantity is required for hard-cased cylindrical and prismatic formats¹⁸. Here, we choose 80% to capture an “average” electrolyte fill quantity that spans all three cell formats. Knowledge of electrolyte density enables subsequent calculation of $\text{g}\cdot\text{Ah}^{-1}$ quantities.

Supplementary Note 10: Cell modeling validation with experimental data

To demonstrate the utility and accuracy of the above modeling approach, we validate against publicly available information on 12Ah large-format pouch cells produced by UK-based Na-ion battery developer Faradion (now Reliance-owned). Faradion's "Gen 2" layered oxide cathode is a 2/3 – 1/3 blend of an O3- and P2-type material¹⁰. The O3-type end member has a stoichiometry of $\text{NaNi}_{0.333}\text{Mn}_{0.333}\text{Mg}_{0.167}\text{Ti}_{0.167}\text{O}_2$ and the P2-type end member has a stoichiometry of $\text{Na}_{0.667}\text{Ni}_{0.300}\text{Mn}_{0.600}\text{Mg}_{0.033}\text{Ti}_{0.067}\text{O}_2$, delivering close to 150 mAh-g⁻¹ when discharged from 4.25V to 2.0V vs Na/Na⁺¹⁹. Additionally, Faradion's internally-developed hard carbon has been demonstrated to have up to 330 mAh-g⁻¹ capacity with 91.9% first cycle efficiency¹⁹. Half-cell voltage curves for the first desodiation-sodiation (charge-discharge) for the Gen 2 cathode were extracted from published data¹⁹. Similarly, half-cell voltage curves for the first sodiation-desodiation for Faradion's hard carbon material were also extracted from published data¹⁹. Electrode composite formulations for positive and negative electrodes were informed by yet other publicly available literature published by the same company, along with realizable mass loadings, calender densities, and cathode/anode mass balancing¹⁷. Finally, dimensional analysis was performed on images presented by Faradion in publicly available symposiums¹⁰ on their 12Ah pouch cell platform to obtain anode and cathode electrode areal footprints (Supplementary Figure 66).

Based on this information, we produce full cell predictions summarized in Supplementary Figure 67 showing good agreement with Faradion's published results. Not only do predicted cell parameters match Faradion reported values, but our predicted theoretical voltage curves (black) also match near-identically with Faradion's full-cell voltage profiles (orange). Especially given the sloped voltage curves of the layered oxide cathode and hard carbon anode, matching full-cell voltage profiles this accurately gives confidence in our ability to capture realistic cell designs and parameters. Comparing between Supplementary Figure 67a and Supplementary Figure 67b, we see the effect of derating the cell upper cutoff voltage from 4.2V to 4.0V. Given various degradation mechanisms that dominate at higher operating voltages, Faradion demonstrated the ability to extend cycle life from 1,000 cycles to 3,000 cycles by lowering the cutoff voltage within the same cell design (i.e. no change to cathode loadings or cathode/anode balancing)¹⁹. However, the same unit cell system will therefore result in much higher N/P ratios, which is penalizing from an energy density perspective, summarized in Supplementary Figure 67c, which will in-turn negatively affect cost in \$-kWh⁻¹. See Supplementary Figure 30 for additional commentary on voltage ranges as it relates to systems integration with power conversion electronics.

Supplementary Note 11: BatPaC modifications

The Battery Performance and Cost model, BatPaC v5.1 (last update August 2023)³², developed by Argonne National Laboratory was used to generate cell designs and manufacturing cost overheads. To reconcile BatPaC with the unit cell electrode-level balancing discussed in Supplementary Note 9, some modifications were made to BatPaC to ensure the cells featured the same unit cell design.

For the new chemistry couples modeled here that do not come pre-loaded in the default version of BatPaC, such as NaNM|HC, NFPP|HC, NaNM|Sn, NFPP|Sn, new columns were added in the “Chem” tab per the instructions of the BatPaC Manual³⁶. Additionally, the “Open circuit voltage” section (“Chem” tab, rows 95-106) is updated to match outputs from our models. Once balanced unit cell designs were obtained from voltage curve matching, the “Positive electrode active material capacity”, “Positive electrode porosity”, “Positive electrode active material weight %”, and “Maximum thickness limit for positive electrode” fields were overridden (per instructions of the BatPaC Manual). The specific capacity, formulation, and porosity fields of the negative electrode were similarly adjusted. Then, the “Negative-to-positive capacity ratio after formation” field was tweaked to ensure the final “Selected electrode Thicknesses” (“Battery Design” tab, rows 281-283) matched our model. In some cases where the assumed electrode thickness is higher than normal (such as for high-loading NFPP cathodes, see Supplementary Figure 39), the “Design electrodes to meet charging requirements?” toggle was turned off in the “Dashboard” tab, and in some cases, the “Optional positive electrode thickness override” on the same tab was utilized. The resulting dimensions of the cathode, anode, and separator sheets were obtained from the “Cell Dimensions” section in the “Battery Design” tab, rows 301-313, and the calculated areas were used to scale the modeled areal capacity loadings. Additional component masses, such as tabs/terminals were also obtained from the same “Battery Design” tab. We also adjust the “Electrolyte per cell” value in the same tab (row 66) to account for the realistic overfill amounts beyond the calculated volume of pores that would result in an underestimation of required electrolyte volume. Some values of the “Cost Input” tab were similarly adjusted, namely the “Direct labor rate” (row 93). The default value of \$25-hr⁻¹ is an overestimation compared to actual labor rates in present-day manufacturing, especially considering the regions where such manufacturing is located. To adjust for regional differences, we rely on studies showing the relative regional share of global production for NMC and LFP cells³⁷, and obtain labor rates for those respective regions³⁸⁻⁴¹ to calculate a globally weighted average. The globally weighted average labor rate for NMC and LFP type cells is \$13.41-hr⁻¹ and \$7.35-hr⁻¹ in 2023, respectively. The higher average labor rate for NMC results from the higher share of manufacturing based in Europe, Korea, Japan, and the U.S., whereas LFP is almost exclusively manufactured in China. For all our Na-ion modeling, we assume a labor rate equivalent to that of LFP.

Apart from labor, all manufacturing costs calculated as a function of capital expenditures (depreciation, overhead, SG&A, R&D, and financing) were further discounted based upon the significantly lower cost of capital equipment in China. As the majority of Li-ion and Na-ion cells are currently produced in China, modeling Chinese prices would be most representative of present-day actuals. Based on reporting in early 2023, the average capital cost of a North American / Western gigafactory was ~\$105M/GWh capacity, whereas plants in China ranged from \$55M/GWh capacity on the low end to \$72M/GWh capacity on the high end⁴². Based on industry feedback, the low end capex figures correspond to LFP plants whereas the high end figures correspond to NMC plants¹⁸. Thus, for polyanionic cathode chemistries that we model (LFP and NFPP), we apply a discounting factor of 0.52 to the BatPaC calculated capex figures (which all correspond to >\$100M/GWh, as expected), and for layered oxide chemistries (NMC, NaNM, NaFM), we apply a discounting factor of 0.685.

Finally, the cell capacity is obtained from the “Summary of Results” tab (row 100), and matched with our model. In general, there is very good agreement between our voltage-based electrode balancing approach and the outputs of BatPaC. The only exception is the calculated “Cell total energy, kWh” (“Summary of Results” tab, row 101).

We found that while the total energy calculations from BatPaC accurately model the energy within Li-ion chemistries, the characteristically slopy voltage profiles of some Na-ion chemistries cause this value to deviate. Therefore, we use our integrated area underneath the discharge voltage curve from our analysis as the basis for energy, which can deviate by up to 3% from BatPaC values.

Finally, although there are inputs for materials costs in the “Chem” tab, we do not utilize this feature as we rely on our dynamic materials pricing informed by our componential learning curves. We only extract the manufacturing costs (discounted, as discussed above) associated with cells manufactured in the present-day to inform our manufacturing overhead cost component, which subsequently experiences its own unconstrained learning rate (see Methods section in Main Text).

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