ENERGY STORAGE
MANUFACTURING SCIENCE

Received December 16 , 2025
Published April 15, 2026
DOI: 10.66655/xrm6tn08

Lessons from CellVision: Battery Materials to Final Cell Cost and Today's Sodium Ion Batteries

Dr. Julia Lamb[1]*, Dr. Rafael Vilá

[1]CellVision LLC, Texas, USA

*Corresponding email: jlamb312@utexas.edu

Abstract

CellVision is a material to cell performance and cost model that was built in excel to test the theory that cheaper sodium raw materials result in cheaper sodium-ion batteries compared to today's lithium-ion batteries. CellVision version 2.3 is now available to the public and the present work covers the methodology and assumptions that went into building the model. The most important variables that influence upfront cell costs are discussed, and commercially relevant sodium-ion battery materials are reviewed for their potential against lithium-ion incumbents.

Background

Sodium-ion batteries are touted as having the potential to be a more affordable alternative to lithium-ion batteries due to their use of cheap and abundant raw materials. The active materials, electrodes, and cells can be manufactured with almost identical methods as their lithium-ion counterparts, allowing for near drop-in replacement on today's lithium-ion battery manufacturing lines. Therefore, sodium-ion batteries appear to be positioned well for commercialization. To predict the best sodium-ion batteries for different product applications and identify the best areas for competition against lithium, CellVision was created.

Results

The three representative sodium cathode materials chosen for comparison against lithium-ion materials are a layered oxide ($O3\text{-}NaNi_{1/3}Fe_{1/3}Mn_{1/3}O_2$ – NFM)(2), phosphate ($Na_{3.6}Fe_{2.6}(PO_4)_{1.6}P_2O_7$ – NFPP) (4) and Prussian blue analog ($Na_{0.647}Fe[Fe(CN)_6]_{0.93}\cdot 2.6H_2O$(6) - PW). In **Figure 1**, representative half-cell discharge curves for each cathode are paired against their respective lithium cathode counterparts. It is already evident that sodium-ion cathodes have lower capacity and lower nominal voltage compared to lithium-ion cathodes.

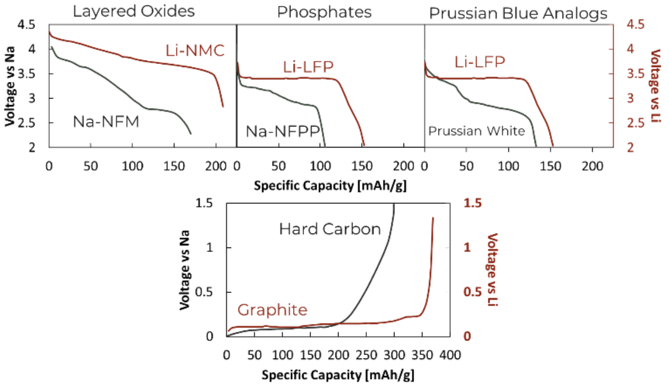

Figure 1. On top are examples of formation half-cell discharge curves for representative lithium and sodium cathode materials. Material chemistries include $O3\text{-}NaNi_{1/3}Fe_{1/3}Mn_{1/3}O_2$(2), $LiNi_{0.8}Mn_{0.1}Co_{0.2}O_2$(3), $Na_{3.6}Fe_{2.6}(PO_4)_{1.6}P_2O_7$(4), $LiFePO_4$(5), and $Na_{0.647}Fe[Fe(CN)_6]_{0.93}\cdot 2.6H_2O$(6). On bottom are the formation half-cell charge curves of hard carbon(7) and graphite(8).

By inputting the cathode and anode materials from **Figure 1** into CellVision, an "energy" type cell with a practical voltage window and electrode loading provides the cell cost results shown in **Figure 2**. The sodium-ion batteries are compared against lithium-ion batteries at three different lithium carbonate price scenarios. Lithium carbonate is about $10/kg at the time of writing and reached a peak of $71/kg back in 2022. Few experts predict that the price of lithium carbonate will indefinitely remain at today's low price, nor are they likely to reach 2022's peak again. According to Benchmark Mineral Intelligence's Q1 2025 Lithium Forecast publication, the long-term base case price projection for lithium carbonate between 2031 and 2040 is $21/kg. (12)

The results from **Figure 2** conclude that sodium-ion battery cost parity with an LFP|Graphite cell would require the price of lithium carbonate to reach $43/kg for a PW|HC cell, $50/kg for an NFPP|HC cell, and $59/kg for an NFM|HC cell. For the purpose of decoupling the influence of the hard carbon anode, anode-free cells are also plotted to show the best-case scenario for an anode material with high energy density and no cost. Sodium-ion battery cost parity with an anode-free LFP cell would require a lithium carbonate price of $21/kg for NFM or NFPP cells, and $23/kg for a PW cell. These results show that both the hard carbon anode and today's sodium cathode materials are insufficient for competing with lithium-ion batteries on upfront cell costs.

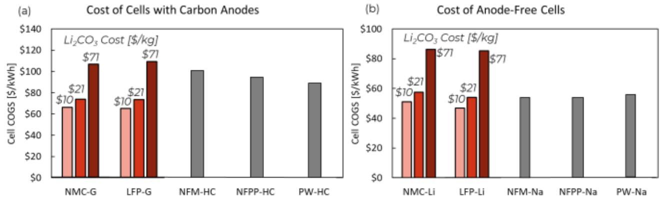

Figure 2. Cell cost of goods sold (COGS) of the cathodes reported in Figure 1 against either (a) the carbon anodes from Figure 1 and (b) an anode-free system. Costs of the LIB cathodes are simulated at three different $/kg rates for lithium carbonate.

The original hypothesis that sodium-ion batteries can achieve cheaper product-level prices than lithium-ion batteries with today's technology and cell manufacturing is therefore null. Clearly, there are improvements that must be made to both the cathode and anode materials for these batteries to be competitive with lithium on upfront cell costs.

Understanding Cell Cost

To improve the cost of sodium-ion batteries relative to lithium-ion, we must first understand the root causes of the higher cell costs. Looking at the cell cost breakdown for each of these chemistries provides an important lesson in volumetric energy density. As shown in the **Figure S3** pie chart in-lay, only 33% of the final LFP|Graphite cell costs are attributed to the cathode and anode active material cost. The other two thirds of the cell cost is inactive materials, manufacturing, business overhead, and profit. Notably, the next highest cost driver of the LFP cell after active materials is 17%, or $11/kwh attributed to depreciation (see **Figure S3**). Decreasing the initial capital required to build cells would have an outsized impact on the final cost of goods sold. **Figure 3a** visualizes the cell cost breakdown of sodium and lithium-ion batteries excluding their active materials. A clear trend emerges, showing that as volumetric energy density increases, non-active material cell costs decrease. Ergo, one of the most impactful ways to decrease cell costs today is to achieve a higher volumetric energy density.

The correlation between volumetric energy density and cell cost is exacerbated by practical electrode limitations. Electrodes are limited either to an upper thickness of 100 µm by traditional wet coating manufacturing limitations or they are limited by ion diffusion, otherwise known as the maximum current loading. **Figure 3b** shows the cathode and anode thickness of the various sodium and lithium-ion batteries. The NMC|Graphite cell is limited by current, meanwhile the LFP and each of the sodium cells are limited by 100 µm manufacturing. Therefore, improving manufacturing capabilities to produce thicker electrodes without flaking, cracking, or peeling will help improve the relative costs of low-capacity sodium-ion batteries.

Volumetric energy density can be improved by either increasing capacity, increasing nominal voltage, or decreasing cell size. Increasing capacity directly improves energy, but it also increases the necessary quantity of anode. Increasing capacity also causes limitations on electrode thickness (ion diffusion/current loading limitations). Voltage, on the other hand, does not have the same limitations. Increasing nominal voltage directly increases volumetric energy density and decreases cell costs, however, increasing nominal voltage is not trivial. Increasing the lower voltage cutoff window decreases usable capacity and the upper voltage is practically limited by electrolyte as well as bulk material degradation due to volume change and phase transitions. That being said, the lower voltage window is often higher in a real product than what is commonly reported in academic studies. In most product applications, the power output of the cell must remain constant no matter the state of charge. And because power is equal to voltage times current, as the battery discharges and voltage decreases, current must increase to compensate. Therefore, practical applications often limit the lower voltage cutoff to a higher value than what is typically measured for R&D purposes, thereby limiting the usable capacity of the cell. The relative proportion of capacity lost in a realistic voltage window scenario for a sodium-ion battery versus lithium-ion battery is visualized in **Figure S2**.

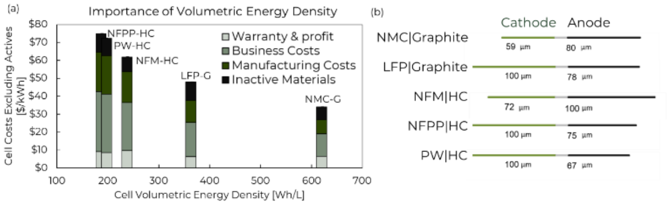

Figure 3. (a) The cell cost breakdown for the chemistries from Figure 1 are plotted versus their volumetric energy density. The cost of active materials for each cell are not included. (b) The electrode thickness for each cell chemistry. Cathode in green, separator in gray, anode in black.

Summary

As modelled, CellVision challenges the hypothesis that sodium-ion batteries are currently capable of competing with lithium-ion batteries on upfront cell costs. The high cell manufacturing costs, low price of lithium, and low volumetric energy density of sodium active materials are all a barrier to the upfront cost of sodium-ion batteries. Despite generally lower cathode material costs, hard carbon is currently more expensive than graphite today with substantially worse volumetric energy density. Practical voltage windowing further decreases the usable energy in a typical sodium-ion cell, exacerbating the worse energy density and higher $/kWh cell costs compared to lithium-ion. Several areas of technical innovation and/or a substantial increase in the price of lithium could eventually enable lower upfront cell costs. Examples of technical innovation include lower cell manufacturing costs or

CAPEX, advanced electrolytes enabling higher cell voltages, reduced cathode and anode manufacturing costs, and improved hard carbon density.

Outlook: Tomorrow's Sodium-ion Batteries

Competing against the incumbent lithium-ion technology requires focusing on the unique features of sodium and sodium-ion materials. Although there can be speed and capital benefits to copying lithium-ion technologies, the greatest competitive advantages come from the places in which the two systems diverge. Sodium-ion batteries benefit from non-geographically limited raw material abundance which may enable battery manufacturing in places without access to critical raw materials. Furthermore, CellVision simulates the initial energy and cost of sodium-ion cells versus lithium-ion cells but fails to incorporate some of the unique properties of sodium-ion chemistries. Specific sodium cathode materials have demonstrated wide operating temperatures, impressive rate performance, and/or excellent longevity. These unique properties could feasibly enable better \$/power performance, lower total cost of ownership, or wide temperature range products that can afford higher upfront cell costs.

Acknowledgements

Inspiration for this work as well as cell manufacturing costs are attributed to Argonne's BatPac V5.2 Copyright © 2022, UChicago Argonne, LLC.

Funding for this work was enabled by the seed investors in Bedrock Materials.

Bedrock team members Dr. Julia Lamb, Dr. Rafael Vila, and Spencer Gore are all contributors to the creation of CellVision. An extra thank you to Spencer for the original idea of CellVision and for all his patience and help with debugging.

References

1. Prismatic LFP Battery Cell (100Ah). Shanghai Metals Market. https://www.metal.com/Battery-Cell-And-Module/202105120003

2. Z. Cheng, X.-Y. Fan, L. Yu, W. Hua, Y.-J. Guo, Y.-H. Feng, F.-D. Ji, M. Liu, Y.-X. Yin, X. Han, Y.-G. Guo, P.-F. Wang, Angew. Chem. Int. Ed. 2022, 61, e202117728; Angew. Chem. 2022, 134, e202117728. https://doi.org/10.1002/anie.202117728.

3. Q. Xie, Z. Cui, A. Manthiram, Unveiling the Stabilities of Nickel-Based Layered Oxide Cathodes at an Identical Degree of Delithiation in Lithium-Based Batteries. Adv. Mater. 2021, 33, 2100804. https://doi.org/10.1002/adma.202100804

4. Dai, B.; Lu, T.; Teng, J.; Huang, J.; Li, E.; Zhang, K.; Wang, Q.; Yin, D.; Liu, S.; Lei, L.; Tang, X.; Li, J. Preparation and Application of the High-Performance Sodium-Ion Battery Cathode Material Na3.6Fe2.6(PO4)1.6P2O7@CNT with Dual-Carbon Coating. Journal of Materials Chemistry A 2025, 13 (10), 7413–7421. https://doi.org/10.1039/d4ta08638d.

5. Scanlan, K.; Manthiram, A. Revealing the Electrochemical Kinetics of Electrolytes in Nanosized LiFePO4 Electrodes. Journal of The Electrochemical Society 2023, 170 (10), 100515. https://doi.org/10.1149/1945-7111/acfc69.

6. Jiang, Y., Yu, S., Wang, B., Li, Y., Sun, W., Lu, Y., Yan, M., Song, B. and Dou, S. (2016), Prussian Blue@C Composite as an Ultrahigh-Rate and Long-Life Sodium-Ion Battery Cathode. Adv. Funct. Mater., 26: 5315-5321. https://doi.org/10.1002/adfm.201600747

7. Kuraray, Kuranode Biohardcarbon. https://www.calgoncarbon.com/app/uploads/KN-brochure-EN-002.pdf

8. Ming, J.; Cao, Z.; Wandi Wahyudi; Li, M.; Kumar, P.; Wu, Y.; Jang Yeon Hwang; Hedhili, M. N.; Cavallo, L.; Sun, Y.; Li, L. New Insights on Graphite Anode Stability in Rechargeable Batteries: Li Ion Coordination Structures Prevail over Solid Electrolyte Interphases. ACS energy letters 2018, 3 (2), 335–340. https://doi.org/10.1021/acsenergylett.7b01177.

9. Xie, L.; Tang, C.; Bi, Z.; Song, M.; Fan, Y.; Yan, C.; Li, X.; Su, F.; Zhang, Q.; Chen, C. Hard Carbon Anodes for Next-Generation Li-Ion Batteries: Review and Perspective. Advanced Energy Materials 2021, 11 (38), 2101650. https://doi.org/10.1002/aenm.202101650.

10. Alvira, D.; Antorán, D.; Manyà, J. J. Plant-Derived Hard Carbon as Anode for Sodium-Ion Batteries: A Comprehensive Review to Guide Interdisciplinary Research. Chemical Engineering Journal 2022, 447, 137468. https://doi.org/10.1016/j.cej.2022.137468.

11. Liu, H.; Baumann, M.; Dou, X.; Klemens, J.; Schneider, L.; Wurba, A.-K.; Häringer, M.; Scharfer, P.; Ehrenberg, H.; Schabel, W.; Fleischer, J.; von der Aßen, N.; Weil, M. Tracing the Technology Development and Trends of Hard Carbon Anode Materials - a Market and Patent Analysis. Journal of Energy Storage 2022, 56, 105964. https://doi.org/10.1016/j.est.2022.105964.

12. Q1 2025 Lithium Forecast publication. Benchmark Minerals. https://www.benchmarkminerals.com/lithium/prices

13. Ortiz-Vitoriano, N.; Drewett, N. E.; Gonzalo, E.; Rojo, T. High Performance Manganese-Based Layered Oxide Cathodes: Overcoming the Challenges of Sodium Ion Batteries. Energy & Environmental Science 2017, 10 (5), 1051–1074. https://doi.org/10.1039/c7ee00566k.

14. Liu, C.; Zhang, Z.; Liao, H.; Jiang, Y.; Zheng, Y.; Li, Z.; Gao, Y. Unlocking the Potential: Na4Fe3(PO4)2(P2O7) Supporting the Innovation of Commercial Sodium-Ion Batteries. Advanced Functional Materials 2025, 35 (23). https://doi.org/10.1002/adfm.202424759.

15. Lu, T.; Sun, B.; Dai, B.; Li, E.; Huang, J.; Yin, D.; Liu, S.; Lei, L.; Teng, J.; Zhang, K.; Tang, X.; Li, J. Efficient Synthesis

of NFPP Sodium-Ion Battery Cathode Materials via a Bimetallic Iron Source Synergistic Framework Strategy. Journal of Energy Storage 2024, 107, 114976. https://doi.org/10.1016/j.est.2024.114976.

16. Chen, Y.; Dong, C.; Chen, L.; Fu, C.; Zeng, Y.; Wang, Q.; Cao, Y.; Chen, Z. “One Stone Two Birds” Design for Hollow Spherical Na4Fe3(PO4)2P2O7/c Cathode Enabled High-Performance Sodium-Ion Batteries from Iron Rust. EcoMat 2023, 5 (10). https://doi.org/10.1002/eom2.12393.

17. Shipitsyn, V.; Zuo, W.; Tran, T.-N.; Li, T.; Lee, S.; Chak, C. M.; Le, P. M.; Ma, L. Electronic Structure and Safety Insights into Prussian Blue Analog Cathode Behavior at Elevated Temperatures in Sodium-Ion Batteries. Energy & Fuels 2025, 39 (39), 19054–19059. https://doi.org/10.1021/acs.energyfuels.5c03083.

18. Philipp Marzak; Moser, P.; Schreier, S.; Scieszka, D.; Yun, J.; Schneider, O.; Bandarenka, A. S. A Cell for Controllable Formation and in Operando Electrochemical Characterization of Intercalation Materials for Aqueous Metal-Ion Batteries. Small Methods 2019, 3 (12). https://doi.org/10.1002/smtd.201900445.

Supplemental Information

Model Design

The present work is derived from CellVision V2.3. Unless otherwise mentioned, the default material and manufacturing inputs were used from this model version. The default cell manufacturing inputs are copied from the "reference plant" in BatPac V5.2. The annual production is assumed to be 100 million cells per year or 14 GWh/year of LFP|Graphite cells. The resulting modeled facility is highly automated with only 70 employees per GWh.

The default "energy" type cell uses a negative to positive (N:P) ratio of 1.1 with a cathode electrode assuming 96% cathode active material content, 1% PVDF, 3% carbon, and 25% electrode porosity. The carbon containing anode electrodes assume 98% active material, 2% PVDF, and 30% electrode porosity.

For all cells, the initial coulombic efficiency is set to 100% by default, meaning all full-cell capacities are a little higher than they should be. Sodium active materials tend to have lower initial coulombic efficiency than lithium active materials, meaning the model is particularly favorable to the sodium-ion cells. Because the default cathode and anode capacities are based on their half-cell formation capacities, the reported cell-level energy densities are based on formation capacity rather than a more common 1C discharge capacity.

The default cell type is a multi-layer pouch cell with dimensions shown in **Figure S1.**

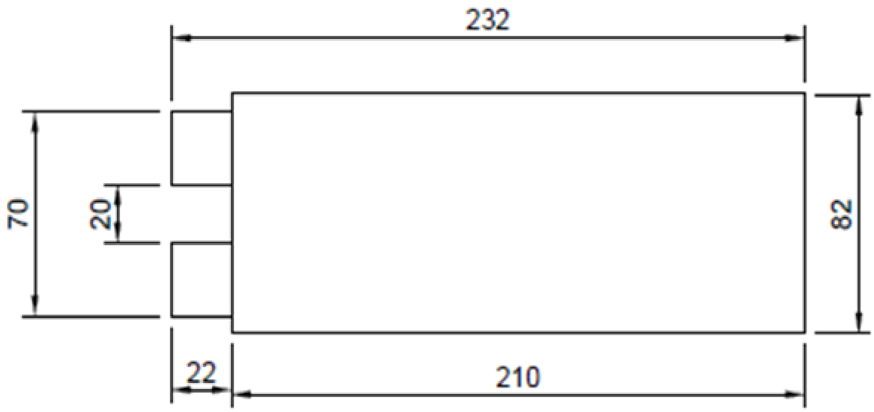

Figure S1, the default multi-layer pouch cell dimensions used for the present work and CellVision V2.3.

Active material costs, inactive material costs, and raw material costs are cited in CellVision using the note feature in excel. Most of the prices are derived from the Shanghai Metals Market with occasional prices from Intratec or Made-In-China.com. **Table S1** summarizes the anode and inactive material costs for this work.

Table S1. Anode and inactive material costs.

Material	Cost	Units
Graphite	$4.16	$/kg
Hard Carbon	$5.93	$/kg
Carbon Additive	$3.00	$/kg
Cathode Binder	$7.60	$/kg
Cathode Solvent	$2.70	$/kg
Anode Binder	$10.00	$/kg
Anode Solvent	$2.70	$/kg
Copper Foil	$0.95	$/m^2
Aluminum Foil	$0.16	$/m^2
Separator	$0.06	$/m^2
Electrolyte	$2.50	$/L

Lithium cathode material costs are from the Shanghai Metals Market. To estimate the at-scale processing costs of the sodium cathode active materials, the processing costs of the closest lithium cathode equivalents were found by subtracting the lithium raw material costs from the current market prices of the respective cathode active materials. By this method, equivalent processes and scales of production are assumed for both the sodium and lithium cathode materials. The processing & overhead costs of NMC and NFM are assumed to be equivalent, and the processing & overhead costs of LFP, NFPP, and PW are assumed to be equivalent.

Subtracting raw material costs from current product costs results in lithium layered oxides with about $4/kg of overhead and processing costs while LFP results in only $0.82/kg of process and overhead costs. While there is no direct equivalent to a Prussian blue analog (PBA) for lithium, PBAs do not have a calcination step during synthesis and are therefore likely to be cheaper to process than layered oxides. PBAs still require a reactor and a very low moisture dry room to synthesize, but without a large-scale equivalent it is hard to predict the processing costs. Therefore, an optimistic at-scale processing/overhead cost of $0.82/kg is assumed for the PBA cathodes.

Table S2. Cathode active material costs

	NMC	LFP	NFM	NFPP	PW	
CAM Cost (real)	18.19	4.5				$/kg
Bill of Materials	14.06	3.68	3.94	1.4	2.12	$/kg
Process & Overhead Cost	4.13	0.82	4.13	0.82	0.82	$/kg
CAM Cost $/kg (simulated)			8.06	2.21	2.93	$/kg

The hard carbon anode charge curve in CellVision is Kuranode type 2, but with a higher density and capacity based on literature (1.6 g/cc and 330 mAh/g)(9,10). The bulk price of hard carbon is about $6/kg which is currently about $2/kg more expensive than graphite. Hard carbon will decrease in price as methods and scale of manufacturing improve, and it may be able to surpass the price of graphite due to lower calcination temperatures needed for synthesis.(11) As shown in **Figure 1**, the sloping nature of the charge curve compared to graphite causes a further nominal voltage penalty for sodium-ion full cells.

The at-scale sodium-ion electrolyte price was assumed to be identical to today's lithium-ion electrolyte price. Assuming identical electrolyte compositions ($NaPF_6$ salt in a carbonate solvent mixture), the solvents and manufacturing of high-purity PF_6 salts are predicted to dominate the price relative to the cost of the working ion. The default electrolyte fill requirement for each cell follows a minimum of either 1 g/Ah or a minimum fill volume calculated as follows: [all of the initial void space within the cell] x [20% excess to account for decomposition] + [any new volume created after the initial charge/discharge].

Volume change of each material was accounted for and calculated under the "volume change" tab. Excess volume needed for material expansion is accounted for as initial electrode porosity in the expanding electrode. Electrolyte displacement during charge/discharge is accounted for as additional void space on the bottom of each cell.

CellVision allows the user to input a desired voltage window for the full cell. In **Figure S2**, the simulated full cell curve of a lithium-ion battery and a sodium-ion battery are plotted along with the charge curve of their respective carbon anode. The voltage for lithium-ion batteries in CellVision is versus lithium and the voltage for sodium-ion batteries is versus sodium, meaning there is a difference of 0.3 V between the two systems. In **Figure S2**, both cells are windowed to the same absolute voltage. The NMC|Graphite cell loses about 5% of the nominal capacity (relative to full depth of discharge) whereas the NFM|HC cell loses 25% of the nominal capacity.

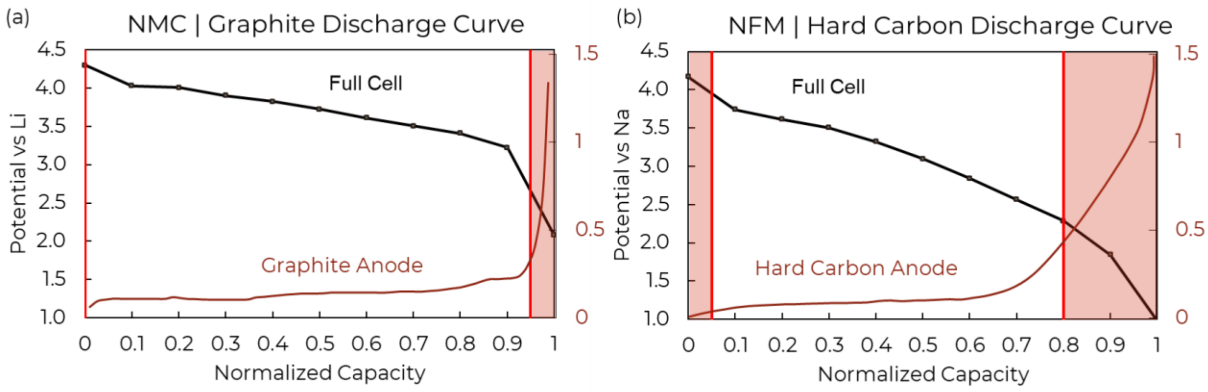

Figure S2. Lithium (a) and sodium (b) full cell curves from CellVision V2.3 plotted against normalized capacity. The red vertical lines represent the capacity achievable within a practical voltage window for a real product application. The voltage window is 2.5 – 4.3 V vs Li or 2.2 – 4.0 V vs Na.

Model Validation

To properly compare the cost of lithium and sodium-ion batteries, CellVision must be capable of accurately predicting the cost of lithium-ion battery cells today. The lithium-ion battery cell in most competition with sodium is the LFP|Graphite cell due to its low price point. Because 99% of the world's LFP is manufactured in China today, Chinese manufacturing prices must be used for both the lithium and sodium-ion battery analysis. Luckily, the Shanghai Metals Market is a publicly available website that reports current lithium-ion battery & raw material prices.

As of November 2025, a 100 Ah prismatic LFP|Graphite cell is reported to cost $51 per kWh (unless otherwise mentioned, all prices include the 13% value added tax that exists in China – VAT). Although prismatic cells are not yet a functionality included in V2.3 of CellVision, we can get a 100 Ah multi-layer pouch cell by increasing cell height under the "cell properties" tab to 41 mm. With today's mid-end EV-grade LFP price of $5.24/kg and today's mid-end EV-grade natural graphite price of $3.80/kg, an "energy" type of cell that is optimized for high energy rather than high power results in a 432 Wh/L, 221 Wh/kg, and $51/kWh cell. However, as explained in the main text, a practical LFP cell is likely limited to voltage window of 2.5 – 3.6 V. This voltage window results in 367 Wh/L, 192 Wh/kg, and $58/kWh. Furthermore, additional $/kWh cost savings can be achieved with vertical integration, government subsidies, or reduced profit margins. Depicted in **Figure S3**, the 13% VAT in China may be bypassed through vertical integration of materials manufacturers and cell manufacturers. 100% vertical integration with this method may enable up to $4/kWh of savings at the cell level. Government subsidies can come in many forms, one of which may include initial capital investment. **Figure S3** shows a potential of up to $8/kWh in savings at the cell level if 100% of the initial capital expenditure is provided by the government.

There is speculation that prices out of China are deflated due to high national competition or to push out international competition. However, according to the results above, a moderately subsidized and moderately vertically integrated cell manufacturer could easily achieve $51/kWh with a practical voltage window while maintaining 5% profit.

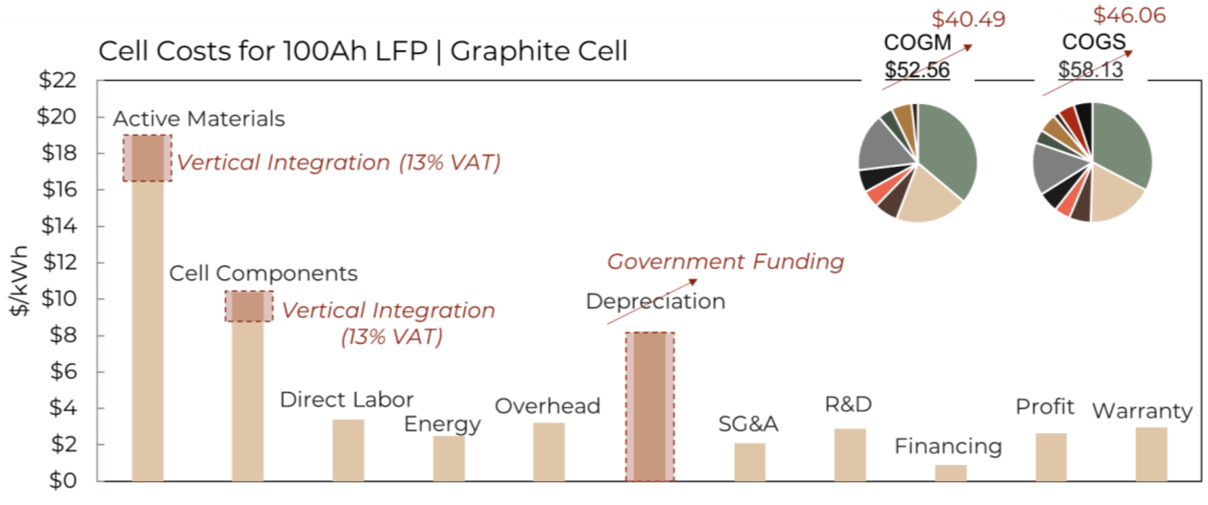

Figure S3. Cell cost breakdown for a 2.5 – 3.6 V, 100 Ah multi-layer LFP | Graphite cell. In red, a second hypothetical scenario shows a maximum of $12/kWh savings at the cell level by simulating active and inactive material vertical integration and eliminating depreciation costs with government subsidies.