

Development of High Performance and Sustainable Na-ion Batteries for Stationary Electrical Energy Storage

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Prepared for
the U.S. Department of Energy under
Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

PNNL REPORT

PNNL-33878-3

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Development of High-Performance and Sustainable Na-ion Batteries for Stationary Electrical Energy Storage

Milestone Report for the DOE-OE Energy Storage Systems Program
(FY23 Quarter 3: April 2023 through June 2023)

Xiaolin Li, Fredrick Omenya, Namhyeong Kim, Alasdair Crawford, Vilayanur Viswanathan, Marcos Lucero, Matthew Fayette, Hyungkyu Han, Bhuvaneswari Sivakumar, Wonkwang Lim, and David Reed

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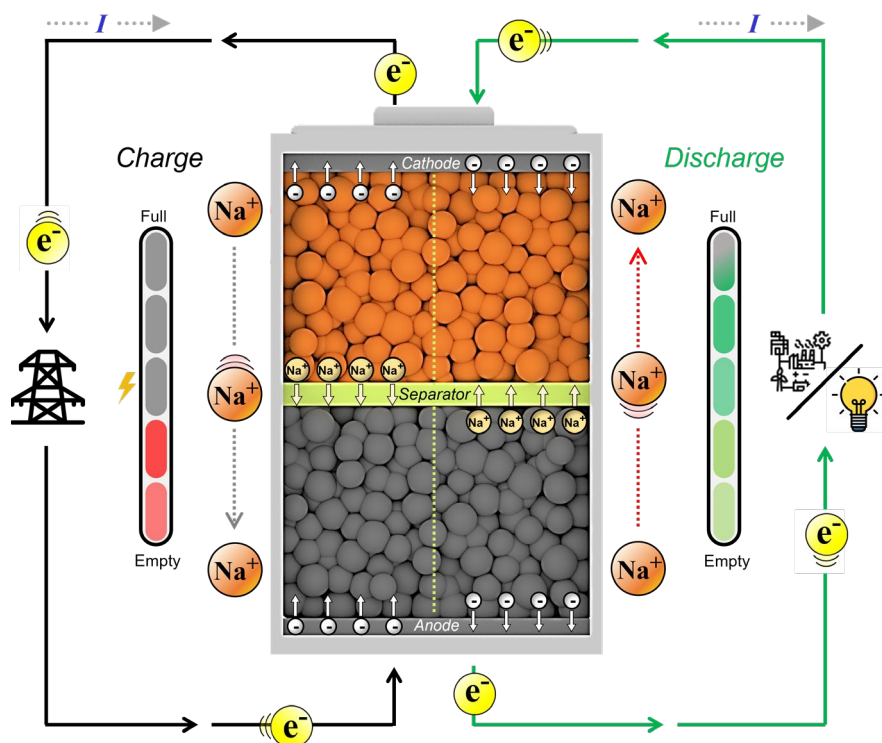
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A schematic illustration of a sodium-ion battery in electric grid energy storage

Abstract

This report describes the status of advanced sodium-ion battery research being performed at Pacific Northwest National Laboratory for the U.S. Department of Energy's Energy Storage Systems Program.

FY23 Target: *Demonstrate novel sodium-ion battery pouch cell with at least 50 mAh capacity capable of achieving \$100/kWh projected materials cost at an energy retention > 80% over 250 cycles.*

Q1 Milestone: Demonstrate 50 mAh capacity in single layer pouch cell with energy retention of > 80% over 100 cycles.

- Milestone completed. A single layer pouch cell using $\text{Na}_{0.85}\text{Ni}_{0.4}\text{Mn}_{0.5}\text{Fe}_{0.1}\text{O}_2$ cathode and commercial hard carbon anode has been fabricated and evaluated at a current density of 0.1C rate (1C = 120 mA/g) and a voltage window between 1.0-4.0 V. The cell delivered an average voltage of ~3 V and a specific capacity of ~ 53 mAh after the formation cycle. The capacity retention was 95% over 100 cycles. The Coulombic efficiency at stable cycling is ~99.9% and the energy efficiency is ~90%.

Q2 Milestone: Optimize electrode composition and density to achieve > 80% energy retention over 250 cycles.

- Milestone completed. The ratio of P2 and O3 phases in the cathode material was optimized for high capacity and stability by tuning the sodium composition and annealing temperature. $\text{Na}_x\text{Ni}_{0.4}\text{Mn}_{0.5}\text{Fe}_{0.1}\text{O}_2$ with x between 0.85-0.95 and an annealing temperature of ~900-950°C delivered an optimized cathode performance. The electrode composition of the active material, conductive carbon, and binder was optimized around 85:8:7 for the cathode and 95:2:3 for the hard carbon anode. Initial Coulombic efficiency has been improved with optimized electrode composition or pre-sodiation treatment. The sodium-ion pouch cell demonstrated 94 % capacity retention after 250 cycles.

Q3 Milestone: Establish baseline materials cost for sodium ion battery technology and costs for selected 1, 10, and 100 MW scale systems at various durations.

- Milestone completed. Employing the well-established BatPaC model with specific Na-ion battery performance parameters, the material cost of the $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ -hard carbon sodium ion battery resulted in \$100/kWh when the cathode active material was priced at \$6.5/kg and the hard carbon cost at \$30/kg. Preliminary modeling suggests that for a 1 to 100 MW system at 1-10 hr duration, the overall system cost, including manufacturing, battery management system, and additional components such as cables and sensors, is not dependent on duration or power levels, and is approximately \$133/kWh.

Q4 Milestone: Evaluate sodium ion pouch cell prototype with optimized electrode composition capable of achieving > 80% energy retention over 250 cycles with a projected MW scale materials cost of \$100/kWh.

Introduction

Stationary energy storage enables efficient shift of a large amount of energy across time for later release on demand. It is a critical component to modern grid that adapts the continuous growth of renewable energy resources from the upper stream and sustains a variety of grid applications along transmission and distribution (T&D) lines at the downstream side. The applications include power quality management through voltage support and frequency regulation, supplementing aging and overrun T&D systems, and providing grid resiliency from outages and brownouts resulting from T&D damage and power demand overrunning supply. The rapid deployment of solar and wind generation introduces the issue of intermittency, which is one of the main barriers regarding modern grid management. Grid energy storage offers a potentially cost-effective approach for reliable renewable integration, balancing the mismatch between supply and demand, and improving overall grid reliability and efficiency. As a promising grid energy storage candidate, the advanced sodium-ion battery (SIB) has a very attractive characteristic in that the battery functions under a similar mechanism to the lithium-ion battery (LIB) but very little challenge on material sustainability.¹⁻⁹ The SIB is a drop-in technology with high rechargeability because of its similar working mechanism to the LIB. The charge carrier difference (Na vs. Li) renders the technology additional benefit on low cost, high sustainability, and good safety.

Sodium is the 6th most abundant element in the Earth's crust and exists in many most common minerals used in our everyday life (e.g., table salts and baking soda) making it dirt cheap and free of supply issue. Sodium also enables the use of more earth abundant elements and more structural diversity on cathode and anode materials.¹⁰ Cathodes for SIBs can be P2 or O3 layered metal oxides, polyanion compounds, and Prussian blue analogues with mainly non-strategical

elements. Carbonaceous anodes used for SIBs can be easily derived from bioproducts or biowaste materials. SIBs with the right design can deliver comparable performance to many types of LIBs with additional enhancement on fast charging and low temperature performance. The use of materials of moderate energy and aluminum as current collectors for both SIB cathodes and anodes are believed beneficial in improving the battery safety during shipping and other operations. The SIB is an ideal and sustainable alternative to the LIB in meeting various requirements for a diverse grid-energy market.

The choice of SIB cathode materials includes transition metal oxides, Prussian blue/white analogues, and polyanion materials while the anode is mainly hard carbon.^{4,11-14} Over the past a few years, various types of P2, O3 or other layer structured transition metal oxides have been developed. P2- $\text{Na}_{2/3}[\text{Fe}_{1/2}\text{Mn}_{1/2}]\text{O}_2$ made from earth-abundant elements delivered a high specific capacity of ~ 190 mAh/g between 1.5-4.3V.¹⁵ Radially aligned hierarchical core-shell structure $\text{Na}[\text{Ni}_{0.58}\text{Co}_{0.06}\text{Mn}_{0.36}]\text{O}_2 @ \text{Na}[\text{Ni}_{0.75}\text{Co}_{0.02}\text{Mn}_{0.23}]\text{O}_2$ cathode delivered a specific capacity of 157 mAh/g and 80% retention over 300 cycles between 1.5-4.1V.¹⁶ A substituted and structurally stabilized sodium nickel oxide, $\text{Na}_a\text{Ni}_{(1-x-y-z)}\text{Mn}_x\text{Mg}_y\text{Ti}_z\text{O}_2$ delivered 157 mAh/g specific capacity and good stability over 100 cycles when cycled between 1.0-4.3V at C/10 rate.¹⁷ The O3- $\text{Na}[\text{Li}_{0.05}\text{Mn}_{0.5}\text{Ni}_{0.3}\text{Cu}_{0.1}\text{Mg}_{0.05}]\text{O}_2$ cathode demonstrated 80% retention over 400 cycles with an initial specific capacity of ~ 125 mAh/g between 2.0-4.0V at 1C rate.¹⁸ Cu and Ti co-substituted O3- $\text{NaNi}_{0.45}\text{Cu}_{0.05}\text{Mn}_{0.3}\text{Ti}_{0.2}\text{O}_2$ and $\text{NaNi}_{0.4}\text{Cu}_{0.1}\text{Mn}_{0.4}\text{Ti}_{0.1}\text{O}_2$ has been made into 18650 cells, which exhibited specific energy of about 115 Wh/kg.¹⁹ While many of them have little challenge from material sustainability, they mostly suffer from limited cycling stability or low specific capacity. Furthermore, the working voltage window of the above batteries often are not ideal because of the severe electrode and electrolyte interaction.

Prussian blue/white have ultra-low material and manufacturing cost and are promising for aqueous batteries while their use in non-aqueous SIBs analogues to commercial state-of-the-art LIBs which face potential safety concerns of releasing highly toxic hydrogen cyanide gas upon abrupt failure such as thermal abuse.^{20,21} Polyanion materials such as sodium vanadium phosphate-based materials also have been demonstrated to have good performance as cathodes. The high cost of vanadium and the limited energy density demonstrated, however, have hampered the widespread adoption of this system.²²⁻²⁵ Sodium iron phosphate would be an ideal cathode material, however, the olivine structure like LiFePO_4 is not thermodynamically favored in conventional synthesis.²⁶ Revolutionary approaches are needed in future research of Prussian blue analogue and polyanion materials.

Metal oxide cathodes among all these different types of cathodes are believed the most promising candidates in SIB commercialization if they could be designed to have high-performance like LIB cathodes while mainly using earth abundant elements to maintain a low cost and high sustainability. We have previously published our research on the development of SIB cathode materials including conventional O3-type Ni-rich cathodes and O3-Mn-rich cathodes with induced vacancies, and the dopant effect on P2-type Mn-rich metal oxides.²⁷⁻²⁹ Recently, we have synthesized Mn-rich cathodes with the core composition of $\text{Na}_x\text{Ni}_{0.5}\text{Mn}_{0.5}\text{O}_2$, with comprehensive examination of various element substitution, X-ray diffraction study, transmission electron microscopy characterization, and electrochemistry yielding materials of pure O3 or P2/O3 hybrid structure that demonstrated excellent cycling stability with >85% capacity retention over 500 cycles and a specific capacity close to 140 mAh/g between 2.0-4.0V.³⁰

Beyond the cathode development, we also have also carried out extensive research on carbonaceous anodes and the electrode-electrolyte interaction. Hard carbon, a carbonaceous material that cannot be converted to graphite, has larger spacing between graphitic basal planes than graphite ($\sim 0.38\text{nm}$ vs. 0.34nm) and no long-range ordering.^{31,32} The large lattice spacing enables fast sodium ion diffusion while the no graphite-like long-range ordering enables it to be free from the exfoliation effect in ether-based electrolyte. The transfer of sodium ions also was found to be very sensitive to the solid-electrolyte interphase (SEI) layers on cathodes and hard carbon anodes. Tuning the SEI by using novel electrolyte or introducing electrolyte additives can greatly control the specific capacity, cycling stability, fast charging capability, and performance at low temperatures.³³⁻³⁵ Commercial hard carbon delivers better performance in tetraglyme-based electrolyte than in carbonate electrolyte at both room temperature and minus 20 °C. The specific capacity at room temperature can reach $\sim 250\text{ mAh/g}$ or higher; the capacity retention over 1000 cycles is $>85\%$ at 0.5C rate.³⁵ Fluorinated ethylene carbonate, which has been known as one of the most effective additives that contributes to SEI formation and helps to improve the cycling stability of many LIB and SIB anode materials, was found to suppress the sodium ion transfer and results in low sodium storage capacity when its concentration in the electrolyte is high ($> 5\text{ wt.}\%$).³³ It is also found that preformation of SEI by pre-cycling of cathodes and anodes can enable long cycle stability of full-cell SIBs. The model cell of $\text{Na}_{0.44}\text{MnO}_2$ -hard carbon coin cell full-cell shows 77% capacity retention over 2000 cycles.³⁴

While the above results were promising on component development and demonstrated viable SIBs in small-scale coin cells, translation to larger, industrial relevant cell sizes are necessary to determine the future of advanced SIBs in MW-scale deployment. Herein, we report the

extension of these tests to pouch cells by selecting our most advanced transition metal oxide cathodes, hard carbon anodes, and electrolyte systems. These tests will provide an industrial relevant path forward for performance optimization, cost projection, and potential deployment/commercialization.

FY23 Quarter 1 Project Status Summary

The FY23 Q1 milestone was to “Demonstrate 50 mAh capacity in single layer pouch cell with energy retention of > 80% over 100 cycles.” As shown in Figure 1, the single layer pouch cell electrode is $\sim 20 \text{ cm}^2$, almost 15 times of the size of a 2032-coin-cell electrode, 1.27 cm^2 ; this is a relatively large increase in terms of electrode size. To achieve this milestone, several items need to be addresses including 1) identify the best cathode composition and scale up the material synthesis reliably 2) control the homogeneity and temperature in the mixing of large amount of slurry/paste 3) exercise high quality electrode fabrication to ensure electrode homogeneity/uniformity over large electrode areas, and 4) perfect the skills on battery manufacture and applying testing apparatus for single layer pouch cell fabrication and performance evaluation.

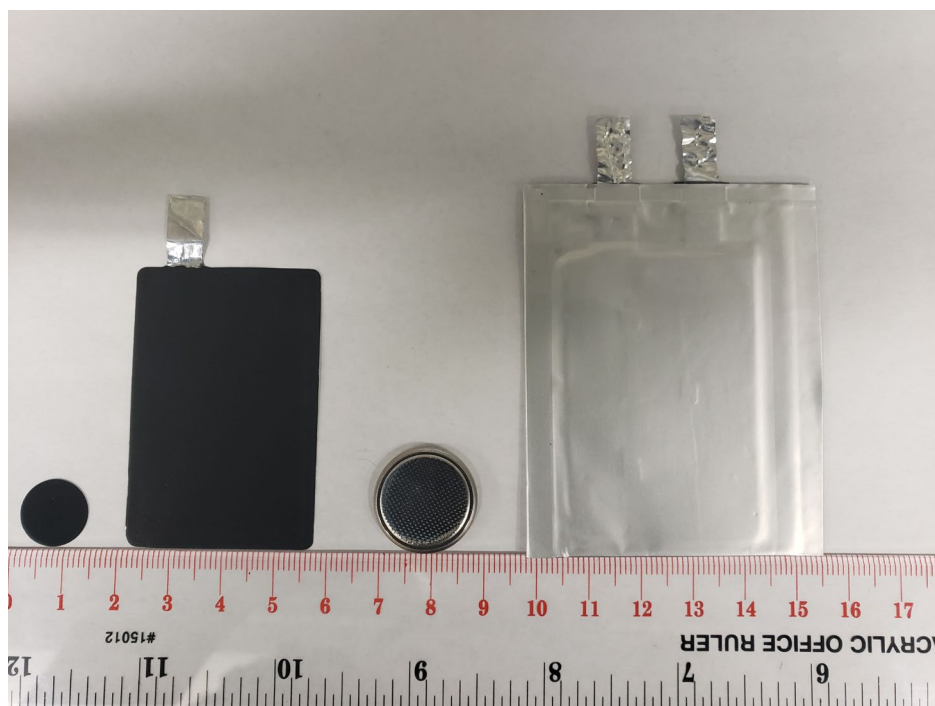


Figure 1. Illustration of the prepared electrodes for coin cell, pouch cell and the corresponding cell formats.

To identify the best cathode composition, we previously have screened various sustainable and low-cost, Mn-rich, and Co-free cathode materials. We narrowed the candidates down to $\text{Na}_x\text{Mn}_y\text{Ni}_z\text{Fe}_{1-y-z}\text{O}_2$, $0.66 < x < 1$, $0 < y < 1$, and $0 < z < 1$ based on our previous work and have focused on three compositions; $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ and $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$. $\text{Na}_x\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, $0.66 < x < 1$ was chosen as the baseline due to its high manganese but low Ni content. To achieve the desired structure control for the different compounds, we investigated various synthesis temperatures; 900 °C was established as the optimal temperature for most compounds studied. At this temperature, $\text{NaMn}_{0.6}\text{Ni}_{0.4}\text{O}_2$ crystalized into a mixture of P2, O3 and other unidentified phases and was therefore not considered for further studies. When Na content was reduced to 0.85, pure O3/P2 phase mixtures were identified in powder X-ray diffraction (XRD). Compositions with $x < 0.85$, were not considered because the low Na content is not suitable for practical application in full cell

without pre-sodiation treatment. Therefore, $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$ was chosen as the baseline cathode material. We also investigated various dopants such as Fe, Mg, and Ti to further improve the electrochemical performance of the Mn-rich cathode materials.

In this quarter, our primary focus was on the Fe substitution materials. The XRD results in Figure 2a shows that $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ forms a mixed P2/O3 phases similar to the parent compound. $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ with increasing the amount of Na to 1.0 forms pure O3 phase, Figure 2b. These results were further corroborated by high-resolution TEM and selected area electron diffraction (SAED) characterization (Figure 2c-2f). The $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ exhibited two sets of interlayer spacings of 5.3 Å and 5.6 Å corresponding to the O3 and P2 phases, respectively. In contrast, only O3 interplanar spacing of 5.3 Å was observed in $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$.

The electrochemical performance of these materials is the most critical factor determining down selection and was initially evaluated in a coin cell half-cell to screen various cathode materials and electrolytes. In any electrochemical system, both electrodes and electrolyte work in tandem to achieve good electrochemical performance. In this work, localized high-concentration electrolyte (LHCE), NaFSI in 1,2-dimethoxyethane- bis(2,2,2-trifluoroethyl) ether, was chosen due to its long-term cycling stability over a wide voltage window. The half-cell electrochemical performance was tested between 2 - 4 V at different current densities. Cycling over a large voltage window, 1.5 - 4.5 V, was also tested. They showed significantly higher initial capacity of around 170 mAh/g-200 mAh/g, however, their capacity retention was worse and could not meet the milestone target. On the basis of the evaluation, the high cut-off voltage for the single layer pouch cell is thus fixed to be 4 V.

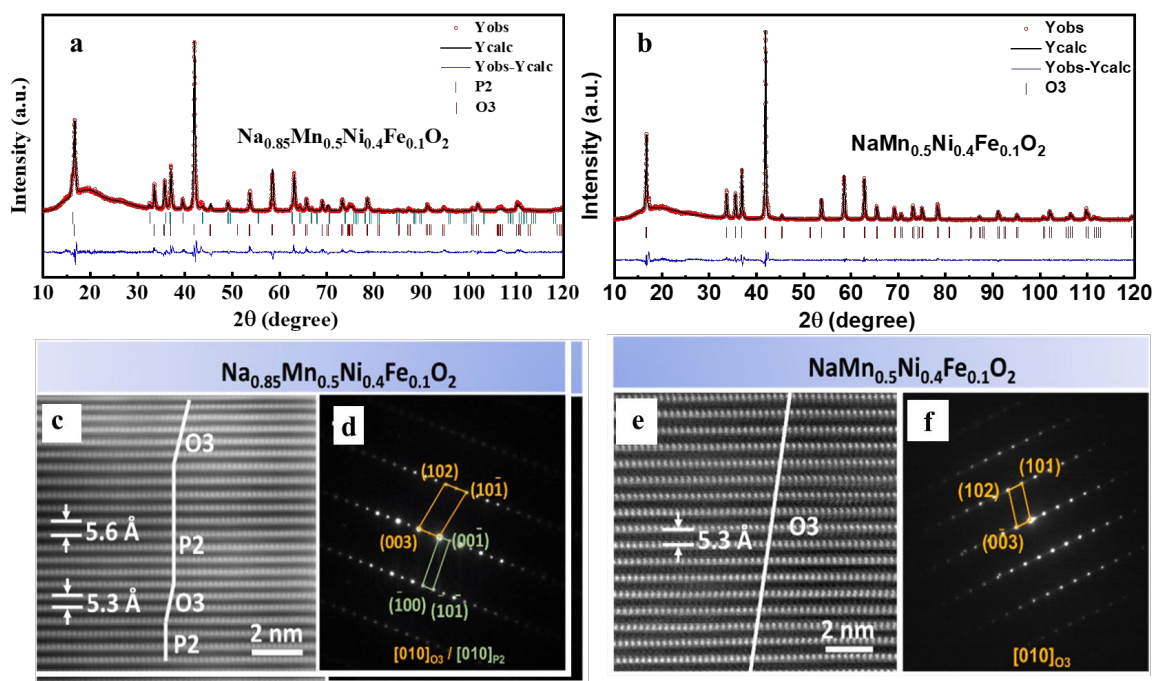


Figure 2. XRD patterns of (a) $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ and (b) $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$; (c-d) HAADF image of $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ and SAED pattern showing two sets of diffraction patterns. (e-f) HAADF image of $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ and SAED pattern showing one set of O3 diffraction pattern.

Figure 3 shows the electrochemical performance of $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, and $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ in LHCE. Figures 3a-3b show typical charge-discharge profiles of these cathode materials at 0.1C rate (1C = 120 mAh/g). The specific capacities are ~111, 147, and 136 mAh/g, respectively. This confirms the potential of dopants to activate untapped redox activities of the baseline compound. The cycling stability of all the samples were tested at 1C rate after 3 formation cycles at 0.1C. As shown in Figures 3c-3e, the $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, and $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ exhibited high cycling stability with a capacity retention of 86.2%, 80.6%, and 81.6%, respectively, after 500 cycles. Furthermore, both Fe-substituted samples demonstrated a high-rate capability that delivers over 60% of the capacity at 10C compared to that at 0.1C. In comparison, the baseline material $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, only delivered 20% under similar test conditions (Figure 3f). Despite the baseline having good capacity retention, its initial low specific capacity and poor rate capability

hinders its use in Na-ion battery applications. $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ was therefore considered as the choice cathode material for scale-up due to its overall superior performance on specific capacity, cycling stability and rate capability.

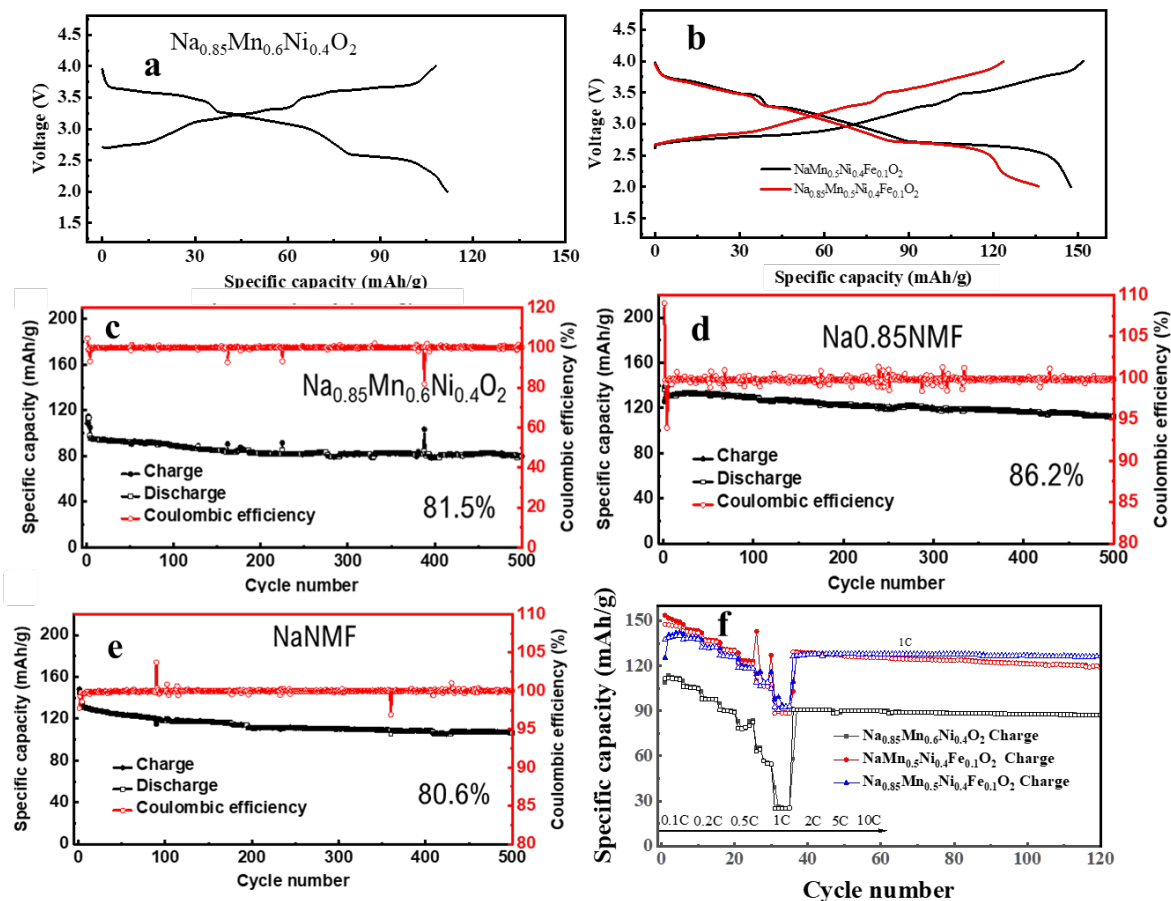


Figure 3. Electrochemical performance of $\text{Na}_x\text{Mn}_y\text{Ni}_z\text{Fe}_{1-y-z}\text{O}_2$ -based cathodes. Initial charge/discharge curves of (a) $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, (b) $\text{Na}_x\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, $x = 0.85$ and 1.0 ; Cycling performances of (c) $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, (d) $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, and (e) $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, between 2-4V at 1C with the first 3 cycles under 0.1 C (1C=120 mA/g); (f) Rate performances of $\text{Na}_{0.85}\text{Mn}_{0.6}\text{Ni}_{0.4}\text{O}_2$, $\text{NaMn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$, and $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$.

High-performance of the anode in a full-cell demonstration is as critical as the cathode. Hard carbon has become the anode of choice for Na-ion batteries. Similar to graphite in Li-ion battery, hard carbon has been chosen due to its low cost, low operating voltage, high capacity and good cycling stability. A commercial hard carbon was initially tested in a half-cell using LHCE to determine the parameters required for full-cell testing. The hard carbon achieved a

high specific capacity of >250 mAh/g between 0.05 V - 1 V in a half-cell (Figure 4a). The charge/discharge curves can be divided into two regions; a linear voltage profile above 0.1 V and a relatively flat voltage below 0.1 V. Figure 4b shows that the material demonstrated a stable cycling performance and achieved a reversible capacity of over 270 mAh/g. These results are better than or comparable to those achieved with traditional carbonate-based electrolytes.^{18,33,34,36}

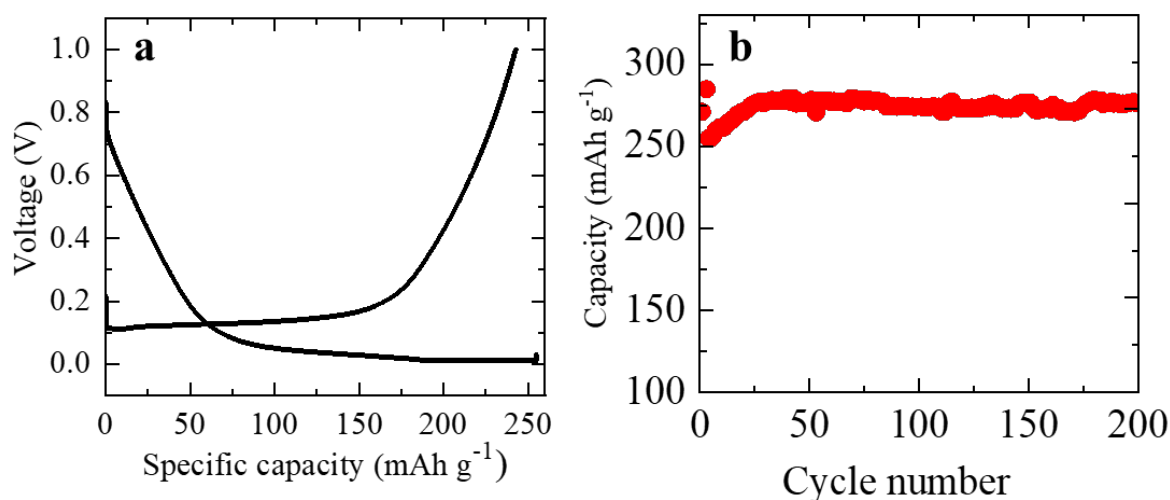


Figure 4. Charge-discharge curves (a) and cycling performance (b) of a hard carbon half-cell with LHCE electrolyte.

Single layer pouch cell pouch cell with $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ as the cathode and commercial hard carbon as the anode were fabricated in the dry room in PNNL's Advanced Battery Facility (ABF). To achieve the FY23 Q1 milestone of 50 mAh capacity, the cathode active material loading was targeted to be ~ 27.6 mg/cm² (538 mg loading of active material coated on a 3.6 cm by 5.4 cm Al current collector). The negative/positive (n/p) capacity ratio of 1.1 was chosen as the optimized value. The hard carbon anode loading was determined considering the n/p ratio, hard carbon reversible capacity, and 1st cycle Coulombic efficiency. Figure 5 show the charge/discharge curves and cycling performance of a typical single layer pouch cell cycled between 1.0-4.0 V in LHCE. The single-layer pouch cell has an average voltage of ~ 3.0 V

(Figure 5a) delivering a reversible capacity of 53 mAh after the initial formation cycles. The cell demonstrated good stability over 100 cycles and a high coulombic efficiency of 99.9% at stable cycling (Figure 5b). The capacity of the cell after 100 cycles is ~50.5 mAh/g, which is approximately 95% of the initial capacity. These values are above our FY23 Q1 milestone target of 50 mAh capacity and energy retention > 80%.

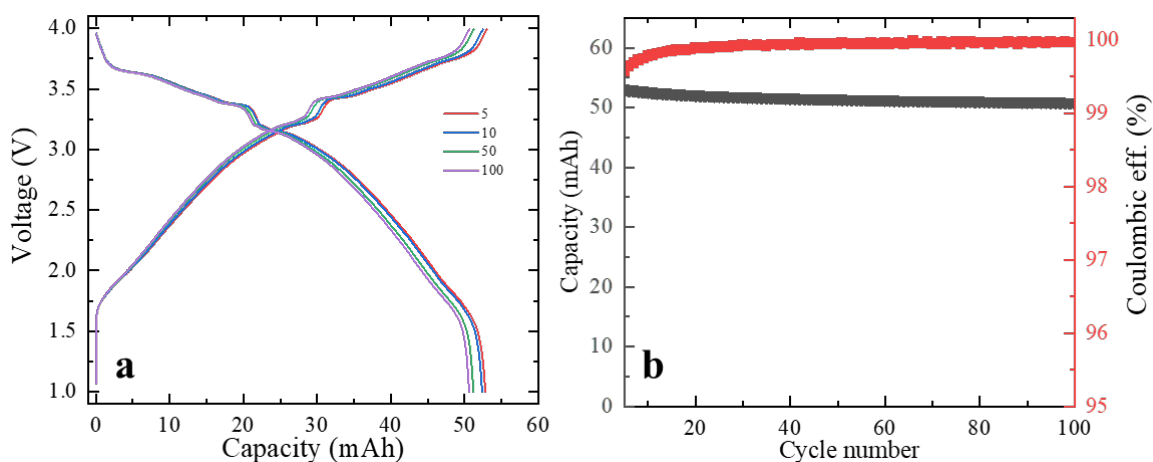


Figure 5. Electrochemical performance of single-layer pouch cell. (a): charge-discharge curves of selected cycle numbers. The cell achieves a stable capacity above 50 mAh. (b): Cycling performance over 100 cycles. The cell demonstrated stable cycling and high coulombic efficiency.

Despite the impressive cell performance achieved in Q1, there are still a lot of challenges to be addressed for Na-ion batteries to be competitive. First, the cathode scale up is very sensitive to the batch size and the actual local temperature in the furnace. Reliable material scale-up and the electrochemical performance rely on the actual control of the material P2/O3 ratio and the particle size. Second, the full cell capacity can be hindered by the high irreversible capacity loss. Capacity losses over 30% of the initial cycle of some cells was observed. The Coulombic efficiency of the first cycle often was in the 70th percentile. This is predominately associated with the irreversible consumption of Na^+ ion from the cathode to form SEI layers. Lastly, the electrode composition, structure, and mechanical integrity influences the Na^+ ion consumption, electrolyte decomposition, and hence long-term cycling stability. Further work is therefore

needed to accurately control the conditions for material scale-up and to optimize the electrode engineering to minimize the Na^+ ion consumption associated with initial irreversible capacity loss, SEI formation and electrode disintegration. The cell performance such as reversible capacity will be significantly enhanced if the 1st cycle capacity loss can be further mitigated. The update will be discussed in the subsequent FY23 Q2 report.

FY23 Quarter 2 Project Status Summary

In this quarter, we worked on the basis of Q1 to optimize electrode composition and density of Na-ion battery single layer pouch cell to achieve > 80% energy retention over 250 cycles. It is known that the cathode synthesis temperature plays a significant role in determining the morphology, crystallinity, phase formation, and property of sodium layered oxide cathode materials. Hence, we first systematically investigated and optimized the annealing process for various compositions of $\text{Na}_x\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ prepared by solid-state reactions. The sample batch size and sample location as well as the oxygen flow rate are fixed in the investigations. The precursors were mixed using similar wet planetary ball-milling method and then annealed at 900-1000 °C temperature ranges. Typical $\text{Na}_x\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ (Na_xNMF) materials with x of ~0.85, 0.92 and 0.95 crystallize into P2, O3 or a hybrid of the two phases. Figure 1 shows powder XRD patterns of the samples annealed at different temperatures. $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ (Na_{85}NMF) crystallizes into a P2/O3 mixture at 900 °C (denoted as $\text{Na}_{85}\text{NMF}_{900}$). With increasing the annealing temperature (950 °C), the percentage of P2 phase decreases in the product ($\text{Na}_{85}\text{NMF}_{950}$) at the expenses of the increase of the O3 phase. At 1000 °C, XRD shows primarily O3-phase material ($\text{Na}_{85}\text{NMF}_{1000}$). $\text{Na}_{0.92}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ (Na_{92}NMF) and $\text{Na}_{0.95}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ (Na_{95}NMF) formed pure O3-phase at 900 °C ($\text{Na}_{92}\text{NMF}_{900}$ and $\text{Na}_{95}\text{NMF}_{900}$) and 950 °C ($\text{Na}_{92}\text{NMF}_{950}$ and $\text{Na}_{95}\text{NMF}_{950}$) as shown in Figures 1b &

1c. Increasing the temperature to 1000 °C led to the formation of unidentified impurity phase in Na₉₂MNF, marked with a diamond symbol in Figure 1b.

As electrochemical performance is the ultimate determining factor in the material optimization, we investigated the effect of calcination temperature on material specific capacity, cycling stability and rate performance. The electrochemical cycling of Na_xMn_{0.5}Ni_{0.4}Fe_{0.1}O₂ (Na_xNMF) materials was done at 0.5C (1C= 120 mAh/g) between voltage ranges of 2.0 V to 4.0 V. The cycling results are summarized in Table 1. Although the initial specific capacities are similar for most samples, there are observable differences in their specific capacities and capacity retention. From the results, pure O3-phase samples usually exhibit capacities above 130 mAh/g. The O3 structure Na₈₅MNF_1000 delivered a maximum specific capacity value of ~137 mAh/g and a 94% capacity retention over 250 cycles. The P2/O3 hybrid structure Na₈₅MNF_900 delivered a specific capacity of ~128 mAh/g and ~96% retention over 250 cycles. From the comparison, higher capacities are achieved by the O3-phase samples but the P2/O3-hybrid phase had better capacity retention. Further analysis of the electrochemical performance of Na₉₅MNF_950, Na₉₂NMF_950 and additional control sample of NaMNF_900 (NaMn_{0.5}Ni_{0.4}Fe_{0.1}O₂_900) further demonstrated that sodium deficiency is important for long term cycling of O3 materials. The Na₉₅MNF_950 and Na₉₂NMF_950 showed capacity retention of ~94% after 250 cycles. While NaMNF_900 even though also delivered similar initial capacity of 133 mAh/g, exhibited very poor capacity retention, 94% after 125 cycles.

Rate performance of the sodium deficient materials was investigated between 0.2C to 5C. Figure 2b exhibited high-rate capability of all of these Na_xMNF electrodes. The Na₈₅NMF_900, Na₉₂NM_950, and Na₉₅NMF_950 and Na₈₅NMF_1000 demonstrated similar capacity, delivering 132, 138, 140 and 143 mAh/g respectively at 0.2C. At 5C, the Na₈₅NMF_900, Na₉₂NM_950, and Na₉₅NMF_950 exhibited a high-rate performance,

delivering 83% of the discharge capacity at 0.2C. While Na85NMF_1000 delivered 79% discharge capacity of that at 0.2C. The results further corroborate the benefit of the sodium deficiency. Also, according to the above discussion, the sodium content is optimized to be ~ 0.85 to 0.95 and the annealing temperature is ~ 900 -950°C for high overall electrochemical performance.

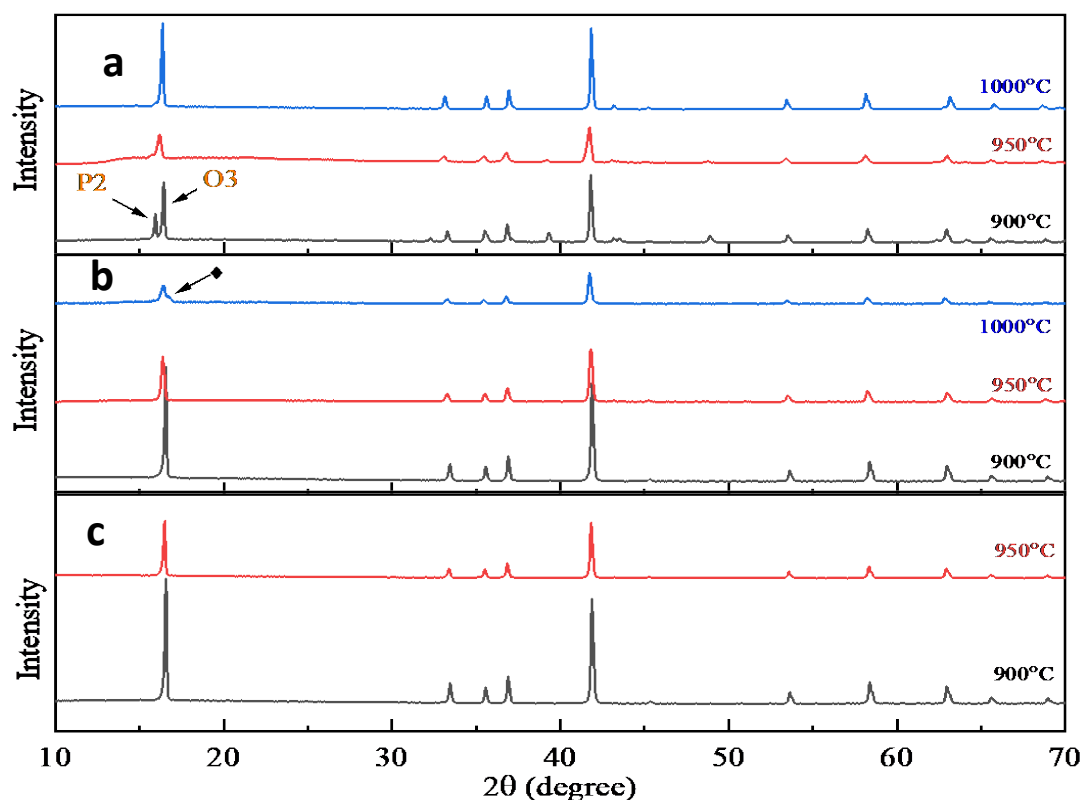


Figure 1. XRD patterns of (a) Na85MNF, (b) Na92MNF and (c) Na95MNF annealed at various temperatures.

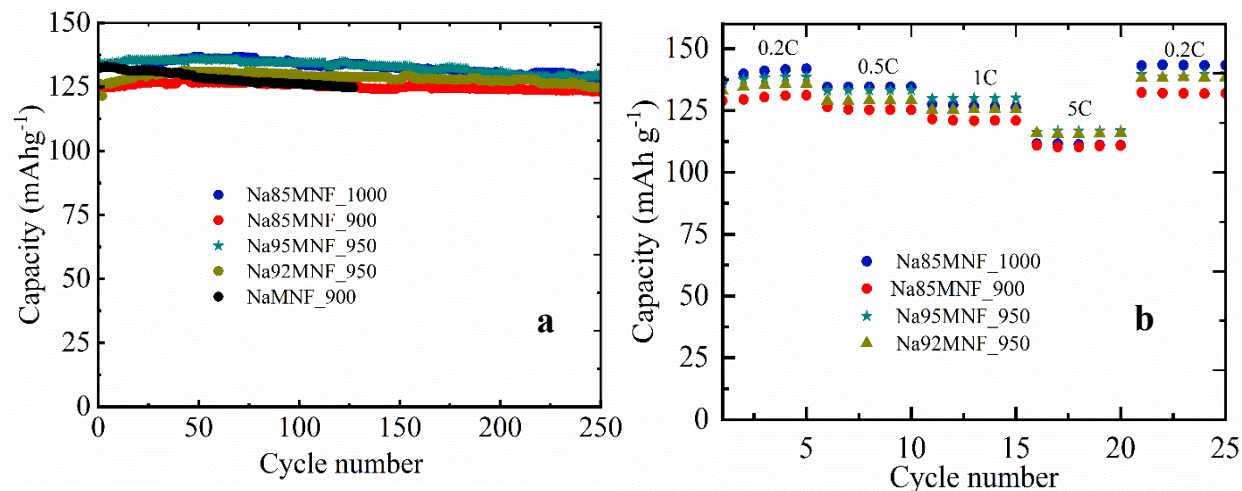


Figure 2. The cycling performance (a) and rate capability (b) results of Na_xNMF synthesized under various temperatures.

Table 1. Summary of electrochemical results of various Na_xNMF samples and their synthesis conditions

Sample	Temperature (°C)	Phase	Capacity at 0.5C (mAh/g)	Cycle number	Capacity retention (%)
NaMn _{0.5} Ni _{0.4} Fe _{0.1} O ₂	900	O3	133.0	125	94.0
Na _{0.95} Mn _{0.5} Ni _{0.4} Fe _{0.1} O ₂	950	O3	136.0	250	94.8
Na _{0.92} Mn _{0.5} Ni _{0.4} Fe _{0.1} O ₂	950	O3	131.0	250	94.6
Na _{0.85} Mn _{0.5} Ni _{0.4} Fe _{0.1} O ₂	900	P2/O3	128.0	250	96.1
Na _{0.85} Mn _{0.5} Ni _{0.4} Fe _{0.1} O ₂	1000	O3	137.0	250	94.2

To understand the structural origin of the difference in the cycling stability of Na_xNMF materials, in-situ synchrotron XRD was employed to track the phase evolution along with battery cycling. Figure 3 below shows the results from representative O3-NaNMF and P2/O3-Na_{0.85}NMF cathodes synthesized at 900 °C. As we can see, O3-NaNMF undergoes a two-phase reaction during charging, characterized by the O3 to P3 phase transition at ~2.8V. Further charging, from 2.8 – 4.0 V, is characterized by continuous peak shifting of P3 peaks. A reverse process is observed during discharge suggesting the reversibility of the process (Figure 3a). The

O3 phase transition in the P2/O3-Na85NMF material during charging can be divided into three regions: region 1 (below ~ 3 V) with no observable phase transition, region 2 (3-3.5V) with O3 to P3 two-phase reaction, and region 3 (above 3.5V) single phase reaction characterized by the shift of P3 phase. A reverse process is observed during discharge suggesting the reversibility of the process (Figure 3b). The bi-phasic reaction of the O3 phase Na85NMF started to show up at a slightly higher voltage than the O3-NaNMF sample (3V vs. 2.8V). The P2-phase in the hybrid structure does not show observable phase transition. It is possible this P2/O3 structure stabilized the phase transition of Na85NMF during cycling.

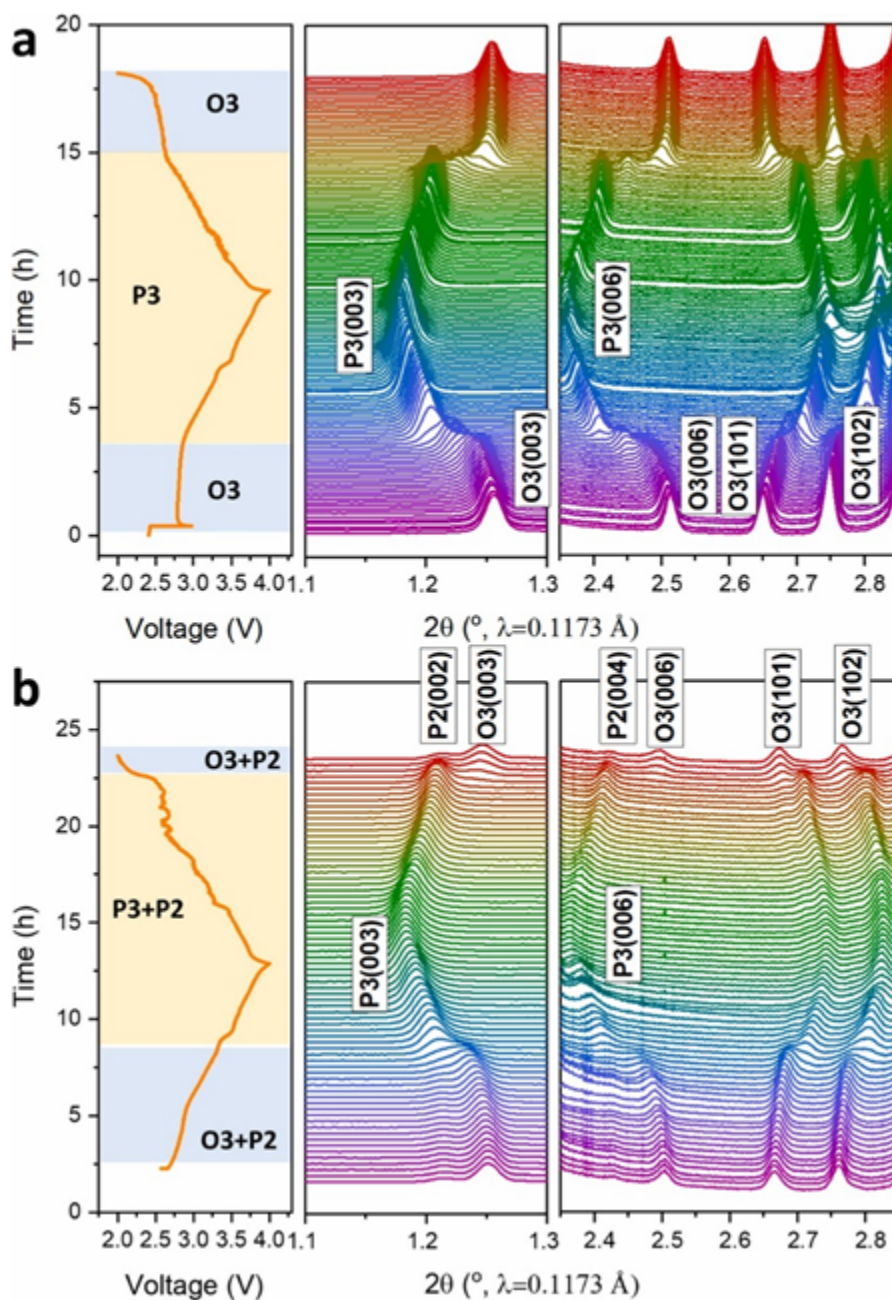


Figure 3. In-situ XRD patterns of (a) O3-Na/NMF and (b) P2/O3-Na85NMF.

Our second major optimization effort was on the initial Coulombic efficiency (ICE), which is essential to the electrochemical performance of the pouch cell of limited sodium inventory. The low ICE of hard carbon (HC) anodes is one of the many important reasons that can lead to the low capacity and CE of full cells. In Q1, the ICE sometimes is ~70%. In this quarter, we have investigated the electrode composition effect on the CE of hard carbon anodes. Pre-sodiation and electrode composition optimization of HC anodes have been tried to improve the ICE.

Figure 4 shows the charge-discharge curves of electrodes with various HC, carbon black and binder ratios of 80:10:10, 90:5:5 and 95:2:3. Table 2 summarizes the specific capacity and ICE of these anodes. All these hard carbon anodes show similar specific capacity of ~ 280 mAh/g based on the active HC material. The ICE increases from $\sim 84\%$ to $\sim 87\%$ with reducing the amount of carbon black and binder from 10% to less than 5%. From Figure 4 and Table 2, the ICE does not show much change when the carbon black and binder amount was $<5\%$. However, the difference of ICE between the electrodes with 95:2:3 and 90:5:5 will be slightly bigger if the charge cut-off is set at ~ 1.0 V.

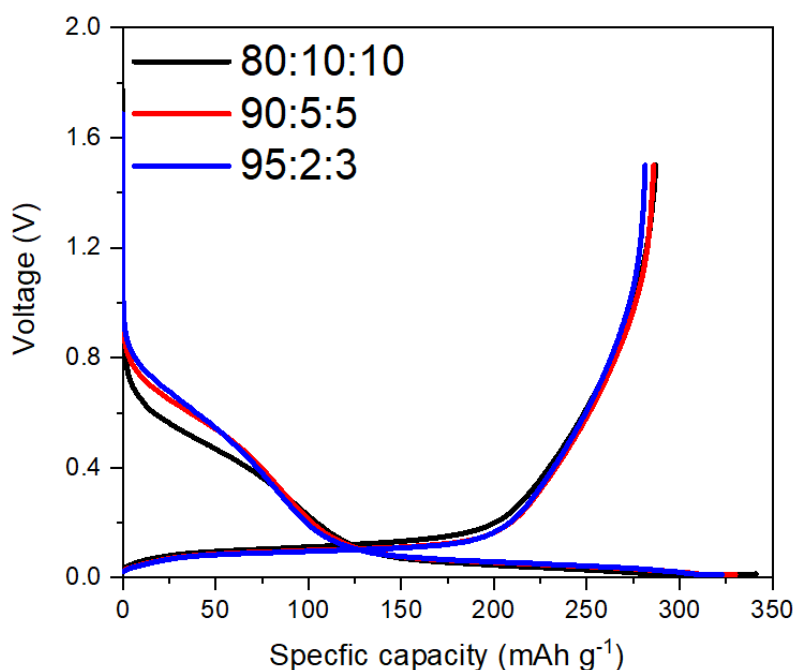


Figure 4. The first charge-discharge curves of HC anodes with various compositions.

Table 2. Specific capacity and initial Coulombic efficiency (ICE) of hard carbon anodes of various electrode compositions.

	80:10:10	90:5:5	95:2:3
Specific capacity	284.2 mAh/g	286.0 mAh/g	281.5 mAh/g
ICE	84.2 %	86.6 %	87.3 %

We also have investigated the use of pre-sodiation to compensate for the irreversible sodium loss from the cathode and improve the ICE of pouch cells. The pre-sodiation could be achieved by directly contacting HC and Na metal in the presence of electrolyte. The electrolyte provides the pathway for sodium ion migration from the Na metal to the HC and helps preform the SEI layer on the HC anode. We studied various contact times from 0 min to 1 h to control the pre-sodiation degree. The increase of the open circuit voltage (OCV) of the HC/Na85NMF cell with the pre-sodiation time indicates that the pre-sodiation works. The OCV increases from 0 to 0.44, 0.65 and 2.2 V with the pre-sodiation time increased from 0 to 15, 30, and 60 mins. The OCV results revealed that 60 mins pre-sodiation probably is too long and the HC anode probably was “over sodiated” because the OCV was very close to that of the Na/Na85NMF half-cell, 2.6 V. The full cell ICE, charge-discharge voltage profile and capacity retention further corroborated the estimation from the OCV result. From Figure 4, the ICE of the cell with 60 min pre-sodiated HC anode is >100%. The charge-discharge curves are very similar to a Na_xMNFO half-cell. The battery fades quickly with capacity retention of ~50% over 25 cycles. The poor capacity retention can be attributed to the over-sodiation of HC which may lead to the plating of Na metal on HC during cycling.¹⁰

The voltage profiles from the HC anodes with 15 min and 30 mins pre-sodiation are very similar to that of an untreated-HC/ Na85NMF cell indicating there probably is no Na plating during cycling. The ICE for untreated and 15 mins pre-sodiated HC anodes was ~75% and ~80%, respectively. The cell with 15 mins pre-sodiated HC showed the best overall performance. It exhibited a high specific capacity of 101 mAh/g, higher than the full cell with untreated HC (~94 mAh/g). The capacity retention is ~98% over 100 cycles, also higher than the full cell with the untreated HC, 96% retention after 100 cycles. It is believed the pre-sodiation enables the

sodium deficient Na85NMF to take extra Na from the HC leading to higher discharge than charge capacity.

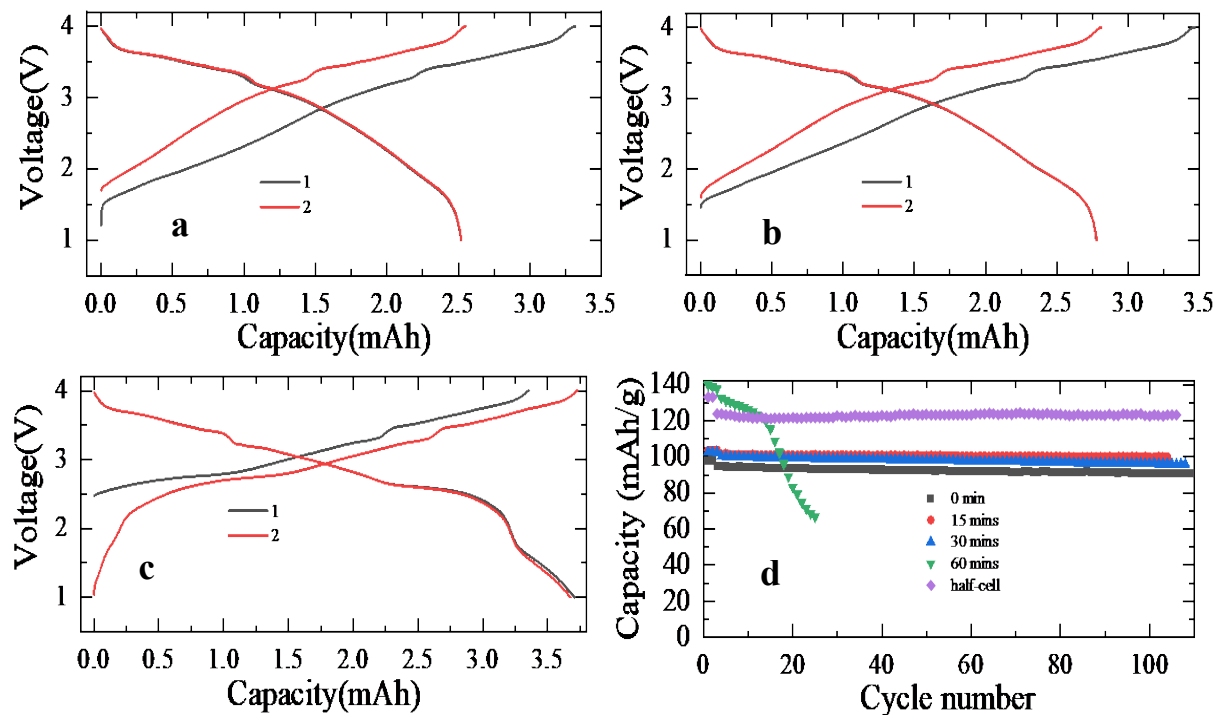


Figure 5. Selected HC/Na85MNF charge-discharge voltage profiles of (a) untreated-HC, (b) 15 mins, (c) 60 mins pretreated-HC. (d) Cycling performance of HC/Na85MNF full cells with different levels of pre-sodiated HC.

Optimized single-layer pouch cell delivers desired high performance. Figure 6 shows the typical long-term cycling performance. The charge discharge curves show almost no significant voltage polarization even after 250 cycles. The capacity retention is ~94.3% after 250 cycles, much higher than the targeted 80% retention. The CE at stable cycling is >99.9%. On the basis of the

pouch cell data and projected lifetime, we will work with PNNL's battery economists in Q3 to estimate the baseline materials cost for various large sized systems.

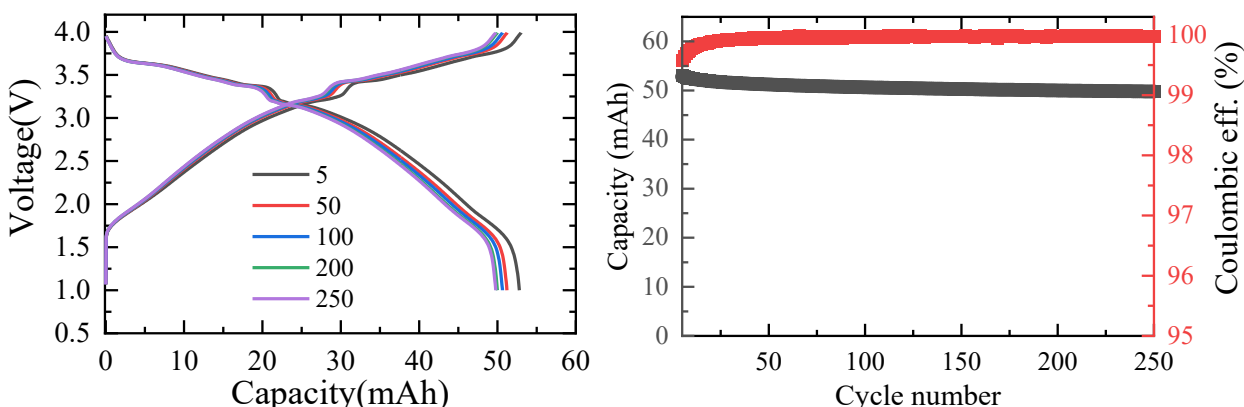


Figure 6. Electrochemical performance of an optimized pouch cell. (a): Selected charge-discharge curves, and (b): Cycling performance over 250 cycles. The cell achieves >94% capacity retention after 250 cycles.

FY23 Quarter 3 Project Status Summary

In this quarter, a cost performance model was developed based on results from FY23 Q2 on the optimized $\text{Na}_{0.85}\text{Mn}_{0.5}\text{Ni}_{0.4}\text{Fe}_{0.1}\text{O}_2$ -hard carbon (Na85MNF-HC) single layer pouch cell to estimate materials cost and costs for 1, 10 and 100 M systems for durations 1, 2, 4 and 10 hours. The cost-performance model leverages previous findings and learnings at PNNL in designing Li-ion battery cells to improved specific energy³⁷ and cost-performance modeling of redox flow battery systems.^{38,39}

Methodology

Our preliminary analysis on the material cost of the cell utilizes the Argonne National Laboratory's established Battery Performance and Cost (BatPaC) model, version 5.0.⁴⁰ The original Li-ion battery parameters within the BatPaC model have been substituted where appropriate, with the parameters derived from the Na85MNF-HC Na-ion pouch cell. Given the focus of this study on the direct current (DC) material costs, we have excluded costs associated

with the Power Conversion System (PCS), switchgear, contactors, breakers, and containerization, while battery management system (BMS), manufacturing costs for the DC battery energy storage system (BESS) including cell, module and rack manufacture, along with purchased items for cells, modules and racks have been retained in the estimation of the cost for selected systems at various durations¹.

Cell design input parameters

The adapted model is configured using experimental data obtained in FY 23 Q2 from the 20 cm² single layer pouch cell. The cathode comprises an active material-carbon-binder weight ratio of 85:8:7, whereas the corresponding anode ratio is 95:2:3. A negative-to-positive capacity ratio of 1 is assumed in the model.

In the laboratory, a capacity loss of ~31% during formation was observed, resulting in specific capacities of the cathode and anode of 92 mAh/g and 195 mAh/g respectively. The estimated costs for this case is referred to as the “near term” cost. Note that with suitable modifications to cell formulation such as pre-sodiation of the cathode/anode, a pathway to limiting formation capacity loss to 5% capacity could be achieved. The estimated cost based on this lower loss is referred to as the “optimistic” cost. This corresponds to cathode specific capacity of 126 mAh/g and anode specific capacity of 267 mAh/g.

With respect to material densities, we incorporate values from two distinct studies. The cathode active material exhibits a density of 4.15 g/cm³,⁴¹ aligning with typical layered oxide densities. For the anode's hard carbon active material, a density of 1.5 g/cm³ is used.⁴² Densities

¹ A list of retained cost categories along with key components in each category is presented later in this report.

corresponding to the binder and carbon additives have been maintained at BatPaC's default parameters.

BatPaC's underlying performance model utilizes an Open Circuit Voltage (OCV) curve, an SOC-dependent area-specific resistance, and an exchange current density related to the kinetics. Our initial model incorporates the Na85MNF-HC 20 cm² pouch cell voltage curves from C/10 rate cycling data (Figure 1). For area-specific resistance (ASR) estimation purposes, it is assumed that the voltage profile is unchanged when cycled at C/2 rate for an optimized cell design.

The OCV is determined as the value halfway between the charge and discharge voltage at a specific SOC, while the ASR is established from the ΔV between charge and discharge. The OCV and ASR are input as a function of SOC into BatPaC. Since activation polarization related to charge transfer is incorporated in the ASR, the exchange current density at each electrode is assigned a high value so that the corresponding overpotential is zeroed out, resulting in a linear voltage model. This forms the basis for our preliminary cost/performance model. Table 1 provides a summary of cell design input.

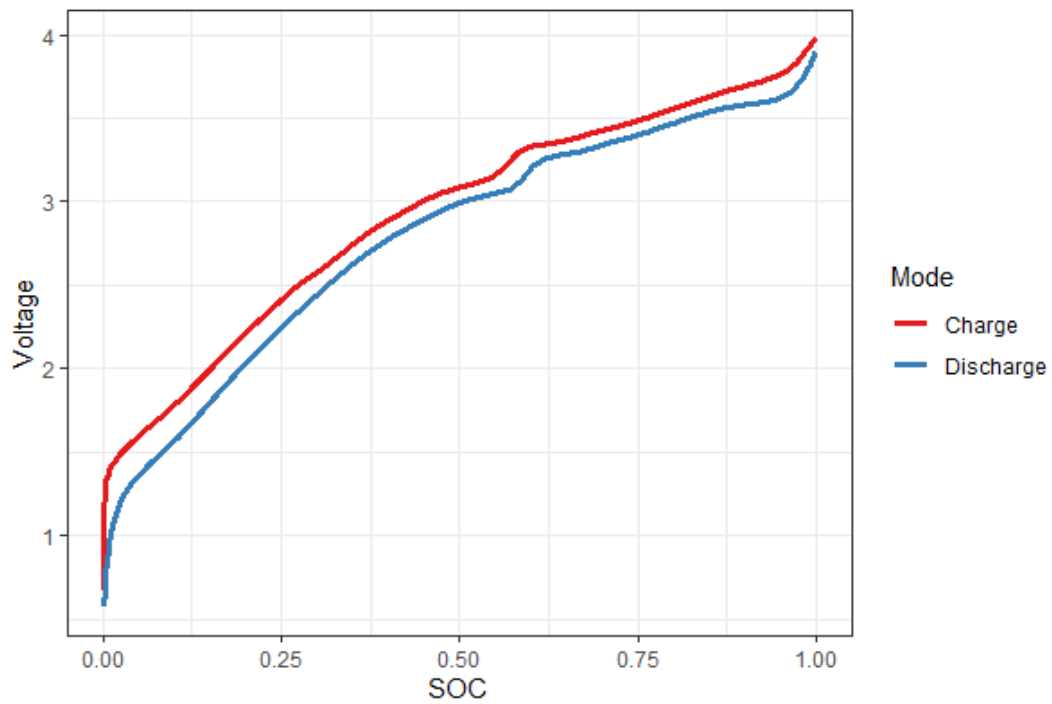


Figure 1. Voltage profile during charge and discharge at the C/10 rate using data from Figure 6 of FY 23 Q2 report.

Table 1. Cell Design Inputs

Physical Quantity	Value	Units	Notes
N/P capacity ratio post formation	1	1	
Upper cutoff SOC	95	%	
Lower cutoff SOC	10	%	
Positive active material specific capacity	126/92	mAh/g	Related to optimistic and near-term formation losses, respectively
Positive foil thickness	15	μm	Aluminum foil
Positive electrode active material/carbon additive/binder weight fraction	85/8/7	%	
Positive electrode active material density	4.15	g/cm^3	Room for increase in packing density with optimized material synthesis and scale-up
Positive electrode carbon additive density	1.83	g/cm^3	BatPaC default
Positive electrode binder density	1.77	g/cm^3	BatPaC default
Positive electrode porosity	25	%	BatPaC default
Negative active material specific capacity	267/195	mAh/g	Related to optimistic and near-term formation losses, respectively
Negative foil thickness	10	μm	Aluminum foil
Negative electrode active material/carbon additive/binder weight fraction	95/2/3	%	
Negative electrode active material density	1.5	g/cm^3	Room for increase in packing density with optimized hard carbon synthesis
Negative electrode carbon additive density	1.95	g/cm^3	BatPaC default
Negative electrode binder density	1.1	g/cm^3	BatPaC default
Negative electrode porosity	25	%	BatPaC default
Separator thickness	15	μm	BatPaC default
Separator porosity	50	%	BatPaC default
Separator density	0.47	g/cm^3	BatPaC default
Electrolyte density	1.2	g/cm^3	BatPaC default

Cell material cost

For evaluating material costs, the costs for active materials in both cathode and anode have been replaced, with the remaining carbon additive and binder costs retained as BatPaC's default parameters. For the cathode, we adopted a regression-based cost per kg from values provided for a variety of layered oxide cathode materials for Na-ion batteries.⁴¹ Applying a linear model to estimate the cost based on the weight fraction of each material, we estimated a projected cost

for Na85MNF as 6.5 \$/kg, in line with similar materials in the table, and with cost for sodium manganese oxide (NMO) cathodes.⁴³ The nickel component significantly drives this cost, and our regression model predicts a lower cost associated with a reduced nickel composition, aligning with other similar materials in the table. Note that replacement of lithium with sodium is expected to reduce cathode cost by 3.4 \$/kWh,⁴³ related to an order of magnitude lower cost for the source material sodium carbonate compared to lithium carbonate.

The hard carbon anode's price was sourced from a 2022 hard carbon market analysis,⁴⁴ giving an average price of 30 \$/kg, with potential to decrease to 4 \$/kg at higher volumes. Note that this cost of 30 \$/kg is a conservative estimate, with a lower cost of 15 \$/kg assumed in other work.⁴³ The 30 \$/kg results in hard carbon contributing to a major percentage of the cell's cost, with significant potential for cost reduction.

While sodium-based cathodes are lower cost compared to their lithium based counterparts, due to lower amount of lithium (or sodium) present in the electrolyte, the electrolyte cost is reduced by an insignificant amount of 0.2 \$/kWh.⁴³ Hence, in this work, the electrolyte cost used was the same as that for a Li-ion battery electrolyte. Table 2 provides the cell component cost inputs to the model.

Table 2: Cell Component Cost inputs

Quantity	Value	Units	Notes
Cost of active material for positive electrode, \$/kg	6.5	\$/kg	Regressed from list of Na-Ion layered oxide cathodes
Cost of carbon additive for positive electrode, \$/kg	7	\$/kg	BatPaC default
Cost of binder for positive electrode \$/kg	15	\$/kg	BatPaC default
Cost of solvent of positive electrode \$/kg	2.7	\$/kg	BatPaC default
Cost of active material for negative electrode, \$/kg	30	\$/kg	Average cost from market analysis, floor of 0.4 \$/kg
Cost of carbon additive for negative electrode, \$/kg	7	\$/kg	BatPaC default
Cost of binder for negative electrode \$/kg	10	\$/kg	BatPaC default
Cost of solvent of negative electrode \$/kg	0	\$/kg	BatPaC default
Positive current collector foil, \$/m ²	0.2	\$/m ²	Aluminum
Negative current collector foil, \$/m ²	0.2	\$/m ²	Aluminum
Separators, \$/m ²	0.9	\$/m ²	BatPaC default
Electrolyte, \$/L	8.1	\$/L	BatPaC default

Cost categories in BatPac used in this work

This section provides key cost components in each category used in this work. As discussed, power conversion systems, switchgear, contactor, circuit breaker costs have not been considered. Furthermore, the profit margin was set to zero.

I. Cell materials:

- Positive active material, binder, carbon black
- Negative active material, binder, carbon black
- Electrolyte
- Separator
- Positive and negative current collectors

II. Purchased items

Cells

- Cell terminals
- Cell casing

III. Modules

- Module management system
- Cell interconnects and interconnect panel
- Module terminals

- Module enclosure
- Gas release provision

IV. Battery Rack

- Rack Material
- Module interconnects
- Elastomer pads between modules
- Bus bar for battery
- Rack terminals
- Thermal management system

V. Manufacturing costs comprise of the following:

- Electrode materials processing, preparation, and mixing
- Electrode coating
- Calendaring
- Vacuum drying of electrodes
- Dry room cell assembly - Electrode slitting, Cell stacking, Current collector welding, X-ray cell inspection, Cell insertion in container, Electrolyte filling, Formation cycling, Module assembly, Rack Assembly, Shipping & Receiving, Building & Supporting Systems

Design inputs

The framework for the design of the grid scale battery system architecture was obtained from the recently deployed 1 MW, 4 MWh Li-ion battery energy storage system (BESS) at Horn Rapids in Eastern Washington⁴⁵. The Horn Rapids DC BESS consists of 34 cells in series per module, with 10 modules in series per rack and 18 racks operating in parallel. This was used as the basis for sizing the system, with 222 kWh energy stored per rack. Table 3 provides the design parameters for the DC BESS.

Table 3: Battery Design inputs for the DC BESS

Quantity	Value	Units	Notes
Energy per rack	222	kWh	Horn Rapids design
Number of cells in series per module	10	1	Horn Rapids design
Number of cells in parallel per module	1	1	Horn Rapids design
Number of modules in series per rack	34	1	Horn Rapids design
Number of modules in parallel per rack	1	1	Horn Rapids design

Results

We analyzed costs for a near-term case based on Ah-capacity loss of 31% during formation and an optimistic case using a capacity loss of 5%. As the cost is very sensitive to the active material's specific capacity, this is an important comparison. Our cost analysis results in cell materials cost of 132 and 99 \$/kWh for the near term and optimistic cases respectively for 1-100 MW, 1–10-hour systems. When including the additional costs associated with Battery Management System (BMS), manufacturing and purchased items, the DC BESS costs are 166 and 133 \$/kWh respectively. The cost breakdown by component is given in Figure 2. Note that when the analysis is repeated with the ASR determined using C/10 rate cycling, the hard carbon cost needs to drop to \$27/kg to meet the \$100/kWh target for the optimistic case.

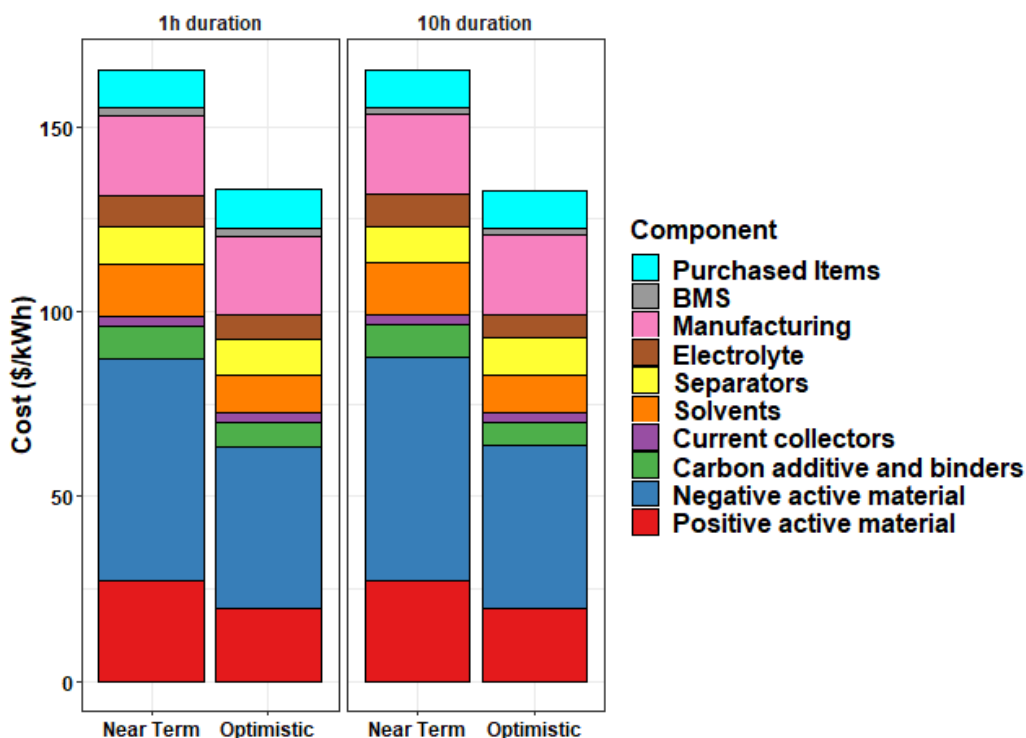


Figure 2. Total Cost and Cost Breakdown for 1-100 MW, 1-hour and 10-hour Systems.

The hard carbon negative active material significantly contributes to the total cell cost at \$44/kWh for the optimistic case. This finding is especially important considering the substantial potential for cost reduction in this area. The reference for our hard carbon price had a floor of 4 \$/kg, which would significantly reduce the overall cost per kWh of the Na-ion system by 38 \$/kWh.

Manufacturing-related expenses are the second highest, at 21 \$/kWh for the optimistic case, highlighting the importance of process optimization in minimizing manufacturing costs. As noted later, cell design has a significant impact on cell, module and rack manufacturing costs, thus offering additional opportunities to reduce manufacturing costs.

While the price per unit weight for the cathode is nearly 5 times lower than that for anode, its specific capacity is slightly less than half of that for the anode. Due to the low specific capacity, the positive active material is the third most expensive component, at \$20/kWh for the optimistic case.

Solvents, separators and electrolyte cost \$29/kWh, offering additional opportunities for cost reduction. Optimization of electrode loading is expected to reduce the area of electrodes (and separators) per kWh, reducing separator costs and lowering contribution from other passive elements in the cell. This will also lower manufacturing costs, since the number of modules and racks will be lower for a fixed energy content as cell Ah capacity increases. The team will explore alternatives to expensive solvents during electrode processing and continue its research on electrolytes to improve performance and lower cost.

Our cost analysis showed no significant dependence of costs on the BESS duration (energy-to-power ratio). This is most likely because BatPaC is developed for, hybrid, plug-in and electric vehicle batteries; hence the rated power is assumed to be the power sustained over a 10-second pulse, with the electrode loading adjusted to deliver this pulse power. Since the 1 to 10-hour grid scale energy storage durations considered in this work are much greater than 10 seconds, the BatPac model is not able to adequately differentiate among these durations. It should be noted that the electrode loading set by the model was 3.3 mAh/cm², about the same as the loading of our 20 cm² cells, leaving room for increased loading as duration increases. Furthermore, scaling advantages at different power levels are not reflected in the model.

This analysis serves as a preliminary investigation into the cost structure of a Na-ion system. Our current findings provide a baseline for future work aimed at developing a more robust cost-performance model taking into account the effect of cell electrode design and architecture on performance & cost for systems of various durations, while incorporating scaling for costs related to various power levels. The potential for cost reduction, especially of hard carbon negative active material, is a promising avenue for further research and development. For our future work, a Li-ion performance model developed by this group along with other collaborators will be leveraged upon to optimize loading levels and electrode architecture (and hence the ASR) for various durations to minimize passive component contribution to cell and system cost.³⁷ Such a model would integrate the performance characteristics of the Na-ion system more effectively, thus providing a more realistic cost model that includes the influence of the energy-to-power ratio (or duration) and scaling related to power levels on the cost.

Future work.

Some potential opportunities to improve performance and lower costs are listed below:

- Perform a detailed bottom-up analysis on hard carbon cost taking into account the lower processing temperature and the wide availability of biowaste/bioprocess-based precursors.
- Improve the hard carbon specific capacity, cycle life, as well as 1st cycle and cycling Coulombic efficiency to lower the cost.
- Lower the nickel content of cathode material to further reduce cost
- Continue development of electrolyte that enables improved performance and lower cost.
- Optimize electrode loading and architecture at various durations to lower
 - Separator, current collector costs at the cell level

- Purchased items cost at the cell, module and rack levels
- Manufacturing costs
- Explore eliminating solvent use for electrode fabrication, leveraging upon latest developments in the Li-ion space.

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