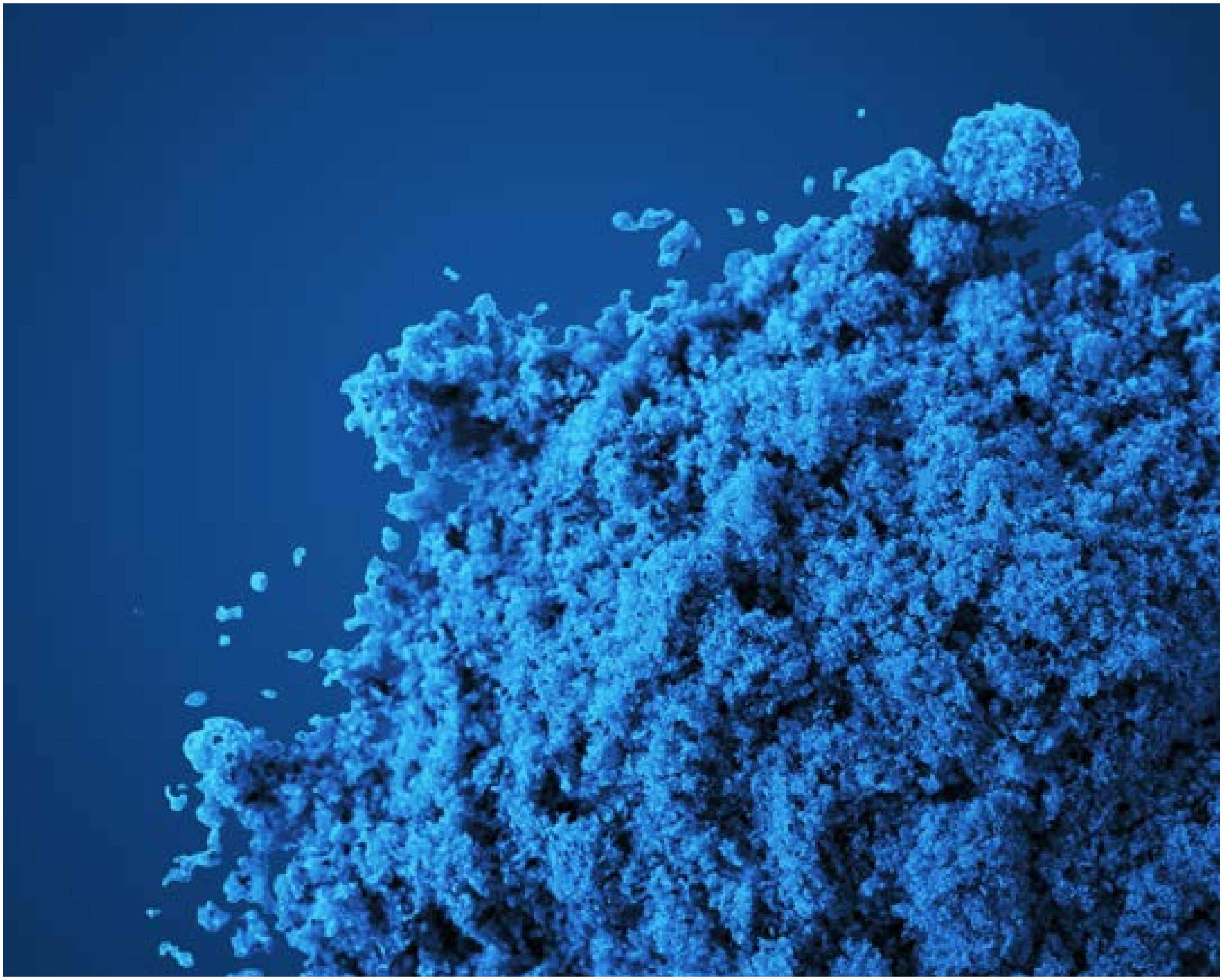
Natron Energy

Prussian Blue Sodium-Ion Batteries

Cell Theory of Operation



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Introduction

An increasing number of decarbonization initiatives require advanced battery energy storage technologies. For instance, in the United States major legislation, such as the Inflation Reduction Act of 2022, stress the importance of decarbonizing and mandate the transition to more sustainable power options.[1] The United States Bureau of Labor Statistics reports a forecasted 40-50% electric vehicle adoption rate by 2030 as the United States works to meet decarbonization goals.[2] Energy storage is required both for those vehicles and for the electric grid and industrial power infrastructure required to manufacture and operate them. Similar decarbonization initiatives have been implemented in other countries and regions.

The two leading commercial battery technologies, lithium-ion and lead acid, are limited by performance, safety, and supply chain challenges:

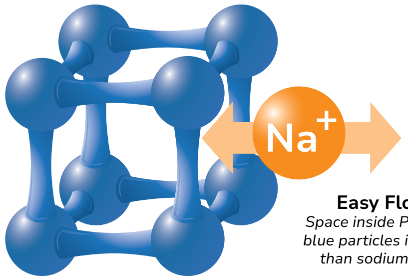
- Performance: Limited discharge and recharge capability, limited cycle life (see table below).
- Safety: Lithium-ion batteries are highly flammable and are associated with many recent high-profile fires. Lead acid batteries pose significant chemical hazards including the release of corrosives and heavy metals.[3]
- Supply chain: Lithium-ion batteries are manufactured from rare minerals including lithium, cobalt, nickel, and copper, which poses a significant challenge for establishing domestic/regional supply chains.[4]

New battery technology solutions that offer higher performance, enhanced safety, and the opportunity for robust, local supply chains are essential to meeting global demand and addressing the challenges ahead. Natron Energy's advanced sodium-ion battery technology is one of these solutions.

This white paper explains the chemistry behind Natron's Prussian blue-powered sodium-ion battery technology and how it differs from – and solves many of the problems inherent to – lithium-ion batteries.

Natron Battery Technology

Battery technology platforms containing sodium have been studied for over a century, and in the late 20th century the first sodium-based platforms were commercialized.[5] Early systems relied on sodium metal, which posed safety hazards during operation. More recently, a variety of sodium-ion technologies that contain no sodium metal and that do not pose a fire risk have been developed. Today, just as there are different "flavors" of lithium-ion batteries such as NMC and LFP, so too are there different flavors of sodium-ion batteries.

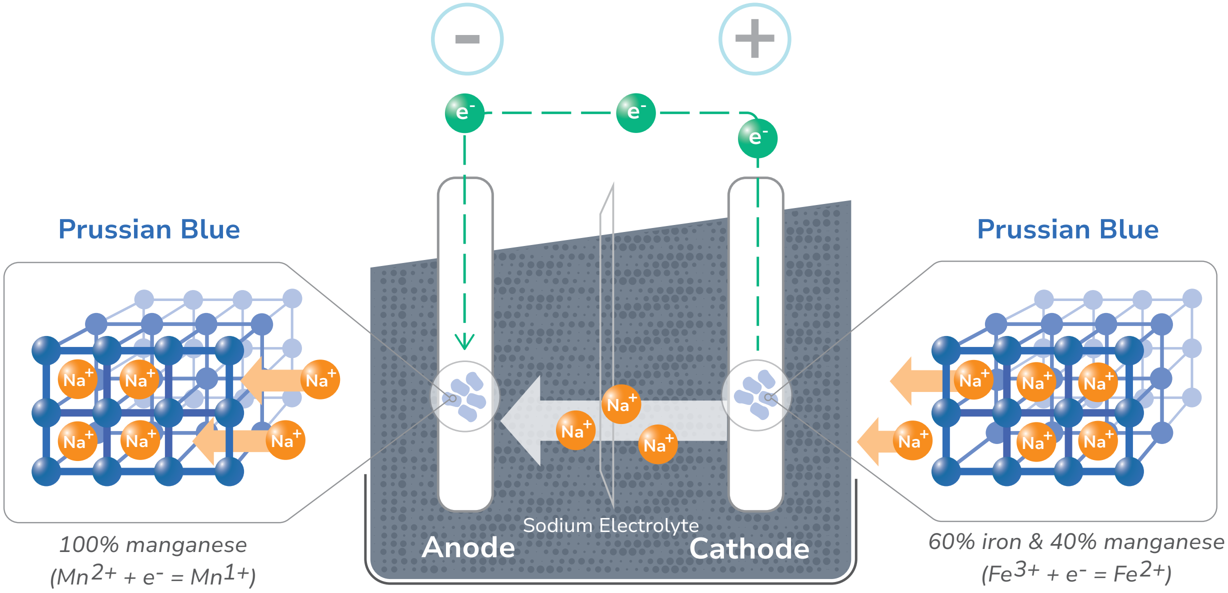


Easy Flow
Space inside Prussian blue particles is larger than sodium ions.

The particular materials platform found in Natron's battery technology is based on a family of electrodes known as Prussian blue. While produced and used commercially for pigments and dyestuffs for centuries, only in the past decade has Prussian blue emerged as a candidate for sodium-ion energy storage. The same advantages Prussian blue offers to the pigment industry, including chemical stability and non-toxicity, make it an attractive material for use in batteries.

Natron battery cells have the same architecture as traditional lithium-ion and lead acid batteries, including a positive electrode (cathode), a negative electrode (anode), a porous separator between the two electrodes, and a liquid electrolyte that enables charge (ions) to pass back and forth between the electrodes. All these cell components are packaged into a sealed container, with positive and negative terminals that allow the cell to be connected to an electric circuit. Natron's critical technology innovation is to use Prussian blue materials for sodium-ion energy storage in both the cathode and anode electrodes. Natron chose Prussian blue as its energy storage materials platform because of its unique atomic structure. The atoms in Prussian blue particles are arranged in large, cubic cages that contain empty spaces (pores) between them. These pores are larger than sodium ions, which allow the Prussian blue particles to rapidly absorb and release those ions through a process called "intercalation."

The presence of these large pores that enables fast intercalation makes Prussian blue different from conventional energy storage materials such as those found in lithium-ion and lead acid cells. For instance, the most common anode in a lithium-ion cell is graphite. The empty spaces between the carbon atoms in graphite particles are smaller than lithium ions. When those ions are inserted, the atoms move apart, causing the entire graphite particle to expand. When the lithium is removed from the graphite during discharge, the graphite particles shrink back to their original size. In contrast, the Prussian blue structure does not expand and contract as it charges and discharges sodium ions. This "zero strain" mechanism results in greater chemical stability and avoids the particle degradation that limits cycle life in other batteries.



Natron's Sodium Ion Cell
Charging Phase
(Discharge Phase - The flow would reverse)

At the device level, the result is that Natron's sodium-ion batteries avoid the limitations other technologies suffer in charge and discharge rates, cycle life, heat generation, and safety. For example, a Natron battery can be fully recharged from 0% to 100% state of charge (SOC) from 100% depth of discharge (DOD) in under 15 minutes, and no thermal settling or waiting period is required before the next discharge can begin. In essence, Natron has harnessed more advanced materials science to deliver better device performance.

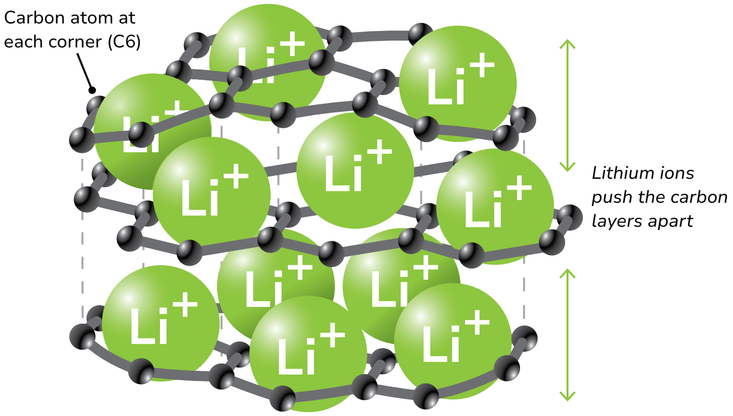
Among the various flavors of sodium-ion battery technologies, Natron's platform is unique because both the cathode and the anode are based on grades of Prussian blue. This is different from most sodium-ion and lithium-ion batteries, which use various grades of carbon in the anode. Natron's cathode-grade Prussian blue is based on a blend of iron (Fe) and manganese (Mn), which enables a high operating potential suitable for a cathode. Natron's anode-grade Prussian blue is based on pure manganese, which operates at low potential. The potential difference between the two electrodes is the cell voltage, and cells can be arranged in series to achieve higher system voltages as required. A critical benefit of Natron's selection of its cathode and anode Prussian blues is that only iron and manganese are used, so Natron's batteries do not face the same supply chain challenges as conventional lithium-ion cells or other sodium-ion technologies that require nickel and other expensive minerals.

Lithium-Ion Battery Technology

Lithium-ion cells have the same architecture as a Natron sodium-ion cell, including a cathode, an anode, a separator layer, an electrolyte, and outside packaging. During manufacturing, lithium-ion cells require an additional processing step, in which the cell is charged in a very specific way (formation) to stabilize the surface of the carbon anode with a solid electrolyte interphase (SEI). Natron's sodium-ion cells do not contain SEI layers on the electrodes, so the formation manufacturing step is not required. With this exception, the two technologies are used in cells of similar design, and which are manufactured using the same tools and processes. Similarly, their operation is essentially the same.

To illustrate the differences between sodium-ion and lithium-ion cells, it is worthwhile to consider the structure and charge storage mechanism in graphite, which is the most common carbon anode found in commercial lithium-ion cells. Within each graphite particle, carbon atoms are arranged in hexagonal sheets, or layers. During charging of the cell, lithium ions are inserted between the carbon layers. A challenge for the charging process is that the lithium ions are quite large in comparison to the distance between the carbon layers. The lithium ions do not easily fit between them.

Graphite Structure Detail



Graphite with lithium ions intercalated
("Lithiated" graphite or Graphite C6Li)

For this reason, during intercalation of lithium into graphite, the graphite particle must swell to accommodate the lithium ions. Conversely, when lithium is discharged back out of the graphite particle, it shrinks back to its initial size. This mechanical expansion and contraction (strain) to the entire particle and at the atomic level inevitably degrades the graphite and limits the cycle life of the cell. Furthermore, the process of straining the graphite particles generates heat, which requires external cooling. The strain and resistance to fast charging of graphite particles limits the maximum charging rate of lithium-ion cells and introduces the risk of lithium metal plating and dendrite growth during charging. Many lithium-ion fire incidents are attributable to lithium dendrites, and by extension, the fundamental materials science of graphite.[6]

Other Battery Chemistries

The table below compares Natron's sodium-ion batteries to other battery chemistries based on performance characteristics.

Chemistry	Time to full charge	Flammability	Number of deep charge cycles	Operating Temperature Range	Total Power per Energy (W/Wh)
Natron sodium-ion	**5-15 minutes with no thermal waiting or settling required**	**Nonflammable per UL9540A with published, unredacted test results**	**50,000**	**-20°C to +50 °C**	**40/1**
Lithium-ion	2-4 hours	Extremely flammable	2,000	0°C to 40°C	10/1
Lead-acid	8-12 hours	Somewhat flammable but hazardous electrolyte leak possible	< 1,000	22°C to 30°C	7/1
Nickel Zinc	5 hours	Nonflammable	500	20°C to 35°C	11/1

Conclusion

Sodium-ion battery technology is more sustainable and more efficient than lithium-ion batteries when used for fast-discharge, fast-recharge applications such as data center uninterruptable power supply (UPS) systems, peak load shaving systems, grid stability systems, power factor correction, industrial power applications, and electric vehicle (EV) recharging stations.

Using Natron's patented Prussian blue chemistry, sodium-ion batteries demonstrate clear advantages over traditional lithium-ion battery technology – in addition to providing a safer, more powerful, sustainable battery solution.

For more information or with any questions, visit natron.energy.

References

[1] Inflation Reduction Act of 2022

[2] https://www.bls.gov/opub/btn/volume-12/charging-into-the-future-the-transition-to-electric-vehicles.htm

[3] A recent example was a major data center fire in South Korea, https://www.datacenterknowledge.com/business/data-center-fire-triggers-lithium-ion-battery-doubts-south-korea

[4] https://www.bloomberg.com/news/features/2022-05-25/lithium-the-hunt-for-the-wonder-metal-fueling-evs#xj4y7vzkg **and** https://www.business-humanrights.org/en/from-us/briefings/transition-minerals-sector-case-studies/human-rights-in-the-mineral-supply-chains-of-electric-vehicles/

[5] https://borates.today/sodium-ion-battery/

[6] https://theconversation.com/lithium-ion-battery-fires-are-a-growing-public-safety-concern-heres-how-to-reduce-the-risk-209359