The Emergence of Sodium-Ion (Na-Ion) Batteries

By John Benson

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1. Introduction

It was February 23, when I discovered my latest Issue of Science contained an excellent article on the title-subject of this paper, and I was two-days away from posting a paper, "Next-Gen Rechargeable Battery Designs," a much broader subject, but one that included this title subject. I made a sensible decision, post "Next-Gen…" as planned, and continue with a paper for Early-April that focused on the title subject of this paper. I had been working on the earlier paper for several months, and its primary reference was almost a year old, and a year is an eternity in the development of leading-edge components like a new generation of rechargeable batteries. The primary source for this paper is referenced here.[1]

Lithium-ion batteries are ubiquitous, not just in earbuds, phones, and cars, but also in massive facilities that store renewable energy for when the Sun doesn't shine or the wind dies down. But lithium itself is relatively scarce and available from just a few countries. A world that runs on renewable energy would need 200 times more battery capacity than exists today—and that probably means a different kind of battery. "I don't know if we can get there with just lithium-ion," says Y. Shirley Meng, a battery chemist at the University of Chicago.

A decades-old technology may be rising to the challenge: batteries that use sodium rather than lithium ions to carry and store charge. Sodium is everywhere, in seawater and salt mines, so supply and cost aren't problems. But the metal isn't as good at storing charge as lithium because its ions are three times bigger, hampering their ability to slip in and out of existing battery electrodes. Labs worldwide are developing new electrode materials to address that shortcoming, and in the past 6 months, several groups have announced sodium batteries that hold as much energy as low-end lithium cells. "The progress has been amazing," says Dan Steingart, a battery chemist at Columbia University. Meanwhile, commercial sodium-ion batteries are starting to roll off the assembly lines for electric vehicles, scooters, and grid power storage.

2. Transition Issues

Researchers caution that sodium batteries are not ready for widespread deployment. "We're not there yet," says Jean-Marie Tarascon, a solid-state chemist at the College of France. The batteries are still far from matching the performance of the best lithium-ion cells. And the economic incentive for a shift is lacking for now: Lithium shortages remain only a theoretical concern, and the price of the metal actually dropped 70% in the past 3-years because of an oversupply.

[1] Robert F. Service, Feb 21 Issue of Science Magazine, "Sodium batteries power up," https://www.science.org/doi/epdf/10.1126/science.adw8627

Like lithium batteries, those based on sodium work by passing positively charged ions between a pair of electrodes separated by an ion-conducting electrolyte. During charging, electrons are fed to the negatively charged anode, attracting metal ions to flow through the electrolyte from the positively charged cathode. During discharge, electrons are drawn out of the battery, causing the ions to travel back from anode to cathode.

Because sodium ions are larger than lithium ions, fewer of them can squeeze into the anode to store charge. The need for larger cells to hold the same amount of power adds cost and bulk. Sodium batteries have struggled to reach even half the storage capacity of the best lithium batteries, which hold more than 300 watt-hours of energy per kilogram (Wh/kg). But Gui-Liang Xu, a battery chemist at Argonne National Laboratory, says, "There are multiple avenues to go down" to address the challenge.

3. Current Status

One path is changing the composition of the anode. Most lithium-ion cells use graphite, a form of carbon whose tightly layered structure tends to exclude sodium ions. Many researchers have turned to an alternative form of carbon, called hard carbon, made up of a jumble of carbon particles that leaves pores into which sodium ions can wiggle.

Unfortunately, all those pores also reduce an anode's energy-storing volume. But researchers have found that adding tin to the anode can help. When stabilized on a carbon support, each tin atom can bind up to 3.75 sodium ions, boosting an anode's ability to hold sodium, and thus energy. For example, batteries developed at the San Diego–based startup UNIGRID[2] hold 170 Wh/kg. Although this remains less than the 200 Wh/kg of a low-end lithium battery, "it looks very exciting," says Yan Yao, a sodium-ion battery expert at the University of Houston.

Another improvement comes from tweaking the composition of the positively charged cathode, typically made of metal oxides, for better sodium storage and flow. One of the most popular new materials is a mixture of sodium, vanadium, phosphorus, and oxygen (NaVPO), which tends to form a layered structure that allows sodium atoms to readily enter and exit. For now, NaVPO's energy density is moderate compared with that of cathodes in lithium cells. But researchers led by Pieremanuele Canepa, a chemist at the University of Houston, recently used computer modeling and x-ray diffraction to identify a promising tweak to NaVPO's crystalline structure. In a reported posted online on 23 October 2024 in Nature Materials, Canepa and his colleagues reported not only synthesizing the new material, but incorporating it into a sodium-ion battery cathode that could hold 15% more energy than previous NaVPO designs.

A more radical approach is to make cathodes out of organic compounds, which can also form layered structures able to hold and release sodium ions. Many organics decompose in the presence of a battery's electrolytes, but in the 5 February issue of the Journal of the American Chemical Society, researchers led by Mircea Dincă at the Massachusetts Institute of Technology reported creating a more durable layered organic cathode, called TAQ. The material not only proved stable for thousands of charge and discharge cycles, but TAQ's energy density was among the highest of any sodium-ion cathodes ever made. Canepa calls it "a beautiful piece of chemistry."

[2] https://unigridbattery.com/

As a result of these and other advances, "Industry's interest is really high right now," says Laurence Croguennec, a chemist and managing director of the Institute of Condensed Matter Chemistry of Bordeaux. In November 2024, CATL, the world's largest battery-maker in China, unveiled its second-generation sodium-ion battery, which it claims holds 200 Wh/kg, up from 160 Wh/kg in its first-generation cells. Meanwhile, BYD, one of CATL's rivals, says it is building a factory to produce 30 gigawatt-hours' worth of sodium-ion batteries per year by 2027, in part for renewable-energy storage. At least a half-dozen other startups around the world are also jumping in with their own tweaks to battery chemistry.

Author's comment: There are two major markets for both lithium-ion and sodium-ion (NA-Ion) batteries: EVs and grid-storage. Although there are some segments of the EV-market that are less weight (mass) sensitive than others, the largest EV segments are highly sensitive to battery weight and volume. Most segments of grid-storage are much less weight and volume sensitive, including "…renewable energy storage…" as mentioned above. Furthermore, the renewable energy storage segment is growing rapidly due to the need to mitigate intermittency, and thus is a primary target for Na-Ion batteries.

Still, many battery experts remain both cautious about sodium's future and skeptical of some company announcements. "There's a lack of transparency" about the details of battery design and performance, says UNIGRID CEO Darren Tan.

4. Challenges

The hurdles aren't just technical. For now, the current low cost of lithium undercuts sodium's chief selling point, Steingart[3] says. Na-Ion battery manufacturers also remain too small to benefit from economies of scale. In November 2024, such challenges upended one of the field's pioneers when the Swedish Na-Ion battery firm Northvolt filed for bankruptcy.

Politics is another wild card. When U.S. President Donald Trump swept into office last month, he immediately announced a halt to federal support for wind and solar power projects, a step that could shelve plans to deploy large-scale backup battery systems. (In a move that perhaps cuts the other way, in January China announced new export restrictions on graphite, a key component of lithium-ion batteries, in response to new 10% tariffs on Chinese goods announced by the Trump administration.)[4]

But William Chueh, a materials scientist at Stanford University, says it's technological advances that will decide how cost-effective Na-Ion batteries become. Steingart believes those advances are coming. When it comes to understanding the basic chemistry of Na-Ion batteries, he says, "we're still in the early days."

[3] Dan Steingart, a battery chemist at Columbia University. Also quoted on page 1 of this paper.

[4] China also hosts the world's largest known natural graphite reserves at 81 million metric tons (MT). Brazil, Mozambique, Madagascar and Tanzania round out the top five largest graphite reserves by country, and also rank among the top 10 graphite producers.

5. Advances to Date

Author's comment: The good news is that I found a large paper by a prestigious team (William Chueh, quoted in the above paragraph, led this team). The problem was that this paper mainly focused on the details of, and techniques used for the study, not the results or conclusions, also it was quoted by a bunch of other professionals, leading to a reference-jungle that took me some time to hack through and find another recent source that I <u>could</u> use (below).

Na-Ion batteries for electric vehicles and energy storage are moving toward the mainstream. Wider use of these batteries could lead to lower costs, less fire risk, and less need for lithium, cobalt, and nickel.[5]

On November 18, CATL, the world's largest battery manufacturer, announced its second-generation Na-Ion battery, mass production of which would begin in 2027. The China-based company said the new battery has an energy density of 200 watt-hours per kilogram, which is an increase from 160 watt-hours per kilogram for the previous generation that launched in 2021. Higher energy density in an EV battery translates into more driving range.

CATL's first-generation Na-Ion battery. Credit: CATL

On Nov. 21, a consortium of seven US national laboratories announced a new initiative in which they would spend $50 million to foster collaboration to accelerate the development of Na-Ion batteries. The partnership is led by Argonne National Laboratory in the Chicago area.

The two announcements are part of a larger shift as governments, researchers, and companies look for alternatives to lithium-ion batteries, the dominant technology for EVs and energy storage.

[5] Dan Gearino, Inside Climate News, Ars Technica, "Lower-cost sodium-ion batteries are finally having their moment," Dec 6, 2024, https://arstechnica.com/cars/2024/12/lower-cost-sodium-ion-batteries-are-finally-having-their-moment/

For now, there are no passenger cars or trucks sold in the United States that use Na-Ion batteries. Some Na-Ion models are available in China and countries that import vehicles from China.

"The reason we're pursuing this is very simple," said Venkat Srinivasan, a battery scientist at Argonne and the director of the new collaboration. "It's because the huge demand in lithium-ion batteries has meant that we have a supply-chain constraint.

"We have a problem with cobalt. We have a problem with nickel," he said, naming two of the metals often used in lithium-ion batteries.

Cobalt, nickel, and lithium carry a variety of concerns, including the environmental damage of mining. Also, much of the supply is controlled by US geopolitical rivals such as China, and some of the mining takes place in countries with inadequate labor standards.

In contrast, a Na-Ion battery relies on an element—sodium—that you can find in table salt and ocean water.

Among the other benefits, Na-Ion batteries perform better than lithium-ion batteries in extreme cold. CATL has said its new battery works in temperatures as low as -40° Fahrenheit.

Also, a Na-Ion battery has much lower risk of fire. When lithium-ion batteries sustain damage, it can lead to "thermal runaway," which triggers a dangerous and toxic fire.

The process of manufacturing Na-Ion batteries is similar to that of lithium-ion batteries, or at least similar enough that companies can shift existing assembly lines without having to spend heavily on retooling.

But Na-Ion batteries have some disadvantages. The big one is low energy density compared to lithium-ion. As a result, an EV running on a Na-Ion battery will go fewer miles per charge than a lithium-ion battery of the same size.

Author's comment: As I pointed out above, I believe that grid-storage will be the primary market for Na-Ion batteries, at least initially. This has a more predictable charge/discharge cycle than EVs, allowing their design to be optimized for this cycle.

"That is just what nature has given us," Srinivasan[6] said. "From a physics perspective, sodium batteries inherently have lower energy density than lithium batteries."

A typical Na-Ion battery has an energy density of about 150 watt-hours per kilogram at the cell level, he said. Lithium-ion batteries can range from about 180 to nearly 300 watt-hours per kilogram.

[6] Venkat Srinivasan, a battery scientist at Argonne, also quoted at the top of this page.

I asked Srinivasan what he makes of CATL's claim of a Na-Ion battery with 200 watt-hours per kilogram. "We tend to be skeptical of news releases from companies," he said. He specified that his comment applies to all battery companies.

The national labs' initiative has a five-year timeline, with a goal of developing Na-Ion batteries with energy densities that match or exceed those of today's iron phosphate-based lithium-ion batteries. Researchers would do this by finding various efficiencies in design and materials.

The project is happening alongside the labs' ongoing work to develop and improve other kinds of batteries.

Lithium-ion batteries dominate today's market. This year, global production of lithium-ion batteries was about 1,500 gigawatt-hours, and production of Na-Ion batteries was 11 gigawatt-hours, or less than 1 percent, according to Benchmark Mineral Intelligence.

However, Na-Ion battery production is growing and is projected to reach 140 gigawatt-hours by 2030, about 13 times its current level, according to Benchmark. Lithium-ion production also is projected to nearly triple by 2030.

"The key market driver for Na-Ion batteries is their potential to be cost competitive with lithium-ion batteries," said Catherine Peake, an analyst for Benchmark.

But cost competitiveness is a challenge right now because lithium prices are unusually low. The global supply of lithium has grown more quickly than demand since 2022, leading to lower prices.

Researchers and analysts expect that Na-Ion batteries will have a cost advantage over lithium-ion in the long run. McKinsey and Co. said last year that Na-Ion batteries have the potential to be 20 percent less costly than lithium-ion batteries. (Srinivasan agreed that 20 percent savings is plausible.)

Final author's comment: The main feature that might bootstrap Na-Ion batteries into the grid storage market sooner rather than later is their increased fire-safety given headline-grabbing news like the recent Moss Landing Battery-Fires in Monterey County, California.[7]

[7] https://www.cbsnews.com/sanfrancisco/news/monterey-county-sheriff-issues-evacuation-orders-due-to-moss-landing-power-plant-fire/