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Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage

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Sodium-ion batteries are an emerging battery technology with promising cost, safety, sustainability and performance advantages over current commercialised lithium-ion batteries. Key advantages include the use of widely available and inexpensive raw materials and a rapidly scalable technology based around existing lithium-ion production methods. These properties make sodium-ion batteries especially important in meeting global demand for carbon-neutral energy storage solutions.

Introduction

With an increasing need to integrate intermittent and unpredictable renewables, the electricity supply sector has a pressing need for inexpensive energy storage. There is also rapidly growing demand for behind-the-meter (at home or work) energy storage systems. Sodium-ion batteries (NIBs) are attractive prospects for stationary storage applications where lifetime operational cost, not weight or volume, is the overriding factor. Recent improvements in performance, particularly in energy density, mean NIBs are reaching the level necessary to justify the exploration of commercial scale-up.

Sodium-ion batteries offer the UK an opportunity to take a global market-leading role. By building on current advantages, the UK can establish a large-scale domestic manufacturing capability creating new jobs, as well as economic benefits across the wider supply chain.

NIBs are most likely to compete with existing lead-acid and lithium iron phosphate (LFP) batteries. However, before this can happen, developers must reduce cost by: (1) improving technical performance; (2) establishing supply chains; and (3) achieving economies of scale.

Due to an immature supply chain, NIB companies currently produce cells in relatively small batches. In contrast, manufacturers produce lithium-ion batteries (LIBs) in enormous numbers with significant economy-of-scale cost advantages. Even though NIBs offer meaningful material cost advantages, improvement in performance is needed. Enhanced battery energy density and cycle life, in particular, will greatly increase the commercial attractiveness of NIB technology, which is on the cusp of commercialisation.

NIBs have the same general operating principles as LIBs but use sodium ions in place of lithium ions. Both batteries shuttle ions between electrodes, storing them in the negative electrode when charged, and the positive electrode when discharged. This is not a trivial change; sodium ions are larger than lithium and have different reactivity. The challenge is to discover new functional materials and optimise their interactions to produce attractive batteries.

UK Research and Innovation

Benefits of Sodium-ion Batteries

(1) Cost and Sustainability

NIBs should become less expensive than LIBs as sodium's abundance and ubiquity ensures an economical and predictable supply of raw materials.[1,2] Sodium is the seventh most abundant element and 1,200 times more common than lithium.[3] Sodium compounds are synthesised from seawater and limestone, via established processes.[4] This means that there are no concerns about the scarcity of sodium, and likely to be many possible suppliers. In the future, a secure supply and a predictable price seem likely.

NIB cells also need no copper current collectors, which are a necessary and expensive component in many LIBs. NIB manufacturers replace dense and expensive copper with lighter aluminium, which reduces cost. In addition, NIBs do not use cobalt, a scarce and expensive metal used in high energy density LIBs. The majority of the world's cobalt supply comes from the Democratic Republic of Congo, where unregulated mining can cause social issues.[5]

The bill-of-materials for NIB could be 20-30% lower than for LFP LIBs once production and economies of scale reach similar levels.[6] Improving the energy storage, power and lifetime characteristics should further lower costs.

NIBs do not have the safety, environmental and ethical issues associated with lead-acid batteries and LIBs as illustrated in Table 1. For example, lead-acid batteries have high recycling rates but have the potential to leak lead. Key elements used in LIB production, such as lithium, nickel, and cobalt, are also geographically concentrated and the supply chain could experience bottlenecks and shortages in the long-term.

Table 1: Selected sustainability considerations for sodium-ion and competing battery technologies.

	Sodium-ion batteries	Lead-acid	Lithium-ion
Materials	Ubiquitous and abundant	Toxic	Expensive, geographically concentrated and under increasing pressure
Recycling	Limited recycling at present	High recycling rates	Limited recycling at present
Social costs	None	High cost to human health (where regulatory safeguards not followed)[7]	Social and environmental issues in cobalt mining
Safety	Can be shipped and stored in its zero energy state Excellent safety testing results	Risk of explosion due to hydrogen evolution Strongly acidic electrolyte	Must be partially charged when shipped

(2) Safety

NIBs offer safety advantages over LIBs, making them easier to transport and more attractive for safety-critical applications. Specifically, manufacturers can transport NIBs with the battery terminals directly connected and the voltage held at zero.[8] As the battery remains fully discharged, the risk of fire is significantly reduced and expensive safety mitigation measures are not necessary, reducing the cost of transportation.

In contrast, the copper current collectors of most LIBs start to dissolve at zero volts, so manufacturers have to transport LIBs in a partially charged state. The presence of this stored energy creates a safety risk while in transit. Moreover, if users do not treat LIBs with care, current collector dissolution can still occur and lead to performance degradation, internal short-circuiting, and even fire. These problems do not arise in NIBs.

Sodium-ion electrolytes also have a higher flash point (defined as the minimum temperature where a chemical can vaporise to form an ignitable mixture with the air) than conventional lithium-ion chemistries. Thus, sodium-ion electrolytes are less likely to ignite, further reducing the fire risk.

(3) Clear Route to Manufacturing at Scale

A significant barrier to the commercialisation of any new battery technology is the need to establish and scale-up novel manufacturing methods. Once researchers perfect a battery in the laboratory, extensive capital investment is needed by manufacturers to increase volume production and lower unit cost. Supply chains can also take time to develop and reach the scale required to drive down material costs.

While sodium-ion and lithium-ion active material compositions are different, they are synthesised and handled in similar ways, with the production process largely the same. Existing lithium-ion battery plants and cell formats can therefore be used to manufacture NIBs. Indeed, some manufacturers already make prototype NIBs in this way without displacing existing facilities.

The UK is a Technology Leader in Sodium-Ion Batteries

NIB technology offers the UK an opportunity to take a global market-leading role. By building on current advantages, the UK could establish a large-scale domestic manufacturing industry and associated supply chains. In comparison to LIBs, there are currently relatively few NIB patents, but the rate of filings is accelerating as innovation intensifies.[9]

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[1] Wanger TC. The lithium future—resources, recycling, and the environment. Conservation Letters 2011, **4**(3): 202-206.

[2] Kim S-W. et al. Electrode Materials for Rechargeable Sodium-Ion Batteries: Potential Alternatives to Current Lithium-Ion Batteries. Advanced Energy Materials 2012, **2**(7): 710-721.

[3] Abundance of Elements in the Earth's Crust and in the Sea, CRC Handbook of Chemistry and Physics, 97th edition (2016–2017), p. 14-17.

[4] The Solvay or ammonia-soda process is the commercial and industrial process for producing soda ash (sodium carbonate) from brine and limescale, which is used in products such as soap, textiles and glass.

[5] See Faraday Insight 7 (May 2020), Building a Responsible Cobalt Supply Chain for a more detailed discussion.

[6] Rudola, A. et al. Commercialisation of high energy density sodium-ion batteries: Faradion's journey and outlook. Journal of Materials Chemistry A, 2021, doi:10.1039/D1TA00376C.

[7] UN News (30 July 2020) Revealed: A third of world's children poisoned by lead, UNICEF analysis finds.

[8] Storage and/or transportation of sodium-ion cells, J. Barker and C.J. Wright, 17 Aug 2017, Pub. No.: US 2017 / 0237270 A1.

[9] Chayambuka, K. et al, Sodium-Ion Battery Materials and Electrochemical Properties Reviewed. Advanced Energy Materials 2018, 8.

The UK already has well-established firms in the field:

- Faradion Ltd (Sheffield) is the world-leader in non-aqueous NIB technology with a layered metal oxide technology. Faradion was amongst the first in the field and their technology is the most developed with 30 patent families.
- AMTE Power Ltd (Thurso) is a prominent LIB manufacturer, and licensee of Faradion's technology, planning NIB production.
- Deregallera Ltd (Caerphilly) is a leading materials development company focused on NIBs.

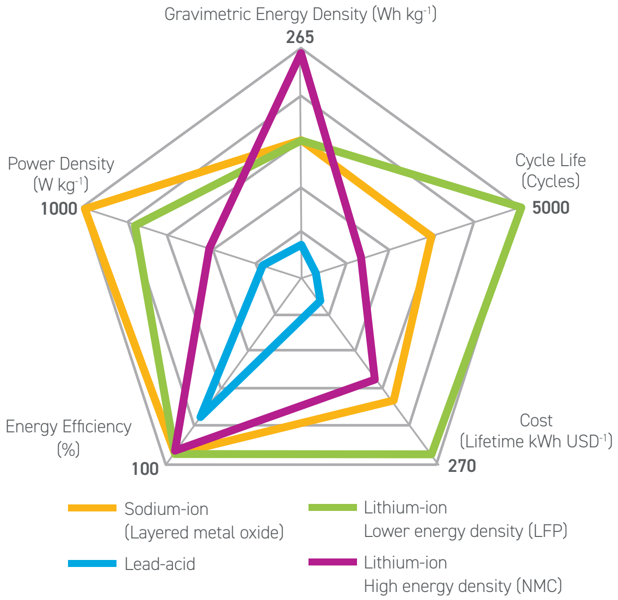
International competitors include HiNa Battery (China), Natron Inc (USA), TIAMAT (France) and Altris AB (Sweden).

The UK also boasts leading suppliers of materials and equipment. In mapping the chemicals supply chain for LIBs, the Advanced Propulsion Centre identified over 60 UK companies that were already supplying LIB manufacturers or could do so in the future.[10] The vast majority of these companies (e.g., manufacturers of electrode materials, additives, binders, metal salts, electrolytes, polymer films, solvents and metals foils) could also cater for sodium-ion manufacture. Coordinating the integration of the UK supply chain now, whilst sodium-ion technology is in its infancy, will accelerate progress to mass-manufacture ahead of the international competition, capturing maximum value for the economy.

Applications

NIBs currently offer characteristics well suited to applications where cost, sustainability, power density, temperature range and safety, rather than energy density, are of critical importance (Figure 1).

Figure 1: A comparison of selected figures-of-merit for sodium-ion and competing battery technologies[11,12,13]



Note: NIB costs based on production at scale.

Early Applications

NIB technology is becoming attractive where high power is advantageous (e.g., power tools) and in early-stage uninterruptible power supply (UPS) applications in the telecommunications sector. As the costs of ownership fall, NIBs are also building momentum in numerous stationary energy storage applications.

Near-term Applications

End-users have already begun trials in large markets including the replacement of diesel generators in regions where there is no electricity network or where the network is unreliable. Specific applications in these locations include community mini-grids and home solar systems. Diesel generators carry out this role currently, but users are increasingly supplementing or replacing them with batteries. Batteries are especially attractive where users operate diesel generators in conjunction with renewable generation such as solar panels.[14]

The replacement of diesel generators represents a significant financial and environmental opportunity. They have a lower upfront cost but higher ongoing costs than batteries, making them more expensive over time since they also require a secure supply of expensive fuel, which results in greenhouse gas emissions and air pollution.[15] Vivid Economics estimate the demand for weak and off-grid energy storage in developing countries will reach 720 GW by 2030, with up to 560 GW from a market replacing diesel generators.[16]

Utility-scale energy storage helps networks to provide high quality, reliable and renewable electricity. In 2017, 96% of the world's utility-scale energy storage came from pumped hydropower. However, the increasing global integration of variable renewable generation makes battery technology much more suitable for the task. IRENA[12] estimates growth in utility-scale battery storage from 10 GWh in 2017 to between 45 and 187 GWh by 2030. Load levelling is an example of a utility-scale application, which stores energy in periods of low demand and then releases energy when there is high demand. Prototype NIB batteries can already meet the technical requirements for load levelling, but further cost reduction is needed for the technology to compete.

The cost of ownership for NIBs promises to be less than lead-acid batteries. Although the upfront cost for lead-acid batteries is less (120 vs 225 $/kWh), NIBs have a high cycle life (300 vs 3,000 cycles) and round-trip-efficiency (75% vs 93%), and so can be charged more often and waste less energy. Faradion estimates that users need to replace their lead-acid batteries five times more often and overall NIBs are two-thirds the cost of lead-acid.[6]

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[10] Advanced Propulsion Centre Report (April 2019), Automotive batteries: A £4.8bn a year supply chain opportunity by 2030 for UK chemical and material companies.

[11] Bauer A et al. The Scale-up and Commercialization of Nonaqueous Na-Ion Battery Technologies. Advanced Energy Materials 2018, 8(17): 1702869.

[12] IRENA (October 2017), Electricity Storage and Renewables: Costs and Markets to 2030.

[13] Under preparation. NEXGENNA roadmap paper. Journal of Physics: Energy 2 (2020).

[14] This is likely to be a substantial market in developing countries. See Faraday Insight 3 (October 2019), Bringing Cheap, Clean and Reliable Energy to Developing Countries.

[15] IFC World Bank report (September 2019) The Dirty Footprint of the Broken Grid.

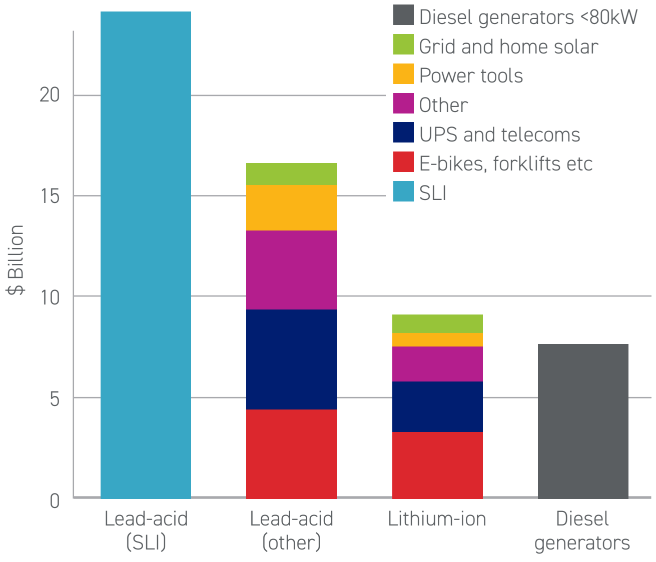
[16] Vivid Economics (October 2019) Rapid Market Assessment of Energy Storage in Weak and Off-grid Contexts of Developing Countries.

Future Applications

A substantial future market comes from the replacement of the lead-acid batteries used for starting-lighting-ignition (SLI) in car engines. SLI batteries are inexpensive and operate across a broad temperature range. NIBs are an excellent fit with the SLI application, outperforming lead-acid batteries by providing the specified power across the same temperature range but with lighter batteries. They also waste less energy, have a longer lifetime, and avoid toxic lead. The relatively high upfront cost and the need to realise economies of scale mean NIBs are unlikely to penetrate the SLI market within the next 5 years (Figure 2).

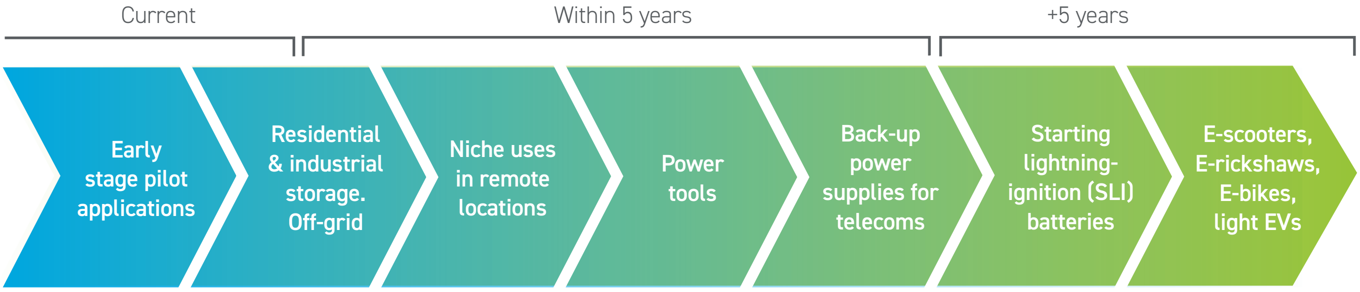
Recent advances have enabled the manufacture of NIBs with high energy density (~160 Wh/Kg). These are comparable with the lower cost end of the LIB market such as LFP batteries (~160 Wh/Kg). When economies of scale are sufficient to decrease costs to a similar price point, NIBs may be able to displace LIBs in low-cost markets such as auto-rickshaws, e-bikes and short-range or light electric vehicles.

Figure 3: Size of global markets in 2018 addressable by NIBs by incumbent technology[17,18]



Existing markets addressable by sodium-ion batteries.

Figure 2: Proposed timeline for the deployment of NIBs at scale in various markets



Market Size for Sodium-ion Batteries

Most early revenues are likely to arise from the disruption of markets where users desire an alternative to the incumbent LFP lithium-ion battery due to safety concerns, even if at a significant price premium. These early markets are small compared with the total addressable market for NIBs (Figure 3), but they will be key in establishing the manufacturing scale and supply chains needed for later high-volume applications.

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[17] Avicenne Energy (2020), Worldwide Rechargeable Battery Market 2019-2030.

[18] Grand View Research (July 2020) Diesel Generator Market Size, Share & Trends Analysis Report by Power Rating (Low Power, Medium Power, High Power), By Application, By Region, And Segment Forecasts, 2020 – 2027. In 2019, low power gensets (<80kW) account for 43.7% of a 17.5 Bn USD market.

[19] Hasa I et al. Challenges of today for Na-based batteries of the future: From materials to cell metrics. Journal of Power Sources 2021, 482: 228872.

Box 1: NEXGENNA and the Research Challenge

NEXGENNA is the Faraday Institution's flagship project to develop the **NEX**t **GEN**eration of **Na**-ion batteries. Led by the University of St Andrews it brings together the Universities of Cambridge, Lancaster, Sheffield, UCL, and the Science and Technology Facilities Council, with the UK's pre-eminent industry players. Its mission is to improve NIB energy storage, power, and lifetime while maintaining safety and cost advantages.

The performance of NIBs is already sufficient for key early markets. However, success is not certain and research challenges remain to reduce costs and drive commercialisation. Exchanging lithium for sodium is not straightforward. The unique physical and chemical properties of the two elements mean that the resulting materials have different characteristics. NEXGENNA's approach is to investigate and understand these differences to develop the best possible materials. The project has three research streams, each targeting a crucial research challenge:

(1) Electrode Material Design

Sodium metal oxides ($NaMO_2$, M = Ni, Mn, Fe) are the most promising of the NIB positive electrode materials. They are analogous to commercial lithium metal oxides ($LiMO_2$, M = Ni, Mn Co, Al). However, due to the larger size of the sodium ion, they adopt a greater variety of structures. NEXGENNA is investigating this rich structural chemistry to optimise energy, power or cost. A particular target is to minimise the use of expensive nickel.

Perhaps the best hope for early breakthroughs come from the negative electrode. LIBs typically use graphite as the negative electrode (capacity of ~370 mAh/g). Hard carbon (HC) has become the most popular choice for NIBs. However, HC demonstrates lower capacity (270-300 mAh/g) and greater first cycle losses (~22% vs ~8%) meaning that the cells are heavier. HC is poorly understood, with much debate about both its structure and the mechanism of sodium insertion. By understanding and improving HC to improve capacity and voltage there is scope to increase energy density and reduce cost.

(2) Organic Electrolytes and Electrode-Electrolyte Interfaces

The electrolyte is critically important largely because of its interface with the negative electrode. In LIBs, scientists have studied the interface in detail. It forms when the electrolyte decomposes and deposits a solid layer on the anode. The layer is crucial because it eventually thickens and slows decomposition without inhibiting ion transport. In NIBs, the decomposition products are less stable and so degradation continues, resulting in a diminished cycle life as the electrolyte degrades. NEXGENNA is exploring novel electrolytes and their electrode interfaces to improve cycle life, power and safety.

(3) Scale-up, Processing and Pouch Cell Demonstration

NEXGENNA is working closely with industry to scale NIBs. This will involve the synthesis of large quantities of new active materials, optimising the relationships between structure, processing and properties and testing combinations of new materials in industrially relevant battery formats.

Conclusion

NIBs share many of the strengths of LIBs. They have the same basic form and operating principles as LIBs, but they also offer substantial performance and cost advantages, with further improvements expected in the coming years.

Intense scientific investigation of sodium-ion technology is a relatively recent occurrence. Sodium-ion chemistry is comparatively unexplored, but due to their similarity and the ability to use the same manufacturing plants as LIBs, decades of experience can be harnessed.[6] There are relatively few patents in NIBs, but UK and international innovation is accelerating. There is now a window of opportunity to build a critical mass of intellectual property in the UK and create value and jobs for the UK economy.

NIBs still require focused research and significant innovation but, unlike many new technologies, there is no need for the development of new manufacturing processes to reach market. With safety, sustainability, power and cycle life advantages, NIBs are already on the cusp[19] of commercial application in large and growing markets. Coupling increased volumes with improvements in functional materials will see the widespread adoption of NIBs.

NIBs offer the UK an opportunity to take a market-leading role. The UK is already an established leader in the field and home to internationally important development companies. By building on current advantages, the UK can establish large-scale domestic manufacturing with additional economic benefits across the supply chain and from downstream applications. In doing so, this new domestic supply chain should give UK companies a foot-in-the-door of the international battery market, opening up substantial new markets, generating jobs and significant economic value for the UK. The Faraday Institution's NEXGENNA project is working with the leading UK companies to accelerate commercialisation.

However, if the UK is to seize the opportunity to maintain and expand its position in the face of accelerating international competition it must make significant and urgent investments. These investments might include:

- An expansion of support for sodium-ion research to support the transition to manufacture
- Investments in demonstration projects to support industry efforts to show reliability and manufacture at scale.
- Significant incentives and support to encourage the establishment of large-scale sodium-ion battery manufacture in the UK.

Sodium-ion batteries offer inexpensive, sustainable, safe and rapidly scalable energy storage suitable for an expanding list of applications and offer a significant business opportunity for the UK.

About the Faraday Institution and Faraday Insights

The Faraday Institution is the UK's independent institute for electrochemical energy storage research, skills development, market analysis, and early-stage commercialisation. We bring together academics and industry partners in a way that is fundamentally changing how basic research is carried out at scale to address industry-defined goals.

Our 'Faraday Insights' provide an evidence-based assessment of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government. If you would like to discuss any issues raised by this "Faraday Insight" or suggest a subject for a future Insight, please contact Stephen Gifford.

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