Frequently Asked Questions

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Why Beyond-Li?

As our transition away from fossil fuels accelerates, the demand for Lithium-ion batteries (LIBs) is spiking quickly. There is significant concern regarding the short-term supply and long-term sustainability of LIBs due to the limited and geographically concentrated lithium, cobalt, and nickel resources. Group1 and Potassium-ion batteries (KIBs) can provide a viable alternative to bridge this supply gap. KIBs are more sustainable as it uses K which is more than 1000x abundant vs Li, does not use any rare elements like Co and Ni that come from abroad and conflict areas enabling the domestic supply chain.

Lithium shortage is widely accepted and is a structural issue for LIBs. It is based on the fact that Lithium almost does not exist in the mineral form of spodumene. Most of the Lithium exists in the underground brine form in a very small part of the world. Together brines and spodumene constitute mineable reserves of lithium in the world. Of course, there is lithium in seawater at parts per million levels but there is no economic way to extract it. Figure 1. Is a chart from global mining company, Rio Tinto, showing known reserves versus the demand of Lithium that is needed to support electrification plans. The demand-supply gap is 10x to 40x and there is no known way to close it in the period past 2030. Figure 2. is from a report by McKinsey and Co. covering the next period until 2030 and shows primary and secondary supplies hitting the limit at 2025. Early-stage supplies are very speculative with a low probability to materialize in time to match global battery demand.

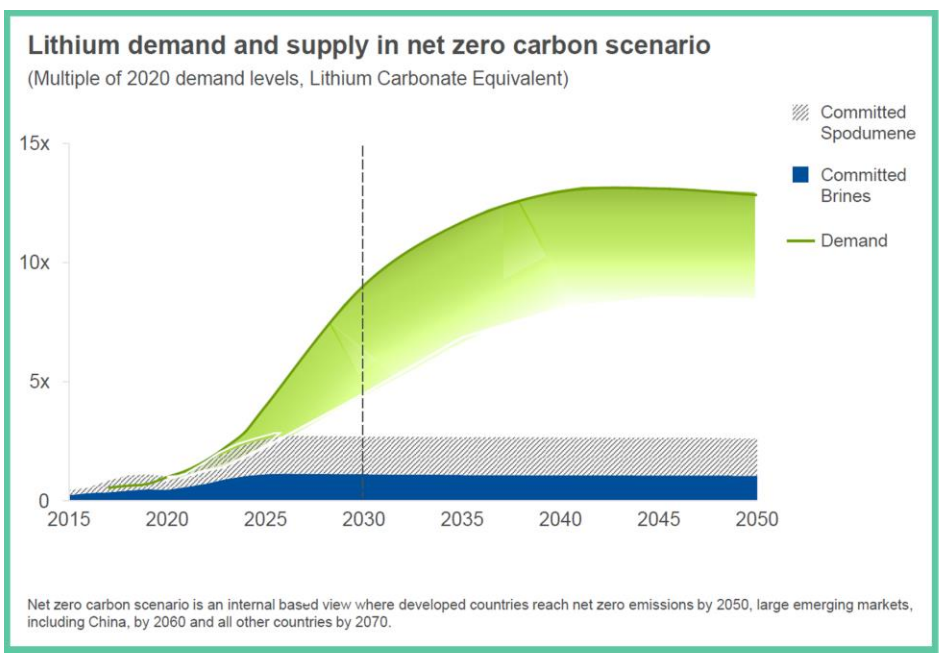

Figure 1. Significant supply gap emerging for lithium. [Source: Rio Tinto. 2021 October 20, *Investor Seminar 2021 Slides*. Online Access.]

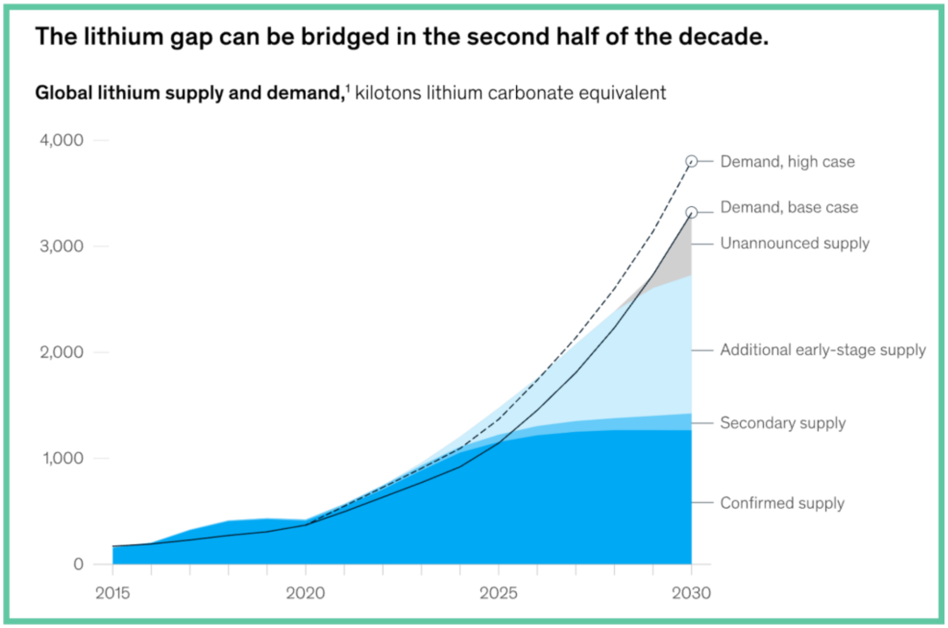

Figure 2. Global lithium supply and demand. Mined production volume. Forecasted potential production accounts for historical utilization as a result of external disruptions and economic constraints (7%) – modeled at 93% of available capacity. Production includes volumes that may not have been refined, including stockpiled direct shipping ore and spodumene content. [Source: Mckinsey and Company (2022, April 12). *Lithium mining: How new production technologies could fuel the global EV revolution*. Online Access]

Articles of Interest:
Lithium mining: How new production technologies could fuel the global EV revolution
Assessment of lithium criticality, existential supply gap

What is the KPW (Potassium Prussian White)?

It is low-cost high-energy potassium cathode material invented from the laboratory of Nobel laureate Professor John Goodenough at UT-Austin, the scientist and the first author is one of Group1 co-founders, Dr Leigang Xue. Its 4V voltage and 156 mAh/g capacity deliver a higher energy density than LiFePO4.

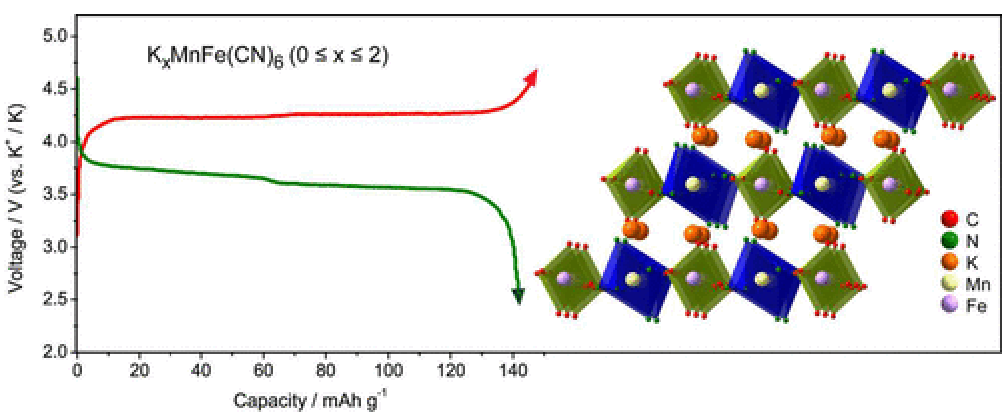

Figure 3. Voltage profile and structural illustration of Potassium Prussian White cathode material. [Source: Leigang Xue, Yutao Li, Hongcai Gao, Weidong Zhou, Xujie Lu, Watchareeya Kaveevivitchai, Arumugam Manthiram, and John B. Goodenough. *Am. Chem. Soc*. 2017, 139, 6, 2164–2167]

Articles of Interest:
[How KPW was discovered]
[Leigang's seminal publication about KPW as K-ion battery cathode]
[Why K-version has a higher energy density than Na-version in Prussian White]

What would make Group1's K-ion batteries more sustainable?

- KIB are more sustainable as it uses K which is more than 1000x abundant vs Li.
- Group1's KPW cathode does not use any rare elements like Co and Ni that come from abroad and conflict areas enabling the domestic supply chain.
- KPW materials are produced using low-temperature sustainable processes vs high-temperature cathode materials for LIBs

Advantages of K-ion battery vs. Na-ion battery?

- KIBs can use graphite anodes providing a critical advantage over sodium-ion batteries (NIBs); K+ electrochemically intercalates into graphite to form KC8, compared with Li+, occurs at a higher potential (0.3 V versus K+/K compared with 0.1 V versus Li+/Li), and presents a theoretical specific capacity (279 mAh/g compared with 372 mA h/g).
- KIB has a higher energy density than NIB because of its 4V voltage vs. 3.4V of NIB;
- K+ has much higher mobility than Na+ due to the weaker bonding forces on its electron cloud by other electrode materials or electrolyte solvents.

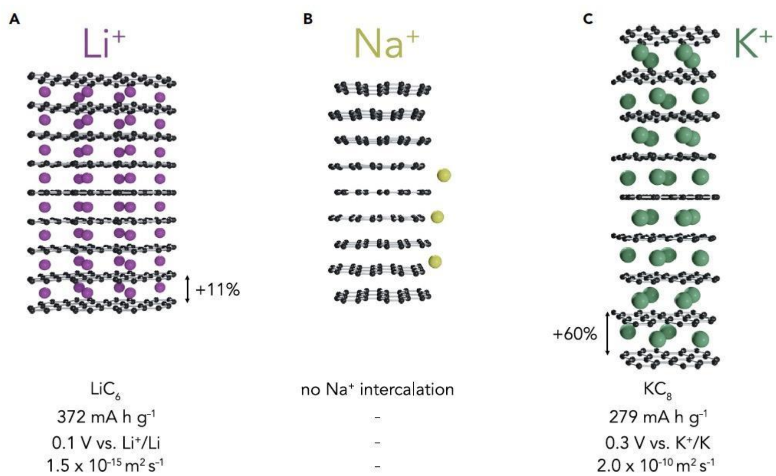

Figure 4. Comparison of the Graphite Intercalation Properties of Li+, Na+, and K+ Including Composition, Theoretical Specific Capacity, Operating Voltage, and Bulk Diffusion Coefficient. [Source: Dhir, S., Wheeler, S., Capone, I., & Pasta, M. (2020). *Chem*, 6(10), 2442–2460.]

Articles of Interest:
[Overlook on K-ion batteries.]
[Why Na doesn't Intercalate in Graphite]

What is the current state of K-ion battery Composition?

The current state of cathodes/anodes in small cells is very promising in energy density, cycling life, and rate capability. Group1's current effort is to transfer this material from small cells into pouch cells format and scale up the manufacturing process. This is where we are currently spending time on optimizations and engineering (such as purity, defects, particle size, surface area, etc.). As a part of our roadmap, we will continue to develop KPW cathode materials that will enable our customers to increase Energy Density at material and pack levels, deliver faster charging and longer-lasting materials for heavy mobility, and materials that work with inherently safe electrolytes. Group1 will be using G1 Smart platform to reduce development time and maximize performance.

Articles of interest:
Performance example of K-ion battery with KPW cathode and graphite anode

What is the energy density of the KPW-enabled K-ion battery?

LFP is our benchmark.
(KPW: 4V, 156 mAh/g ; LFP: 3.4V, 170 mAh/g).
As more and more EVs are being powered by $LiFePO_4$ (lithium iron phosphate), we consider LFP as our benchmark comparison in LIB material systems, which delivers 170mAh/g operating at 3.4V, with lower energy density but cheaper and safer than NMC. For example, Tesla previously announced that its Q1 2022 production number had jumped to over 310,000 vehicles, and close to 150,000 of these had the LFP pack. Group1's KPW cathode is 4V and 156 mAh/g and will deliver comparable energy density to LFP, at further lower cost and improved safety because it is Co/Ni/Li/O-free. It is the next-generation sustainable cathode material competitive with LFP. Both of these cathode materials were invented in laboratory of Nobel laureate (and LiB co-inventor) Professor John Goodenough.

What is the target market?

Because of the energy density previously, KPW-enabled K-ion battery has an energy density on par with LFP-based Li-ion batteries widely used in BYD and Tesla cars today. In addition, a K-ion battery should support charge faster and has better low-temperature performance due to K^+ having superior transport properties compared Li^+. In addition, KPW provides a open, stable structure to facilitate strain-free insertion of large ions such as K^+. This results in greater cycle-stability than LFP, both ESS and EV are target markets. Ultimately, any application that uses LFP cathode technology is suitable for KIB powered by KPW.

Does K-ion battery have a dendrite problem when used with graphite anode?

Graphite anodes, the industry standard for LiBs, can be used as the anode for KIBs. K^+ electrochemically intercalates into graphite to form KC_8, K^+ intercalation into graphite, compared with Li^+, occurs at a higher potential (0.3 V versus K^+/K compared with 0.1 V versus Li^+/Li). There is a greater difference between the K^+ graphite intercalation potential versus the K-metal plating potential, that is, E(K-graphite) - E(K-plating) > E(Li-graphite) - E(Li-plating). This greater difference in potential allows larger overpotentials to be experienced without reaching the K plating potential thus reducing the risk of dendrite formation.

Articles of Interest:
[Value Proposition Validation: Performance of K-ions in graphite anode]

What science supports faster rate-kinetics of K-ion battery compared to LFP-based Li-ion battery?

Counter-intuitively, K+ has a smaller stokes radius than Li+ or Na+ when in organic electrolyte this is primarily due to K+ having a larger ionic radius resulting in weaker solvation energy. K+ electrolyte thus has the highest conductivity (Figure 5).

Graphite also supports superior rate performance in KIBs compared with LIBs. The diffusion coefficients of Li+ and K+ in graphite LiC6 and KC8 were calculated from density functional theory (DFT) modeling as 1.5×10^{-15} and 2.0×10^{-10} m2/s, respectively. Additionally, there is a greater difference between the K+ graphite intercalation potential versus the K-metal plating potential, in comparison with the Li equivalents, i.e., E(K-graphite) - E(K-plating) > E(Li-graphite) - E(Li-plating). This greater difference in potential allows larger overpotentials to be experienced without reaching the K plating potential. This overpotential currently limits LIB charging rates.

KPW cathode has wide channels with access in 3 dimensions, this promotes rapid diffusion of K+ in KiBs.

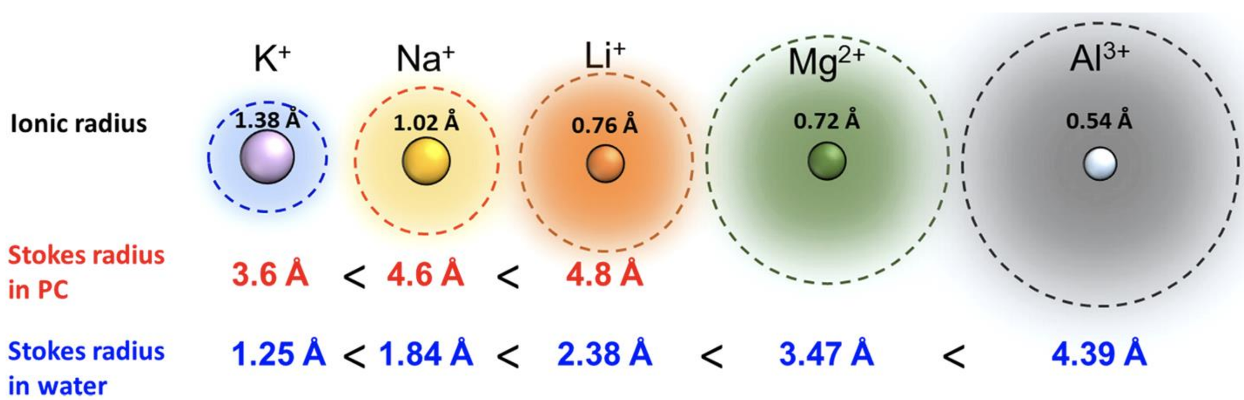

Figure 5. Comparison of Shannon's ionic radii and Stokes radii in water and PC among Li+, Na+, and K+ ions. The values of Shannon's ionic radii and Stokes radii in water are also compared with those of the Mg2+ and Al3+ ions. [Source: Tomooki Hosak,Kei Kubota, A. Shahul Hameed, and Shinichi Komaba, *Chem. Rev*. 2020, 120, 6358 – 6466]

Articles of Interest:
[Research development on K-ion batteries.]

How stable is the KPW structure? Does it have long cycle-life?

It is widely accepted in the research community that KPW has a very stable, zero-strain structure. KPW has an open framework that allows K+ to insert into the PW host with minimal mechanical strain on the material. Fig 6 shows KPW cell demonstrating the material’s fundamental stability.

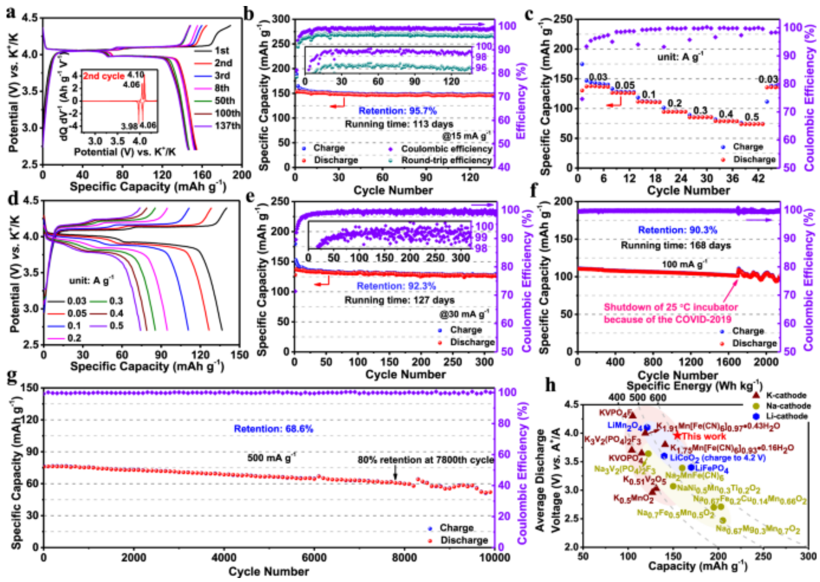

Figure 6. Electrochemical performance of the KMF-EDTA | K metal cells within 2.7–4.4 V (vs. K+/K). [Source: Deng, L., Qu, J., Niu, X. et al. *Nat Communications* **12**, 2167 (2021)

Articles of Interest:
[Demonstrative performance of KiBs full-cell design]
[Additional demonstration of KiB full-cell]

Can KPW cathode be paired with silicon anodes?

There is very preliminary work done in this field that shows K+ is more mobile than Li+ in amorphous silicon anodes. The field is still nascent, but promising.

Articles of Interest:
[Promising molecular studies of KiB with silicon anode]

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