MOLYBDENUM

Powering Next-Generation Batteries

Increasing social concern regarding the global energy crisis and environmental pollution has stimulated worldwide research of the sustainable and renewable energy storage systems. Today, the way that energy is stored is as important as how it is generated. Modern battery technology moves electric cars, assists with storing emergency power, keeps satellites used for national security in orbit and powers portable electronic devices which has made nearly every aspect of life, mobile. Emerging technology is making it conceivable that airplanes and even entire cities could soon be powered by batteries and solar energy.

Reducing the use of fossil fuels has reached critical importance. Power generation, storage and transmission has become challenging worldwide. The Fukushima nuclear disaster in 2011 and the current power grid crisis facing Puerto Rico in the wake of Hurricane Maria has heightened the awareness of the need for highly efficient and sustainable clean energy sources, such as solar and wind power. These circumstances compel the discovery of reliable power sources that can support a highly-efficient energy cycle. Furthermore, the production of renewable energy is inherently uneven, and the demand for energy storage systems is increasing worldwide.

Batteries were first developed in 1799 but only since 1991 have sufficient advances been made to diversify their use for a variety of portable devices and automobiles. The most common types of modern batteries include: lead-acid, nickel-cadmium (NiCd), nickel metal hydride (NiMH) and lithium-ion (Li-ion). Rarer types of batteries include sodium-ion (Na-ion), potassium-ion (K-ion), aluminum-ion (Al-ion) and lithium-sulphur (Li-S).

There are two factors that are critical when comparing batteries:

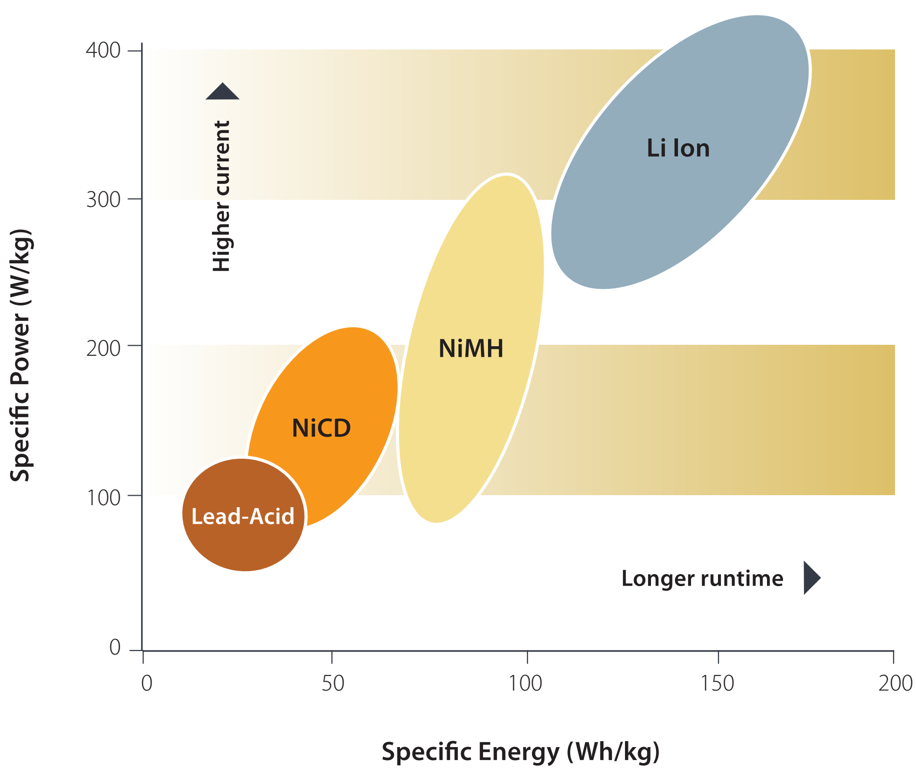
- **Specific Energy**, also referred to as capacity, is likened to the amount of water in a tank. It's the total amount of energy a battery holds which is most critical because without supply there is no electric current to deliver.
- **Specific Power**, also referred to as current density, is likened to the speed at which water can pour out of the tank. It's the amount of current a battery can supply for a given use. Critical to this point is the rate at which a battery will drain or recharge.

To date, lithium-ion batteries (LIBs) are the most reliable power sources due to their high energy capacity and long cycle life. However, the current energy density of LIBs is not sufficient for building large, megawatt-hour-scale LIBs. Although, a variety of approaches have been examined for improving LIB performance, the energy density of LIBs is believed to be the most important factor. To overcome this challenge, an active material must be developed that has a high capacity and a reliable cycle life.

Specific Energy and Specify Power of a variety of modern batteries.

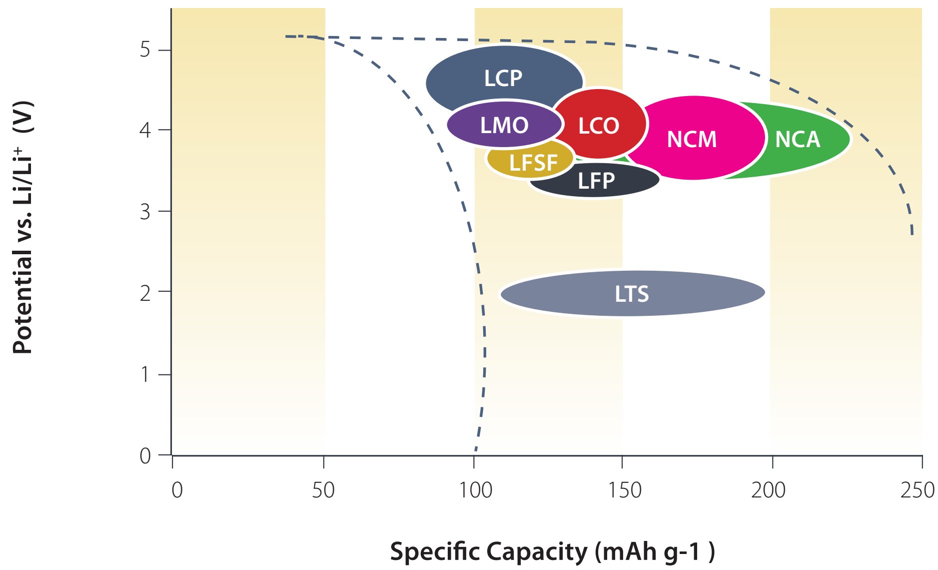
Note that LIBs nearly break the scale.

Specific Energy components must be analyzed and noted in comparing proposed battery technologies.



Current state of the art commercial, large-scale LIBs with a Specific Energy ranging between 100 and 225.

This data is relevant in analyzing various, recent academic studies on energy and battery technology.



LCO or "lithium cobalt oxide", (apple); LMO for "lithium manganese oxide", (Nissan); NCM for "nickel cobalt manganese oxide", (tesla power wall); NCA for "nickel cobalt aluminum oxide", (tesla cars); LCP for "lithium cobalt phosphate", LFP for "lithium iron phosphate", (Starter Batteries); LFSF for "lithium iron fluorosulfate", and LTS for "lithium titanium sulfide".

To increase performance and reduce costs of batteries for large scale usage, the world's scientists have and are studying various elemental groups and combinations to be used in evolving modern batteries to optimize efficiency.

The commercialization of cobalt into the technology has resulted in increased demand and prices for cobalt, a boost in capacity to the 225 Specific Energy level and a reduction in costs of the batteries. The nickel cobalt aluminum oxide (NCA) and nickel cobalt manganese oxide (NCM) in the figure above shows marked improvement in Specific Energy. According to current estimates, lithium-ion technology is improving at the meager rate of 6 to 7-percent per year. However, recent studies are exploring new advancements in the technology which may revolutionize batteries, their capacity and applications.

molybdenum
improves
battery performance

graphene/graphite
stablilizes
materials

achieving
4 times Specific Energy
of the best commercial batteries

MOLYBDENUM

Energy for the Future

Since mid-2016, numerous academic studies have been published, worldwide, demonstrating that the use of **molybdenum** in various states and compounds improves battery performance by several times. Research indicates that the improvements are evident in all types of batteries not only lithium-ion batteries. Currently, scientists are refining the various materials to optimize the technology. With these developments, it is certain that new **molybdenum**-based materials will revolutionize the battery market and increase the demand for **molybdenum.**

Molybdenum, in battery usage, developed through using the strategic metal in electrodes. Research data illustrates a major leap in performance from the current Specific Energy Level which is in the 150 to 240 range to the **molybdenum**-enhanced level of 500 to 700 range.

Initial tests displayed instabilities in the use of bulk **molybdenum** which resulted in conductivity problems. During 2016-2017, scientists investigating **molybdenum** began mixing **molybdenum** with various compounds including graphene/graphite which appears to have resolved problems by stabilizing the materials and their use in batteries.

Findings from recent studies (Choia et al April 2017, Korea)[1] on molybdenum(MOS_2) usages in lithium-ion batteries.

The Bare MOS_2 line shows excellent initial Specific Energy (capacity) but over time (cycles) the performance degrades. By mixing in various percentages of graphene with the **molybdenum** (MOS_2) the stability and consistency improves to reach a stable Specific Energy of over 1000 units which would be 4 times the current Specific Energy of the best commercial batteries.

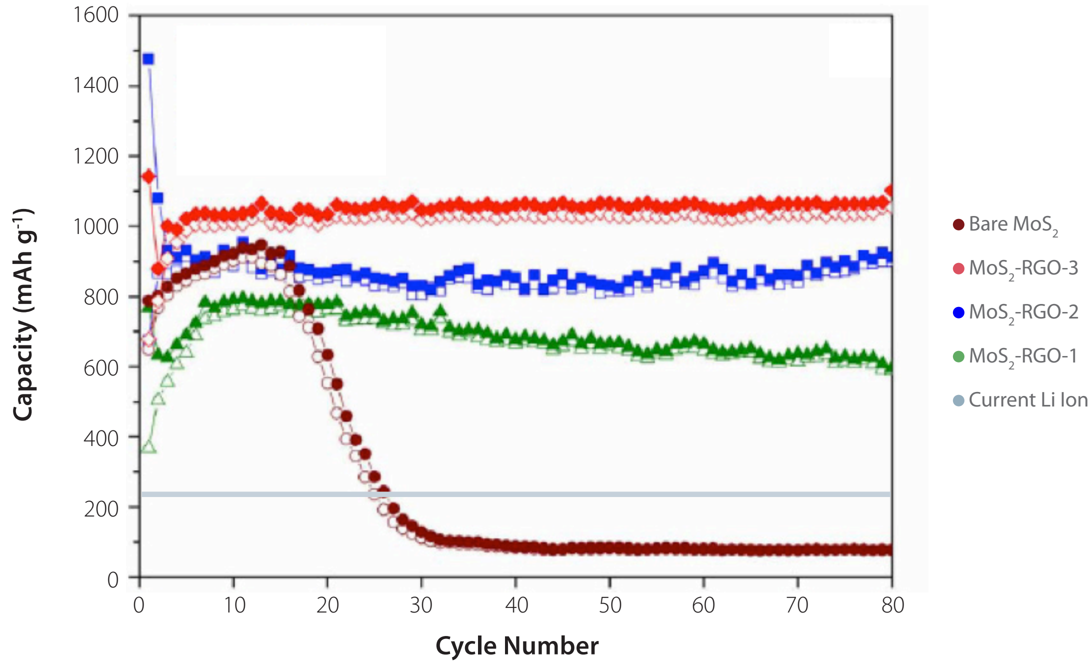
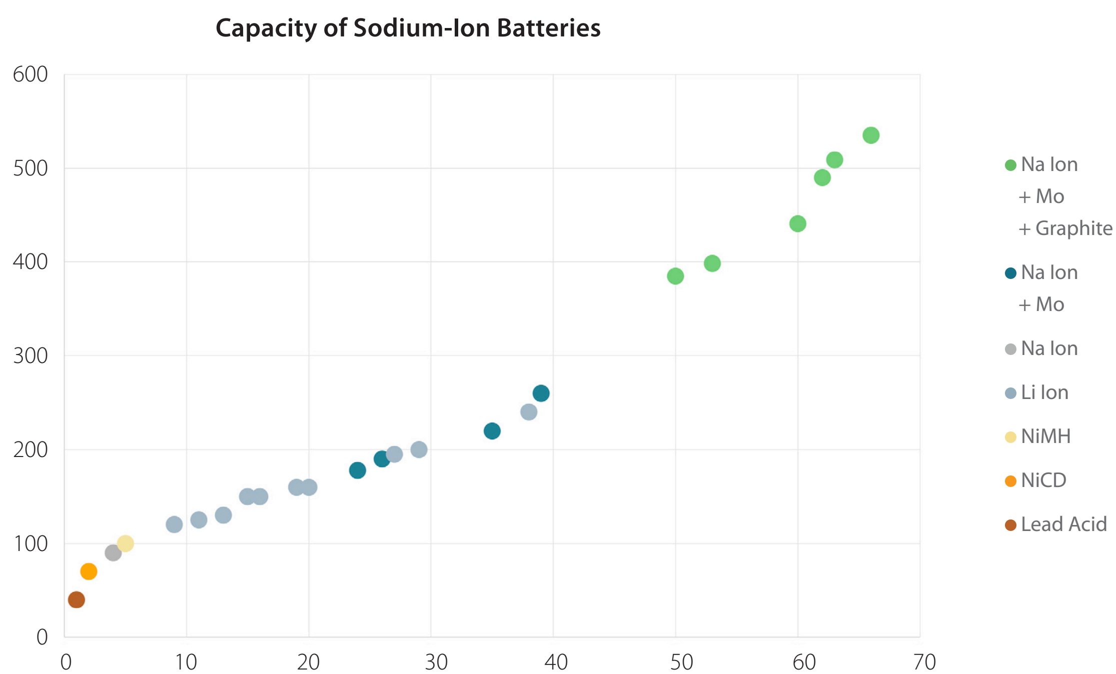


Figure taken from article: One-pot synthesis of molybdenum disulfide–reduced graphene oxide (MoS_2-RGO) composites and their high electrochemical performance as an anode in lithium-ion batteries; Mugyeom Choia, Jieun Hwanga, Handi Setiadib, Wonyoung Changc, Jaehoon Kima,b ; Journal of Supercritical Fluids 127, April 4, 2017

Researchers continue to make significant improvements and innovations to the technology for all battery types.

Sodium-ion and potassium-ion batteries are being studied as a possible replacement for lithium as materials are a lot more abundant (and less costly) than lithium, despite the fact the lithium outperforms sodium and potassium.

Sodium-Ion Battery Improvements



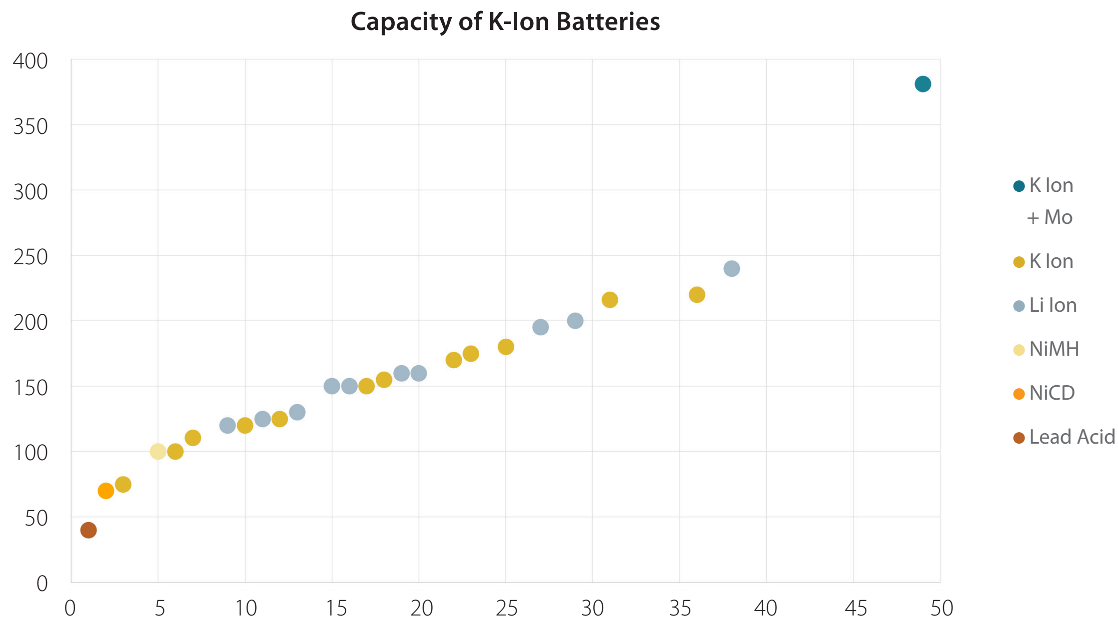
Data regarding the effect of molybdenum-based electrodes on sodium-ion batteries.

The existing battery technology for both sodium and lithium is indicated by the grey dots. Adding **molybdenum** increases the Specific Energy to the top end of the existing batteries upgrading to 260 units. Adding both **molybdenum** and graphite to the battery electrode increases performance to almost 550 units which doubles the power of the existing technology.

Recent articles of sodium-ion batteries for example:

1. Enhanced Reversible Sodium-Ion Intercalation by Synergistic Coupling of Few-Layered MoS_2 and S-Doped Graphene; Ge Li, Dan Luo, Xiaolei Wang,* Min Ho Seo, Sahar Hemmati, Aiping Yu,and Zhongwei Chen. (Canada and Korea), November 16, 2017; Advanced Functional Materials Journal 2017
2. MoS_2@rGO Nanoflakes as High-Performance Anode Materials in Sodium Ion Batteries, Ruxing Wang, Shu Gao, Kangli Wang, Min Zhou, Shijie Cheng & Kai Jiang; (China); August 16, 2017; Nature Scientific Reposts 7:7963, 2017

Potassium-Ion Battery Improvements



The effect of molybdenum-based electrodes on potassium-ion batteries.

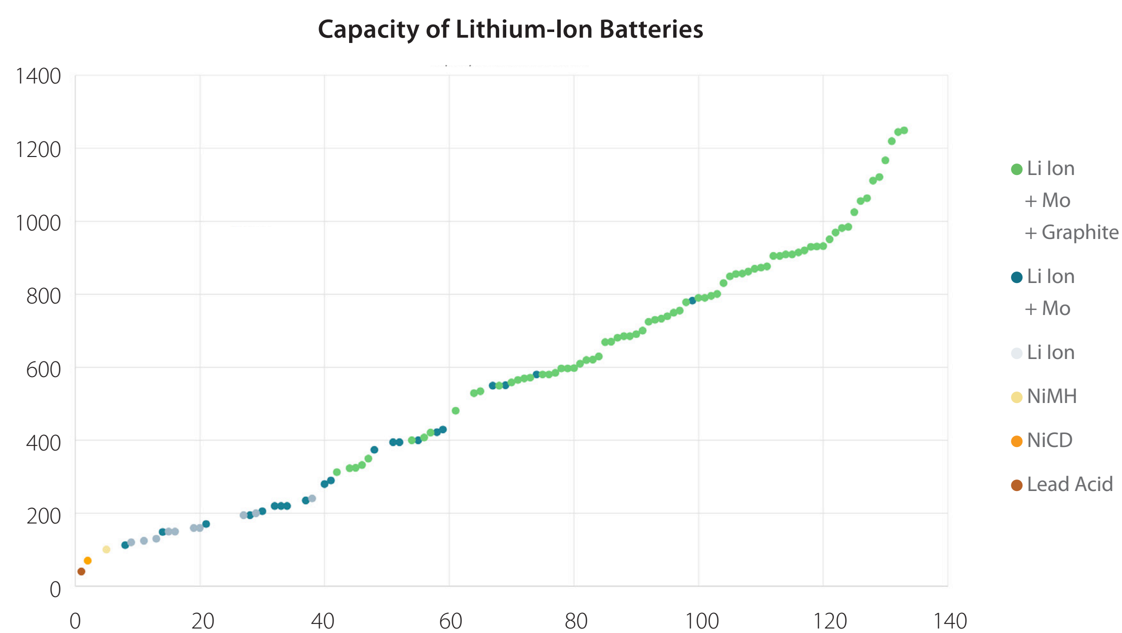
The magenta dot tops the graph and is evidence of the improvements that **molybdenum** is making in Specific Energy of potassium-ion batteries.

Recent article of potassium-ion batteries for example:

1. Superior Potassium-Ion Storage via Vertical MoS_2 "Nano-Rose" with Expanded Interlayers on Graphene; Keyu Xie, Kai Yuan, Xin Li, Wei Lu, Chao Shen, Chenglu Liang, Robert Vajtai, Pulickel Ajayan, and Bingqing Wei; (USA and China); September 22, 2017; Small Journal Energy Storage (2017), 13,1701471.

Lithium-Ion Battery Improvements

By far, the largest sector in the battery industry is lithium-ion based batteries. Experiments worldwide have heavily concentrated research and development in this area. Three types of studies involving **molybdenum** have been completed using either bulk **molybdenum**, mixing lithium and **molybdenum** together, or **molybdenum** graphite/graphene combinations.



Data relative to Specific Energy (capacity).

Current lithium-ion battery capacity indicates between 125 and 240 units. The addition of **molybdenum** shows improvements over existing technology up to 783 units. The addition of both **molybdenum** and graphite/graphene increase performance to over 1200 units which is 5 to 6 times that of current battery technology.

Recent article of potassium-ion batteries for example:

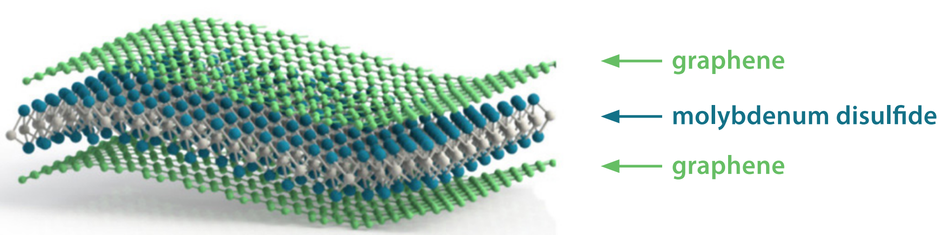
1. Ternary lithium molybdenum oxide, $Li_2Mo_4O_{13}$: A new potential anode material for high-performance rechargeable lithium-ion batteries; Rakesh Verma a, Chan-Jin Park b, R. Kothandaraman a, U.V. Varadaraju a,; (India and Korea); December 2, 2017; Electochimica Acta (2017), 12,008.
2. Vertically Aligned MoS_2 Nanosheets Patterned on Electrochemically Exfoliated Graphene for High-Performance Lithium and Sodium Storage; Gang Wang, Jian Zhang, Sheng Yang, Faxing Wang, Xiaodong Zhuang, Klaus Müllen, and Xinliang Feng; (Germany); November 30, 2017; Advance Energy Materials 2017 1702254.
3. Carbon-Sheathed MoS_2 Nanothorns Epitaxially Grown on CNTs: Electrochemical Application for Highly Stable and Ultrafast Lithium Storage; (China and Poland); Zijia Zhang, Hailei Zhao,* Yongqiang Teng, Xiwang Chang, Qing Xia, Zhaolin Li, Jiejun Fang, Zhihong Du, and Konrad S´wierczek; December 10, 2017; Advance Energy Materials 2017 1700174.
4. 3D Conductive Network Supported Monolithic Molybdenum Disulfide Nanosheets for High-Performance Lithium Storage Applications; Mingkai Liu, Yuqing Liu, Buzheng Tang, Peng Zhang, Yan Yan, and Tianxi Liu; (China); March 8, 2017; Advance Material Interfaces 2017 1601228

Conclusion

Overwhelming scientific research makes the case for the addition of **molybdenum** to existing battery technology. It clearly demonstrates that the next generation of electric batteries will integrate the use of a combination of **molybdenum** and graphene/graphite. It is projected that there will be increasing supply constraints and associated increases in prices for **molybdenum**, as a result of the demand for **molybdenum** in battery requirements, which will coincide with the upcoming increase in demand from steel mills.

Molybdenum-based electrodes and advancements in battery technology may lead to large shortfalls in the global **molybdenum** supply. Currently, **molybdenum** prices are depressed but the upcoming increase in demand will result in serious price appreciation in the short term. An examination of the battery industry demand for cobalt shows that it has affected all aspects of the production and development of cobalt.

Based on this research, **molybdenum** technology could replace cobalt and deliver at least 4 to 5 times more power than the cobalt-based batteries. The impact of **molybdenum** on the battery industry is still developing but all research is projecting favorable outcomes.



MOVE OVER COBALT – HERE COMES MOLYBDENUM

CuMo PROJECT

AMERICAN CuMo

638 Millbank Road
Vancouver, BC V5Z 4B7
CANADA
cumoco.com

T: 604.689.7902
F: 604.689.7816
TF: 1.800.667.0873
info@cumoco.com