Batteries Not Included: The Need for Rechargeable Battery Technologies

Moriah Locklear, PhD; Claire Costenoble-Caherty, PhD; Sharon Layani

STEPS: SCIENCE, TECHNOLOGY, ENGINEERING, AND POLICY STUDIES

ISSUE 7, 2022

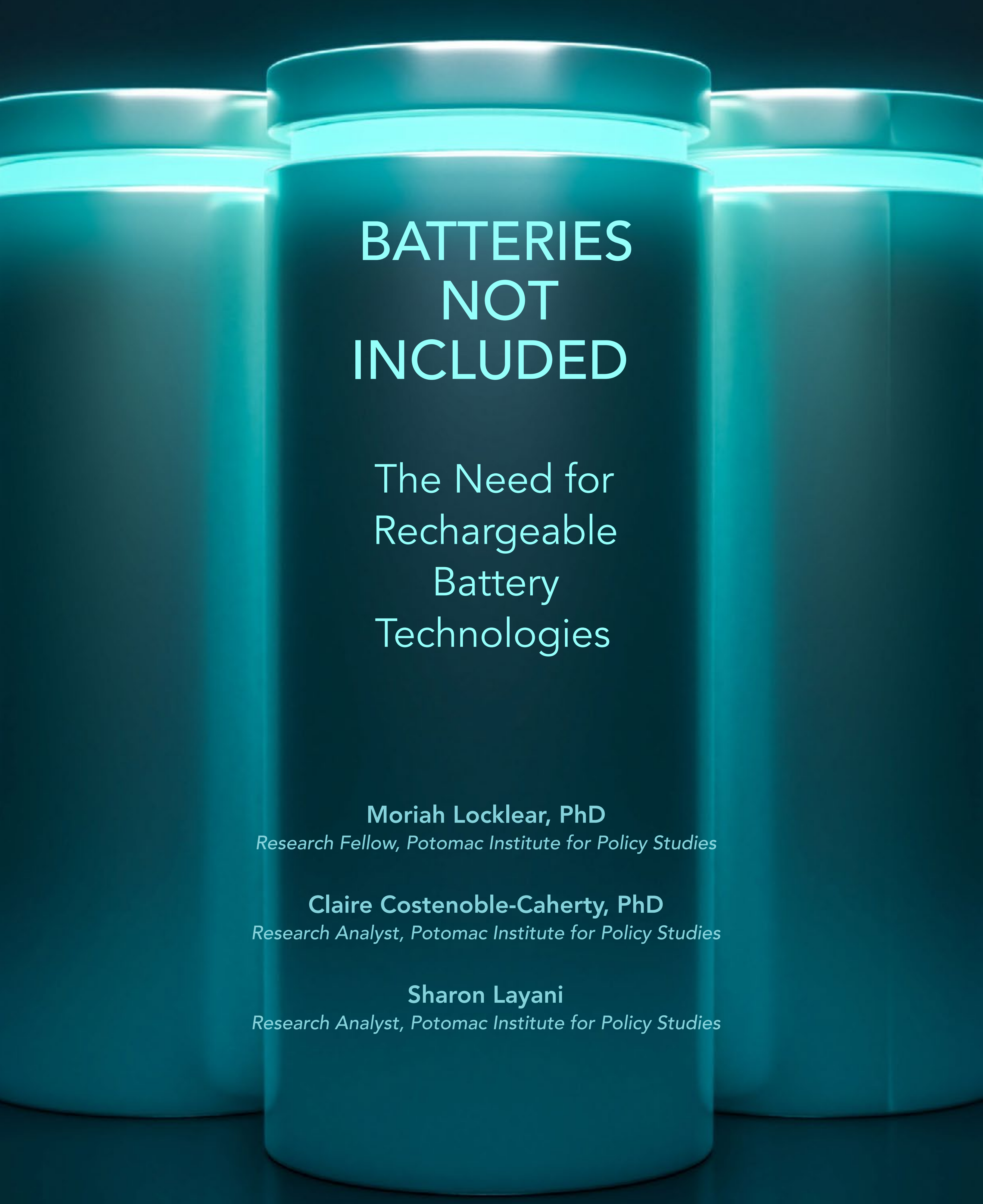
STEPS (Print) ISSN 2158-3854
STEPS (Online) ISSN 2153-3679

Moriah Locklear, PhD;
Claire Costenoble-Caherty, PhD;
Sharon Layani. "Batteries Not Included: The Need for Rechargeable Battery Technologies," *STEPS* 7 (2022): 43-49.

POTOMAC INSTITUTE PRESS

STEPS: Science, Technology, Engineering, and Policy Studies
is published by Potomac Institute Press of the
Potomac Institute for Policy Studies.

Access to *STEPS* is available free online at:
www.potomacinstitute.org/steps.



BATTERIES NOT INCLUDED

The Need for Rechargeable Battery Technologies

Moriah Locklear, PhD
Research Fellow, Potomac Institute for Policy Studies

Claire Costenoble-Caherty, PhD
Research Analyst, Potomac Institute for Policy Studies

Sharon Layani
Research Analyst, Potomac Institute for Policy Studies

Introduction

Since their development in the 1980s and scale manufacturing in the 1990s, lithium-ion (Li-ion) batteries have come to dominate the market for rechargeable batteries. The increasing use of Li-ion batteries in consumer electronics, commercial applications, and national defense applications is due to their superior attributes. As the market pushes for energy efficient vehicles, the expectation that Li-ion batteries will power electric and hybrid electric vehicles will increasingly drive demand for Li-ion batteries.

Li-ion batteries have relatively high energy density (technically, specific energy) that can vary from 100 to 265 Watt-hours per kilogram (Wh/kg), and specific power of around 250 to 340 Watts per kilogram (W/kg). This is better than alternative rechargeable batteries, which include lead-acid (Pb-acid), nickel cadmium (NiCd), and nickel metal hydride (NiMH) batteries,[1] by factors of two or more in both measures.

Batteries fall short of the energy content of gasoline and other petrochemicals. Gasoline has a specific energy of around 12,700 Wh/kg and can deliver high power depending on size of the internal combustion engine (which, of course, is heavy—partially offsetting the advantage of the high specific energy of the petrochemical). Batteries are also not a match for hydrogen, which has three times the energy content of gasoline but requires a heavy storage system.

Given the desire to move away from petrochemicals for transport energy, rechargeable batteries are the preferred technology. The electrical energy to charge the batteries can then be obtained from renewable sources, nuclear power, and potentially more exotic energy resources, thus making them a zero-emission power source. However, to replace petrochemicals, Li-ion batteries must be affordable, efficient, convenient, and regularly available.

The Demand for Rechargeable Batteries

The demand for battery storage is exploding. One estimate predicts a 14-fold global increase in demand by 2030 compared to 2018.[2] Worldwide Li-ion battery use for vehicles is estimated to be around 600 GWh by 2025, increasing to over 1,800 GWh by 2030.[3] Other applications will increase the demand for Li-ion and other battery storage. A 2022 analysis predicts that by 2026, the annual global battery market will be worth about $175B USD.[4]

This demand will largely be met by Li-ion batteries. Automobiles, light trucks, and other transportation vehicles (perhaps including electric vertical-takeoff and landing aircraft) will be the largest driver of demand, accounting for three-quarters of all Li-ion sales by 2030,[5] potentially amounting to 1400 GWh by 2030.

Other applications will also demand batteries—phones and laptops, smart phones, radios, wearable devices, and home and grid energy storage. Most modern defense systems make use of batteries to power internal electronics. Li-ion batteries tend to also be the battery of choice for these applications. However, they will be in competition with the electric vehicle manufacturers.

Grid storage, which will likely become another market driver, does not necessarily require the light weight and high density of Li-ion batteries, and yet Li-ion is today the battery technology of choice even for grid storage. Grid storage demand is predicted to grow twenty-fold from 2018 to 2030, to 155 GWh of capacity.[6] Supply deficits for other uses are possible as commercial industries and international players compete for these supplies.

Meeting the Demand for Rechargeable Batteries

The US Administration's 100-day review on supply chains, published in 2021, recommends incentivizing every stage of the US battery supply chain to compete in global markets for high capacity batteries.[7] The US currently manufactures around 6% of the world's Li-ion batteries, most coming from the Tesla-Panasonic plant in Nevada.[8] Joint ventures, especially between automakers and battery manufacturers, will build new battery factories that will be operational by 2025, with some located in the US.[9] The Infrastructure Investment and Jobs Act of 2021 contains incentives, [10] including $7B over five years, to boost US production of lithium-based batteries, with the intent of strengthening the US supply, as well as infrastructure and charging stations to spur demand.[11] The US Department of Energy has a "National Blueprint for lithium Batteries" with a vision to "establish a secure battery materials and technology supply chain" by

2030.[12] The blueprint additionally includes a call for strong support for research and development (R&D) to maintain technology leadership and improve battery performance. The Europeans and (undoubtedly) the Chinese have similar research goals.[13] The US Department of Defense has recommended the development of a "defense-specific lithium battery strategy."[14]

Efforts to assure US production sufficient to meet demand will necessarily involve partnerships and agreements with global suppliers. The materials used in making Li-ion batteries are sourced from all over the world. Raw ore is extracted from disparate mines located throughout the earth. That ore is refined into materials and minerals by production plants, which are not necessarily co-located with the mines. Materials and minerals are incorporated into parts such as anodes and cathodes in other plants. Assembly of batteries cells and production of battery packs is performed by battery manufacturers. The supply chain is global, and relatively few of these plants, from mining to refining to manufacturing, are located in the US.

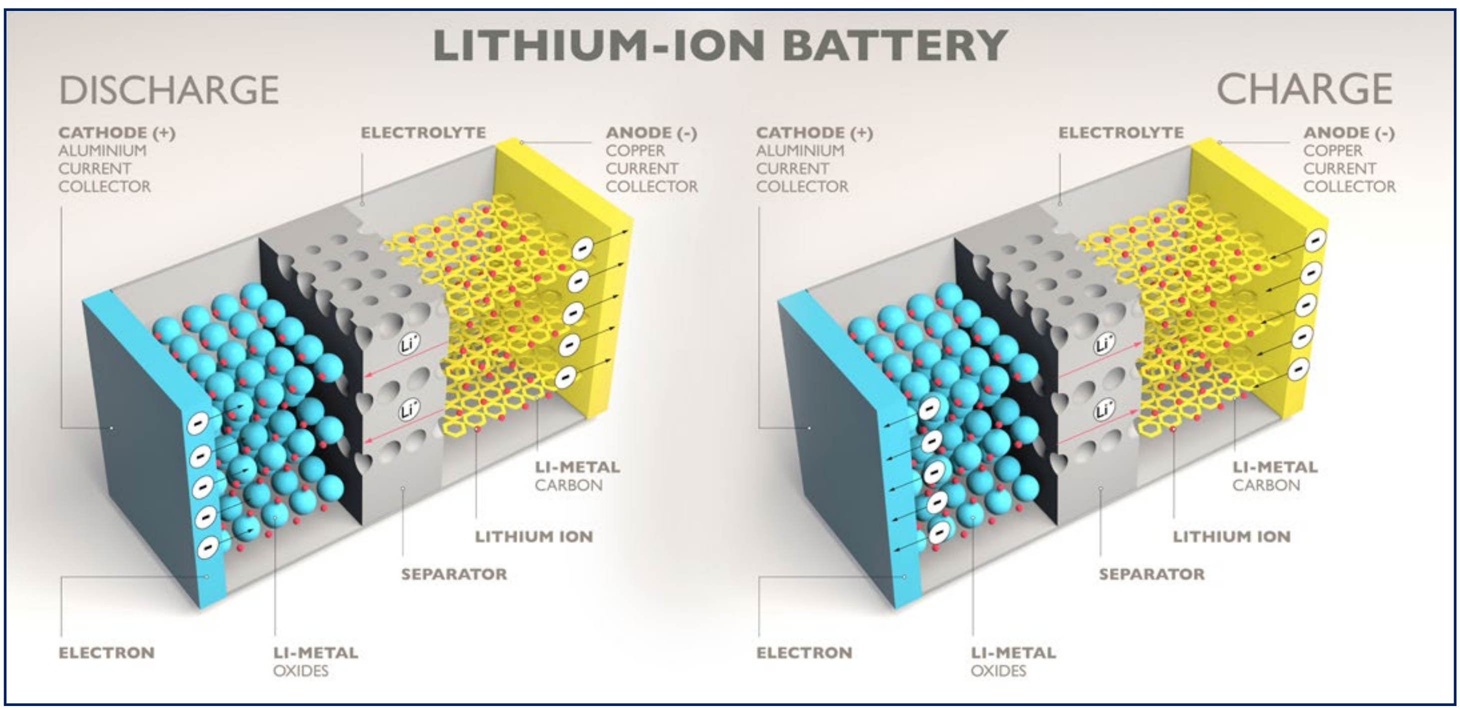
The US must secure sufficient access at all points in the supply chain to produce enough batteries for its own demand. Creating all-US onshore production for each stage is unlikely and uneconomical. But securing supplies through networks of allies and partners with global reach is possible.

What are the Prospects for New Battery Technologies?

One approach to assuring sufficient supplies of rechargeable batteries is to develop alternative battery technologies. Alternatives provide a diversity of supplies and might provide opportunities for market leadership. Many research projects in industry, academia, and government, including government-sponsored research are searching for variants and alternatives to Li-ion batteries. The Federal government has proposed increases to ongoing R&D to improve battery cells.[15]

Current research projects show promise to increase storage capacity and improve performance of batteries, but to date are largely laboratory experiments. The chemistry is complicated, and the development and scalable manufacturing issues are great.

Li-ion batteries commonly use a lithium based cathode, a graphite anode, and a liquid (gel) polymer electrolyte containing a lithium salt. There are many variations possible to increase performance and improve cost, safety, and manufacturability characteristics. For electric vehicles, however, the near-term need is to improve safety. The electrolyte in current Li-ion batteries is a volatile, flammable, toxic liquid that facilitates the formation of "dendrites" that limit lifespan and is prone to explosive thermal runaway.



Accordingly, the next major development in battery technology will likely be the commercialization of solid-state batteries (SSBs).[16] SSBs use a solid electrolyte instead of a liquid electrolyte, which would make them safer and more stable.[17] Various materials can be used as a solid electrolyte, including certain ceramic materials and solid sulfide materials (sulfur in a compound). By virtue of being solid, the electrolyte is not volatile or corrosive and will not spill if the battery is damaged. However, finding the right combination of materials for the solid electrolyte that still permits high power and rapid charging is challenging. Major automobile companies (Ford, BMW, Volkswagen, etc.) are investing in battery companies, some of whom are close to commercialization of SSBs,[18,19,20] with goals of production within the next couple of years.

Solid electrolyte layers also permit the use of alternative materials for the anode and/or the cathode, which can then provide higher storage capacity. Some of the companies completing extensive (and difficult) research are seeking to double current Li-ion battery specific energy capacity.[21] One possibility is to use thin films of lithium metal as the anode, which allows for a much higher theoretical energy density.[22] Commercialization and production at scale remain challenging.[23] A consortium of universities and Department of Energy national labs, called the "Battery500 Consortium" is working to develop a Li-ion battery with a lithium-metal anode and 500 Wh/kg capacity, and has demonstrated a laboratory lithium battery with 350 Wh/kg capacity.[24] A Japanese research group claims a demonstration lithium-air battery with greater than 500 Wh/kg capacity.[25]

Lithium-metal anodes might also be combined with cathodes made of sulfur instead of lithium cobalt oxide or another lithium-containing compound. The primary advantage of a lithium-sulfur battery is that a sulfur cathode can incorporate more lithium ions compared to a traditional lithium-compound cathode,[26] yielding a higher energy capacity per unit weight.[27] Sulfur is light, abundant, cheap, and more easily sourced than materials such as cobalt and nickel used in current Li-ion batteries.[28] The US government is investing in this technology through Advanced Research Projects Agency-Energy (ARPA-E). Industry has shown interest in the approach.[29]

Another possibility is the use of silicon anodes with a solid sulfide-based electrolyte, which provides a theoretical 10-fold increase in specific energy.[30] Much of this work remains in academic and laboratory investigations[31] as they address complex issues including electrolyte-anode interactions and silicon anode swelling during charging. Industries are investigating the approach and multiple research companies are working on the problems.[32]

The extreme supply issues with cobalt have led to significant interest in developing Li-ion batteries that do not need cobalt. Getting rid of the cobalt (and nickel, which is often used in cathodes as well) involves research using sulfur, iron, manganese, or other substances. China's CATL company has hinted that Li-ion batteries can be developed without cobalt or nickel, but performance specifications are lacking.[33]

Finding an alternative to lithium is difficult, because lithium is hard to beat. Sodium is directly below lithium on the periodic table and has similar chemical properties, meaning that sodium-ion batteries are a possibility. Sodium is significantly more abundant than lithium,[34] and is more stable at extreme temperatures.[35] However, sodium-based batteries operate at a lower voltage and sodium is heavier than lithium. There are nonetheless commercial investments into sodium-ion variants.[36] Exploration of magnesium as an alternative to lithium is also ongoing.[37]

Other early-stage investigations include nickel-hydrogen batteries, which have demonstrated 20,000 charge cycles[38] compared to customary 300-500 cycles for Li-ion batteries.[39] However, they weigh three times as much as Li-ion batteries per unit of storage. Metal-air batteries consist of an air cathode and a metal anode made of iron, zinc, aluminum, or other abundant metals.[40] They have a high theoretical energy density by volume; however, they, too, are much heavier than Li-ion batteries.[41]

Another alternative is redox flow batteries, which use dissolved electroactive chemicals such as zinc or vanadium to circulate in tanks of liquid, rather than as solid electrodes.[42] The advantage is that they have high cycle durability since charge/discharge cycles do not physically deteriorate electrodes.[43] However, they have low energy densities and require large volumes of liquid and equipment for circulation.[44] Vanadium redox flow batteries are suited to electrical grids and have been employed commercially for that purpose.[45]

Employing older technologies is also a viable strategy, particularly if weight is not an overriding consideration, as is the case for stationary storage. Lead-acid batteries and other alternatives might be more suitable than any of the Li-ion options due to reduced cost.

Outside of traditional batteries, several other energy storage avenues exist and are being explored.

Battery supercapacitor hybrids (BSHs) combine an electrochemical battery with capacitors to store energy and present exciting possibilities. Capacitors store an electrical charge by holding a charge on metal plates separated by an insulator (a dielectric material). By replacing one of the traditional electrodes with an electrical double layer capacitor,[46] BSHs can provide much higher power by discharging more quickly compared to electrochemical batteries.[47] While energy density per unit volume is low, BSHs, have faster charging/discharging speed, improved lifespan (as measured by the number of charge/discharge cycles) and do not have the same risk associated with thermal runaway when compared to traditional electrochemical batteries.[48]

Fuel cells consume a fuel while discharging. The fuel must be replenished, much as a rechargeable battery must be recharged. Fuel cells are potentially more efficient than an internal combustion engine driving a generator because a fuel cell can convert the chemical fuel directly to electrical energy.[49] Hydrogen fuel cells emit only water,[50] making them zero-emission batteries.[51] The hydrogen fuel can be obtained through electrolysis of water (requiring energy), or by reforming methane and discarding or sequestering the resulting CO_2.

Mechanical energy storage technologies include pumped hydropower,[52] flywheel technologies, and elastomeric and compressed air energy storage.[53] These technologies offer promise for grid storage,[54] but might find other utility. Each technology faces challenges, for example limitations based on geography,[55] loss of cycle durability, and/or self-discharge over time. Thermal, electromagnetic, and other chemical means are other concepts for energy storage.

Research Directions

For commercial and government purposes, one strategy is to pursue research efforts simultaneously in as many directions as possible. The question then becomes: What should be the total level of effort and who should fund that research?

The US currently uses incentives that include grants, tax relief, government laboratory research, and other sponsored research projects that could support a variety of research directions. Given the importance of the technology, greater coordination and increased effort might accelerate development to ensure a leadership position. The government could "grade" the viability of various technologies to prioritize efforts, but breakthroughs might come from surprising directions. Research and development of rechargeable batteries using alternative materials can contribute to economic growth and provide a hedge for supply issues. Technical needs and supply chain issues are important considerations that require a diversity of approaches. Diversification can alleviate supply limitations and provide options for users with smaller-volume orders.

Commercial enterprises stand to gain the most as improved battery technology is obtained, but the US government has a vested interest in assured access for both commercial and government interests. In a competitive environment of rechargeable battery supply, particularly of Li-ion batteries, the US should maintain a leadership position in the development of improvements and alternatives.

An Impending Collision

Barring a breakthrough in battery technology, a Li-ion wreck is imminent. Rechargeable batteries are vital to our way of life, but current Li-ion battery technology is on track to hold a monopoly on future production. The escalating demand for batteries will skyrocket as electric vehicles take over our roads. Further, renewable energy production will require load balancing using battery storage. As rechargeable batteries wear out and replacements are required, demand will swell even further. When demand exceeds supply, price increases and supply disruptions are inevitable.

China has avowed its intention to promote manufacturing that includes "energy saving cars and new energy cars."[56] China's actions by their industries in securing Li-ion supply chains and manufacturing capabilities suggest that their implementation strategy is to lock up the market in the crucial component of Li-ion rechargeable batteries. In the same way that China dominates the solar cell market and Asia dominates semiconductor manufacturing, the US could find itself dependent on China for Li-ion batteries. This dependence could occur despite current efforts to incentivize greater US production, resulting in significant economic impacts for the commercial sector and operational impacts for defense applications.

Moreover, the performance of Li-ion batteries will need improvement to support future applications. Improvements are possible but not automatic. Current trends suggest a lack of focus on developing those improvements, because most efforts are at an emerging research stage. The *Invisible Hand* may not be pushing hard enough because there is an assumption that current technology is good enough or that someone else will satisfy the demand.

Clearly, the US needs to focus on research and development, coordinate efforts, and develop approaches to mitigate supply chain issues and assure future supplies. Approaches that prevent over-reliance on current Li-ion supply chains is important for US economic and national security futures.

Endnotes

1 "**With Market Size Valued at $173.7 Billion by 2026, it's a Healthy Outlook for the Global Battery Market**," *PR Newswire* January 18, 2022**.**

2 **"A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation,**" World Economic Forum, Insight Report, September 2019.

3 "**Building Resilient Supply Chains, Revitalizing American Manufacturing, And Fostering Broad-Based Growth: 100-Day Reviews under Executive Order 14017**," The White House, June 2021.

4 "**Global Battery Market to Reach US$173.7 Billion by the Year 2026**," *GlobeNewswire* April 29, 2022**.**

5 "**Building Resilient Supply Chains**," White House Report: 9**.**

6 Bloomberg New Energy Finance, 2019 Long-Term Energy Storage Outlook, July 31, 2019: 60.

7 "**Building Resilient Supply Chains**," White House Report: 9.

8 Govind Bhutada. "**Mapped: EV Battery Manufacturing Capacity, by Region**," Visual Capitalist February 28, 2022.

9 Fred Lambert. "**13 Battery Gigafactories Coming to the US by 2025 – Ushering New Era of US Battery Production**," Electrek December 27, 2021**.**

10 Also known as the **Bipartisan Infrastructure Law.**

11 Jeff St. John. "**Biden Admin Aims to Make the US A World Leader in Lithium-ion Batteries**," Canary Media, June 9, 2021.

12 "**National Blueprint for Lithium Batteries 2021-2030**," Federal Consortium for Advanced Batteries, June 2021.

13 "**Sustainable Batteries Roadmap to 2030 and Beyond**," Nanowerk February 9, 2022.

14 US Department of Defense, **"Securing Defense-Critical Supply Chains: An Action Plan Developed in Response to President Biden's Executive Order 14017**, February 2022.

15 "**Building Resilient Supply Chains**," White House Report": 147.

16 Kim Byung-wook. "**[Herald Interview] 'Lithium-ion Batteries Are Approaching Theoretical Limits on Energy Density**.' " *The Korea Herald* June 24, 2020.

17 "**What is a Solid-state Battery?**" Samsung, April 27, 2022.

18 Greg Avery. "**Colorado Startup Solid Power Goes Public, Raises Nearly $543M in SPAC Deal**," *Denver Business Journal* December 9, 2021**.**

19 "**Solid-state Battery Developed at CU-Boulder Could Double the Range of Electric Cars**," University of Colorado Boulder, CU Boulder Today, September 18, 2013.

20 "**Building the Best Battery**," QuantumScape, April 27, 2022**.**

21 Alex Scott. "**A Solid Opportunity for Lithium-Ion Batteries**," Chemical & Engineering News September 2, 2021.

22 Jordi Sastre, et al. "**Blocking Lithium Dendrite Growth in Solid-state Batteries with an Ultrathin Amorphous Li-La-Zr-O Solid Electrolyte**," *Communications Material* 2(76) July 2021.

23 Daxian Cao, et al. "**Lithium Dendrite in All-Solid-State Batteries: Growth Mechanisms, Suppression Strategies, and Characterizations**," *Matter* 3(1) July 2020: 57-94.

24 "**Battery500: Progress Update**," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, May 19, 2020.

25 "**Development of a Lithium-air Battery with an Energy Density over 500 wh/kg,**" *Science Daily* January 20, 2022.

26 George Liddle. "What is a Lithium Sulfur Battery?" Lyten, July 26, 2021**.**

27 Mengya Li, et al. "**5 – Progress of Nanotechnology for Lithium-sulfur Batteries**," *Frontiers of Nanoscience* 19 (2021): 137-164.

28 **Mengya Li, et al. "5 – Progress.**"

29 Example companies include Lyten (US) and Graphene Batteries AS (Norway) **Lyten**, May 31, 2022. **and** "**Graphene Enhanced Lithium Sulfur Batteries (Energy Storage Innovations USA 2019)**," IDTechEx, 2019**.**

30 Ioana Patringenaru. "**A New Solid-state Battery Surprises the Researchers Who Created It**," UC San Diego News Center, September 23, 2021.

31 Jieun Lee, et al. "**Issues and Advances in Scaling up Sulfide-Based All-Solid-State Batteries**," *Accounts of Chemical Research* 54(17) August 17, 2021: 3390-3402.

32 Example companies include Sila Nanotechnologies (US), Amprius (US), NanoGraf (US), Nexeon (UK/Japan), and Sicona (Australia). See Rebecca Bellan. "**Sila Nanotechnologies' Battery Technology Will Launch in Whoop Wearables**," *TechCrunch* September 8, 2021**;** "**Amprius Technologies Announces Breakthrough Extreme Fast Charge Capability of 80% Charge in Six Minutes**," *PR Newswire* December 7, 2021**;** "**Our Technology**," NanoGraf, May 31, 2022, "**Consortium Invests $80M in Silicon Anode Company Nexeon; Strategic Partnership with SKC**," Green Car Congress, January 27, 2022**; "About Us**," Sicona, May 31, 2022, **.**

33 "**China's CATL Is Developing New EV Battery with No Nickel, Cobalt, Exec Says**," *Reuters* August 15, 2020.

34 K. M. Abraham. "**How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts?**" ACS Energy Letters 5(11) October 23, 2020: 3544–47.

35 "**The Future Roadmap for Sodium-Ion Batteries**," Blackridge Research & Consulting, February 17, 2022.

36 Sample companies include Natron Energy (US), Faradion (UK), and CATL (China). "**Technology**," Natron Energy, May 31, 2022. "**Reliance New Energy Solar to Acquire Faradion Limited**," Faradion, December 31, 2021**;** "**CATL Unveils Its Latest Breakthrough Technology by Releasing Its First Generation of Sodium-Ion Batteries**," Contemporary Amperex Technology Co., Limited, July 29, 2021.

37 "**Are There Any Lithium Battery Alternatives?**" *New Scientist* April 27, 2022,

38 M.J. Milden. "**Five-Year Update: Nickel Hydrogen Industry Survey**," IEEE Aerospace and Electronic Systems Magazine 6(11) November 1991: 14-16.

39 "**Lithium-Ion Battery Maintenance Guidelines**," Textronix, July 14, 2022**.**

40 Yanguang Li and Jun Lu. "**Metal–Air Batteries: Will They Be the Future Electrochemical Energy Storage Device of Choice?**" *ACS Energy Letters* 2(6) May 5, 2017.

41 Yanguang Li and Jun Lu. "**Metal–Air Batteries**."

42 These liquid electrodes are referred to as the "anolyte" and "catholyte."

43 Alan Michael Pezeshki. "**Impedance-Resolved Performance and Durability in Redox Flow Batteries**," University of Tennessee, Knoxville, 2016.

44 Feng Pan and Qing Wang. "**Redox Species of Redox Flow Batteries: A Review**," *Molecules* 20(11) November 18, 2015: 20499–517.

45 Andy Colthorpe. "**Sumitomo Electric Brings 51MWh Flow Battery Online in Northern Japan**," *Energy Storage News* April 6, 2022.

46 Wenhua Zuo, et al. **"Battery-Supercapacitor Hybrid Devices: Recent Progress and Future Prospects**," *Advanced Science* 4(7) July 2017: 1600539.

47 "**BU-209: How does a Supercapacitor Work?**" Battery University, October 22, 2021.

48 Martin Keenan. "**Hybrid Capacitors Combine Technologies to Get the Best of Both Worlds**," Avnet March 15, 2017.

49 "**Fuel Cells**," U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, August 8, 2022.

50 "**Hydrogen Fuel Cell Vehicles**," United States Environmental Protection Agency, October 4, 2021.

51 "Alternative Fuels Data Center: **Vehicle Search**," US Department of Energy**.**

52 "**Pumped Storage Hydropower**," United States Department of Energy, Office of Energy Efficiency & Renewable Energy, April 27, 2022.

53 "**Mechanical Energy Storage**," Energy Storage Association, April 27, 2022.

54 For instance, pumped hydropower storage accounts for over 90% of the world's energy storage. (See: "**Pumped Hydro**," International Hydropower Association, April 27, 2022)**.**

55 For example, compressed air storage facilities require large underground caverns, and pumped hydropower requires large volumes of water and significant elevation changes, which makes it unsuitable for flat regions such as the Midwest. See: Rachel Carnegie, et al. "**Utility Scale Energy Storage Systems**," State Utility Forcasting Group Report June 2013**.**

56 "'**Made in China 2025**' Plan Issued," The State Council, The People's Republic of China, May 19, 2022**.**