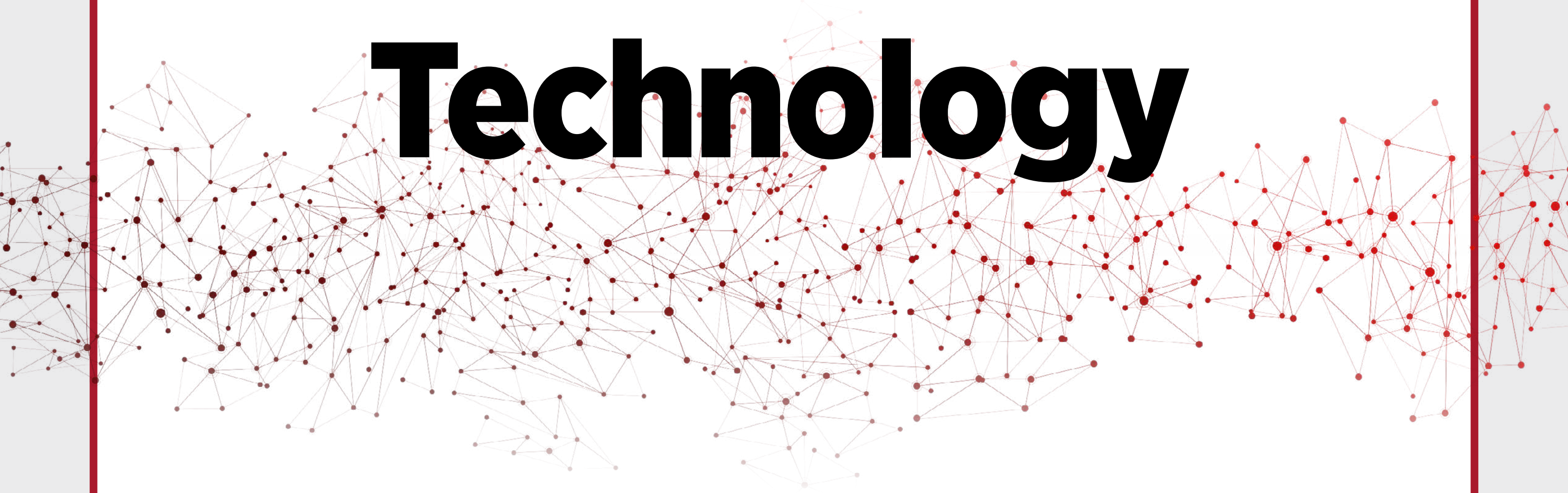
TECH FACTSHEETS FOR POLICYMAKERS

FALL 2020 SERIES

Battery Technology



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The Technology Factsheet Series was designed to provide a brief overview of each technology and related policy considerations. These papers are not meant to be exhaustive.

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Executive Summary

A **battery** is a device which stores chemical energy and converts it to electrical energy.[1] Battery technology is pervasive for individual consumers and in scaled operations, whether that is through the use of smartphone, automotive vehicles, or even large-scale data centers. The most popular battery type currently is *lithium-ion*, which ranges in application from powering small cellular devices to the electrical grid.

Advancements in battery technology have been relatively slow due to the complex chemistry involved and the challenges to commercialize while maintaining safety. Improvements in battery technology, though, would mean enhanced energy availability and consumer electronics performance. The promises of emerging battery technology include enhanced smartphone battery life, reliable electric transportation, more efficient energy storage for large-scale buildings, and even energy storage for the grid.[2] New designs could also address environmental and safety concerns regarding raw material sourcing, as well as battery disposal. However, it remains difficult for even the most promising battery experiments to find their way out of research labs and into the devices we carry. Despite these conditions, there are many researchers and innovators working towards the cause.

At a national level, many countries have acknowledged the important role that novel battery technology will play in clean energy production, as well as competitiveness in the automotive sector. Though the United States has regulations of existing technology and investment plans for emerging technology research and development, there is still an observable gap in policy and the public sector engagement. With the emergence of competitive strategies from other nations and blocs, such as the European Union's Strategic Action Plan on Batteries[3], it is increasingly important for the U.S. to focus and develop a public approach to battery technology investment that capitalizes on the promises of the technology, while minimizing foreseeable harms.

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[1] Bates, M. (2012, May 1). How does a battery work? Retrieved January, 2021, from https://engineering.mit.edu/engage/ask-an-engineer/how-does-a-battery-work/

[2] Goode, L. (n.d.). Batteries Still Suck, But Researchers Are Working on It. Retrieved January, 2021, from https://www.wired.com/story/building-a-better-battery/

[3] European Union, European Commission. (2018). Retrieved from https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/com20180293-annex2_en.pdf

What are Batteries?

A **battery**, made up of one or more separate *electrochemical cells*, is a device which stores chemical energy and converts it to electrical energy.[4] The chemical reactions in a battery produce a flow of electrons through an electric circuit, generating an electric current that can be used to power devices.

More specifically, during the **discharge cycle**, electricity is produced through the flow of electrons from one electrode called the **anode** or negative electrode, to another called the **cathode** or positive electrode.[5] Under discharge, the anode produces electrons through an electrochemical reaction, and generates positive ions that go into the **electrolyte** solution. The negative electrons travel across the external circuit under a voltage difference (creating electric current) to the cathode, where they combine with positively charged ions from the electrolyte. Positively charged ions flow through the electrolyte solution from the anode to the cathode to maintain charge balance. The electrolyte solution has a semi-permeable barrier called a separator or membrane that prevents shorting between the electrodes while allowing the required ion transport.[6] During the **charge cycle**, the process is reversed, as positively charged ions return to the negative electrode through the electrolyte solution and electrons return from the positive electrode.

Battery *performance* can be evaluated along several different metrics:

- **Voltage (SI unit: volts)** is the difference in electric potential between cathode and anode. which in practical terms is the driving force with which electrons are transported through the circuit.[7]
- **Current (SI unit: amperes)** is the amount of electric charge (directly proportional to the number of electrons) per unit of time flowing through the external circuit.[8]
- **Power (SI unit: watts)** is the product of the voltage and current, the rate at which electrical energy can be discharged.[9]

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[4] "How does a battery work?" (2012).

[5] Bhatt, A., Forsyth, M., Withers, R., & Wang, G. (Eds.). (2018, March 05). How a battery works. Retrieved January, 2021, from https://www.science.org.au/curious/technology-future/batteries

[6] Were the separator to break down, dendrites (small metal slivers) form a bridge from the cathode to anode and short the circuit, causing a meltdown. This is what happened to the Samsung Note cell phones in 2016.

[7] Fluke. (2016, October 31). What is Voltage? Retrieved from https://www.fluke.com/en-us/learn/blog/electrical/what-is-voltage

[8] Sevian, H. (2000, Summer). Batteries, current, and Ohm's law. Retrieved January, 2021, from http://physics.bu.edu/py106/notes/Ohm.html

[9] Carruthers, T. (2018, January 19). Battery power explained. Retrieved from https://www.science.org.au/curious/technology-future/battery-power-explained

- **Capacity (SI unit: ampere-hours)** is the amount of stored charge that is usable during battery operation. It impacts the time over which a battery can deliver a steady supply of power and is used to evaluate the length of time a battery can keep a device running.[10]
- Batteries lose their cycling capacity over time due to **self-discharge**, which is when local electrochemical reactions unrelated to generating electricity in the external circuit occur in the battery cell.[11,12,13] These local electrochemical reactions reduce the potential difference across the electrodes, resulting in less driving force for flow of electrons during battery operation. It can also result in a depletion of the usable capacity of the battery over time.
- **Volumetric energy density** is the amount of energy measured in Watt-hours per unit of volume measured in liters.[14] The higher the volumetric energy density, the smaller a battery needs to be for the same given total amount of energy.
- **Specific energy density** is the amount of energy per unit of weight measured in kilograms, meaning that the higher specific energy the lighter the battery.[15]
- **Cycle life** is the number of times a battery can be charged and discharged before it fails to meet its defined requirements, for example, having at least 80% of the original discharge capacity.[16]
- **Charge rate** is the speed with which a battery is charged relative to the battery's capacity.[17]

The chemical composition and construction of different battery types impact battery performance, as well as safety, life span, real estate requirements, and more. These characteristics impact the usability of each battery type in various consumer and commercial applications.

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[10] Honsberg, C., & Bowden, S. (n.d.). Battery Capacity. Retrieved January, 2021, from https://www.pveducation.org/pvcdrom/battery-characteristics/battery-capacity

[11] Garche, J., & Dyer, C. K. (2013). *Encyclopedia of electrochemical power sources*. Amsterdam: Academic Press.

[12] Attia, P. M., Das, S., Harris, S. J., Bazant, M. Z., & Chueh, W. C. (2019). Electrochemical Kinetics of SEI Growth on Carbon Black: Part I. Experiments. *Journal of the Electrochemical Society, 166*. doi:https://doi.org/10.1149/2.0231904jes

[13] Das, S., Attia, P. M., Chueh, W. C., & Bazant, M. Z. (2019). Electrochemical Kinetics of SEI Growth on Carbon Black: Part II. Modeling. *Journal of the Electrochemical Society, 166*. doi:https://doi.org/10.1149/2.0241904jes

[14] Cao, W., Zhang, J., & Li, H. (2020). Batteries with high theoretical energy densities. *Energy Storage Materials, 26*, 46-55. doi:https://doi.org/10.1016/j.ensm.2019.12.024

[15] Lithium-Ion Battery. (2020, September 25). Retrieved from https://www.cei.washington.edu/education/science-of-solar/battery-technology

[16] Severson, K., Attia, P., Jin, N., Perkins, N., Jiang, B., Yang, Z., . . . Braatz, R. (2019, March 25). Data-driven prediction of battery cycle life before capacity degradation. Retrieved from https://www.nature.com/articles/s41560-019-0356-8

[17] *A Guide to Understanding Battery Specifications* (Publication). (2008, December). Retrieved https://web.mit.edu/evt/summary_battery_specifications.pdf

Types of Batteries

Lithium-ion batteries (Li-ion) are the most common modern battery type. They are most common in consumer electronics, but they are also being increasingly adapted to other uses and are the locus of innovation in battery technology today.[18]

In Li-ion batteries, lithium ions shuttle through the electrolyte solution from one electrode to the other. The anode is usually made of carbon-based compounds like graphite. The cathode is usually made of transition metal compounds that contains lithium in their molecular structure[19]. Differences in the battery's cathode, anode, and electrolyte solution give the battery different strengths and weaknesses.[20]

Li-ion batteries tend to outperform the other most common battery type, lead-acid batteries, across every metric, but their increased cost of production and safety concerns have limited broader commercial adoption until the last few years. They remain the focus of most energy storage research today and are expected to have the broadest range of commercial applications in the near future.

Lithium-ion batteries are usually classified by the electrochemical properties of their electrodes. Depending on the intended use case of the lithium-ion battery, different chemistries are used.

Beyond Traditional Lithium-ion batteries

- **Lithium-air** batteries currently in the earliest stages of development would use oxygen from their environment as the cathode material.[21] This would make the battery much lighter than other lithium-ion battery and give it much greater theoretical energy density.[22] One obstacle is finding an electrolyte material that can keep the anode from reacting with the air and becoming unstable. Exposing the battery cell to the air can also result in other chemical reactions that produce compounds that cover the electrode's surface and impede it from working.[23]
- **Lithium-sulfur** batteries have a cathode made of a sulfur-based compound and an anode made of lithium. These batteries have a higher energy density than lithium-ion batteries, and are

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[18] For more information on the history of lithium-ion batteries, read Seth Fletcher's book *Bottled Lightning: Superbatteries, Electric Cars, and the New Lithium Economy*.

[19] "Lithium-Ion Battery" (2020).

[20] Carruthers, T. (2019, September 19). Why are there so many types of batteries? Retrieved from https://www.science.org.au/curious/technology-future/why-are-there-so-many-types-batteries

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[22] Rahman, M., Wang, X., & Wen, C. (2014). A review of high energy density lithium–air battery technology. *Journal of Applied Electrochemistry, 44*, 5-22. doi:https://doi.org/10.1007/s10800-013-0620-8

[23] Girishkumar, G., McCloskey, B., Luntz, A. C., Swanson, S., & Wilcke, W. (2010). Lithium−Air Battery: Promise and Challenges. *The Journal of Physical Chemistry Letters, 1*, 2193-2203. doi:https://doi.org/10.1021/jz1005384

potentially much cheaper, but commercialization remains a long way off due to a lower capacity, higher self-discharge rate, and worse safety.[24]

- **Sodium-ion batteries** have a cathode made of a sodium-based compound. Sodium is more abundant and easily sourced than lithium, making this battery potentially much cheaper than Li-ion alternatives, but has less energy density and is still not widely commercially available.[25,26,27] This makes sodium-ion batteries more likely to be applied in renewable energy storage than consumer electronics in the future.[28]

- **Aluminum-ion batteries** could be much cheaper than other alternatives given the ubiquity of aluminum on Earth. In addition, it offers high theoretical capacity and safety. However, the electrochemical reaction associated with aluminum is fairly sluggish, limiting its power output. This technology has seen focused research over the last five years and is probably at least a decade away from feasibly being deployed at scale.

- **Solid state batteries** refer to lithium-ion batteries where the electrolyte is a solid rather than a liquid. Using a solid electrolyte is safer and lighter than a liquid electrolyte and can be made more compact.[29] This gives solid state batteries higher energy density than traditional lithium-ion batteries. However, this technology is not only more expensive than liquid electrolytes,[30] but also unstable during fast charging when scaled up to the battery pack level. Solid electrolytes come in two variants: solid polymers and ceramics. **Solid polymers** operate at high temperatures of 220 degrees Fahrenheit or greater, while **ceramics** operate at room temperature have the advantage of acting like a liquid without the safety concern.[31] In late 2020, a number of companies such as Toyota, Quantumscape and others claimed to have a feasible solid state battery technology that can be potentially scaled up to electric vehicle battery packs in an economically feasible manner.

- **Lead-acid batteries** are a kind of battery in which the cathode is made of lead oxide, the anode is made of lead, and the electrolyte is a sulfuric acid solution.[32] This battery was the first type of

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[24] Zhang, S. S. (2013). Liquid electrolyte lithium/sulfur battery: Fundamental chemistry, problems, and solutions Author links open overlay panel. *Journal of Power Sources, 231*, 153-162. doi:https://doi.org/10.1016/j.jpowsour.2012.12.102

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[27] Chayambuka, K., Mulder, G., Danilov, D. L., Notten, P. H. L. (2018). Sodium- ion battery materials and electrochemical properties reviewed. *Advanced Energy Materials* 8(16). doi:https://doi.org/10.1002/aenm.201800079

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[30] Battery experts: Solid-state tech could be five years away for EVs. (2019, September 16). Retrieved from https://www.sae.org/news/2019/09/battery-show-solid-state-battery-roundtable

[31] Rathi, A. (2019, April 8). How we get to the next big battery breakthrough. Retrieved from https://qz.com/1588236/how-we-get-to-the-next-big-battery-breakthrough

[32] May, G. J., Davidson, A., & Monahov, B. (2018). Lead batteries for utility energy storage: A review. *Journal of Energy Storage, 15*, 145-157. doi:https://doi.org/10.1016/j.est.2017.11.008

rechargeable battery invented, and remains among the most commonly used, particularly for combustion vehicles and domestic energy storage in developing countries due to their low cost and high current.

- **Flow batteries** decouple the energy storage and power generation by storing the electro-active material in electrolytes in separate chambers. The two electro-active species are circulated by pumps through a separate module (a "stack") where the actual electrochemical reaction takes place.[33] These batteries have a long lifespan, low self-discharge, and the scope to be scaled up flexibly based on real estate availability.[34,35,36,37] However, most traditional chemistries have low energy density, making them better suited to large-scale energy storage than consumer applications.[38]

Battery Recycling

This technology is increasingly important both to alleviate waste management and environmental protection concerns around materials used in Li-ion batteries. Recycling will enable lowering of manufacturing costs by recovering valuable raw materials such as cobalt, nickel, and lithium from end-of-life batteries[39] and from batteries that fail quality control after manufacture. Recovery of raw material is crucial to the battery supply chain being aligned with globally increasing demand, as it buffers the shortfall from the slow mining and chemical processing steps. Recycling technologies are becoming increasingly prevalent inside battery manufacturing plants, but currently the process is quite energy and capital intensive. Steps need to be taken towards making this process sustainable in the long run. Some independent start-ups making huge progress in setting up large-scale recycling plants in 2021 are Li-Cycle and Redwood Materials. Fluctuations in raw material prices also cast long term uncertainty in the economic feasibility of battery recycling at scale.[40,41]

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[33] Pinnangudi, B., Kuykendal, M., & Bhadra, S. (2017). Smart Grid Energy Storage. *The Power Grid,* 93-135. doi:https://doi.org/10.1016/B978-0-12-805321-8.00004-5

[34] Yang, Z. *et al.* (2011). Electrochemical energy storage for green grid. *Chem. Rev.* 111, 3577–3613.

[35] Dunn, B., Kamath, H. & Tarascon, J. M. *et al.* (2011). Electrical energy storage for the grid: A battery of choices. *Science.* 334, 928–935.

[36] Wang, W. *et al.* (2013). Recent progress in redox flow battery research and development. *Adv. Funct. Mater.* 23, 970–986.

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[40] Jacoby, M. (2019, July 14). It's time to get serious about recycling lithium-ion batteries. Retrieved from https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

[41] Harper, G., Sommerville, R., Kendrick, E. *et al.* (2019). Recycling lithium-ion batteries from electric vehicles. *Nature* 575, 75–86. doi:https://doi.org/10.1038/s41586-019-1682-5

Common Applications and Market Development

Lithium-ion batteries were first used on a large, commercial scale in consumer electronics, particularly in smartphones and laptops. In addition to common devices today like smartphones and laptops, increasingly energy dense, safe, and cheaper batteries will be used in flexible devices such as wearable technology.[42] Today, much of the focus of research, in government, academia, and the private sector, is in applying lithium-ion batteries to electric vehicles and as storage of renewable energy.

Li-ion batteries can be used to store energy drawn from wind and solar farms, and smooth power to the electrical grid.[43] Renewable energy sources can be intermittent, and often out of sync with the demand pattern of a given area. Energy storage can be used to store excess energy generated at certain hours of the day and can buffer the deficit during other hours when energy production is insufficient to meet the demand. Lithium-ion batteries for renewable energy storage can be installed in a larger, centralized manner at the utility scale, or in a decentralized manner in homes along with rooftop solar panels.[44] Tesla's home energy storage battery, the Powerwall, is one example of the latter,[45] while the largest player of renewable energy and storage in the centralized utility scale in the U.S. is NextEra Energy.

Electric vehicle (EV) batteries with greater energy density and non-cobalt content promise to lower costs and improve range in a sustainable manner, which would accelerate mass consumer adoption.[46] For electric and electric hybrid planes and maritime shipping, lithium-ion batteries with much greater power and energy density and drastically improved safety will need to be developed.[47] Regulations will also need to be streamlined and adapted to battery-powered planes to enable commercial adoption.[48] As with planes, greater power and energy density can extend the flight time and speed of UAVs (drones), with applications for the consumer drone market, the military, transportation, agriculture, and more.[49]

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[42] Zhang, Z., Wang, P., Miao, X., Zhang, P., & Yin, L. (2020). Flexible and Wearable Lithium- Ion Batteries. *Flexible and Wearable Electronics for Smart Clothing*. doi:https://doi.org/10.1002/9783527818556.ch6

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[45] Powerwall: Tesla. (n.d.). Retrieved January, 2021, from https://www.tesla.com/powerwall

[46] Rathi, A. (2019, April 1). The complete guide to the battery revolution. Retrieved from https://qz.com/1582811/the-complete-guide-to-the-battery-revolution

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[49] Pappalardo, J. (2019, April 16). Lithium-Ion Batteries Aren't Good Enough for Electric Flight. But Maybe Lithium-Metal Is. Retrieved from https://www.popularmechanics.com/flight/drones/a27155551/battery-boeing

Battery Supply Chain

Electric vehicle lithium-ion batteries use three primary elements that are in relatively scarce supply in the Earth's crust: nickel, cobalt and lithium. Even so, they are still present in enough quantities to cater to the global demand for the years to come. Inefficiencies in mining methods, chemical processing and the delocalized global supply chain are the main factors that have held back the growth and cost-competitiveness of the industry.

Lithium is mined in the earth's crust in from three main sources – lithium brines, hard rock (spodumene) mines and lithium clay. The first two account for bulk of the production today in 2021. The lithium ore is concentrated and sent to chemical conversion sites. The conversion sites transform the ores to lithium salts - lithium carbonate (Li_2CO_3) and lithium hydroxide ($LiOH$). These two steps represent the 'upstream' part of the supply chain. The salts are sent 'downstream' to cathode material manufacturers, that turn them into cathode materials such as Li-NMC (Nickel-manganese-cobalt in 1:1:1 ratio; 8:1:1, 6:2:2 and 5:3:2 ratios are also made depending on the application) or Li-NCA (nickel-cobalt-aluminum in 1:1:1 ratio). The cathode active materials are then sent to cell manufacturers that turn them into cells and assemble them into battery packs ready to be put in an EV.

Nickel is primarily sourced from Indonesia, Philippines, Russia, New Caledonia and Australia, while cobalt's main source is the Democratic Republic of the Congo (DRC).

Major companies in the battery technology industry can be categorized by their position along the supply chain:

- **Raw materials producers.** The largest producer of lithium is Albemarle, which owns mines in Australia and Chile. Other main players in the mining space are Livent, Ganfeng Lithium and SQM. Glencore, Norilsk Nickel, Jervois Mining, Zhejiang Huayou Cobalt, and Sociedad Química y Minera (Chile) are some key suppliers of nickel and cobalt. Ores are shipped by Japanese trading companies (like Mitsui) to chemical conversion plants mainly located in China.
- **Active material manufacturers.** After chemical conversion, cathode manufacturing plants that convert the lithium carbonate and lithium hydroxide into NMC and NCA active materials, are mainly located in China and Japan. Contemporary Amperex Technology Limited (CATL)[50], Sumitomo Metal Mining, Umicore, Pulead Technology, and Beijing Easpring are some major players in the cathode material manufacture space. Hitachi Chemical, Shanshan Technology Co.,

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[50] Rathi, A. (2019, April 3). The inside story of how CATL became the world's largest electric-vehicle battery company. Retrieved from https://qz.com/1585662/how-catl-became-the-worlds-biggest-electric-car-battery-company

Ltd., Shenzhen BTR New Energy Materials Co. Ltd. and Mitsubishi Chemical together represent the largest suppliers of anode active material.[51]

- **Cell manufacturers.** Cell manufacturing is located all over the world. CATL, Samsung SDI, BYD[52], Panasonic, LG Chem and SK Innovation together account for most of the lithium-ion cell production in 2020.

The U.S. EV market's push towards new job creation in advanced industries creates the opportunity to "co-locate" lithium mining, lithium chemicals processing with battery production facilities and automotive factories. This would facilitate cost reduction by enhancing efficiency of the supply chain and create opportunities for vertical integration in the energy storage sector. An additional effect of vertical integration within the U.S. would be a reduction in price volatility of lithium and reliable future cash flows, creating conditions conducive for an influx of private investment.

The current market and development landscape demonstrate the need for national policies to incentivize research and development focused on practical battery chemistries that show promise of scalable commercial use in electric vehicles. EV demand is set to grow by ~15x[53] by 2030, but current mining outputs, being a huge bottleneck in the battery supply chain, project a shortage of battery materials of about 40% in 2030[54]. This creates an opportunity for technologies like battery recycling and innovation in mining and chemical processing technology to buffer the shortfall. Good policy-making and well-directed investments could be key in ensuring that the U.S. dominates the transition of this industry towards full electrification.

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[51] Bohlsen, M. (2020, January 16). A Look At The Top Li-Ion Battery Anode Manufacturers. Retrieved from https://seekingalpha.com/research/37628986-matt-bohlsen/5397287-look-top-li-ion-battery-anode-manufacturers

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[54] Kumar, V., Benchmark Mineral Intelligence, Stanford Energy Seminar, March 9, 2020.

Current Governance and Regulation

U.S. Regulation

Section 1502 of the Dodd Frank Wall Street Reform and Consumer Protection Act: Mandates disclosure requirements for companies with supply chains involving select "conflict minerals" in the Democratic Republic of the Congo (DRC).

- **Mercury-Containing and Rechargeable Battery Management Act of 1996:** Legislation mandating the phase-out of mercury in batteries, and providing for the recycling of lead acid, nickel cadmium, and other types of batteries. This is enforced by the Environmental Protection Agency.
- **U.S. Foreign Corrupt Practices Act (FCPA):** Legislation making it illegal for U.S. persons and businesses to give bribes to foreign officials to obtain business. This is enforced by the Department of Justice.
- **U.S. Energy Independence and Security Act of 2007:** Legislation that put forward mandates for energy efficiency and provided subsidies for moving to renewable energy, as well as supporting basic research, including the creation of a loan program for battery research.
- **American Recovery and Reinvestment Act of 2009:** Also known as the "stimulus," this legislation included significant subsidies for renewable energy and research, including in batteries.
- **U.S. Hazardous Materials Regulations:** Regulations enforced by the Department of Transportation that govern the transportation of hazardous materials, including lithium-ion batteries.
- **America COMPETES Act of 2007:** Provided funding and new mandates to encourage basic research. The legislation also created ARPA-E, an agency modeled on DARPA which is focused on renewable energy and related technologies, including lithium-ion batteries.

International Regulation

European Union Conflict Minerals Regulation: Similar to Section 1502 of the Dodd-Frank Act, these regulations enforced by the European Commission mandates companies disclose if their supply chains involve "conflict minerals," and work to avoid them. Unlike the Dodd-Frank Act, this regulation is not limited to minerals from the DRC.

International Governance Frameworks

Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas: Administered by the OECD, gives guidance for how companies can conduct due diligence to ensure their supply chains do not contain conflict minerals.

- **Cobalt Industry Responsible Assessment Framework (CIRAF):** Administered by the Cobalt Institute, this is guidance for cobalt producers and buyers to mitigate supply chain sourcing risks.
- **Mining Principles:** Administered by the International Council on Mining and Metals, this is guidance for companies to implement environmentally sustainable practices.
- **Global Battery Alliance:** Organized by the World Economic Forum (WEF), this is a public-private collaboration to develop sustainable battery supply chains.
- **Extractive Industries Transparency Initiative Standard:** Organized by the Extractive Industries Transparency Initiative, this provides standards for member countries to implement to improve supply chain transparency.

Public Purpose Considerations

- **Efficacy.** Fraudulent claims about battery performance are abundant, as it is difficult for investors—from both private and public funds—to verify performance. Such a popular industry is naturally prone to misinformation or misrepresentation due to inadequacies in the entrepreneur-investor relationship and fragmented policies governing battery testing and quality regulation. In order to protect consumers, it is important for policymakers to consider imposing regulation for ethics and data reporting regarding battery development and commercialization.[55]
- **Environmental Impact.** Decreasing use of fossil fuels for transportation and power could meaningfully combat climate change.[56] In 2019, Volkswagen released a life cycle analysis of the net carbon footprint of an internal combustion engine vehicle (ICEV) versus an electric vehicle[57] where they showed that the *cradle-to-grave* carbon footprint of an EV is much lower. However, inefficiencies in the lithium mining and lithium chemicals purification steps result in a relatively

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[55] BatteryBits. (2020, November 29). Preventing Fraud in the Battery World. Retrieved from https://medium.com/batterybits/preventing-fraud-in-the-battery-world-22e62bfbfbd

[56] Kah, M. (2019). *Electric Vehicle Penetration and Its Impact On Global Oil Demand: A Survey of 2019 Forecast Trends* (Rep.). SIPA Center on Global Energy Policy. Retrieved from https://energypolicy.columbia.edu/research/report/electric-vehicle-penetration-and-its-impact-global-oil-demand-survey-2019-forecast-trends

[57] Ludewig, C. (2019, April 24). Electric Vehicles with Lowest CO2 Emissions. Retrieved from https://www.volkswagen-newsroom.com/en/press-releases/electric-vehicles-with-lowest-co2-emissions-4886

higher *cradle-to-gate* carbon footprint than ICEVs. Public and private investments are needed at this step of the supply chain to mitigate the environmental damage and the associated risks.[58]

- **Access.** Lithium-ion battery types using cheaper materials will expand consumer access to electric vehicles, while those with greater energy density may make electric planes commercially viable.[59] However, other battery technologies are pricier, so ensuring accessibility with alternative energy generation and storage options is an important consideration of public purpose.

- **Consumer Welfare.** Safety concerns around lithium-ion batteries may increase the risk of injury to consumers.[60] The core safety concern from a technical standpoint is the need in most commercial lithium-ion batteries to use a highly flammable liquid electrolyte solution. These safety concerns have motivated much of the research into safer solid electrolytes. The stakes of ensuring safer battery technology rise as lithium-ion batteries are applied to electric cars and planes.

- **Security.** Greater use of lithium-ion batteries can reduce dependence on energy imports from the Middle East and other unstable regions. However, increasing demand for cobalt and other scarce resources used in batteries may increase conflict and human rights violations in fragile states that are the sources of such minerals, such as the Democratic Republic of the Congo (DRC).[61] The DRC accounts for over half of the world's known reserves of cobalt, and given the importance of cobalt to the production of the most popular lithium-ion batteries demand for the metal is expected to grow. In addition, most lithium-ion battery manufacturing capacity is concentrated in China, which raises security concerns as more of these batteries are embedded in automobiles and critical infrastructure in Western nations.[62]

- **Public Health.** Reduced air pollution can improve the incidence and severity of common respiratory health problems, such as asthma and bronchitis.[63] As legacy vehicles running on fossil fuels are replaced by electric vehicles, air quality in major cities such as Los Angeles could improve dramatically as smog diminishes. However, new risks to public health could emerge from the location of waste management sites. It is important to consider the public health of communities when transitioning battery technology, especially at the grid-level.

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[58] *Dirty Metals: Mining, Communities and the Environment* (Rep.). (2004). Retrieved https://www.earthworks.org/cms/assets/uploads/archive/files/publications/NDG_DirtyMetalsReport_HR.pdf

[59] Kapoo, R., MacDuffie, J., & Wilde, D. (2017, February). Analysis Shows Continued Industry-Wide Decline in Electric Vehicle Battery Costs. Retrieved January, 2021, from https://mackinstitute.wharton.upenn.edu/2020/electric-vehicle-battery-costs-decline/

[60] Baker, D. R., & Chediak, M. (2020, January 20). Everyone's Favorite Climate Solution Has a Fire Problem. Retrieved from https://www.bloomberg.com/news/articles/2020-01-28/everyone-s-favorite-climate-solution-has-a-fire-problem

[61] *"This Is What We Die For"* (Rep.). (2016). Retrieved https://www.amnesty.org/download/Documents/AFR6231832016ENGLISH.PDF

[62] United States, United States-China Economic and Security Review Commission. (2018). *United States-China Economic and Security Review Commission: Economics and Trade Bulletin*. Retrieved from https://www.uscc.gov/sites/default/files/Research/December%202018%20Trade%20Bulletin_0.pdf

[63] Schnell, J. L., Naik, V., Horowitz, L. W., Paulot, F., Ginoux, P., Zhao, M., & Horton, D. E. (2019). Air quality impacts from the electrification of light-duty passenger vehicles in the United States. *Atmospheric Environment, 208*, 95-102. doi:https://doi.org/10.1016/j.atmosenv.2019.04.003

Appendix: Key Questions for Policymakers

Industrial Policy

- How can the U.S. government catalyze strategic investment in the development of environmentally conscious and sustainable energy storage? What types of public-private partnerships should be developed with start-up companies in the energy storage or energy mobility space?
- One known barrier is the step from research to commercialization. How can or should the government assist the private sector in commercialization of promising new battery design?
    - There are also large job creation opportunities in "upstream" stages such as lithium mining and chemicals processing. How can the government assist in development of upstream technologies such that vertical integration of the battery supply chain becomes feasible?
    - Should government research support prioritize fundamental research aimed at increasing energy or power density or more practical research surrounding engineering related to scale-up of proven battery chemistries? What would provide larger marginal benefits for current and foreseeable U.S. energy needs?
- How can the government address the issue of misinformation by entrepreneurs and technologists and establish a clear regulatory framework surrounding the progression of breakthrough technologies for energy storage?
- How much should governments focus on subsidizing the adoption of downstream products like electric vehicles versus supporting basic research? Should subsidies favor U.S.-made products or U.S.-owned firms?
- Should policy encourage the development of more speculative uses for lithium-ion batteries, such as electric planes and maritime shipping? How should regulation be streamlined in these sectors to encourage innovation and commercial development?
- Is there a skills gap in battery manufacturing in the United States which has made domestic production nonviable? If so, should the Department of Labor create workforce training specifically for battery manufacturing?

National Security

- What should the United States do to mitigate the national security risks of battery supply chains embedded in fragile states, such as the DRC, and in great power rivals, such as China?
- Should the U.S. government develop policies to encourage the establishment of battery factories in the United States? What about promoting lithium-ion battery recycling?
- Should the U.S. government, through the Committee on Foreign Investment in the United States (CFIUS) or export controls, limit the foreign acquisition of domestic battery start-ups and associated products?
- How can the development of battery technology in the U.S. grid help support initiatives of domestic energy security? How much should battery technology become a focus of energy security initiatives?

Human Rights

- Should governments pass legislation to expand the range of elements covered by conflict minerals laws, in particular to include cobalt and lithium?
- Should the U.S. government mandate the adoption by firms of principles for supply chain transparent, in order for companies mitigate the risks of human rights abuses in their supply chain sourcing for raw materials, particularly in fragile states like the Democratic Republic of the Congo?

Environmental Protection

- What impact will more intensive mining of lithium, cobalt, and other metals have on the environment? Should regulators limit mining in particular regions with important ecosystems?
- Is there sufficient safety regulation around lithium-ion batteries, particularly for use in large-scale energy storage?
- How can battery recycling be done sustainably as well as in an economically feasible manner, given the massive scale of this budding problem?
- How should regulators balance the benefits of expanded lithium-ion battery use with safety concerns?