Reuse and Recycle: Preparing California for a Battery-Reliant Energy System

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Abstract: Lithium ion batteries will play a central role in the transition to a carbon-free economy, powering growing fleets of electric vehicles and providing large-scale storage to balance out the intermittent energy from renewable sources. Given California's ambitious climate goals, a paradigm-shifting transition to a battery-reliant economy is inevitable. It is therefore critical that policymakers be informed about the potential implications of ramping up lithium production, taking proactive steps to ensure that current electrification policies do not lead to unintended environmental degradation. This paper explores current trends in battery material sourcing and end-of-life disposal, as well as the market opportunities for repurposing and recycling Li-ion batteries. Finally, we recommend several policies the state can adopt to encourage the responsible management, reuse, and disposal of batteries.

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1. Background

California has made a name for itself by implementing ambitious climate and energy policies. Two in particular highlight the State's environmental leadership: Senate Bill 32, which expanded the state's mandate to reduce its greenhouse gas emissions by 80% of 1990 levels by 2050; and Senate Bill 100, which committed California to 100% carbon-free electricity by 2045. Achieving these goals will require the electrification of energy services currently served by fossil fuels combined with a shift towards renewable resources.

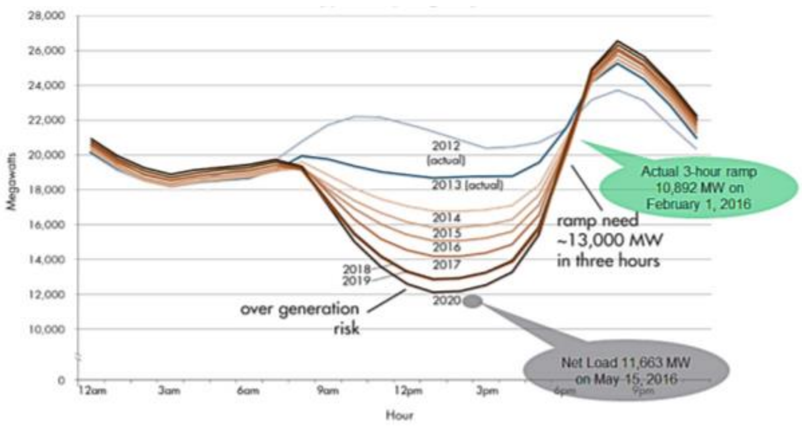


Figure 1: Net load on a typical spring day
Source: CAISO. (2016). *Fast Facts: What the duck curve tells us about managing a green grid.*

Arguably the greatest obstacle to meeting the state's greenhouse gas reduction goal is limiting emissions from the transportation sector, which currently account for 40% of all emissions. Efforts to electrify the transportation sector have focused on encouraging adoption of electric vehicles (EVs) through rebate and incentive programs to bring down costs, and investments in charging infrastructure across the state- including a network of fast chargers along the major highway corridors (CEC 2018). California is home to 47% of all EVs in the United States, and Governor Brown issued an executive order to get 5 million zero-emission vehicles on the road by 2030 (Roberts 2018). OPEC projects there will be 266 million EVs globally by 2040, however recycling rates of lithium ion batteries are currently less than 5% (Gardiner 2017).

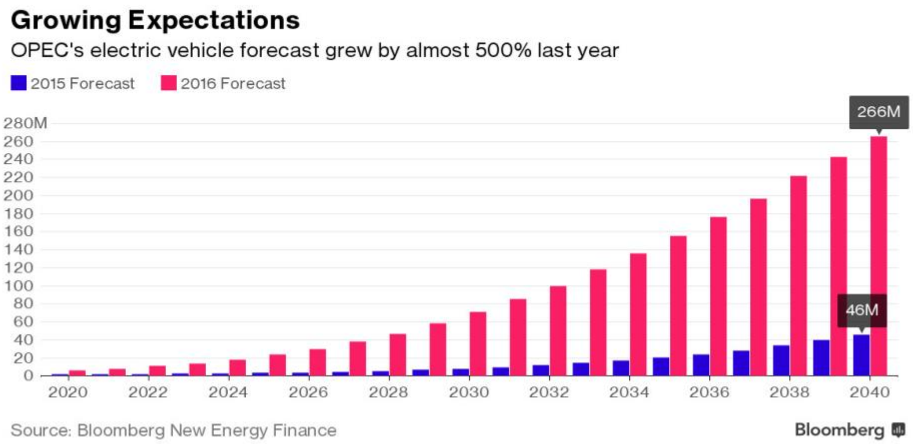
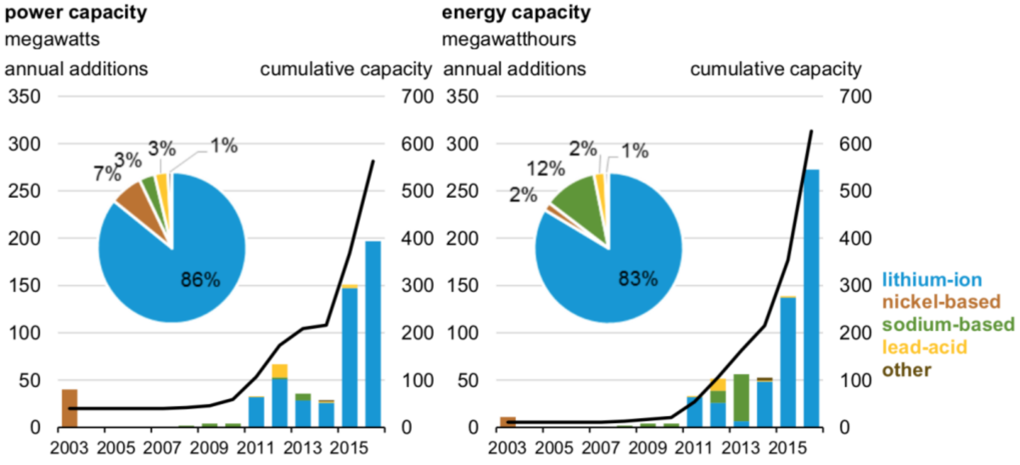


Figure 2: Forecast of electric vehicle demand through 2040

The 100% clean energy goal presents several key challenges. The first is the intermittency of renewables whose generation is dependent on weather conditions, season, and time of day; the second is balancing the supply of renewables with demand profiles. That imbalance is illustrated by the infamous “duck” curve, which shows the steep ramping up of peaker-plants that is required to meet demand in the evenings; folks return home to cook, cool/heat their homes, watch TV, etc., just as the sun is going down and PV electricity goes offline. Part of the solution is demand response; encouraging consumers to modify their behavior and shift energy use to off-peak hours. Utilities such as the Sacramento Municipal Utilities Department have implemented “time of use” electricity rates from 5-8:00 PM, encouraging consumers to reduce demand during peak hours. Another example is PG&E’s Base Interruptible Program, which rewards commercial users for reducing consumption during specific peak events such as heat waves. Even so, many experts agree that California needs to invest heavily in energy storage to balance out the grid.

The Clean Energy Task Force, an energy-policy nonprofit out of Boston, estimates that California needs to install more than 200 times as much as its current energy storage capacity to make up for the loss of its natural gas plants (Malik and Chediak 2018). They also estimate that if the majority of the 100% clean energy goal is met by solar and wind, California would need 36.3 million megawatt hours of energy storage; currently, it only has 150,000 megawatt-hours of storage (CEC 2018). Given the current trends in large scale battery chemistry, lithium-ion batteries will likely serve a large portion of these projected energy storage needs of the state (EIA 2018).

Figure 3: U.S. Large-Scale Battery Storage Capacity by Chemistry (2003-2016).



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

While Li-ion batteries present an exciting opportunity for a cleaner society, any major technological change is accompanied by its own unique winners and losers, and a shift to batteries is no exception. It is therefore critical that policymakers be informed about the potential implications of ramping up lithium production and take proactive steps to ensure that current electrification policies do not lead to unintended environmental degradation. This paper explores the current trends in battery material sourcing and end-of-life disposal, as well as the market opportunities for repurposing and recycling Li-ion batteries. Finally, we recommend several policies the state should adopt to encourage the responsible management, reuse, and disposal of batteries.

2. Current Trends

The modern-day battery has undergone numerous transformations, with centuries of scientific research and debate centered around finding the ideal conductive material. The earliest rechargeable version was the lead-acid battery, which is still used in internal combustion engine vehicles today. However, lead-acid's weight prevented it from being a successful option for electric vehicles. Nickel metal hydride (NiMH) and lithium-ion (Li-ion) are the other two commercially available technologies, with Li-ion generally considered to be superior for EV application (Gerssen-Gondelach & Faaij 2012). The advent of lithium-ion batteries revolutionized electronics, enabling the existence of portable laptops, smartphones, and equipping EVs with a range and performance that can compete with ICE cars (Fletcher 2013). As of 2016, the Li-ion batteries market in the automotive industry had reached $5 billion (Pillot 2015).

2.1 Material Sourcing

Lithium is the lightest metal on the periodic table and conducts electricity well, making it an ideal material for batteries. The element is found in brine and sedimentary rocks. Nearly all the lithium used in US batteries comes from brine in the Salar de Atacama, a 1,200-square-mile salt flat in Northern Chile (Dunn et al. 2015). It is produced by SQM, a Chilean chemical company that is the largest producer of lithium in the world. The other leading producers of lithium are Australia, China, and Argentina (Gaines 2009). Bolivia has extensive untapped resources in Salar de Uyuni, in part because the Morales government is adamant about developing themselves rather than letting a foreign company exploit its resources (Fletcher 2013).

Lithium carbonate can also be produced in Nevada, but the brine is seven times less concentrated. As a result, Argonne National Laboratories found the energy intensity of the resulting LiCO3 to be three times greater in Nevada than in Chile (Dunn et al. 2015). Nonetheless, the lithium deposits in Clayton Valley, Nevada are the only ones in North America, and as such have sparked serious entrepreneurial interest. Lithium Americas is one company that plans to operate, with the construction of a mine in Thatcher Valley scheduled for 2020 ("Lithium Americas"). According to Bloomberg Businessweek, at least six startups had leased claims in the area as of March 2017.

In lithium-ion batteries, the lithium is combined with a transition metal, typically nickel, cobalt, iron, or manganese. Cobalt has historically been the most widespread, as its tighter chemical bond with lithium yields greater stability, and it was widely adopted by the electronics industry (Shunmugasundaram et al. 2017). However, cobalt has a high economic and human cost; over 50% of the world's cobalt is mined in the Democratic Republic of Congo, where adults and an estimated 40,000 children work up to 12-hour days in abusive work environments, exposed to hazardous conditions with no protective gear (Amnesty International 2016). Cobalt is also the most expensive transition metal, with an estimated value of around $30/kg. Consequently, there has been a movement to replace cobalt with other transition metals, such as nickel or manganese. Using different metals changes characteristics such as the energy density, power density, cycle life, safety and cost of batteries (Yoshio, Brodd, & Kozawa 2009).

Lithium manganese oxide batteries are considered one of the promising options, as manganese is more common and much cheaper-- around $2/kg (Yoshio 2009). As such, the Department of Energy models battery life-cycle assessments under the assumption that most batteries in the future will be made with manganese (Dunn et al. 2015). Manganese is considered a critical resource for the US because it is vital to the steelmaking process, and the United States is entirely reliant on imports. The top global manganese producers are South Africa, Australia, and China, who account for 60% of the global market between the three of them (Cannon, Kimball, & Corathers 2017).

The United States is likely to remain reliant on imports of both lithium carbonate and manganese, although the government does not consider this a serious issue since the U.S. has a relatively stable relationship with the producing countries (Gaines 2009). Nonetheless, the availability and sourcing of materials such as lithium, cobalt, nickel, and manganese is a concern that should be taken into consideration when contemplating an increasingly battery-reliant future.

2.2 Battery Production

The production of lithium-ion batteries is heavily dominated by Japanese, Chinese, and Korean companies, as they have historically been used in electronic products manufactured in these countries (Fletcher 2013). However, unlike the raw materials, batteries have the potential to be produced in the United States. The domestic battery production industry was jump-started in August 2009, when the Department of Energy announced that $2.4 billion in stimulus funding would be allocated to battery technology producers as part of the American Recovery and Reinvestment Act (Fletcher 2013). The American industry is concentrated in Michigan; Johnson Controls, A123, Dow Kokam, and Compact Power were the four biggest winners of the stimulus package, and all had plans to build factories in the Detroit area. Detroit is also where GM manufactures the Chevrolet Volt and its batteries.

There are tradeoffs associated with producing batteries domestically versus abroad. Asian battery giants have been producing batteries for much longer and consequently have a more efficient system. However, batteries are heavy, and it is costly from an environmental and economic perspective to transport the commodity from Asia. From an energy security perspective, it is generally advantageous to rely on imports as little as possible for such a crucial element. Furthermore, as recycling processes develop to allow more materials to be reused in the manufacturing process, producing the batteries locally will cut down on the need for importing raw materials.

2.3 End-of-life Disposal

Compared to lead-acid batteries, which have a recycling rate of 99%, lithium ion recycling is much less straightforward. Estimates place recycling rates in North America around 3%, most of which comes from laptop batteries (Heelan et al). Existing battery recycling technologies were designed to recover cobalt and nickel, which are much higher value metals than lithium or manganese. Now, we are seeing battery technology move towards lithium manganese at a faster pace than the battery recycling technology can develop. Current recycling processes can recover lithium-containing materials, but further processing is needed to get them to a usable form (Dunn et al. 2015).

There are four potential battery recycling processes: hydrometallurgical and direct physical recycling, which are both under development, and pyrometallurgical and intermediate physical recycling, which are commercially available. Recycling processes can also be categorized by whether they are closed- or open-loop; can the outputs be directly reused in the battery manufacture process (closed-loop), or are they instead made available to the greater economy (open-loop)?

In hydro- and pyrometallurgical recycling processes, batteries are essentially melted down to recover different elements. The key difference is that hydrometallurgical recycling is better suited to recover materials in a usable form because batteries are broken down into their component parts (cathode, anode, etc.), then crushed and soaked in a chemical solution before heating. This means that aluminum, copper, graphite, and lithium carbonate can all theoretically be recovered and reused by battery manufacturers. Pyrometallurgical recycling only recovers the higher value metals, such as copper, cobalt, nickel. The lithium and manganese end up in a slag that can be used in concrete production, but it is not economically feasible to extract them (Dunn et al. 2015).

Intermediate physical recycling is the only commercially available technology capable of recovering lithium in a useful form (LiCO3). This is the recycling process used by Retriev

Technologies in Anaheim, CA., where batteries are manually disassembled, then crushed and separated into metal-enriched liquid, metal solids, and plastic fluff. Further processing is required to distill and synthesize LiCO3. Direct physical recycling is still in the development phase but is technically able to recover aluminum, copper, and LiMn2O4 so that they can be directly reused in a closed loop battery manufacture processed. Dunn et al. estimate that directly recycling these elements could reduce the energy consumption of the manufacturing process by up to 48% (2015).

The recycling industry in China is far more advanced than that of North America or Europe. According to a report by Creations Inc, 66% of EV battery recycling is expected to take place in China (Messenger 2018). The rapid development of China's recycling capacity is good from a closed-loop, environmental perspective, but if the United States does not catch up, they will lose the opportunity to recover precious materials and instead continue to rely on imports.

American policy around Li-ion battery recycling exists, but is not sufficient to incentivize a large-scale domestic recycling industry. At the national level, the US Environment and Protection Agency regulates the disposal of large quantities of batteries under the Universal Rules of Hazardous Waste. However, these regulations currently do not apply to Lithium-ion batteries (Mancha 2016). In California, the Rechargeable Battery Recycling Act of 2006 covers small rechargeable nickel-cadmium, nickel metal hydride, sealed lead-acid, and lithium-ion batteries not used in vehicles, and requires every retailer to accept batteries at no cost to customers for recycling, reuse, and proper disposal.

On September 27, 2018 California passed AB 2832 which requires the Secretary for Environmental Protection to form a Lithium-Ion Car Battery Recycling Advisory Group to advise and recommend safe and cost-effective policies on the recovery, reuse, and recycling of 100% of lithium-ion car batteries sold within the state to the Legislature by April 1, 2022. Since there are no federal regulations, California and this advisory board should also consider how these policies could be replicated by other states or at the federal level.

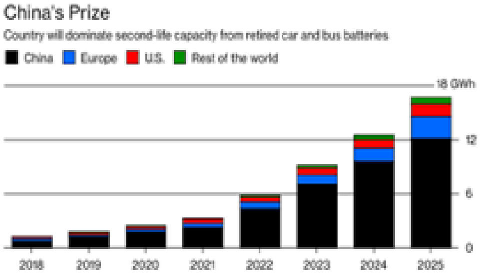
3. Market Opportunities

3.1 Reuse

When an EV battery degrades to eighty percent of its initial capacity, it can no longer be used as vehicle battery for safety reasons (Cready et al 2003). Meaning, when the battery is removed from an EV it still has a significant amount of charge that can be applied to other applications with less demanding energy requirements. Automobile manufacturers, renewable energy suppliers, emerging startups, and utilities are among those trying to create an aftermarket for end-of-life batteries. The most popular second-life for EV batteries currently is stationary storage, though there is a range of innovative re-uses in development across the world.

The case for EV battery reuse is both environmental and economic. As Amrit Chandan, a chemical engineer at the British startup Aceleron notes, “it takes so much energy to extract these materials from the ground. If we don’t re-use them, we could be making our environmental problems worse,” (Gardiner 2017). From an economic standpoint, there is the opportunity to generate second revenue streams for the used batteries (Stringer and Ma 2018). For an estimated five-year second-use life cycle, each battery could yield around $5,000. If these revenues could be factored into the EV business model, there is the opportunity to reduce one of the largest barriers to EV adoption: price.

Figure 4: Installed capacity of second-life batteries in China



Source: Circular Energy Storage

The second life market is primarily growing across the US, Europe, and Asia. According to a recent report by the research group Circular Energy Storage, the global market for end-of-life lithium-ion batteries is predicted to be worth $1.3 billion this year (Willuhn 2018).

By 2025, it is estimated that approximately 75% of spent EV batteries will be reused (Stringer and Ma 2018). The opportunities for reuse are dependent on the amount of battery degradation. Batteries with less than twelve percent of use, or eighty-eight percent of their State of Health (SOH) remaining, can be reused as an EV battery (Casala et al 2017: 272). Batteries with a SOH between 75% and 80% can be used for stationary applications, such as energy storage, peak shaving, and renewable firming (Casala et al 2017: 273). Examples include Nissan subsidiary 4REnergy’s repurposing of Leaf batteries into electricity storage units for a solar plant, and Fiat’s transition of their electric 500e model batteries to solar storage for an e-waste recycler firm called IT Asset Partners (Cunningham 2017). These batteries can also be used for lower load transportation services, such as short-range trucks or cars intended for intra-city travel. Finally, EV batteries with less than 75% SOH are dismantled into modules or cells. They can then be further developed into common batteries for smaller devisees, such as laptops or electric bicycles, or low-demand electric vehicles, such as golf carts (Casala et al 2017: 273).

3.1.1 Reuse Challenges

While the potential for reuse is promising, there are significant challenges. EV batteries are made by different manufacturers with different standards, including variations in construction and chemistry. The chemistry is often unlabeled, and therefore unknown by the third-party refurbisher. Other commonly cited concerns with the practice of reusing or repurposing EV batteries include uneven degradation of the batteries, decreased efficiency, limited life cycles, and undefined safety standards (Robinson 2017). Due to the lack of primary data around repurposing batteries, particularly around the use stage, it is difficult to understand the long-term impacts of reusing batteries at this point (Bobba et al 2018).

Tesla, a major player in the battery industry, has publicly stated their disinterest in pursuing second life uses. They have said their batteries are not suitable for new tasks after ten to fifteen years of use, due to uneven degradation of the batteries. According to Tesla CTO JB Straubel, “by the end of their life, the efficiency has degraded on every cycle, you see lower efficiency, the capacity will have somewhat degraded, and for a lot of reasons, it makes it very difficult to deploy those efficiently back into a grid setting, where you want high reliability and you do want predictability,” (Shahan 2016). Instead, they are focusing their efforts on recovering raw materials from their used batteries.

The market for battery reuse is expected to grow to $3.5 billion by 2025 (Willuhn 2018). As more end-of-life batteries enter the market, the exploration of second uses for them will continue to grow. Given that the automotive battery industry is still in the early stages of EV research and development, experts believe there is the potential for growth in the evolution of the products to improve their capacity for second life applications.

3.2 Recycling

Eventually, an EV battery’s useful life will end. When battery cells have degraded to the point where they cannot hold a charge, or if the battery is physically damaged, there are only two options left: landfill or recycling. The environmental case for recycling EV batteries is clear. The more materials that are recycled, the less raw that will be extracted from limited supplies in the ground, avoiding the significant negative impacts associated with mining and processing ores (Stringer and Ma 2018). The economic case is more difficult to define. Due to the complexity of the battery recycling process, and the low yield of material recovery, the retrieved raw material barely covers the cost of retrieval (Battery University 2019). The lithium-ion recyclers that exist today often have partnerships with a single car manufacturer and have tailored their recycling processes to serve their battery specifications.

Several private companies currently offer EV battery recycling, including American companies Retriev Technologies and Battery Solutions, as well as international companies Li-Cycle and Umicore. Depending on the company, the battery recycling method varies. Battery Solutions uses a specialized “room temperature, oxygen-free, mechanical process,” in which the battery is separated into cobalt and lithium salt concentrate, stainless steel, copper, aluminum and plastic. The products are then re-introduced to the market to be reused (Battery Solutions 2019). Umicore uses a unique pyro-metallurgical treatment and hydro-metallurgical process to recycle Li-ion batteries, resulting in an alloy composed of metals like cobalt, nickel, and copper, and a slag fraction that is typically passed on to the construction industry or further processed for metal recovery (Umicore 2019). There is no standard process between companies because the composition of the batteries used in electric vehicles is not standardized.

Many EV companies, including Tesla, Honda, and Nissan, have developed recycling capabilities for their specific variations of batteries. Tesla has a partnership with Kinbursky Brothers (owner of Retriev Technologies) in the US and with Umicore in Europe, where they have developed a closed-loop recycling system (Kelty 2011). Honda entered the battery recycling business in 2017 in Japan, citing the growing demand for vehicles that use lithium-ion batteries as the reason (Loveday 2016). Like the third-party recyclers, each car manufacturer-processor partnership has developed their own unique recycling process to address the needs of their specific batteries. Additionally, there are many EV batteries that are simply being stored away until there is the necessary amount to make the process more economically viable. According to Bloomberg NEF data, the global stockpile is forecasted to exceed 3 million packs by 2025, up from 55,000 (Stringer and Ma 2018).

3.2.1 Recycling Challenges

As noted, the lack of standardization in battery development presents a challenge to developing an effective recycling process. Since battery technology is still evolving, there is the concern that recycling processes for a specific design could quickly become irrelevant (Gaines 2014). Additionally, lack of regulation is a challenge. There are currently no regulations regarding the recycling of large-format Li-ion batteries. As noted by Gaines, “while this means recyclers face no restrictions in process design, they also face the possibility that restrictive regulations could be imposed after significant resources have been dedicated to establishing the recycling processes. Therefore, processes must be designed to be compliant with anticipated regulations,” (2014: 5). Similar to the future outlook for reuse of EV batteries, much of the future for recycling could be impacted by standardized battery design with more of an emphasis on end-of-life processes. As manufacturers are faced with the consequences of this down the line, there is the opportunity to design for recycling more effectively.

4. Solutions

While most experts agree that EV lithium-ion batteries reaching the end of their life on a large scale is still at least 10 years down the road, *now* is the time to pass meaningful regulations. Policies are necessary to create a sustainable and humane supply chain, promote energy security, and ensure systems will be in place to reuse and recycle these resources when that time comes.

Increasing the reuse of EV batteries, while a short-term solution, is an important part of the plan. China, where roughly half of total EVs are sold, has recently implemented a comprehensive plan to increase the rate at which EV batteries are returned and either reused or recycled (Stringer and Ma 2018). The program, launched in 17 major cities across China in August 2018, ambitiously plans to revise the industrial chain. It places the responsibility on car manufacturers to ensure that EV batteries are recovered by creating recycling channels and facilities where they can be collected, stored and transferred to recyclers (Stanway 2018). They are also expected to provide incentives to owners to ensure old batteries are disposed of correctly.

Simultaneously, China is launching the Regulation on the Battery Recycling and Traceability Management Platform, requiring EV battery manufacturers to code batteries in a standardized manner, similar to a car VIN number (Jiao 2018). Stakeholders who interact with the battery along its lifecycle will be required to upload the battery information onto the traceability management platform, increasing transparency into the battery's lifecycle and disincentivizing owners from illegal disposal (Jiao 2018). While it is unlikely that US regulation will reach the same level of involvement, some lessons can be learned from observing the Chinese program. Sharing second-life and end-of-life responsibilities between the original equipment manufacturers, both battery and vehicle, could encourage more collaboration between stakeholders and improve standardization.

On the supply side, there are two approaches regulators should pursue simultaneously: supporting global efforts to implement sustainable extraction processes and investing in research about different materials. Initiatives such as the World Economic Forum's Global Battery Alliance and the Responsible Cobalt Initiative already exist, and California should be a champion of their cause. Amnesty International also has released reports and guidelines for best practices that policymakers could look to for inspiration; for example, requiring that all EV manufactures be able to state exactly where their materials are sourced (Amnesty International 2016). Minimizing the need for rare earth metals can be accomplished through continued innovation-- improving the performance of batteries made with nickel or manganese while exploring the exciting possibilities offered by new materials such as Lithium-Sulphur or silicon (Fletcher 2013).

In the long-term, promoting a robust domestic battery recycling industry is perhaps the most effective means of minimizing the environmental burden of Li-ion batteries. To that end, the U.S. should follow China's lead in standardizing battery design in order to limit confusion and ensure that batteries end up in the correct recycling channels. Clear guidelines on who is responsible for end-of-life management is necessary; in China and Europe, for example, the onus for recycling batteries falls on the automakers. Incentivizing the use of recovered lithium and manganese in domestic battery plants could be another way to strengthen the U.S. recycling industry while it is still uneconomical for the private sector to do so on its own.

Batteries will play a central role in the transition towards carbon-free electricity and transportation. The rapid development of lithium-ion batteries specifically has enabled the global community to achieve great strides in electrifying transportation and storing energy from renewables. Now is the time to fully consider all the implications of this technological revolution and avoid solving one problem by creating another. By being informed and proactively implementing forward-thinking regulation, policymakers can guide us toward a more sustainable, equitable path forward.

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