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ELECTRIC BATTERY PRODUCTION AND WASTE: OPPORTUNITIES AND CHALLENGES

HEARING

BEFORE THE

COMMITTEE ON
ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

JULY 17, 2019

Printed for the use of the Committee on Environment and Public Works



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COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

ONE HUNDRED SIXTEENTH CONGRESS
FIRST SESSION

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ELECTRIC BATTERY PRODUCTION AND WASTE: OPPORTUNITIES AND CHALLENGES

WEDNESDAY, JULY 17, 2019

U.S. SENATE,
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS,
Washington, DC.

The Committee met, pursuant to notice, at 10:05 a.m. in room 406, Dirksen Senate Office Building, Hon. John Barrasso (Chairman of the Committee) presiding.

Present: Senators Barrasso, Carper, Inhofe, Capito, Braun, Rounds, Sullivan, Boozman, Ernst, Cardin, Whitehouse, Merkley, Markey, Duckworth, and Van Hollen.

OPENING STATEMENT OF HON. JOHN BARRASSO, U.S. SENATOR FROM THE STATE OF WYOMING

Senator BARRASSO. Good morning. I call this hearing to order.

The purpose of today's hearing is to evaluate the environmental challenges and opportunities associated with increased battery demand as well as disposal.

The global market for electric vehicles is expected to rise in the coming years. By 2025, up to 90 percent of the global market for lithium ion batteries will come from electric vehicles. This increase in demand, left unaddressed, will exacerbate current challenges associated with battery production and waste.

Lithium ion batteries use a number of critical minerals. They include lithium, cobalt, graphite, and rare earth elements as well. The United States and the rest of the world have allowed China to dominate control over the production of these minerals. China exerts substantial control over mining operations in countries with vast reserves, including the Democratic Republic of the Congo and Chile.

In May, Foreign Policy published a report entitled—I will hold it up here—Mining the Future: How China Is Set to Dominate the Next Industrial Revolution. So I would like to enter this report into the record, without objection.

[The referenced information follows:]

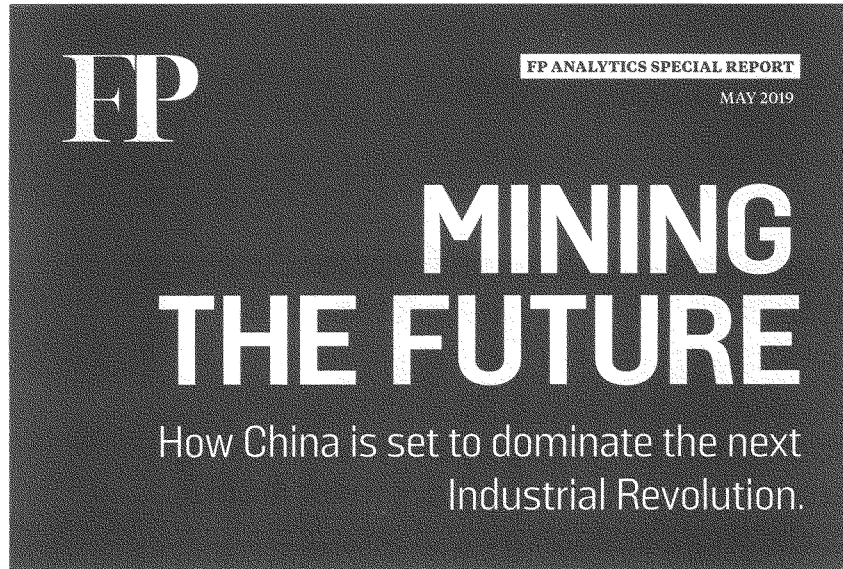


ILLUSTRATION BY GWEN KERAVAL

A fight between the United States and China is brewing over 5G and the question of who can be trusted to control the world's wireless infrastructure. But scant attention is being paid to an issue of arguably greater importance to the future of the world's economy and security: China's control of the raw materials necessary to the digital economy.

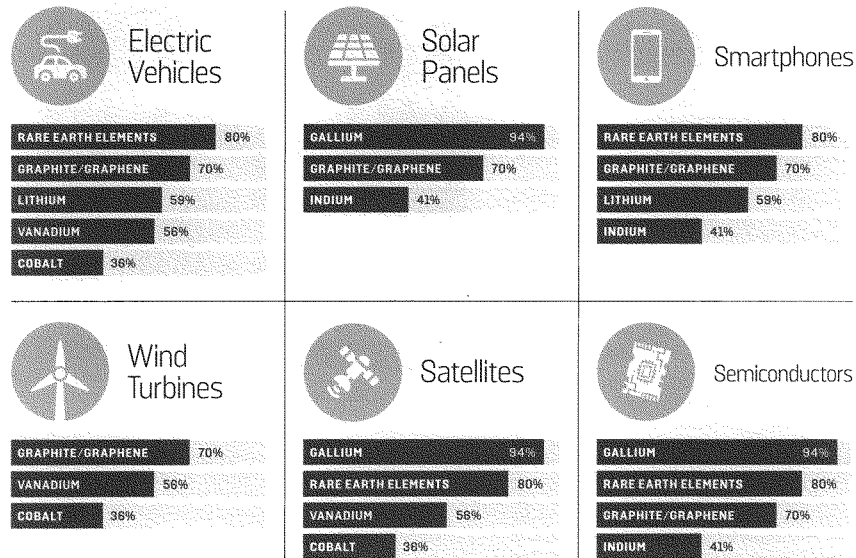
No new phone, tablet, car, or satellite transferring your data at lightning speed can be made without certain minerals and metals that are buried in a surprisingly small number of countries, and for which few commonly found substitutes are available. Operating in niche markets with limited transparency and often in politically unstable countries, Chinese firms have locked up supplies of these minerals and metals with a combination of state-directed investment and state-backed capital, making long-term strategic plays, sometimes at a loss. Through in-depth analysis of company reports and disclosures, mapping of deal flows, quantification of direct and indirect equity stakes, and other primary research, FP Analytics has produced the first consolidated review of this unprecedented concentration of market power. Without rhetoric or hyperbole, this fact-based analysis reveals how rapidly and effectively China has executed its national ambitions, with far-reaching implications for the rest of the world.

China's 13th Five-Year Plan declared 2016 to 2020 a "decisive battle period" for the nonferrous metal industry and for building a well-off society.¹ Its hallmark initiative,

"Made in China 2025," aims to build strategic industries in national defense, science, and technology. To meet these objectives, in October 2016, the Ministry of Industry and Information Technology announced an action plan² for its metals industry to achieve world-power status: By deploying state-owned enterprises and private firms to resource-rich hot spots around the globe, China would develop and secure other countries' mineral reserves—including minerals in which China already holds a dominant position.

The timing could not have been better. The fall in metal commodities prices from 2011 to 2015 left many mining companies desperate for capital. Even the largest global players, such as Anglo American, had to slash their workforces and shed assets.^{3,4} By directly acquiring mines, accumulating equity stakes in natural-resource companies, making long-term agreements to buy mines' current or future production (known as "off-take agreements"), and investing in new projects under development, Chinese firms traded much-needed capital for outright control or influence over large shares of the global production of these resources. Despite China's slowing growth and a

A Vast Sum of Parts *China's control or influence over critical minerals and metals that power modern technology is unrivaled.*



SOURCES: USGS; FPA ANALYSIS OF COMPANY FILINGS, DEAL FLOWS, EQUITY STAKES AND OFF-TAKE AGREEMENTS

major pullback in its foreign direct investment in other sectors, the government has maintained robust financial support for resource acquisition; mergers and acquisitions in metals and chemicals hit a record high in 2018.³

PART I

'Going Out and Bringing In'

Though it boasts a rich endowment of natural resources at home, China lacks significant reserves of three resources vital to its tech ambitions: cobalt, platinum-group metals, and lithium. It has successfully employed two strategies to secure control of them. One is driven by China's state-

owned enterprises (SOEs), which use development finance and infrastructure investment to embed themselves in higher-risk countries, establishing close ties with government leaders. The second is investment by state-linked private firms in market-based economies. Both strategies have shown agility and an ability to effectively adapt to local circumstances to achieve the same end.

SOE Strategy, Cobalt, and the Case of the Democratic Republic of the Congo

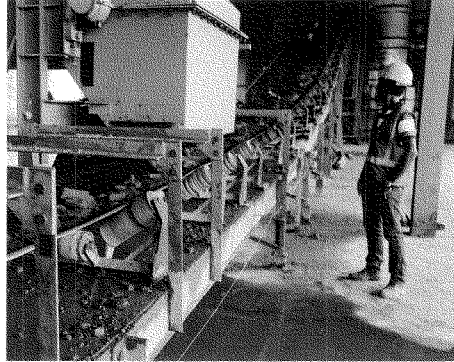
With few governments having articulated, let alone implemented, an explicit resource strategy, China is more than a decade ahead in the game. At a gathering last June in

Lubumbashi, the mining capital of the Democratic Republic of Congo (DRC), representatives from 35 Chinese mining companies announced the creation of the Union of Mining Companies with Chinese Capital to coordinate communication with the DRC's government.⁶ The announcement was less an inauguration than a formalization of the deep, long-term relationships between Chinese industry and DRC government officials that have been cultivated for decades: China now owns or has influence over half of the DRC's cobalt production,⁷ and has a massive stake in its mining industry. Six months ahead of the presidential elections, the event also sent a strong message to candidates about China's deep investment in copper and cobalt mining—which constitutes 80 percent of the DRC's export revenue⁸ and thousands of jobs—and its capacity to influence the future of the DRC's economy.

China's notably high tolerance for political and security risk and its ability to embed firms in the development of local industry have not only enabled Chinese SOEs to gain footholds in complex natural-resource markets, but given them a competitive edge over their rivals in the industry. Its patient acquisition of the DRC's cobalt resources serves as a case in point.

The DRC is home to nearly two-thirds of the world's cobalt production and half of its known reserves.⁹ Those resources are the prime target of investors for the booming battery industry. Over a decade of steady engagement, China has staked out a dominant position by developing strong political ties and investing in production assets and related infrastructure. Using development financing, in 2007, the Export-Import Bank of China issued¹⁰ \$6 billion for infrastructure (a figure later reduced to \$3 billion) and \$3 billion for copper and cobalt mine development.¹¹ Projects were run by Sinohydro and China Railway Group in exchange for a 68 percent mineral stake in the Sicomin copper and cobalt mine, thought to be one of Africa's largest.¹² China deepened the DRC's reliance on Chinese capital by committing to finance the revitalization of the DRC's state-run company Gécamines,¹³ strengthen the country's core industrial sector, and create needed jobs through additional sector investments.¹⁴

By targeting debt-stressed mining companies already established in the DRC, China's SOEs and private firms have secured equity shares and influence over a majority of its mines, including majority stakes in the Tenke Fungurume mine, which holds one of the world's largest, highest-grade deposits of copper and cobalt. China Molybdenum bought the majority stake (56 percent) from U.S. company Freeport-MacMoRan in 2016, and recently bought an additional 24 percent stake from Chinese private-equity firm BHR Partners.^{15,16,17} Over time, China has secured ownership over 10 out of the DRC's 18 major operational mines, six major development projects, and a



A worker watches a conveyor belt loaded with chunks of raw cobalt at a plant in Lubumbashi, the mining capital of the Democratic Republic of the Congo, on Feb. 16, 2018. SAMIR TOUNSI/AFP/GETTY IMAGES

three-year off-take deal from the DRC's (and the world's) largest cobalt mine,¹⁸ effectively establishing influence over 52 percent of the country's production.¹⁹

Recognizing the continued demand from global industry, former President Kabila and DRC officials implemented a 50 percent tax on superprofits in a revised mining code,²⁰ creating even more uncertainty about the country's future cobalt production. Before leaving office, Kabila declared cobalt a "strategic" metal and tripled the royalty tax, to boost local governments' profit share from the sector.²¹ Similar taxes are being considered in neighboring Zambia.

Despite the DRC's recent election and uncertainty about how the new president will engage with the mining industry, China and its local firms continue to reinforce their impact on the local economy and engage collectively with the DRC's political establishment. The recent formalization of the Union of Mining Companies with Chinese Capital has been set up to do just that.

Replicating the State-Owned Enterprise Model

China's SOE-driven strategy remains dominant throughout Africa, where adverse market sentiment and financial hardship in the mining industry have opened the door for SOE investment across the region. Notably, SOEs, in partnership with the China-Africa Development Fund, a Chinese state-funded institution, have expanded in South

Africa's Bushveld Complex,²² a mineral-rich geological formation that contains the world's largest reserves of platinum-group metals²³—critical for making catalytic converters, which are essential for reducing automobile emissions—and the world's highest-grade and third-largest deposit of vanadium, a resource integral to a broad range of high-tech industries, from renewable-energy storage to aerospace and defense.

By leveraging state resources, China's SOEs and private firms have made at least eight major equity and off-take plays in platinum-group metals in the Bushveld Complex.²⁴ Such investments in South Africa's highly concentrated and strategic resource deposits have helped make metals the country's leading source of export growth,²⁵ with nearly 50 percent of its metal exports going to China²⁶—tying South Africa's economic welfare directly to Chinese investment.

Private Firms and the Extension of State Strategy Abroad

China is also proving agile at adapting to conditions in market-oriented, democratic countries, using privately owned companies that are backed by state capital. By incrementally acquiring equity stakes in major local resource companies and financing junior developers, Chinese firms are strengthening their market presence while overcoming local concerns about foreign control over strategic domestic resources, such as niobium in Brazil and tantalum in Australia. Nowhere is this privately driven resource strategy more evident than in the three countries where nearly 90 percent of global lithium production and more than three-quarters of the world's known lithium reserves are located: Chile, Argentina, and Australia.²⁷ In just six years, China has come to dominate the global market: More than 59 percent of the world's lithium resources are now under its control or influence.²⁸

With the backing of state-owned banks, China's industrial chemical giants—Tianqi Lithium and Ganfeng Lithium—have become the world's third-largest producer of lithium²⁹ and third-largest producer of lithium chemical compounds,³⁰ respectively. The chairmen of both companies have risen within the ranks of Chinese politics over the past few years, just as China was beginning to prioritize securing supplies of rare metals. In 2013, Tianqi's chairman, Jiang Weping, became a member of the Standing Committee of the Political Consultative Conference of Sichuan province,³¹ and he was made a delegate to the National People's Congress in 2018.³² Ganfeng's chairman, Li Liangbin, became a member of the Standing Committee of the 12th Political Consultative Conference of Jiangxi province in 2018.³³ These two companies, along with other Chinese firms, have expanded their investments and integrated operations in three distinct markets by acquiring

a major stake in the leading producer in Chile, financing new development in Argentina, and acquiring mines and building up processing capacity in Australia.

Growing Equity in Latin America's Lithium Leaders

In early 2018, Tianqi Lithium made a bold play to acquire a 24 percent stake in Chilean rival Sociedad Química y Minera (SQM), the world's second-largest lithium producer. Chile is home to 57 percent of the world's known lithium reserves,³⁴ the world's largest known concentration, and SQM controls roughly half the country's production. In the industry's biggest mergers-and-acquisitions deal to date, Tianqi made a \$4.1-billion bid on SQM's shares, \$3.5 billion of which was financed by China's CITIC Bank International,³⁵ whose parent company, CITIC Group, is among China's largest state-owned financial and industrial conglomerates.³⁶

The Chilean government has traditionally held a relatively tight rein on its lithium resources, which have long been considered strategic for the nation's nuclear industry. The size of the deal with Tianqi heightened concerns in Chile over a foreign entity controlling those resources, and the potential for a cartel to form—spurring public opposition and antitrust and constitutional court challenges by SQM's majority shareholder. After months of legal battles and debate, the Constitutional Court of Chile dismissed the antitrust claims,³⁷ allowing Tianqi to secure the deal in December. Though the final agreement³⁸ included restrictions on Tianqi's board and committee participation and its access to SQM's sensitive data, Tianqi's equity position still confers considerable influence over SQM.

But the SQM deal is just one piece of a deepening economic relationship³⁹ with Chile, including Chinese investments in the local lithium industrial base, exports of electric buses to Chile, and an upgraded trade agreement between the two countries that just came into force in March 2019.⁴⁰ In April 2018, China's ambassador to Chile, Xu Bu, stated to local news outlets that opposition to the sale “could leave negative influences on the development

In just six years, China has come to dominate the global lithium market: More than 59 percent of the world's lithium resources are now under its control or influence.



Chinese Resource Strategy

China is securing minerals and metals for which it is net import reliant.

COBALT

Democratic Republic of the Congo

PRODUCTION: 61%

RESERVES: 49%

CHINA'S INFLUENCE:
Influence over 52% of cobalt production with equity stakes and supply agreements

NICKEL

Brazil

PRODUCTION: 88%

RESERVES: 80%

CHINA'S INFLUENCE:
Stakes in 100% production

PLATINUM

South Africa

PRODUCTION: 54%

RESERVES: 91%

CHINA'S INFLUENCE:
Stakes in 4% of all major PGM sites

LITHIUM

Argentina

PRODUCTION: 10%

RESERVES: 14%

CHINA'S INFLUENCE:
Stakes in 41% of major planned projects accounting for 37% of reserves

Australia

PRODUCTION: 58%

RESERVES: 19%

CHINA'S INFLUENCE:
Stakes in 61% of production

Bolivia

PRODUCTION: None

RESERVES:
Believed to be among the world's largest

CHINA'S INFLUENCE:
Stakes in 100% of development via an equity agreement

Chile

PRODUCTION: 21%

RESERVES: 57%

CHINA'S INFLUENCE:
Stakes in 67% of Chile's output

PRODUCTION AND RESERVES FOR 2017. SOURCES: USGS, IFA ANALYSIS OF COMPANY FILINGS, DEAL FLOWS, EQUITY STAKES AND OFF-TAKE AGREEMENTS

of economic and commercial relations between both countries,⁴⁰ and has since reportedly made other economic threats.⁴² Tianqi is now seeking permission to develop Salar de La Isla, Chile's second-largest lithium brine deposit,⁴³ in partnership with U.S.-based lithium company Albemarle, the other major player in Chile's lithium industry. Tianqi has the majority stake in the joint venture.⁴⁴

Leveraging Capital Across Developing and Developed Markets

In a cash-strapped industry, Chinese firms are financing mine expansion and new development in exchange for a guaranteed supply of lithium in both mature and emerging markets. In Argentina, where President Mauricio Macri is eliminating mineral export taxes, reducing corporate tax rates, and allowing profit repatriation, China is establishing a dominant position in the nascent sector with "streaming deals," which provide development capital in exchange for future lithium yields to help projects get off the ground. Chinese firms, led by Ganfeng, have stakes in 41 percent of the country's major planned projects that account for 37 percent of Argentina's reserves.⁴⁵ This raw-material strategy is already coming to fruition: Lithium export volumes from Argentina to China rose nearly fourfold from 2015 to 2017,⁴⁶ and China has secured access to the country's lithium for the longer term.

This same strategy, combined with asset acquisition, has also been successful in Australia, whose proximity to China, significant lithium reserves, and broad political support for mining investment have attracted Chinese investment. Tianqi and Ganfeng have established stakes in 91 percent of the lithium mining projects underway and 75 percent of the country's reserves, including some of the world's largest.⁴⁷ By taking over Talison Lithium, Tianqi captured a majority stake in the Greenbushes mine, which accounts for roughly 40 percent of global lithium production.⁴⁸ Together, Chinese firms have secured deals with nine of the 11 major operations and projects in the pipeline in Australia, two-thirds of which are exclusive.⁴⁹

Growing the Global Footprint

Having already consolidated control over global lithium supplies, Tianqi and Ganfeng are just getting started. Both filed for initial public offerings last fall with the intent to raise capital for further expansion. Ganfeng raised \$421 million in its October 2018 initial public offering,⁵⁰ which included four state-linked cornerstone investors.⁵¹ Last November, Tianqi received the necessary approvals from the China Securities Regulatory Commission to prepare for its Hong Kong listing,⁵² the proceeds from which will be deployed in global markets.

PART 2

China Reinforcing Its Resource Dominance

China is also making moves to take an even stronger position in resources it already controls on the global market. Natural resources are abundant in China; it is the No. 1 producer and processor of at least ten critical minerals and metals⁵³⁻⁵⁴ that are essential to high-tech industries and upon which China's commercial and strategic competitors depend. To reinforce its strength, Chinese firms are acquiring mines and output from the next-largest producers and reserves, giving China both an economic edge in the next high-tech industrial revolution and increasing geopolitical power.

Perhaps the best-known example both of China's natural-resource dominance and its willingness to exploit it is rare-earth elements, a group of 17 elements that (despite their name) are commonly found, but rarely in concentrations that can be economically extracted. They are important materials for the defense, aerospace, electronics, and renewable energy industries. Over the past two decades China has produced more than 80 percent of the world's production of rare-earth elements and processed chemicals.⁵⁵ In 2010 it cut off exports to Japan⁵⁶ amid rising tensions over the East China Sea, and the following year it imposed export quotas⁵⁷ that threw governments and manufacturers into a panic.⁵⁸ But with the exception of Japan, the attention to this critical vulnerability was short-lived, and little action was taken by other countries reliant on imports to diversify their resources or develop minerals action plans of their own.

China declared rare-earth elements a strategic resource in 1990 and prohibited foreign investment in the sector.⁵⁹ Six state-owned enterprises control the industry, and the government cut production quotas in 2018 by 36 percent.⁶⁰ With global demand for rare-earth elements projected at a compound average growth rate of more than 17 percent to 2025,⁶¹ a supply crunch is likely approaching—and China is already securing other nations' supplies.

Chinese firms have been increasing stakes in mines and securing off-take deals from the world's largest deposits of rare-earth elements. While Russia strictly limits foreign participation in rare-earth element development, Chinese firms have accumulated off-take agreements and stakes in rare-earth element mines in Australia and Brazil. Though Australia's Foreign Investment Review Board denied a 2009 takeover of Australian company Lynas' mine at Mount Weld,⁶² the second-largest rare-earth element oxide producer outside China, Chinese firms have locked in output from the site.⁶³ Northern Minerals, owned

HP MINING THE FUTURE PART 2

by Chinese firms,⁶⁴ is also developing Australia's other major rare-earth elements site, Browns Range; 100 percent of the mine's dysprosium, an element used in magnets and superalloys, will go to China's Lianyungang Zeyu New Materials Sales Co. Ltd.⁶⁵

And in the United States in 2017, China's Shenghe Resources and two U.S. private equity firms acquired the sole U.S. and North American rare-earth element producer and processor, Molycorp, and its idled mining operations at Mountain Pass, California.⁶⁶ The operation went bankrupt in 2015 due in large part to low prices for Chinese supplies of rare-earth elements, and its sale briefly spurred debate over whether the deal posed risks to national security,⁶⁷ but opponents could not make the legal case to block it. Shenghe holds rights to the mine's output; meanwhile the United States' rare-earth element imports continue to increase, at a cost of \$160 million in 2018 alone.⁶⁸ Though President Donald Trump has since called for a defense review and assessment of critical minerals, the Committee on Foreign Investment in the United States has not taken further action on the site. Meanwhile, Shenghe and its subsidiaries are continuing to expand internationally, with a major joint-venture development project in rare-earth elements now underway in Greenland.^{69,70} China's decades-long consolidation of strategic resources has only compounded its commercial and geopolitical capabilities, and it shows no sign of slowing down.

Vanadium and Graphite

China is also seeking to expand its dominant market position in vanadium and graphite, securing additional supplies and building integrated supply chains. Vanadium is a transition metal that is used in flow batteries, superconducting magnets, and high-strength alloys for jet engines and high-speed aircraft. Chinese firms already produce 56 percent of the world's vanadium domestically, and China is home to 48 percent of the world's reserves.⁷¹ Now, they are targeting South Africa, ranked third in vanadium production and reserves behind China and Russia.⁷²

In 2015, Hong Kong-based International Resources Ltd., a company whose ownership is opaque, executed a takeover of a major vanadium mine from Russia's Evraz Highveld Steel and Vanadium, which was facing bankruptcy.⁷³ In 2016, China's Yellow Dragon Holdings Ltd. co-invested with Bushveld Minerals, the primary vanadium developer in South Africa's massive Bushveld Complex, to acquire Strategic Minerals, which owned the Vametco vanadium mine and plant.⁷⁴ Yellow Dragon subsequently increased its investment in Bushveld Minerals and has become the fifth-largest shareholder.⁷⁵ The holdings deepen China's influence over South Africa's vanadium resources and its role in the country's emerging high-tech sector. Bushveld



A worker walks across the Jin Yang graphite factory in the town of Mashan, China, on May 28, 2016. MICHAEL ROBINSON CHAVEZ/THE WASHINGTON POST VIA GETTY IMAGES

Minerals is moving to develop an integrated platform to produce vanadium redox flow batteries for distributed energy across South Africa.⁷⁶ The vanadium resources will also flow toward China, feeding its battery industry and the National Development and Reform Commission's planned rollout of 100-megawatt stationary energy storage stations to manage its wind and solar energy.⁷⁷

China's position is even stronger in graphite, a crystalline form of the element carbon whose high conductivity makes it a major component in electrodes, batteries, and solar panels, as well as industrial products such as steel and composites. For the last 20 years, China has been the leading global supplier of graphite, representing nearly 70 percent of the world's production in 2018 and 24 percent of its reserves.⁷⁸ While synthetic graphite, which is produced from petroleum coke, is an alternative, unfavorable economics constrain its use.

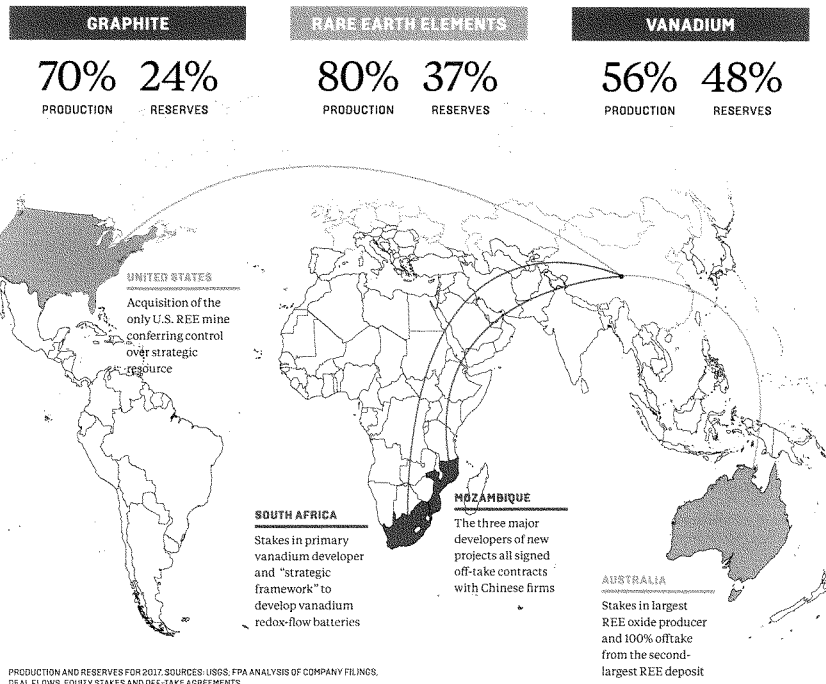
Rapidly growing demand for batteries and other end uses, coupled with environmental restrictions in China, are driving prices higher and stimulating investment. New projects are concentrated in Mozambique, where the world's largest graphite mine and fourth-largest known reserves are located.⁷⁹ Already, Chinese firms have secured off-take agreements with the three major developers in Mozambique for the majority of their graphite production,^{80,81} and they are financing new development.⁸²

Now that it controls most of the world's graphite, China has expanded down the supply chain, becoming the world's

Building on Domestic Resource Dominance

China is supplementing its own supplies with investments abroad.

DOMESTIC PRODUCTION AND RESERVES



leading producer of anodes, positively charged electrodes that are essential for making lithium-ion batteries. That industry is also highly concentrated: China's Shenzhen BTR New Energy Materials accounts for roughly 70 percent of global anode production.⁴³ The next-largest player is Japan's Hitachi Chemical, at 20 percent;⁴⁴ Japan is 90 percent reliant on China for its graphite.⁴⁵ China is channeling increasing volumes of graphite toward its booming domestic battery and new electric-vehicle industries, stockpiling domestic production and reducing graphite exports, which could result in a supply crunch for other end users. In 2016, China consumed 35 percent of the world's graphite production.⁴⁶

PART 3

Controlling the Fuel of the Future

This resource consolidation could determine whether China is able to overcome the last major hurdle to achieving its ambitions: a competitive semiconductor industry. The lifeblood of high-tech industries, semiconductors are made of the very minerals and metals over which China is securing control. Semiconductors can be pure elements or compounds and altered with impurities to improve their conductivity. Several materials are now being used to improve speed and performance, including rare-earth elements, graphite, indium, gallium, tantalum, and cadmium. China is the dominant producer of five out of the six, controls more than 75 percent of the world's supply of three,⁴⁷ and is consolidating control over them all.

However, China still lacks the technological capability to produce semiconductors on par with the industry's leading companies and remains highly dependent on imports, at a cost of roughly \$260 billion per year.⁴⁸ The government is keenly focused on ending its dependency by

acquiring the technological expertise to surpass its rivals. It poured nearly \$20 billion into highly targeted research and development to that end from 2014 to 2017,⁴⁹ and it is only intensifying its focus.

Should China succeed technologically, its capacity to scale production and flood markets (as it has already done with solar panels and wind turbines) has serious implications not only for leading semiconductor producers, but also for national security, if Chinese-manufactured chips are embedded in the devices upon which our data-driven lives, our economies, and our defense systems increasingly depend. While government and industry officials have started to restrict semiconductor sales and scrutinize Chinese acquisition of technology firms—e.g., the United States' temporary ban on selling semiconductors to ZTE, or the recent flare-up over Huawei—such moves are strengthening China's resolve to develop its domestic industry. More attention should be paid to its efforts to consolidate critical raw materials and the computing power they confer.

This is not a foregone conclusion. It will, however, require us to fundamentally rethink how we understand strategic industries and the long-term investments needed to ensure economic prosperity and national security in the digital age. Some countries are waking up to these strategic vulnerabilities and starting to act on them. In April, U.S. government officials announced plans to meet with lithium industry leaders and automakers with the intention of developing a national electric-vehicle supply chain strategy. It is a start.



This report was produced by FP Analytics, the research division of the FP Group. Access it online at ForeignPolicy.com/miningthefuture (requires subscription).

Endnotes

- ¹ Ministry of Industry and Information Technology of the People's Republic of China, "Nonferrous Metal Industry Development Plan 2016-2020," October 2016, <http://www.miit.gov.cn/n1146290/n4388791/c5288773/content.html>.
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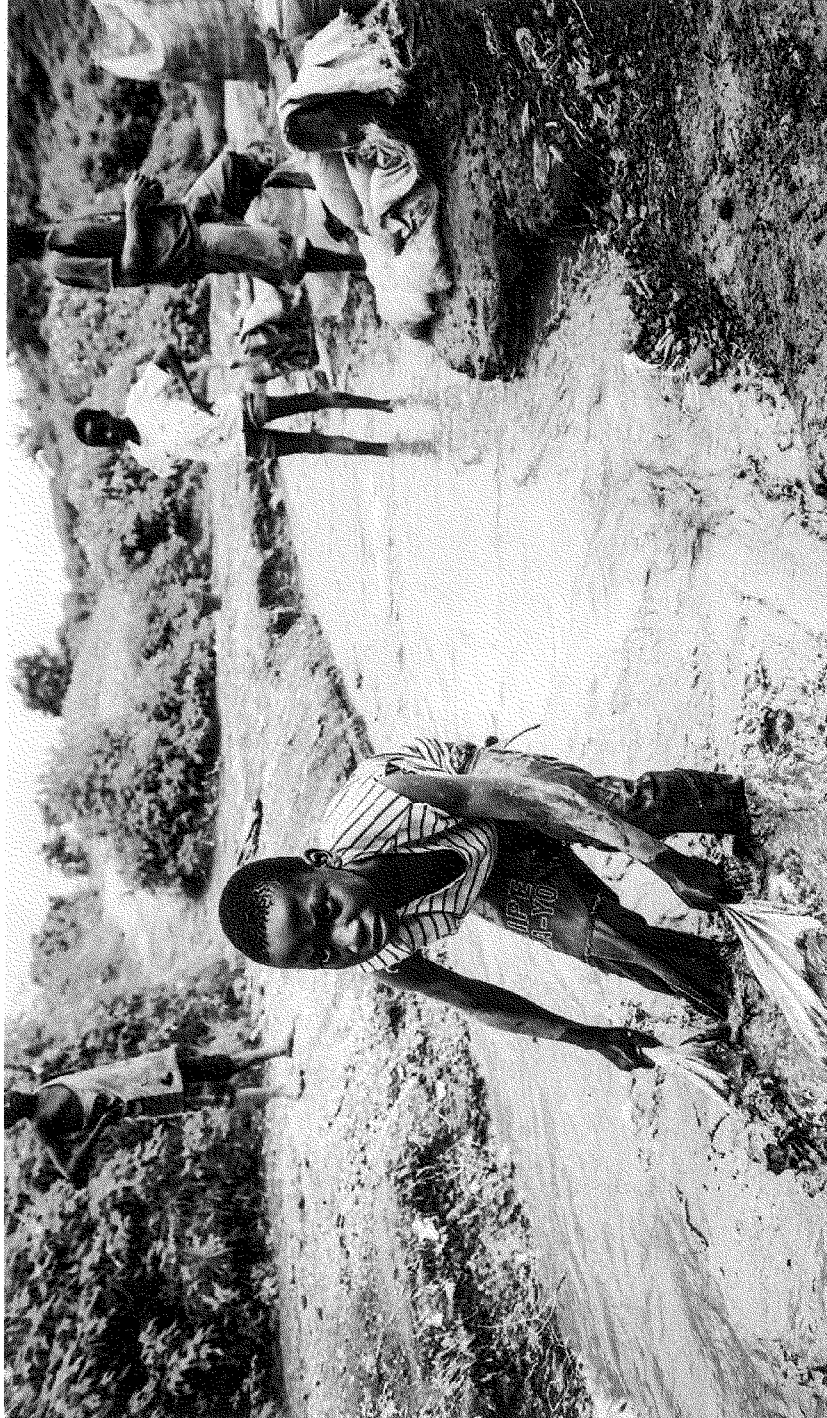
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Senator BARRASSO. The Secretary General for Amnesty International has stated that, "Every stage of battery life cycle, from mineral extraction to disposal, carries human rights and environmental risks." Approximately 60 percent of the world's cobalt is currently mined in the Democratic Republic of the Congo.

This photograph shows a child cleaning cobalt there. It is a child in the Congo.

Jim, you take a look, I know you have been in that country.

[The referenced information follows:]



Senator BARRASSO. In Chile, lithium production is affecting the local water supplies. The evaporation process to produce lithium requires pumping brine into pools like the one pictured here.
[The referenced information follows:]



Senator BARRASSO. China also has a hold on battery manufacturing. Chinese battery production also has significant environmental impacts. As we all know, China's environmental regulations are not on a par with ours.

China uses less advanced manufacturing techniques than the United States. One study found that producing a lithium ion battery in China emits about three times as much carbon dioxide as producing the battery in the United States.

Environmental challenges continue once a battery reaches the end of its life. Lithium ion batteries are recycled at a rate of less than 5 percent. Between 2018 and 2030, over 11 million tons of spent lithium ion batteries will be discarded across the world.

Now is the time for this Committee to evaluate the looming waste challenge as well as the opportunity that it presents. I say opportunity, because we have had past successes with other types of battery recycling in this country. About 99 percent of lead acid batteries from cars and trucks are recycled today—99 percent.

In the case of lithium ion batteries, recycling could have multiple benefits. First, it could cut down on the waste that goes into landfills, and in landfills, if not carefully managed, lithium ion batteries pose fire risks as well as electrocution risks.

Recycling also could cut down on emissions and other environmental impacts. From its creation to its disposal, an electric vehicle can have higher environmental impacts in some areas than a standard automobile. For example, an electric vehicle over its full life scale consumes more water resources than your average car. Emissions of sulfur oxides are also higher.

In addition to enhancing environmental and sustainability goals, recycling can also address broader economic and security risks. If we recycle more, we can rely less on overseas production of the raw materials. Recycling should be part of a broader discussion that also includes more raw material production and battery manufacturing here in the United States.

If the pace of electric vehicle demand continues, recycling alone will not be enough. My home State of Wyoming contains substantial reserves of critical minerals, including rare earth elements.

I am a co-sponsor of S. 1317, the American Mineral Security Act, which is sponsored by the Energy and Natural Resources Committee, with Chairman Murkowski and Ranking Member Manchin, so it is bipartisan. That bill passed the committee yesterday. The bill recognizes we must improve the permitting process to produce more critical minerals in the United States.

Before we move to our witnesses, I would like to turn to my friend, colleague, and Ranking Member, Senator Carper, for his remarks.

**OPENING STATEMENT OF HON. THOMAS R. CARPER,
U.S. SENATOR FROM THE STATE OF DELAWARE**

Senator CARPER. Thanks, Mr. Chairman.
Again to our witnesses, welcome.

There is a very young son, 10-year-old son sitting behind one of our witnesses, who is there to keep an eye on his dad. We are going to watch and see if his lips move when you speak. We will see how that goes.

[Laughter.]

Senator CARPER. I also would like to ask a couple of unanimous consent requests to submit for the record, three documents. One is by McKinsey and Company that highlights the untapped opportunities of recycling electric vehicle batteries to meet our future electric vehicle battery mineral needs. The second is a recent article by OilPrice.com. That article highlights the tens of millions of dollars being invested by folks like Toyota, Tesla, and some U.S. startup companies in more sustainable batteries.

And the third is a study by the Institute for Sustainable Futures, which found policies that encourage recycling and responsible electric battery sourcing can promote global environmental stewardship and help address the human rights concerns raised by our Chairman, with battery recycling being the most important policy.

I would ask unanimous consent to submit those.

Senator BARRASSO. Without objection.

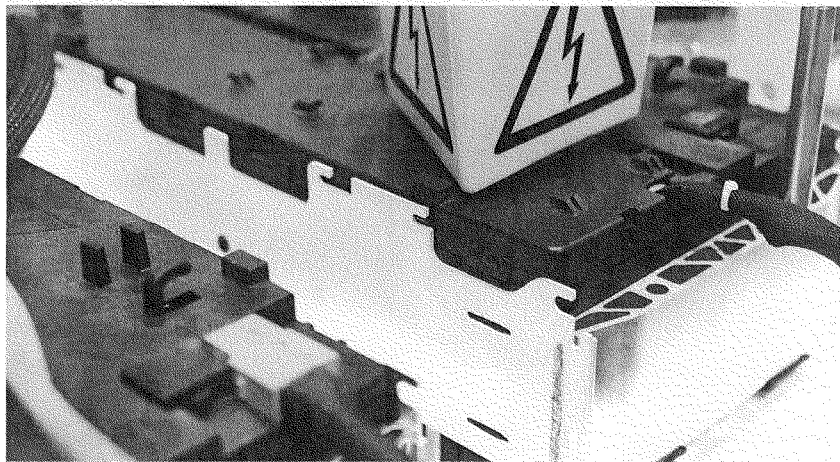
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McKinsey Center for Future Mobility

Second-life EV batteries: The newest value pool in energy storage

With continued global growth of electric vehicles (EV), a new opportunity for the power sector is emerging: stationary storage powered by used EV batteries, which could exceed 200 gigawatt-hours by 2030.

by Hauke Engel, Patrick Hertzke, and Giulia Siccardi



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April 2019

During the next few decades, the strong uptake of electric vehicles (EVs) will result in the availability of terawatt-hours of batteries that no longer meet required specifications for usage in an EV. To put this in perspective, nations like the United States use a few terawatts of electricity over a full year, so this is a lot of energy-storage potential. Finding applications for these still-useful batteries can create significant value and ultimately even help bring down the cost of storage to enable further renewable-power integration into our grids.

Potential to spark a second life

EV batteries have a tough life. Subjected to extreme operating temperatures, hundreds of partial cycles a year, and changing discharge rates, lithium-ion batteries in EV applications degrade strongly during the first five years of operation and are designed for approximately a decade of useful life in most cases. Yet, these batteries can live a second life, even when they no longer meet EV performance standards, which typically include maintaining 80 percent of total usable capacity and achieving a resting self-discharge rate of only about 5 percent over a 24-hour period. After remanufacturing, such batteries are still able to perform sufficiently to serve less-demanding applications, such as stationary energy-storage services.

When an EV battery reaches the end of its useful first life, manufacturers have three options: they can dispose of it, recycle the valuable metals, or reuse it (Exhibit 1). Disposal most frequently occurs if packs are damaged or if they are in regions that lack necessary market structure. In most regions, regulation prevents mass disposal. Recycling can make sense if the battery electrodes contain highly valued metals such as cobalt and nickel, because there could be a sufficient gap between the procurement and recycling cost, especially given the predicted tight supply of nickel and potentially cobalt in the 2020s. While having an additional source of battery metals through recycling can be compelling to battery makers looking to secure

supply, it will be critical to develop a recycling process that is sufficiently cost-competitive with mining for this path to gain scale; however, new processes that recover more material are not yet fully mature.

Reuse can provide the most value in markets where there is demand for batteries for stationary energy-storage applications that require less-frequent battery cycling (for example, 100 to 300 cycles per year). Based on cycling requirements, three applications are most suitable for second-life EV batteries: providing reserve energy capacity to maintain a utility's power reliability at lower cost by displacing more expensive and less efficient assets (for instance, old combined-cycle gas turbines), deferring transmission and distribution investments, and taking advantage of power-arbitrage opportunities by storing renewable power for use during periods of scarcity, thus providing greater grid flexibility and firming to the grid. In 2025, second-life batteries may be 30 to 70 percent less expensive¹ than new ones in these applications, tying up significantly less capital per cycle.

Large volumes with large challenges

Due to the rapid rise of EVs in recent years and even faster expected growth over the next ten years in some scenarios, the second-life-battery supply for stationary applications could exceed 200 gigawatt-hours per year by 2030. This volume will exceed the demand for lithium-ion utility-scale storage for low- and high-cycle applications combined (Exhibit 2), which by 2030 will constitute a market with global value north of \$30 billion.

However, to unlock this new pool of battery supply, several challenges in repurposing EV batteries must be overcome.

The first is the large number of battery-pack designs on the market that vary in size, electrode chemistry, and format (cylindrical, prismatic, and pouch). Each battery is designed by the

¹ Comparing cost outlook on new packs versus on second-life packs, which includes costs of inspection, upgrades to hardware, and upgrades to the battery-management system.

Exhibit 1

Spent electric-vehicle batteries can still be useful in less-demanding applications.

Electric-vehicle (EV) battery life cycle, illustrative

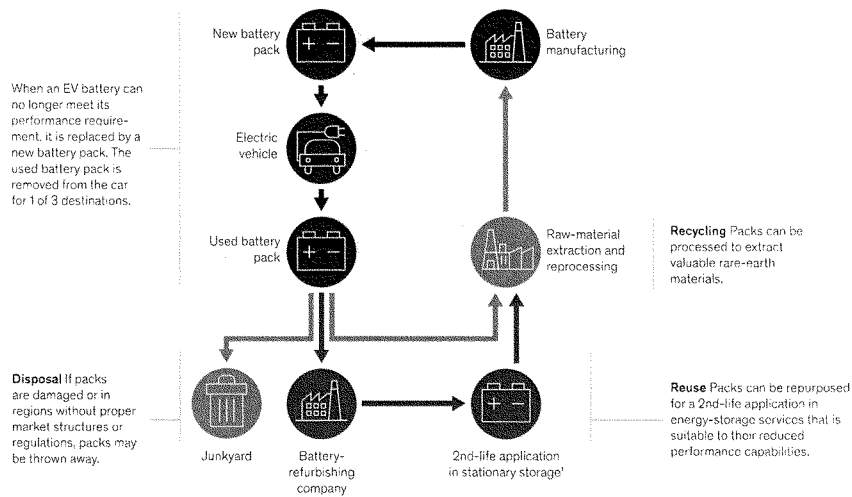


Fig. improve gwp performance, integrate renewables, charge Pvs, etc.
Source: IEA, short literature, market research reports, McKinsey analysis

battery manufacturer and automotive OEM to be best suited to a given EV model, which increases refurbishing complexity due to lack of standardization and fragmentation of volume. Up to 250 new EV models will exist by 2025, featuring batteries from more than 15 manufacturers.

The second challenge involves falling costs for new batteries. As new batteries become cheaper, the cost differential between used and new diminishes, given that the rate of decline in remanufacturing cost is expected to lag the rate of decline in new manufacturing cost. We estimate that, at current learning rates, the 30 to 70 percent cost advantage

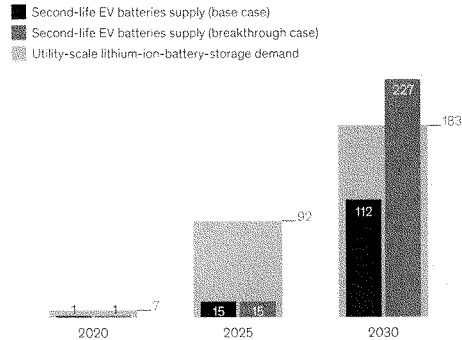
that second-life batteries are likely to demonstrate in the mid-2020s could drop to around 25 percent by 2040. This cost gap needs to remain sufficiently large to warrant the performance limitations of second-life batteries relative to new alternatives.

Challenge number three concerns the nascency of second-life-battery standards. No guarantees exist regarding second-life-battery quality or performance, and few industry standards focus on battery-management systems or state-of-health disclosures, let alone standard performance specifications for a battery that is to be used for a given application.

Exhibit 2

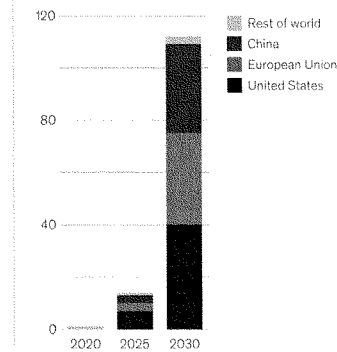
Second-life lithium-ion battery supply could surpass 200 gigawatt-hours per year by 2030.

Utility-scale lithium-ion battery demand and second-life EV¹ battery supply,² gigawatt-hours/year (GWh/y)



¹Electric vehicles.
²Only for batteries from passenger cars.

Second-life EV battery supply by geography (base case¹), GWh/y



The fourth challenge is the immature regulatory regime. Today, while most markets have some form of regulation requiring the recycling or remanufacturing of consumer electronics in general, most markets do not have EV-battery-specific requirements or delineations of responsibility between the producer and the consumer, save a few examples where goals have been set (such as in California and China). The lack of regulation creates uncertainties for OEMs, second-life-battery companies, and potential customers. The lack of regulation also gives rise to regional differences regarding whether recycling or reuse is the dominant pathway.

While these challenges are significant, they can be overcome by targeted action from the suppliers, end users, and regulators in the sector, enabling a sustainable second-life-battery industry to emerge. In fact, many of these targeted actions are

already being taken by forward-looking players and industry associations.

To start, to handle the growing number of EV models and batteries, automakers can design their EVs with second-life applications in mind. For example, Nissan formalized a partnership with Sumitomo Corporation to reuse battery packs from the Nissan Leaf for stationary distributed and utility-scale storage systems. In September 2018, Renault announced its Advanced Battery Storage Program. This collaboration involves several partners in the energy sector and is expected to result in a 70 megawatt/60 megawatt-hours used EV battery installation in Europe by 2020, the largest in Europe to date.

To remain competitive in the face of falling costs for new lithium-ion batteries, companies can industrialize and scale remanufacturing processes

to reduce costs and thus maintain the value gap between new and used batteries.

Regarding the lack of standards, a variety of global agencies and private-sector coalitions consisting of OEMs and second-life-battery companies are already working on industry-wide second-life-battery safety standards. These standards would essentially classify batteries based on their performance potential and classify storage applications based on their performance needs in order to create transparency into product supply and market demand. Given the dynamic nature of the EV-battery industry and the relentless focus on design, manufacturing, and performance breakthroughs, establishing a body to regularly review and refine battery standards and report annually on average cost and operating benchmarks could further catalyze growth in battery deployment.

Finally, in the absence of directive regulation outlining whether recycling or reuse is the path required to avoid mass disposal of batteries, the stakeholders involved—including battery OEMs, second-life companies, automotive OEMs, and utilities—have an opportunity to shape the ecosystem. Not only can they identify the value-maximizing path between recycling and reuse, they can develop new business models to fully capture the value at hand. Renault, for example, engages in both recycling and reuse programs with industry partners and a structured process in each pathway, rooted in regional context. By building relationships with end customers, whether those be utilities or commercial or industrial players, and by gaining insight into their capacity expansion plans,

automotive OEMs such as Renault, and even battery OEMs, can intelligently select their end-of-life management pathway (that is, determining whether there is sufficient demand from applications suitable to remanufactured batteries or whether recycling would be preferable).

Battery-ownership models may evolve as well. Today, automotive OEMs and battery OEMs are comfortable relinquishing battery ownership to car owners. However, as second-life markets stabilize, owning the battery system will become more attractive due to the system's confirmed residual value, which automakers and battery makers will not want to give away. Accordingly, we may see a rise in EV-battery leasing such that the automotive OEM or battery OEM can maintain ownership of the battery's second revenue stream.

The shift of electric vehicles into mainstream use has already disrupted the automotive value chain in significant ways and is now on the verge of disrupting the energy-storage value chain as well. The need to dispose of millions of EV batteries in the future has already led to the emergence of new recycling and reuse industries, creating new value pools with new potential to harness and integrate renewable power into our grids. While these industries face the stark challenge of being on the cutting edge of market creation, corporations and their regulatory bodies have the power to take action to position themselves to capture the value that second-life batteries promise. They just need to look ahead.

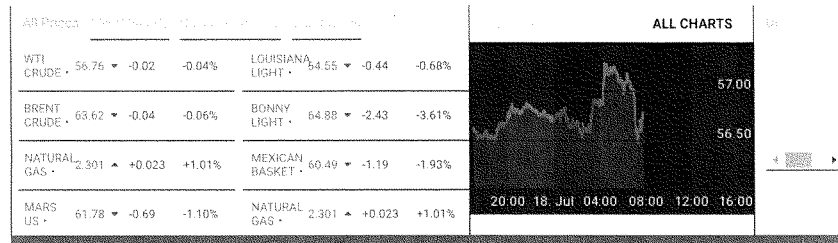
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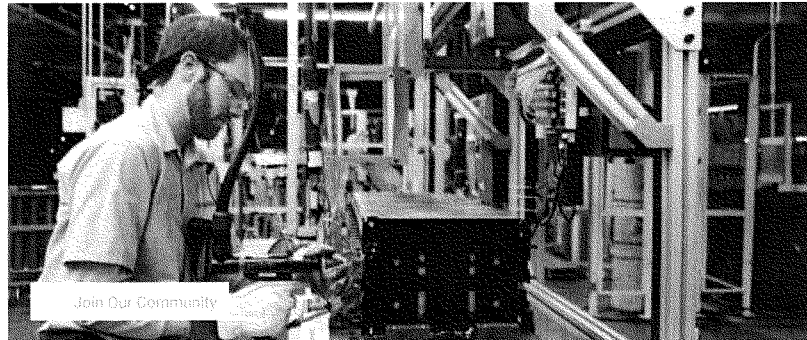
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Solid State Batteries: The Next Big Thing In Electric Cars

 By [Jon LeSage](#) - Jun 26, 2019, 12:00 PM CDT


Plug-in vehicle sales have been seeing sizable growth in recent years, with Tesla grabbing most of the attention. Now the race is on with Toyota and several other global automakers taking steps forward in being truly Tesla-competitive for the first time.

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At 2.1 million sold worldwide last year, sales of battery-electric and plug-in hybrid electric vehicles only saw a peak moment of 3.8 percent of new vehicle sales in December — and only 2.2 percent of sales for the year. For that number to reach 10 percent or higher, they'll need to go 400 or more miles per charge and able to be recharged in about 10 minutes. That's still a long ways off, but Toyota, Jaguar, Audi, Volkswagen, and Porsche are making real strides toward that benchmark.

Toyota's announcement this month of dedicating much of its new vehicle build to plug-in vehicles will be based on the introduction of solid-state batteries, which Toyota believes could happen as soon as 2020 — two years earlier than originally planned by the company. It will be part of reaching 5.5 million electrified vehicles sold — a target now moved up five years from 2030 to 2025. That will include battery-electric vehicles, hydrogen fuel-cell vehicles, and hybrids.

While Toyota is best known for its love of hybrids like the Prius, and its more recent Mirai fuel-cell vehicle, much of Toyota's expanded vision will be made up of electric vehicles. Solid-state batteries offer greater energy density than the lithium-ion batteries being used by Tesla and other competitors. These EV batteries use a solid electrolyte instead of the liquid electrolyte used in the lithium-ion batteries.

"If possible, by the time we have the Olympic games next year, we would like to make sure that a solid-state battery can be unveiled to the public," Toyota research and development boss Shigeki Terashi said during a recent presentation.

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Automakers using solid-state batteries will be able to increase the range of electric cars without having to make battery packs bigger. Solid-state electrolytes are also expected to be nonflammable, unlike current lithium-ion batteries. Tesla, Nissan, and General Motors, have had their share of battery pack fires to deal with.

The Japanese automaker is poised to share its battery technology with three partners, Subaru, Suzuki, and Mazda. Subaru and Suzuki established a technology-sharing relationship with Toyota years ago, and some industry experts say that Mazda will be next. Toyota has convinced them to join an alliance that shares common platforms, technologies, and batteries, with solid-state batteries likely to take the lead.

Toyota's move is also happening during a time when Tesla's battery pack partner, Panasonic, is moving away from Tesla and toward the company's competitors. In April, Tesla and Panasonic were said to have frozen plans to expand the Gigafactory, with the Japanese electronics company taking a hit from the turmoil coming from Tesla's factory production and missed targets in getting enough Model 3s to the market as originally promised to investors and car buyers who'd been putting down deposits.

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In January, [Toyota forged a relationship with Panasonic](#) to manufacture EV batteries, with much of it aimed at China's booming EV market. In the deal, Panasonic will transfer ownership of five battery manufacturing facilities in China and Japan to their newly formed entity.

Toyota, Tesla, and other global makers want to compete with top-selling Chinese EV makers BAIC and BYD, but they have to establish a substantial presence in the China auto market. For Toyota, Panasonic will open that doorway.

Competition with Tesla's EV dominance is also coming on the luxury vehicle side, and from a start-up and another giant automaker beyond Toyota and GM, Volkswagen.

Tesla competitors include the Jaguar I-Pace, Audi E-tron, and the Porsche Taycan that's set to debut in September with a 300-mile range. The I-Pace and E-tron are in the low-200s for total miles traveled per charge. But it is a leap forward for the European makers, who've finally gotten around to mass producing high-performance EVs.

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Startup battery maker 24M received funding [for its SemiSolid](#) lithium-ion battery in December, and now has a new partner for the energy storage market. 24M has struck a deal with [Kyocera](#), [a Japanese multinational](#) ceramics and electronics manufacturer headquartered in Kyoto, for initial production of cells for stationary storage applications.

Volkswagen is now [promising a more stout battery warranty](#) for its ID electric vehicle lineup. This month, the manufacturer announced it will guarantee the capacity of its batteries for eight years or 100,000 miles, whichever comes first. VW's warranty promises that the battery pack will retain at least 70 percent of its capacity during that period of coverage. The company will apply the warranty to future ID sub-brand EVs if they're operating off the same platform — competing directly with Tesla's warranty program.

Other global automakers have bought into the importance and functionality of solid-state batteries. VW and BMW have invested in solid-state battery startups QuantumScape and Solid Power, respectively. Fisker Karma creator Henrik Fisker says that using solid-state batteries will allow his new Emotion EV to travel more than 500 miles on a single charge.

It's still a bit early in the development process to know whether solid-state batteries will become the new leading technology powering EVs.

By Jon LeSage for Oilprice.com

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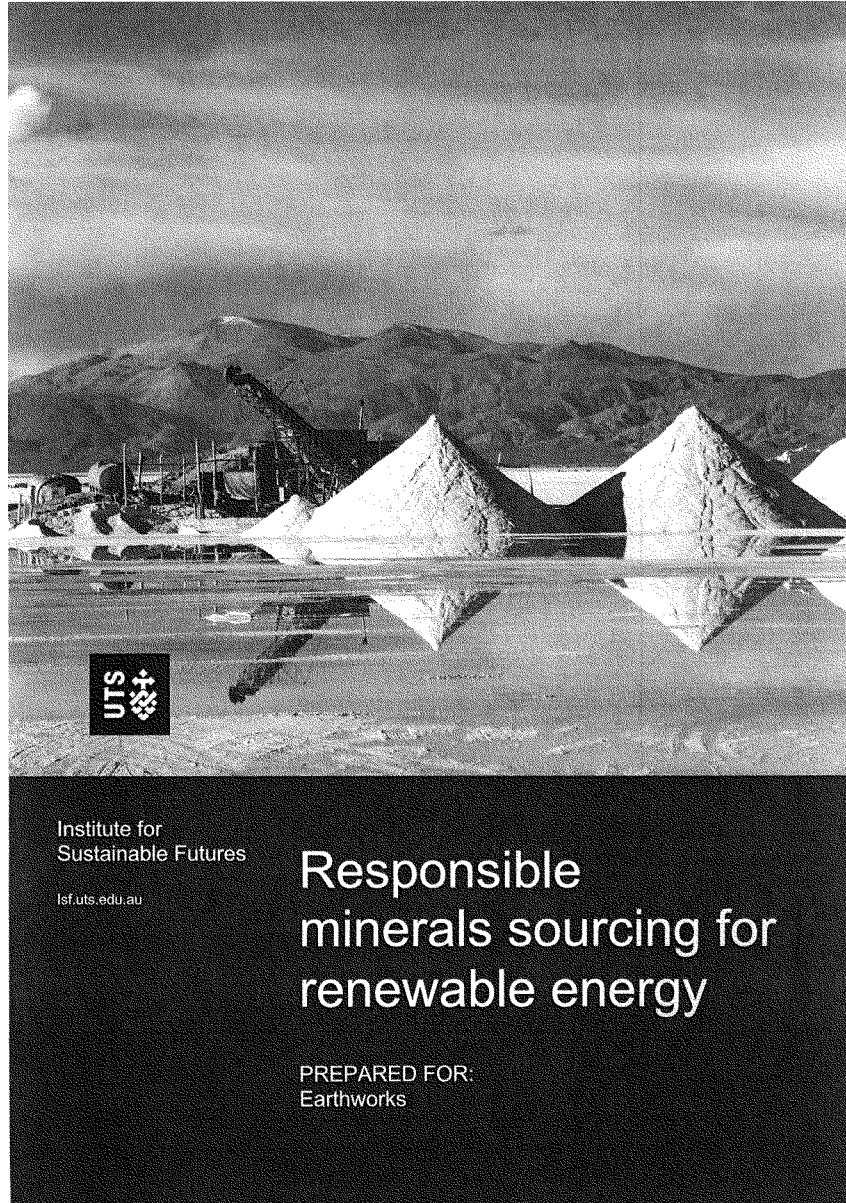
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Balderash! If it don't pollute, it don't compute. Give me an oil burner any old day.



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Responsible minerals sourcing for renewable energy

PREPARED FOR:
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About the authors

The Institute for Sustainable Futures (ISF) is an interdisciplinary research and consulting organisation at the University of Technology Sydney. ISF has been setting global benchmarks since 1997 in helping governments, organisations, businesses and communities achieve change towards sustainable futures.

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Cover photograph: Lithium mine at Salinas Grandes salt desert in Jujuy province, Argentina

Executive summary photograph: A creuseur, or digger, descends into a copper and cobalt mine in Kawama, Democratic Republic of Congo (Photo by Michael Robinson Chavez/The Washington Post via Getty Images)



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Executive Summary

Introduction:

The transition to a 100% renewable energy system is urgently needed to meet the goals of the Paris Climate Agreement and increase the chance of keeping global temperature rise below 1.5 degrees. Renewable energy technologies are now the most cost competitive technologies for new installations – and recent investment in new renewable energy infrastructure globally has been double that of new energy investment in fossil fuels and nuclear.

Renewable energy technologies, electric vehicles and battery storage require high volumes of environmentally sensitive materials. The supply chains for these materials and technologies need to be appropriately managed, to avoid creating new adverse social and environmental impacts along the supply chain.

This report presents the findings of an assessment of the projected mineral demand for fourteen metals used in renewable energy and storage technologies, the potential to reduce demand through efficiency and recycling, and the associated supply risks and impacts. Solar photovoltaic (PV) and wind power have been chosen for this assessment because these two technologies make up the majority of new global renewable electricity installations. Batteries have been assessed because of their importance for use in electric vehicles (EVs) and energy storage systems.

This research aims to identify the main 'hotspots' or areas of concern in the supply chain, including technologies, metals and locations, where opportunities to reduce demand and influence responsible sourcing initiatives will be most needed.

Key metals for renewable energy and storage technologies

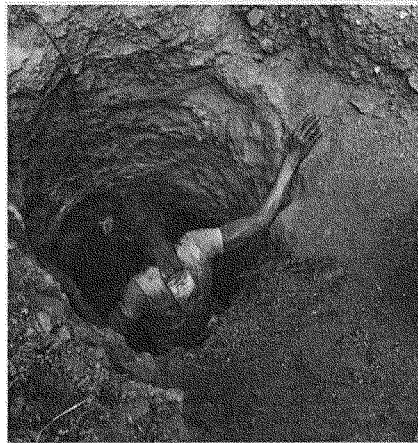
Lithium-ion batteries: cobalt, lithium, nickel, manganese

EVs: rare earths (neodymium and dysprosium)

Solar PV: cadmium, indium, gallium, selenium, silver, tellurium

Wind power: rare earths (neodymium and dysprosium)

Aluminium and copper used in all technologies



Research overview:

The key findings presented in this report are drawn from an assessment of five important factors:

- The challenges for substitution, efficiency and recycling to offset demand
- The projected metal demand in a 100% renewable energy scenario
- The supply risks, considering concentration of producers and reserves, and the share of end-use for renewable energy technologies
- The social and environmental impacts of supply
- Current levels of industry awareness and responses

The overall key findings are outlined below, followed by the detailed findings for each of these factors.

Key findings:**Encouraging recycling and responsible sourcing are the key strategies to promote environmental stewardship and the respect of human rights in the supply chain.**

The transition towards a renewable energy and transport system requires a complex mix of metals – such as copper, cobalt, nickel, rare earths, lithium and silver – many of which have only previously been mined in small amounts. Under a 100% renewable energy scenario demand for these metals could rise dramatically, and require new sources of primary and recycled metals. Recycling and responsible sourcing are fundamental to improving the sustainability of the renewable energy transition.

Recycling is the most important strategy to reduce primary demand.

Recycling of metals from end-of-life batteries was found to have the greatest opportunity to reduce primary demand for battery metals, including cobalt, lithium, nickel and manganese. Increasing efficiency or shifting away from cobalt also has a significant impact (although this may increase demand for other metals including nickel and lithium). Many electric vehicle (EV) and battery manufacturers have been proactive in establishing recycling initiatives and improving the efficiency of battery technologies. However, there is potential to improve recycling rates as not all types of metals are currently being recovered in the recycling process (e.g. lithium and manganese), or only at low rates.

Improving the efficiency of material use was found to have the greatest potential to reduce primary demand for metals for solar PV, owing to the long lifetime of these products. The industry has already made significant improvements to minimising the demand for materials, improve performance and reduce costs. However, the PV industry also needs to engage further in recycling to avoid future waste streams, and recover more metals from the process. Recycling remains a particular challenge for the solar PV industry as there is not always a strong business model.

Overall recycling is the most important strategy for the renewable energy and battery industries going forward, as the industry is already very focused on improving the efficiency of material use, which is expected to continue to improve over time.

Responsible sourcing is needed where supply cannot be met by recycled sources.

Recycling can significantly reduce primary demand, especially for batteries, however it cannot meet all demand and there is a time delay for when recycled metals become available. New mining is likely to take place to meet demand in the short term, and new mines are already under development linked to renewable energy (e.g. for cobalt, copper, lithium, rare earths, nickel). If not managed responsibly, this has the potential for new adverse environmental and social impacts.

Impacts associated with the mining of key metals used in renewable energy and storage include pollution and heavy metal contamination of water and agricultural soils, and health impacts on workers and surrounding communities. When supply cannot be met by recycled sources, engaging in responsible sourcing through verified certification schemes and due diligence of supply chains is needed to reduce potential negative social and environmental impacts.

The EV and battery industries have the most urgent need to avoid negative impacts in their supply chains.

Cobalt, lithium and rare earths are the metals of highest concern, considering their projected future demand and supply risks. Batteries for EVs are the main driver of demand for these metals, rather than stationary storage or wind power. The industry as a whole can engage further with responsible sourcing, and by doing so will encourage more mines to engage in responsible practices and certification schemes. As EV manufacturers are strong consumer facing brands, they can drive change up the supply chain and influence their suppliers upstream.

It is expected that with the renewable energy transition, renewable energy technologies will consume a growing share of these metals and in many cases may be the major driver of demand. The renewable energy transition is an opportunity to promote stewardship of both primary sources and technologies at end-of-life. This has the potential to improve the sustainability of the supply chain for these metals more broadly.

Challenges for substitution, efficiency and recycling:

Copper, lithium, silver and rare earths are the metals most challenging to reduce total demand through substitution and efficiency, and offset primary demand through recycling.

Copper is used in all technologies, and is difficult to substitute, as it is used for its high electrical conductivity. Lithium is challenging to substitute as it is used in the dominant battery technologies, as well as technologies predicted to be important in future, and currently only has limited recycling from batteries. Silver is used in 95% of PV panels, and while the industry is continuously increasing its efficiency in material use, it is not currently recycled and is technologically difficult to do so. Similarly, the rare earths neodymium and dysprosium are not currently recycled, and substitution is possible but currently nearly all EVs use this technology.

There are less challenges to reduce demand for the remaining metals as they have high recycling rates (such as aluminium, cobalt and nickel) or can more easily be substituted with other metals or other technology types (e.g. cadmium, tellurium, gallium, indium and selenium are only used in niche PV technologies). These challenges inform the projections of future metal demand.

Projected metal demand in a 100% renewable energy scenario:

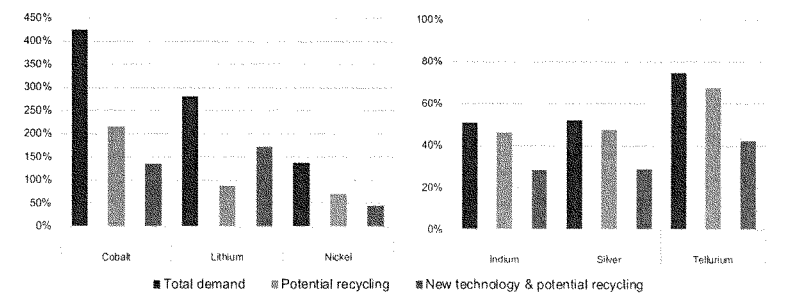
The potential metal demand from clean energy has been modelled against an ambitious scenario for a 100% renewable electricity and transport system by 2050, that limits climate change to 1.5 degrees. This scenario estimates material demand for high levels of solar PV and wind power, which provide two-thirds of electricity by 2050, as well as batteries for electric passenger cars, commercial vehicles, buses and stationary storage.

This study focuses only on the metal demand for renewable energy and storage technologies, and does not consider other demands for these metals, which may also increase or decline over time. It is also important to note that this scenario is an ambitious renewable energy scenario based on current technologies, and these results should be considered a high-demand scenario, as over time new technologies may become more efficient or new technologies may emerge. The potential to reduce primary demand is based on recycling at end-of-life of the three technologies in this study, and using recycled metals from other sources could further reduce primary demand.

• Demand compared to reserves:

Demand from renewable energy and storage technologies could exceed reserves for cobalt, lithium and nickel, and reach 50% of reserves for indium, silver, tellurium.¹ Primary demand can be reduced significantly, with the greatest potential to reduce demand for metals in batteries through high recycling rates, and for PV metals through materials efficiency.

Figure A: Cumulative demand from renewable energy and storage by 2050 relative to reserves in three scenarios for selected battery metals (left) and solar PV metals (right)



¹ Reserves are the estimated amount of a mineral that can be economically mined under current conditions. Reserves are a subset of resources, which are the total known amount of a mineral for which extraction may be potentially be feasible.

- **Increases in production:**

The rapid increase in demand for cobalt, lithium and rare earths is of the most concern. Demand for lithium and rare earths from lithium-ion batteries for EVs and storage exceeds current production rates by 2022 (for all uses). Demand for cobalt and nickel exceeds current production rates by around 2030.

The more rapid increase for these metals is owing to the predicted rapid electrification of the transport system and expansion of battery storage that has only begun to accelerate in the last few years, compared to established technologies of solar PV and wind.

- **Supply risks:**

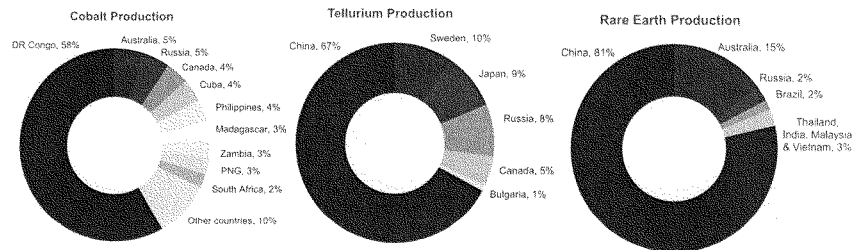
To review the risks of security of supply of the metals in renewable energy supply chains, the geographical distribution of producers and reserves, and the renewable energy share of end-use was examined. Cobalt is the metal of most concern for supply risks as it has highly concentrated production and reserves, and batteries for EVs are expected to be the main end-use of cobalt in only a few years.

The supply chains for renewable energy technologies are opaque and involve a vast number of countries and companies. Chinese companies have significant control of supply chains, including mining, processing and manufacturing, and China is also the largest end-market.

- **Concentration of production and reserves:**

The concentration of supply in a single or very few countries is a risk for manufacturers to secure ongoing supply and make the metal more vulnerable to price fluctuations. The metals for which supply is concentrated in a single country are cobalt, rare earths and tellurium (Figure B). Australia, Chile, DR Congo and South Africa have large shares of the production of metals for lithium-ion batteries and Japan, Korea, Canada and Russia have significant production levels of metals for PV, in addition to China. Although DR Congo is the major producer of cobalt and Australia of lithium, the majority of both of these metals is shipped to China for processing. China dominates the manufacturing of solar PV and lithium-ion batteries, as well as being the largest market for these technologies.

Figure B: Concentration of production



Cobalt has the highest concentration of potential supply, with nearly 50% of reserves in DR Congo. The majority of other metals are found in many regions across the globe, with Australia, Chile, Brazil and China having significant shares of many metals. Rare earths are found in many countries, but are not always economically viable to mine. Despite rare earth production being highly concentrated in China, countries including Brazil, Vietnam and Russia, have a significant share of global reserves, but currently only a very small share of production.

- **Renewable energy share of end-use:**

The metals for which renewable energy is a significant share of end-use are cobalt, lithium, rare earths and tellurium. Lithium-ion batteries for EVs and storage are currently responsible for between 4-8% of demand for cobalt and lithium, and this could be up to 43% of demand for cobalt in 2020. For lithium this could be even higher, with EVs and storage expected to consume 50% of lithium by 2020. Permanent magnets for wind turbines and EVs are the current end market for approximately 32% of neodymium and dysprosium. Solar PV is already a large end market for tellurium (40%), gallium (17%), indium (8%) and silver (9%), and is expected to remain so.

Supply impacts:

If not managed responsibly, there are significant environmental and social impacts associated with the mining and processing of metals. These include:

- **Cobalt:** Heavy metal contamination of air, water and soil has led to severe health impacts for miners and surrounding communities in DR Congo, and the cobalt mining area is one of the top ten most polluted places in the world. Around 20% of cobalt from DR Congo is from artisanal and small-scale miners who work in dangerous conditions in hand-dug mines and there is extensive child labour. New cobalt mines are proposed in DR Congo, as well as in Australia, Canada, Indonesia, the US, Panama and Vietnam.
- **Copper:** Copper mining can lead to heavy metal contamination, as seen in Chile, China, India and Brazil, has led to environmental pollution from a major tailings dam spills in the US and there are health impacts for workers in China and Zambia.
- **Lithium:** The major concern over lithium mining is water contamination and shortages in the lithium triangle of Argentina, Bolivia and Chile, and the inadequate compensation for affected local communities.
- **Nickel:** Damage to freshwater and marine ecosystems has been observed in Canada, Russia, Australia, Philippines, Indonesia and New Caledonia.
- **Rare earths:** Rare earth processing requires large amounts of harmful chemicals and produces large volumes of solid waste, gas and wastewater. There have been impacts in China, Malaysia and historically in the US, and new mines are proposed for Canada, Greenland, Malawi, South Africa and Uganda.
- **Silver:** There has been heavy metal contamination of soil and water from recent and historical mines in the US, Mexico, Peru and Bolivia, and social conflicts in Guatemala.

Although recycling is generally environmentally preferable to mining, it needs to be done responsibly. The informal recycling of e-waste in many parts of the world is done in hazardous working conditions, that only ends up recovering a fraction of what could otherwise be recovered, and emits dangerous toxins, heavy metals and acid fumes into the surrounding environment, leading to severe illnesses.

With the growing demand for these metals from renewable energy, responsible operations are necessary to avoid negative environmental health impacts for workers and local communities, and to ensure the respect of human rights and guarantee an equitable sharing of benefits.

Industry awareness and responses:

The renewable energy, EV and battery manufacturing industries are very aware of issues around supply risks for key metals. The main concern of the industry is the ability to guarantee long-term supply of key metals at a stable price, particularly for cobalt and lithium.

The renewable energy and battery industries have made significant improvements to the efficiency of technologies, to improve performance, minimise demand for materials and reduce production costs. Current recycling infrastructure remains underdeveloped and/or not optimised for high value metal recovery, with the exception of recycling of wind turbines which relies on existing scrap recycling. The wider application of lithium-ion batteries is driving advances in recycling and the industry is very aware of the looming volumes from EV. PV recycling is demonstrated but not optimised for high value metal recovery. Policy to ensure take-back and recycling at end-of-life of batteries and solar PV will be needed if the industry does not establish effective voluntary schemes.

EV companies are beginning to engage in responsible sourcing and certification, but they are concerned about the ability to secure adequate volumes of supply from responsibly sourced mines. If the auto industry makes public commitments to responsible sourcing, it will encourage more mines to engage with responsible practices and certification schemes.

There are a large number of responsible sourcing initiatives, that promote environmental stewardship and the respect of human rights in the supply chain, most of which are voluntary and industry-led. If these initiatives are harmonised and widely adopted, it may lead to more responsible supply chains. Responsible sourcing initiatives need to ensure that they do not lead to unintended negative consequences, such as increasing poverty, by avoiding sourcing from countries with poorer governance.

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Acronyms and abbreviations

ASM	Artisanal and small-scale mining
BEV	Battery electric vehicle
CCCMC	China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters
CdTe	Cadmium telluride (type of solar PV cell)
CI	Cobalt Institute
CIGS	Copper indium gallium (di)selenide (type of solar PV cell)
CO₂	Carbon dioxide
c-Si	Crystalline silicon (type of solar PV cell)
CV	Commercial vehicle (including light-duty and heavy duty vehicles)
DR Congo	Democratic Republic of Congo
DSM	Deep sea mining
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hours
IRMA	Initiative for Responsible Mining Assurance
ISA	International Seabed Authority
LFP	Lithium iron phosphate (type of LIB)
LIB	Lithium-ion battery
Li-ion	Lithium-ion (battery)
Li-S	Lithium-sulfur (battery)
LCO	Lithium cobalt oxide (type of LIB)
LMO	Lithium manganese oxide (type of LIB)
LSM	Large-scale mining
NMC	Nickel manganese cobalt (type of LIB)
NCA	Nickel cobalt aluminium (type of LIB)
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in hybrid electric vehicle
PNG	Papua New Guinea
PMG	Permanent magnet generator
RCI	Responsible Cobalt Initiative
RMI	Responsible Minerals Initiative
Solar PV	Solar photovoltaic
USA	United States of America
WEEE Directive	Waste Electrical & Electronic Equipment Directive (EU)

1 Introduction

The rapid increase of renewable energy and the electrification of the transport system is necessary to meet the Paris Climate Agreement and keep global temperature rise at 1.5 degrees. Renewable energy technologies are now the most cost competitive technologies for new installations – and an estimated 70% of net additions to global power capacity in 2017 was renewable, mainly solar PV and wind power.²

The environmental benefits of renewable energy in a future energy and transport system has been established, with positive benefits for climate mitigation and reducing pollution.³ However, it is important to assess the material requirements of any new technology in order to minimise potentially adverse impacts that may arise, and to make sure new environmental and social impacts are not created elsewhere along the supply chain.

Renewable energy and storage technologies typically have high and diverse mineral resource requirements (Table 1). Associated with the resource requirements are potentially significant environmental and social impacts that need to be appropriately managed from resource extraction to recovery at end-of-life, in order to realise a sustainable energy system. As the renewable energy industry is comparatively new, the potential to offset the supply of primary resources with secondary resources and technological innovation is not well understood.

Table 1: Key metals required for renewable energy and storage technologies

	 Batteries			 Solar PV			 Wind Power	
	Li-ion	Li-S	EV	c-Si	CIGS	CdTe	PMG	Non-PMG
Aluminium	X	X		X	X	X	X	X
Cadmium						X		
Cobalt	X							
Copper	X	X		X	X	X	X	X
Dysprosium			X				X	
Gallium					X			
Indium					X			
Lithium	X	X						
Manganese	X							
Neodymium			X				X	
Nickel	X							
Silver				X				
Selenium					X			
Tellurium						X		

² REN21., 2018., Renewables 2018 Global Status Report, Paris: REN21 Secretariat. Available at: http://www.ren21.net/wp-content/uploads/2018/06/17-8662_GSR2018_FullReport_web_final.pdf

³ Hertwich, E.G. et al., 2014. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, 112(20), pp.6277–6282. Available at: <http://www.scoop.us.com/inward/record.uri?eid=2-s2.0-84929404255&partnerID=tZ0tx3y1>.

1.1 Project objectives

This report presents findings from an assessment of the metal requirements, supply risks and impacts for renewable energy and storage technologies. The objective of this project is to understand:

- the projected demand for minerals required for renewable energy, and the potential to offset this through secondary sources, materials efficiency, substitution or technology innovation;
- the supply risks, looking at major present and future supply regions, as well as social and environmental impacts associated with supply;
- current levels of industry awareness and responses

Through considering the above findings, this research aims to identify the main 'hotspots' or areas of concern in the supply chain, including technologies, metals and locations, where opportunities to reduce demand and influence responsible sourcing initiatives will be most needed.

1.2 Project scope

This research investigates three technologies used in renewable energy systems: battery storage systems (for transport and stationary energy storage), solar photovoltaics (PV) and wind power, and fourteen metals associated with their production as shown in Table 1.⁴ For these major technologies we consider the types of technologies that are dominant today, and those that might be important in the future. For PV we consider crystalline silicon (c-Si); and, thin film technologies, copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe). For batteries we focus on lithium-ion batteries (LIB), which encompasses a range of different types, and also look at lithium-sulfur (Li-S) as the most prospective candidate to replace LIB. For wind, we differentiate between those technologies with and without permanent magnet generators (PMG).

These technologies have been assessed because of their current and future importance for a renewable energy system. This analysis does not include other technologies that may emerge as important in future, and could influence future mineral requirements, supply risks and impacts, including hydrogen fuel cell vehicles, as their potential uptake is less certain.

Our assessment is based on interviews with industry experts and a review of literature including academic publications, market reports and investment news (Chapters 2, 4 and 5). The methodology developed to model future metal demand is described in Chapter 3.

1.3 Report overview

The research findings are presented in the following sections:

- **Metal requirements for renewable energy and storage technologies:** A review of renewable energy and storage technologies; supply chains and market trends; the metal requirements and potential to offset demand through secondary sources, materials efficiency or substitution (Chapter 2)
- **Projected metal demand for 100% renewable energy:** Projections of future demand for metals, modelled against an ambitious renewable energy scenario (Chapter 3)
- **Supply risks:** An assessment of supply risks including the concentration of production and reserves, renewable energy share of end-use and supply chain criticality (Chapter 4)
- **Environmental and social impacts of supply:** A review of known environmental, health and human rights impacts in mining (Chapter 5)
- **Industry awareness and responses:** A review of the current level of awareness of the industry of supply risks and impacts, and current initiatives to reduce demand and ensure responsible sourcing (Chapter 6)

⁴ This is not a comprehensive list of all the metals that could potentially be used in clean energy technologies, but focuses on metals that are found in substantial amounts. However, this does not include steel, which is likely to be one of the largest metal requirements. This analysis also does not include material requirements for include new transmission and distribution, or vehicles themselves except for the rare earths in permanent magnets.

2 Metal requirements for renewable energy and storage technologies

Renewable energy and battery storage are complex technologies, requiring a wide range of metals. This chapter gives an overview of the key metals used for electric vehicles, battery storage, solar PV and wind power. Solar PV and wind power are the dominant renewable technologies and will most likely continue to be into the future. Solar PV accounted for more than half of newly installed renewable power capacity in 2017 and wind power approximately one-third.⁵ Batteries, alongside other storage technologies, are considered to be important for future energy systems with large amounts of electricity from variable renewables. Advances in battery technologies have also enabled the electrification of the transport system, and it is electric vehicles that are driving the increased demand for batteries.⁶

These technologies are rapidly developing and evolving, and there are various sub-technologies designed for specific applications, which adds to the complexity of material use. Renewable energy and storage technologies typically have higher and more diverse metal requirements than fossil fuel power generation. However, once these technologies are manufactured and installed, there are no ongoing requirements for fuel, such as coal or natural gas.

Base metals, namely aluminium and copper, are essential for almost all renewable technologies, and are used in high amounts compared to other metals (see Tables 2 and 3). Rare earths, specifically neodymium and dysprosium, also have very high importance for renewable energy, as they are used for permanent magnets in the engine of nearly all electric vehicles (EVs) and around 20% of wind turbines. Other metals that are of high importance are cobalt, lithium, nickel and manganese used in lithium-ion batteries (LIBs), and silver for use in the majority of solar panels. There are also range of specialty metals used for thin-film solar panels for specialist applications.

The material intensity of each metal is shown in Table 2, and highlights the opportunities and challenges to offsetting demand through substitution, efficiency or recycling. The recyclability of metals *within each technology* is discussed, for example, although silver has an overall recycling rate of 30–50%,⁷ almost no recycling happens of silver from PV panels. A current recycling rate is given for each metal in Table 3, as well as a potential recycling rate, based on what could be technologically possible (but is not currently economic). This analysis focuses on fourteen key metals, but there are many more metals used in these technologies, and other metals may emerge as important in future. Details on the material intensity and recyclability for each technology is discussed in Sections 2.1 to 2.3.

⁵ REN21., 2018., *Renewables 2018 Global Status Report*, Paris: REN21 Secretariat. Available at: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final.pdf

⁶ Bloomberg New Energy Finance, 2018., *Electric Vehicles*. Available at: <https://bnef.burfi.co/story/evo2018?teaser=true>

⁷ Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F. and Sonnemann, G., 2011. *Recycling rates of metals: A status report*. United Nations Environment Programme. Available at: http://www.resourcepanel.org/file/381/download?token=he_rldvr

Table 2: Material Intensity for renewable energy technologies

Technology		Aluminium	Copper	Cobalt	Lithium	Manganese	Nickel	Dysprosium	Neodymium	Silver	Gallium	Indium	Selenium	Cadmium	Tellurium
Batteries [t/GWh]	Li-ion	220	220	124	113	406	415								
	Li-S	220	220		411										
EVs [kg/vehicle]								0.083	0.695						
	c-Si	32,000	4,000							4 – 20					
Solar PV [t/GW]	ClOS	32,000	4,000								2 – 9	7 – 28	17 – 41		
	CdTe	32,000	4,000											19 – 70	17 – 60
Wind [t/GW]	PMG	560	3,000					27	188						
	Non-PMG	560	3,000												

Table 3: Recycling rates at end-of-life for renewable energy technologies

Technology		Aluminium	Copper	Cobalt	Lithium	Manganese	Nickel	Dysprosium	Neodymium	Silver	Gallium	Indium	Selenium	Cadmium	Tellurium
Batteries	Current	70%	70%	90%	0%	0%	90%								
	Potential	95%	95%	95%	95%	95%	95%								
Electric vehicles	Current							0%	0%						
	Potential							95%	95%						
Solar PV	Current	77%	34%							0%	0%	0%	0%	77%	77%
	Potential	81%	81%							81%	81%	81%	81%	81%	81%
Wind	Current	80%	90%					0%	0%						
	Potential	95%	95%					95%	95%						

2.1 Electric vehicles and battery storage

Technology overview and markets

Lithium-ion batteries power almost all electric vehicles in the market today as well as most stationary energy storage applications.⁸ At this very early stage of adoption, EVs represent less than 1% of the global passenger vehicle market with cumulative sales reaching about two million in 2016.⁹ Most of this early adoption has been supported by government incentives in China and Europe.¹⁰ However, major future expansion of the EV market is anticipated as part of a broad decarbonisation strategy, and to mitigate urban air pollution.¹¹ Sales of EVs reached a record 1.1 million vehicles worldwide in 2017.¹² Most major auto-manufacturers are now producing EVs, offering battery electric vehicles (BEV) and/or a plug-in hybrid electric vehicles (PHEV). Several auto-manufacturers (including General Motors and Toyota) have announced plans to sell only EV or hydrogen fuel cell vehicles in the near future, and several countries plan to phase-out or ban sales of petrol and diesel powered cars.¹³ The main battery cell manufacturers are based in China, Korea, Japan and the US, with a small amount of manufacturing in Europe, and cathode materials are mainly produced in China.¹⁴

The electrification of the transport system is also underway for electric buses, commercial vehicles and 2-wheelers. Electric buses are now in use in Europe and China, particularly for short inner-city trips, and this is expected to continue growing.¹⁵ The electrification of commercial vehicles will be important to reduce fossil fuel consumption in the transport sector, as trucks make up around 20% of fuel demand in the transport sector, although they only represent 5% of the vehicle stock.¹⁶ Electric Light Duty Vehicles are now emerging on the market¹⁷. However, electric Heavy Duty Vehicles for long-distance freight will take longer to become economically viable, owing to the large size of and cost of battery required to power a large vehicle over long distances¹⁸, and hydrogen fuel cells may emerge as a more suitable technology.¹⁹ There are already around 200 million electric bicycles, scooters and motorbikes in China, following a ban on petrol scooters in many cities, and Europe is the second biggest market.²⁰

The market for battery storage systems is also growing, however in most markets it is secondary to EVs. Batteries can be used at either utility scale or behind-the-meter, to ensure energy system adequacy and security. LIBs are commonly used for storage applications, as the very high round-trip efficiency of charge-discharge makes them attractive compared to most alternatives. However, there are various other battery types which are suitable, as most storage applications do not require the high energy density of LIBs. Lead-acid batteries have traditionally been used for off-grid storage applications, and may continue to do so in some regions due to their low cost. Sodium and flow batteries are the most likely battery technologies to gain market share from LIB for storage applications in the future. There are also a range of other technologies that can help with storage needs including pumped hydro, concentrated solar power with thermal storage and hydrogen.

⁸ Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: <https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/>

⁹ Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3(4), p.279.

¹⁰ For example the European Automobile Manufacturers Association (ACEA) provides an 'Overview on Tax Incentives for EVs in EU' that is available at: https://www.acea.be/uploads/publications/EV_incentives_overview_2018.pdf

¹¹ IEA, 2017, Energy Technology Perspectives 2017. Available at: <http://www.iea.org/etp2017>; IEA, 2017, Global EV Outlook 2017: Two Million and Counting. Available at: <https://www.iea.org/publications/freepublications/publication/global-ev-outlook-2017.html>

¹² Bloomberg New Energy Finance, 2018., Electric Vehicles. Available at: <https://bnef.burfi.co/story/evs2018?teaser=true>

¹³ Eisenstein, P., 2017, NBC News, 3 October 2017. Available at: <https://www.nbcnews.com/business/autos/gm-going-all-electric-will-ditch-gas-diesel-powered-cars-n806806>

¹⁴ Major companies include Panasonic, BYD, CATL, LG Chem and Samsung SDI.

¹⁵ Bloomberg New Energy Finance, 2018., Electric Buses in Cities. Available at: http://www.ourenergypolicy.org/wp-content/uploads/2018/04/1726_BNEF_C40_Electric_buses_in_cities_FINAL_APPROVED_2.original.pdf

¹⁶ Energy Insights by McKinsey, 2017. Available at: <https://www.mckinseyenergyinsights.com/insights/new-reality-electric-trucks-and-their-implications-on-energy-demand/>

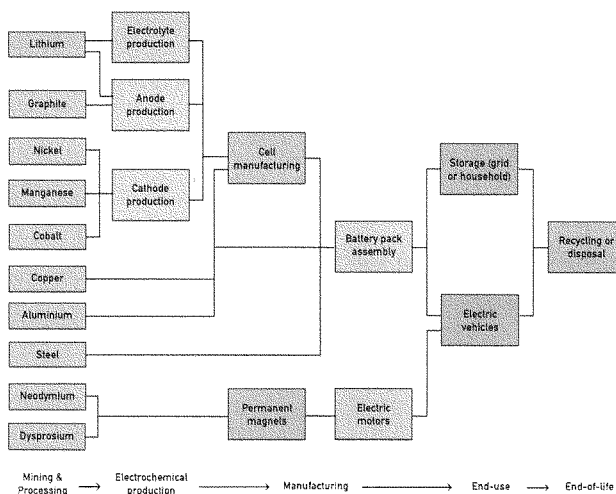
¹⁷ Sripad, S. and Viswanathan, V., 2017. Evaluation of current, future, and beyond li-ion batteries for the electrification of light commercial vehicles: Challenges and opportunities. *Journal of The Electrochemical Society*, 164(11), pp.E3635-E3646.

¹⁸ Sripad, S. and Viswanathan, V., 2017. Performance metrics required of next-generation batteries to make a practical electric semi truck. *ACS Energy Letters*, 2(7), pp.1669-1673.

¹⁹ Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3(4), p.279.

²⁰ Fishman, E. and Cherry, C., 2016. E-bikes in the Mainstream: Reviewing a Decade of Research. *Transport Reviews*, 36(1), pp.72-91.

Figure 1: Overview of lithium-ion battery supply chain



Material requirements

Lithium-ion batteries are made of two electrodes (anode and cathode), current collectors, a separator, electrolyte, container and sealing parts. The anode is typically made of graphite with a copper foil current collector. The cathode is typically a layered transition metal oxide with an aluminium foil current collector. In between the electrodes is a porous separator and electrolyte. All of these components are typically housed in an aluminium container. LIBs are generally referred to by the material content of the cathode that accounts for 90% of the material value and about 25% of the total weight.²² A simplified overview of the lithium-ion battery supply chain, including key materials (for the NMC chemistry) and sub-components, is shown in Figure 1.

The size and chemistry of the battery has the biggest impact on the material requirement. Since commercialisation of LIB technology in the 1990s a range of different types ('chemistries') have been developed for different applications, named by the metals in the cathode. The most common LIB types for EV applications are Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), Nickel Cobalt Aluminium (NCA) and Lithium Manganese Oxide (LMO).²³ In most markets, NMC is the most common battery type for passenger vehicles, followed by NCA, with a small share for LMO. However, in China LFP has been the dominant chemistry. Electric buses have traditionally used LFP batteries²⁴ and lead-acid batteries are the most common for 2-wheelers in China and South East Asia, however LIBs are projected to become more common as the costs reduce.²⁵ For energy storage, NMC and NCA are most common of the lithium-ion chemistries. Rare earth permanent magnets (based on neodymium and dysprosium) are common in most electric vehicles, enabling high performance motors.²⁷

²² Gratz, E., Sa, Q., Apelian, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. *Journal of Power Sources*, 262, pp.255-262.

²³ Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013.

²⁴ Bloomberg New Energy Finance. 2018. *Electric Buses in Cities*. Available at: http://www.ourenergypolicy.org/wp-content/uploads/2018/04/1726_BNEF_C40_Electric_buses_in_cities_FINAL_APPROVED_2_original.pdf

²⁵ Yan, X., He, J., King, M., Hang, W. and Zhou, B., 2018. Electric bicycle cost calculation models and analysis based on the social perspective in China. *Environmental Science and Pollution Research*, pp.1-13.

²⁷ Values from: Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

Potential to offset demand

Material efficiency

The range of future battery types, and hence material inputs, are expected to be very different in the future. There is already a focus on reducing the amount of cobalt within LIBs with a shift towards 'NMC811' that contains Nickel Manganese Cobalt in a ratio of 8:1:1 in the cathode, compared to the most common chemistry 'NMC111' that contains equal parts of each metal.²⁸ This will see an increase in demand nickel and decrease in cobalt and manganese, and has implications for future recycling because the high value of the cobalt is an important economic driver.

At the same time many companies are aiming to reduce cobalt use, Chinese battery manufacturers are shifting towards NMC batteries, away from LFP batteries. This shift is driven by the superior performance of NMC chemistry and because of government policy introduced in 2016 that sets a minimum energy density for batteries that cannot be met by LFP. Therefore, it is likely NMC chemistries will continue to be the preferred technology in the short term.²⁹

Emerging battery technologies not yet on the market may also affect material requirements in the future, and reduce demand for the more valuable metals. A recent evaluation of the range of available and emerging battery technologies argued that the critical factors for scale-up are reducing cost, overcoming limited capacity that is associated with 'range anxiety', and improving safety.³¹ A continued shift away from the dominant cobalt-rich LIB types and a broader shift away from LIB technology is predicted to meet future requirements for three important market sectors: long-range, high-utilisation (freight and public transport), and the low-cost market. Lithium-sulfur (Li-S) is considered the most prospective candidate to replace the currently dominant LIB types.³²

The size of the battery presents the most simple way to reduce the material consumption of batteries for electric vehicles. The battery size can vary hugely, with the batteries in passenger vehicles ranging between 15 and 100kWh.³³ There is a trend for luxury auto-manufacturers to increase the size of the battery to extend the range, however other manufacturers are focused on more affordable vehicles with smaller sized batteries. Other motor technologies which replace rare earths with lower cost materials are under development and already used in some vehicles, but rare earth magnets are expected to remain the standard in electric vehicles for the foreseeable future.³⁴

Recycling

The collection efficiency of batteries at end-of-life is likely to be very high, as although the recycling process is not mature, the collection channels already exist (i.e. auto dealerships). Battery collection is required by European law, and in certain jurisdictions where regulations do not apply manufacturers already offer cash rebates to incentivise battery take-back.³⁵

Lithium-ion batteries can be recycled through two main processes, pyro-metallurgical or hydro-metallurgical, and there are various process routes combining these key processes that are under development. Current recycling processes prioritise the recovery of valuable cobalt and nickel while the less valuable metals including lithium and manganese are not usually recovered, but may be down-cycled for lower value applications.³⁷ Although lithium and manganese are 'technically recyclable' they are hard to separate from the other metals without the use of expensive organic reagents for solvent extraction.³⁸ As demand increases for these metals the economic drive to recover these may justify recovery.

²⁸ Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: <https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/>

²⁹ Castellano, R., 2017. How to minimise Tesla's cobalt supply chain risk. Seeking Alpha. Available at: <https://seekingalpha.com/article/4113417-minimize-teslas-cobalt-supply-chain-risk>

³¹ Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3(4), p.279.

³² Li-S is an emerging rechargeable battery with a sulfur cathode and a lithium metal anode. The potential future importance of this emerging rechargeable battery type has also been observed by several studies.

³³ Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013

³⁴ Widmer, J.D., Martin, R. and Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies*, 3, pp.7-13.

³⁵ For example: <https://www.toyota.com.au/hybrid/battery-recycling>

³⁷ King S. Boxall NJ, Bhatt AI., 2018. Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

³⁸ Gratz, E., Sa, Q., Apellan, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. *Journal of Power Sources*, 262, pp.255-262

An overview of current and potential recycling rates used for this study is given in Table 4. Recycling rates were determined based on a collection efficiency and a recovery efficiency for each metal in the recycling process. The current recycling rate for cobalt and nickel is assumed to be 90%³⁹, assuming a collection efficiency of 100% for all batteries. It is assumed around 10% of lithium is currently recycled, considering that lithium recovery is possible based on hydro-metallurgical processing routes that are utilised by several global recyclers (including Umicore, Recupyl and Batrec). However, pyrometallurgical processing routes where lithium recovery is typically not recovered account for most of the current global recycling capacity.⁴⁰ Copper and aluminium can also be recovered during mechanical pre-processing at rates of approximately 70%, however recyclers have reported higher recovery rates.⁴¹

We estimate a potential future recycling rate of 95% recovery for all metals noting that 100% recovery has been reported in the laboratory⁴² and a number of companies are promoting 100% recovery on the basis of 'proof of concept' pilot trials.⁴³ Nonetheless, some losses are inevitable, for instance the generation of metal dust during pre-processing.⁴⁴ Neodymium and dysprosium are currently not recycled, although up to 95% is assumed to be technologically possible.⁴⁵

Table 4: Battery and EV material intensity and recycling rates

Materials	Aluminium	Copper	Lithium	Cobalt	Nickel	Manganese	Dysprosium	Neodymium
Current materials intensity [t/GWh]	220	220	113	124	415	406	0.083 kg/ vehicle	0.695 kg/ vehicle
Future technology [t/GWh]	220	220	411	0	0	0	0.083 kg/ vehicle	0.695 kg/ vehicle
Current recycling rate [%]	70%	70%	0%	90%	90%	0%	0%	0%
Potential recycling rate [%]	95%	95%	95%	95%	95%	95%	95%	95%

Note: Current materials intensity based on an assumed market share of a range of LIB technologies: NMC (60%), LMO (20%), NCA (15%), and LFP (5%)⁴⁶. Future technology based on introduction of Li-S batteries.⁴⁷ Current recycling rate based on a collection efficiency of 100% and recovery rates from various studies. Potential recycling rate based on assumption of 95%.

Reuse of EV batteries for stationary storage

The reuse of LIBs used for EVs is emerging as an important end-of-first-life option. The reuse of batteries extends the useful life of a battery and can offset demand for new materials with minimal additional energy requirements compared to recycling. Owing to the performance requirements of batteries for EV applications, LIBs may be considered to have reached end-of-life when they approach 80% of their original capacity; however, these batteries may remain useful for alternative applications, such as stationary storage.⁴⁸ Many of the major manufacturers are exploring stationary energy storage applications, for example Renault in partnership with Powervault are trialling the reuse of EV batteries for home storage systems.⁴⁹ If reuse becomes an important option for end-of-life EV batteries, new policies may be needed to assure consumers that reused batteries are safe and reliable and to fairly allocate responsibilities for management at the end-of-second-life.

³⁹ Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H. and Rutz, M., 2012. Development of a recycling process for Li-ion batteries. *Journal of power sources*, 207, pp.173-182.

⁴⁰ King S. Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

⁴¹ Assumption based on interviews. Australian recycler Envirostream have reported recovery rates of 100% of Cu and Al

⁴² Gratz, E., Sa, Q., Apellan, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries. *Journal of Power Sources*, 262, pp.255-262.

⁴³ See: <https://americanmanganeseinc.com/investor-info-3/investment-proposition/>

⁴⁴ Pers comms Boxall, N. CSIRO, Australia

⁴⁵ Fraunhofer Institute, 2018. Recycling of rare earth magnets. Available at: https://www.materials.fraunhofer.de/en/business-areas/energy_and_environment/recycling-of-rare-earth-magnets.html

⁴⁶ Values from: Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013

⁴⁷ Simon, B., Ziemann, S. and Weil, M., 2015. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. *Resources, Conservation and Recycling*, 104, pp.300-310

⁴⁸ King S. Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

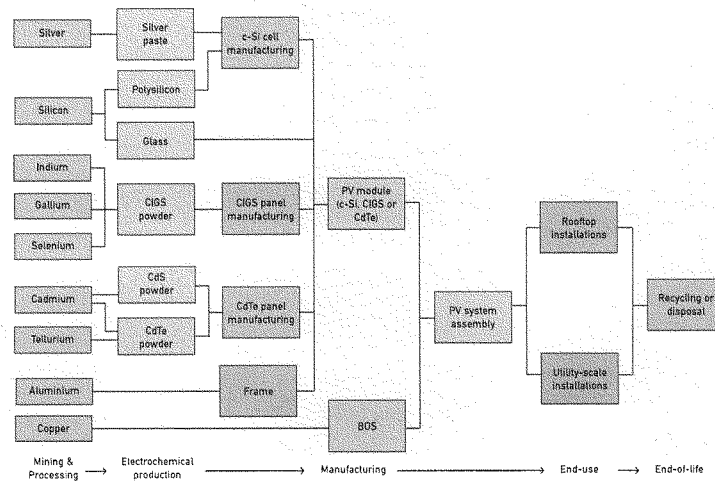
⁴⁹ See: <https://media.group.renault.com/global/en-gb/media/pressreleases/92203/renault-et-powervault-donnent-une-seconde-vie-aux-batteries-des-vehicules-electriques1>

2.2 Solar PV

Technology overview and markets

There are two main types of PV panels used today, crystalline silicon (c-Si) and thin film technologies. Crystalline silicon technology dominates the global market with more than 95% of market share.⁵⁰ Thin film technologies including copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe) make up the remainder of the market, and are used in more specialist applications. A simplified diagram of the PV supply chain, including key materials and sub-components, is shown in Figure 2.

Figure 2: Overview of solar PV supply chain



The manufacturing of c-Si PV panels is concentrated in a small number of countries, and is led by China where the size of the industry far exceeds that of all other countries combined. China is the world's largest producer and exporter of end-products (PV modules) and sub-components (cells), followed by Taiwan and Japan. The United States, Germany and South Korea are the largest exporters of polysilicon, mainly to China and Japan, however China is still the largest producer. Silver pastes are produced in China, Japan, South Korea and Taiwan. The largest end markets are China, United States, Japan and India⁵¹.

Material requirements

A typical crystalline silicon PV panel contains about 76% glass (panel surface), 10% polymer (encapsulant and back-sheet foil), 8% aluminium (frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (e.g. tin and lead).

⁵⁰ Fraunhofer Institute for Solar Energy Systems, 2018. Photovoltaics report. Available at: <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

⁵¹ Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: <https://www.nrel.gov/docs/fy17osti/65619.pdf>

Thin film technologies require less material overall compared to crystalline silicon. For CdTe panels the glass content is 96-97%, 3-4% polymer and less than 1% for semiconductor material (CdTe) and other metals (e.g. nickel, zinc, tin). CIGS contain about 88-89% glass, 7% aluminium, 4% polymer with less than 1% semiconductor material (indium, gallium, selenium) and other metals (e.g. copper).⁵²

Potential to offset demand

Material efficiency

The material use in PV panels has decreased significantly since the commercialisation of the technology, particularly for silver and polysilicon that are the most expensive materials in c-Si panels. This reduction of silver is expected to continue, and could halve in the next decade.⁵⁶ The future substitution of silver with copper, a less expensive material, is envisioned by the industry. However, there are no technologies currently on the market, and the International Technology Roadmap for Photovoltaic (ITRPV) expects that copper-based c-Si technologies will be introduced to mass-production but will reach less than <15% of the market by 2028.⁵⁷

Recycling

Recycling of PV panels is not a mature industry owing to the typical long-life expectancy of most modules (approximately 30 years). The volumes of end-of-life panels are generally too low for recycling to be economically favourable at present, however there are recycling schemes in place in some jurisdictions.⁵⁸

Most current recycling of PV panels focuses on recycling glass, aluminium and copper, and the small amounts of other metals are not recovered. Even silver is not usually recovered, although it is the most valuable metal in a typical panel representing nearly 50% of the material value.⁵⁹ Presently PV panels are recycled in existing recycling plants (for glass and scrap metal) using manual and mechanical methods. These processes can achieve high recovery of glass and aluminium (> 90%),⁶⁰ and around 40% of copper.⁶¹

The other metal components predominantly end up in the glass and encapsulant (polymer e.g. ethylene-vinyl-acetate) fractions following mechanical processing. The main technical challenge is the removal of the encapsulant that is designed to last for decades in harsh environments without losing its functional properties.⁶² Thus, while 'technically recyclable', recovering the small amounts of valuable (e.g. silver, copper), scarce (e.g. indium, tellurium), or most hazardous materials (e.g. cadmium, lead, selenium) requires additional thermal treatment, or the use of organic solvents. Cadmium and tellurium from CdTe panels are able to be recovered at around 90% efficiency, and the largest manufacturer First Solar has a recycling program in place.⁶³

In order to estimate an overall recycling rate for each metal for this study, we have multiplied the recovery efficiency discussed above by a collection efficiency. We have assumed a current collection efficiency of 85% for all panels, based on the target from the EU.⁶⁴ This is an estimate, noting that the location and type of installation will likely have a major impact on collection efficiency. For example, the collection of small rooftop PV systems, or systems in remote locations, will be more expensive to collect and transport to recycling facilities compared to large utility-scale PV. The assumed material intensity and recycling rates are shown in Table 5.

⁵² These are average values drawn from a range of published sources as summarised by Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

⁵⁶ Ibid

⁵⁷ The International Technology Roadmap for Photovoltaics (ITRPV) is a public resource made available by VDMA that is a major industry group representing PV (c-Si) manufacturers and suppliers, available at: <http://www.itrpv.net/Home/>

⁵⁸ Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

⁵⁹ Ibid

⁶⁰ Assuming aluminium from frame that is manually removed

⁶¹ Based on LCA study. Latunussa, C.E.; Ardente, F.; Blengini, G.A. and Mancini, L., 2016. Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Solar Energy Materials and Solar Cells*, 156, pp.101-111

⁶² Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

⁶³ Based on conference presentation from FirstSolar that suggests 95% recovery of semiconductor material in metals rich filter cake based on wet process

⁶⁴ More details available here: http://ec.europa.eu/environment/waste/weee/index_en.htm

Table 5: Solar PV material intensity and recycling rates

Materials	All PV		c-Si	CIGS			CdTe	
	Aluminium	Copper	Silver	Gallium	Indium	Selenium	Cadmium	Tellurium
Current materials intensity [t/GW]	32,000	4,000	20	9	28	41	70	60
Improved materials intensity [t/GW]	32,000	4,000	4	2	7	17	19	17
Current recycling rate [%]	77%	34%	0%	0%	0%	0%	77%	77%
Potential recycling rate [%]	81%	81%	81%	81%	81%	81%	81%	81%

Note: Aluminium⁶⁵ and copper⁶⁶ are used in all three technologies and the intensity is assumed to remain the same as these are not a focus for efficiency. Data for the current materials intensity of silver is from a survey of the PV industry which also projects improved materials intensity.⁶⁷ Data for the remaining metals is from Kavlak et al. and gives a high value for current materials intensity and the lowest value for improved materials intensity. These are theoretical figures calculated by varying the assumed thickness of the cells, the module efficiencies and material losses during manufacturing.⁶⁸ Current recycling rate based on a collection efficiency of 85% and recovery rates from various studies. Potential recycling rate based on assumption of 95% recovery efficiency and when considering the 85% collection efficiency, this give an overall potential recycling rate of 81%.

⁶⁵ Bodeker, J.M., Bauer, M., Pehnt, M. Aluminium and Renewable Energy Systems—Prospects for the Sustainable Generation of Electricity and Heat; Institut für Energie und Umweltforschung Heidelberg GmbH: Heidelberg, Germany, 2010

⁶⁶ The Warren Centre. The Copper Technology Roadmap 2030 Asia's Growing Appetite for Copper

⁶⁷ International Technology Roadmap for Photovoltaic (ITRPV), 2018, International Technology Roadmap for Photovoltaic Results 2017, Ninth Edition. Available at: <http://www.itrpv.net/Reports/Downloads/>

⁶⁸ Kavlak, G., McNerney, J., Jaffe, R.L. and Trancik, J.E., 2015. Metal production requirements for rapid photovoltaics deployment. *Energy & Environmental Science*, 8(6), pp.1651-1659. We have used the high values for gallium and indium and the medium values for selenium, cadmium and tellurium, as these are closest to the averages given in other studies.

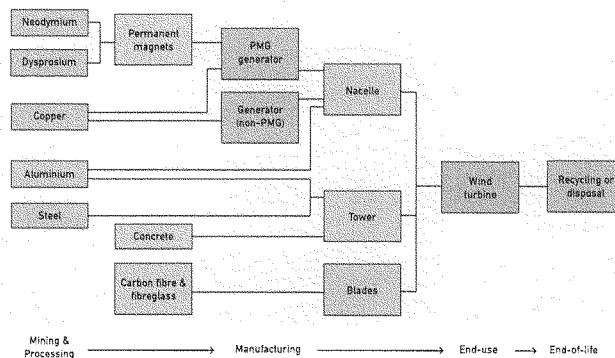
2.3 Wind

Technology overview

Wind power is the most established new-generation renewable technology and most competitively priced. The installed capacity exceeds all other non-hydro renewables, reaching 539 GW globally in 2017.⁶⁹ The valuable wind resource at sea is now being harnessed by offshore wind farms with foundations embedded in the ocean floor and new floating wind turbines. However, owing to the higher costs of wind turbines off-shore, on-shore technology is expected to remain the dominant application in the near to midterm.

Until the early 2000s, the manufacture of wind turbine components mostly occurred in the EU and then transported around the world. More recently manufacturing is happening in dozens of different locations serving local and regional markets. This shift corresponds with a significant increase in size of wind turbine components, leading to transport cost savings. For example, there are 5 of 10 large wind turbine manufacturers located in China meeting Chinese demand and these manufacturers are also exporting sub-components to the global wind industry.⁷⁰

Figure 3: Overview of wind power supply chain



Material requirements

Although a range of wind turbine technologies exist for different conditions, the predominant design is a horizontal-axis turbine with three blades that rotate upwind around a horizontal axis on a 80 to 120m tower. The major raw materials required for the manufacture of wind turbines are bulk commodities: steel, copper, aluminium, concrete and carbon. The steel structural components account for about 80% of the total weight of the turbine.

Some turbine generator designs use direct-drive permanent magnet generators (PMG) that contain rare earth metals, neodymium and dysprosium (Figure 3). The development of direct-drive PMGs by major producers (e.g. Siemens and General Electric) simplifies the design by eliminating the gearbox and this is particularly attractive for off-shore applications because it minimises maintenance requirements.⁷¹ It is estimated that about 20% of all installed wind turbines (including on-shore and off-shore) use rare earth permanent magnets.⁷²

⁶⁹ Global Wind Energy Council, 2018, Global Wind Report. Available at: <http://gwec.net/global-figures/wind-energy-global-status/>

⁷⁰ Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: <https://www.nrel.gov/docs/fy17osti/65619.pdf>

⁷¹ Zimmermann, T., Rehberger, M. and Gößling-Reisemann, S., 2013. Material flows resulting from large scale deployment of wind energy in Germany. Resources, 2(3), pp.303-334.

⁷² Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: <https://www.nrel.gov/docs/fy17osti/65619.pdf>

Potential to offset demand

Material efficiency

The material use of bulk metals is not expected to change significantly. As the most established next-generation renewable technology, material use for wind turbines is already very efficient, and advances in turbine technology have enabled capacities up to 7MW in a single machine.

Off-shore technology tends to have higher material requirements, mostly bulk materials for foundations and extended towers or for transmission, so an increase in off-shore turbines could increase metal requirements. As noted above, only about 20% of all installed wind turbines use permanent magnet generators with rare earths. This limited share is likely linked to supply constraints, with China currently manufacturing about 90% of all rare earth magnets while consuming about 75% of the global supply. It is speculated that increases in the use of rare earth magnet generators could occur if new rare earth mines and processing facilities are established.⁷⁶

Future innovations that may lead to material savings, for example lighter towers and blades enabled by the use of carbon fibre or other composites, are possible but have not been considered in this analysis.

Recycling

Recycling of the bulk materials (steel, aluminium, copper) used in wind turbines is well established, with high recycling rates, as shown in Table 6.⁷⁷ These materials account for about 80-95% of the materials used in wind turbines by weight. There is currently no recycling of dysprosium or neodymium from permanent magnets, but this could be technologically possible, and making it economically viable is the focus of significant research and development at the laboratory scale.⁷⁸

Table 6: Wind power material intensity and recycling rates

Materials	Aluminium	Copper	Dysprosium	Neodymium
Current materials intensity [t/GW]	560	3,000	0	0
PMG materials intensity [t/GW]	560	3,000	27	198
Current recycling rate [%]	80%	95%	0%	0%
Potential recycling rate [%]	95%	95%	95%	95%

Note: The assumed material intensity for aluminium⁷⁹, copper⁸⁰, dysprosium and neodymium⁸¹ are based on on-shore technologies. Current recycling rate based on a collection efficiency of 100% and recovery rates from various studies. Potential recycling rate based on assumption of 95%.

⁷⁶ Clean Energy Manufacturing Analysis Center (CEMAC). 2017. Benchmarks of global clean energy manufacturing. Available at: <https://www.nrel.gov/docs/ty17osti/65619.pdf>

⁷⁷ Zimmermann, T., Rehberger, M. and Gößling-Reisemann, S., 2013. Material flows resulting from large scale deployment of wind energy in Germany. *Resources*, 2(3), pp.303-334.

⁷⁸ Fraunhofer Institute, 2018, Recycling of rare earth magnets. Available at: https://www.materials.fraunhofer.de/en/business-areas/energy_and_environment/recycling-of-rare-earth-magnets.html

⁷⁹ Average of values from three studies: Bödeker, J.M.; Bauer, M.; Peñt, M. Aluminium and Renewable Energy Systems—Prospects for the Sustainable Generation of Electricity and Heat; Institut für Energie und Umweltforschung Heidelberg GmbH: Heidelberg, Germany, 2010; Kleijn, R. and Van der Voet, E., 2010. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and Sustainable Energy Reviews*, 14(9), pp.2784-2795; Elshkaki, A. and Graedel, T.E., 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production*, 59, pp.260-273.

⁸⁰ Value from: Wilburn, D.R. Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030, 2011. Available online: <http://pubs.usgs.gov/sir/2011/5036/>

⁸¹ Value from: Hoenderdaal, S., Espinoza, L.T., Marscheider-Waidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

2.4 Summary of challenges to reducing demand

Copper, lithium, silver and rare earths are the metals most challenging to reduce total demand through substitution and efficiency, and offset primary demand through recycling.

Copper is used in all technologies, and is difficult to substitute, as it is used for its high electrical conductivity. It is challenging to reduce demand for lithium as it is used in the dominant lithium-ion battery technologies, and currently only has limited recycling. Lithium is also used in Li-S batteries which are a promising future technology for EVs, but other technologies which don't use lithium (such as sodium) could be used for storage in future. Silver is used in 95% of PV panels, and while the industry is continuously increasing its efficiency in material use, it is not currently recycled and is technologically difficult to do so. Similarly, the rare earths neodymium and dysprosium are not currently recycled, and substitution is possible but currently nearly all EVs use this technology.

Aluminium is also very important as it is used in all technologies, as well as cobalt and nickel which are used in main Lithium-ion battery chemistries. However, these metals can be substituted (with some loss of performance) and currently have high recycling rates. The remaining metals are of less concern as they can more easily be substituted with other metals or other technology types (e.g. cadmium, tellurium, gallium, indium and selenium are only used in niche PV technologies and can be avoided by switching to alternative panel types in many cases). A summary of the challenges to offsetting metal demand is shown in Table 7.⁸²

Table 7: Summary of challenges to reducing demand

		Importance to renewable energy		Materials efficiency or substitution		Current recyclability
Aluminium		High – used for wind, PV & batteries		With some loss of performance (steel, plastic)		~70-80% recycled
Cadmium		Low – CdTe small share of PV market		Efficiency increasing, can shift to other PV types		~77% recycled
Cobalt		Medium – Li-ion dominant battery technology		Efficiency increasing, can shift with loss of performance (LFP)		90% recycled
Copper		High – used for wind, PV & batteries		Difficult to substitute in most applications		~34-95% recycled
Dysprosium		High – used for wind & batteries		Can shift to other magnet or motor types, or non-PMG wind		Not currently recycled
Gallium		Low – CIGS small share of PV market		Efficiency increasing, can shift to other PV types		Not currently recycled
Indium		Low – CIGS small share of PV market		Efficiency increasing, can shift to other PV types except flexible		Not currently recycled
Lithium		Medium – Li-ion dominant battery technology		Efficiency increasing, but used for all Li-ion and Li-S		~10% recycled
Manganese		Medium – Li-ion dominant battery technology		Efficiency increasing, can shift to other battery types (LFP, NCA)		Very limited recycling
Neodymium		High – used for wind & batteries		Can shift to other magnet or motor types, or non-PMG wind		Not currently recycled
Nickel		Medium – Li-ion dominant battery technology		Efficiency increasing, can shift with loss of performance (LFP)		90% recycled
Silver		Medium – cSi large share of PV market		Efficiency increasing, copper possible but not commercialised		Not currently recycled
Selenium		Low – CIGS small share of PV market		Efficiency increasing, can shift to other PV types		Not currently recycled
Tellurium		Low – CdTe small share of PV market		Efficiency increasing, can shift to other PV types		~77% recycled

⁸² A 'traffic light' rating scheme is used to give an indication of the potential or challenges to offset demand for each metals. For importance to clean energy, red represents metals that are of high importance (used in multiple technologies and therefore harder to replace), orange represents medium importance (used in the dominant sub-technology) and yellow is for the least importance (used in less dominant sub-technology). For materials efficiency or substitution, red represents the metals most difficult to reduce or substitute (either metals in the technology or between sub-technologies), orange can be substituted but with some loss of performance and yellow are the most suitable for efficiency or substitution. Lastly recyclability is rated based on current rates of recycling, from red (not currently recycled), orange (some recycling) and yellow (currently recycled).

3 Projected metal demand for 100% renewable energy

This chapter presents scenarios for the demand for metals in a future renewable energy system. The aim of this analysis is to determine projected total demand and production rates, and how primary demand could be offset through changes in technology or recycling rates. This is useful for understanding which metals may present as bottlenecks to the deployment of renewable energy technologies, where new primary or secondary supply will be needed, and which strategies have the greatest impact on reducing primary demand for each metal and technology.

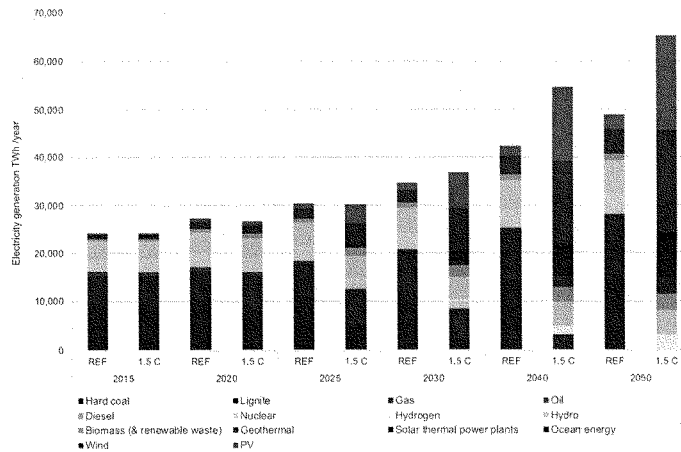
3.1 Future energy and resource scenarios

The future demand for metals has been modelled against an ambitious scenario for a 100% renewable energy and transport system by 2050. This energy scenario was developed by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS), in partnership with the German Aerospace Centre (DLR), Institute for Engineering Thermodynamics, Department of Systems Analysis and Technology Assessment (STB).⁸³

The ISF/DLR scenario was developed to limit anthropogenic climate change to a maximum of 1.5 C degrees above the pre-industrial levels, in line with the aims of the Paris Climate Agreement.⁸⁴ This scenario is more ambitious than other published scenarios; for example the IEA scenario projects the global development of renewable power and electric mobility under the assumption that current policies will not change.

Renewable power generation – in particular solar PV and wind – are the most cost competitive electricity generation technologies compared to all other power generation technologies for installations and are projected to increase their market share (see Figure 4 and data in appendix). In this scenario solar PV generates 30% of electricity and wind power 33% of electricity by 2050. Lithium-ion batteries account for approximately 6% of stationary energy storage (which is dominated by pumped hydro and hydrogen).

Figure 4: Projection of 100% renewable electricity by 2050

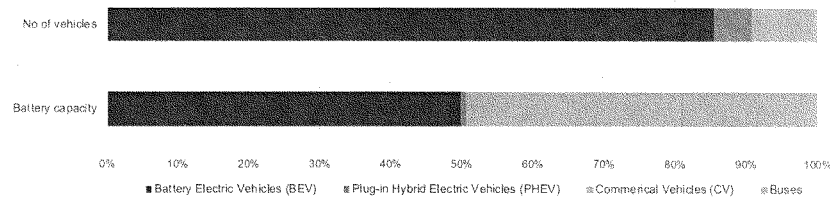


⁸³ See: <https://oneearth.uts.edu.au/>

⁸⁴ See: <https://unfccc.int/resource/bigpicture/#content-the-paris-agreement>

The scenario assumes a high electrification level of the transport sector in order to replace oil as the main fuel. In the transport system we focus on the material requirements for batteries used in road transport, as other types of transport do not require batteries or are assumed to rely on other forms of energy (e.g. biofuels for aviation). In 2050 most of the energy for road transport comes from electricity (55%) and hydrogen (22%) and the remainder is from biofuels and synfuels. In the 1.5°C scenario the required batteries for electrifying road transport are given for electric buses and passenger cars, including battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), and commercial vehicles.

Figure 5: Share of vehicles and total battery capacity between vehicle types in 2050



Passenger cars (BEV and PHEV) account for 90% of vehicles and 51% of total battery capacity, whereas commercial vehicles are projected to account for 48% of battery capacity, although they make up only 9% of the total fleet of vehicles (as shown in Figure 5). This is because battery sizes for commercial vehicles (assumed to be 250 kWh in 2015 and rising to 600 kWh in 2050) are larger than those for passenger vehicles (5–15kWh for PHEV and 38–62kWh for BEV). Buses account for a small percentage (1%) of both vehicles and batteries. Electric bikes and scooters have been excluded, as although they are currently a growing market in Asia, by 2050 their share of electricity consumption is negligible compared to the predicted uptake of electric passenger and commercial vehicles.

For comparison, metal demand has also been modelled against a reference scenario that continues to have a high share of fossil fuels (with 30% renewable energy by 2050), and does not meet climate change targets.

Scenarios for metal demand

Five scenarios were developed to estimate metal demand, based on the current market trends and likelihood of changes in materials efficiency or technology described in the previous chapter (shown in Table 8).

Table 8: Summary of resource scenarios

Scenario name	Market share/ materials efficiency	Recycling	Colour in figures
Total demand	Current materials intensity and current market share of sub-technologies	No recycling	Red
Current recycling	Current materials intensity and current market share of sub-technologies	Current recycling rates	Pink
Potential recycling	Current materials intensity and current market share of sub-technologies	Improved recycling rates	Orange
Future technology	Improved materials efficiency for PV and current market share of sub-technologies Technology shift for batteries	No recycling	Dark blue
Future technology & potential recycling	Improved materials efficiency for PV and current market share of sub-technologies Technology shift for batteries	Improved recycling rates	Light blue

The predicted metals demand for renewable energy in each year is estimated based on the capacity of each technology introduced in a specific year in the energy scenario (GW of solar PV or wind

power, or GWh of battery capacity for EVs and storage). This introduced stock accounts for new capacity and replacement of technologies at end of life, based on a lifetime distribution curve for the average lifetime for each technology.

The metal demand each year is then estimated based on the material intensity of a specific metal for each technology (given in Table 2). The values for metal intensity are given as tonnes/GW for solar PV and wind power, tonnes/GWh for batteries and kg/ vehicle for rare earths in EVs.

The **“total demand” scenario** is the total metal demand if the current materials intensity and market share continue into the future, without recycling or efficiency improvements. For batteries, the materials intensity is based on an assumed market share of a range of LIB technologies: NMC (60%), LMO (20%), NCA (15%), and LFP (5%).⁸⁵ For solar PV we assume the current market share of 95.8% c-Si panels (containing silver), 1.9% CIGS and 2.3% CdTe⁸⁶ and for wind we assume 20% of turbines use rare earth permanent magnet generators.⁸⁷

Table 9: Key variables for scenarios

	Batteries	EVs	Solar PV	Wind
Lifetime	10 years	15 years	30 years	25 years
Current market share of sub-technologies	100% Li-ion	100% contain PMG	c-Si 95.8% of market, CIGS 1.9% & CdTe 2.3%	20% contain PMG
Future technology	Li-S 50% by 2050, beginning from 2030		Market share as above with improved material efficiency	

To evaluate the impact of recycling, primary demand is estimated by multiplying the discarded products at end-of-life by a recycling rate. The **“current recycling” scenario** uses the current recycling rates at end-of-life, summarised in Table 3. The **“potential recycling” scenario** uses an improved recycling which is considered to be technologically possible, but does not currently happen as it is not economic. Note for some metals there is no “current recycling” data displayed on the graph, this is because there is no recycling currently happening (e.g. silver, manganese, neodymium, dysprosium), so the result is the same as “total demand”.

For metals used in batteries and solar PV we have two further scenarios, to understand the potential to offset primary demand through future improvements in technology. For batteries it is likely that the technologies used in the future will not be the same as those commercialised today (unlike solar PV and wind that are unlikely to change dramatically). Therefore, for the **“improved technology” scenario**, we assume that Lithium-sulfur batteries are the most likely technology to replace LIB for electric vehicles⁸⁸ and have a modelled a scenario of a future market where Li-S achieves a 50% market share for EVs by 2050, beginning in 2030. We assume the technology does not change for storage batteries. For solar PV, as the industry is focused more on efficiency rather than changes in technology, in the “improved technology” scenario we assume improved material efficiency using the lower values given in Table 2. The **“improved technology and potential recycling” scenario** then applies the potential recycling rate to the improved technology scenario.

Key indicators of demand

For all metals, two key indicators are analysed:

- Cumulative demand by 2050 compared to current reserves and resources, to highlight the scale of demand relative to physical availability of stocks
- Annual primary demand compared to current production across the period, to determine the amount of production in a given year and to highlight if there may be bottlenecks in supply or short term restrictions.

⁸⁵ Based on Vaalma, C., Buchholz, D., Weil, M. and Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials*, 3, p.18013

⁸⁶ Fraunhofer Institute for Solar Energy Systems, 2018. Photovoltaics report. Available at:

<https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

⁸⁷ Clean Energy Manufacturing Analysis Center (CEMAC), 2017. Benchmarks of global clean energy manufacturing. Available at: <https://www.nrel.gov/docs/ty17osti/65619.pdf>

⁸⁸ Based on Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3(4), p.279.

The current annual production rates, reserves and resources are shown in Table 10, based on data from the US Geological Survey and other sources.⁸⁹

Table 10: Production rates, reserves and resources for key metals

	Annual production (tonnes)	Reserve (tonnes)	Resources (tonnes)
Aluminium	60,000,000	30,000,000,000	55 –75,000,000,000
Cadmium	23,000	500,000	6,000,000
Cobalt	110,000	7,100,000	25,000,000
Copper	19,700,000	790,000,000	3,500,000,000
Dysprosium	1,800	1,100,000	1,980,000
Gallium	315	110,000	1,000,000
Indium	720	15,000	47,000
Lithium	46,500	16,000,000	53,000,000
Manganese	16,000,000	680,000,000	unknown
Neodymium	16,000	12,800,000	23,040,000
Nickel	2,100,000	74,000,000	130,000,000
Selenium	3,300	100,000	171,000
Silver	25,000	530,000	1,308,000
Tellurium	420	31,000	48,000

Reserve and resource definitions

Reserves are the estimated amount of a mineral that can be economically mined under current conditions.⁹¹ Reserves are a subset of resources, which are the total known amount of a mineral for which extraction may be potentially be feasible. Reserves and resources can both change over time depending on changing economic conditions, discovery of new deposits and technological developments.

Over time, resources may be reclassified as reserves, for example if higher prices and strong demand justify the mining of lower grade or more challenging ore deposits or if new technological advancements makes extraction viable. On the other hand, reserve estimates can also be downgraded over time, but are more likely to increase. Data on reserves is available for many metals, however data on resources is less certain, so reserves are more commonly used in comparing future demand to availability.⁹²

This study focuses only on the metal demand for renewable energy technologies, and does not take into account other demands for these metals, which may also increase or decline over time. It is expected that renewable energy technologies will consume a greater share of these metals and in many cases may be the major driver of demand for the metal. For our projections, the potential to offset demand through recycled content comes only from metals from the same technologies at end-of-life, however demand could potentially be offset from other secondary sources of the metal. This scenario is a very ambitious renewable energy scenario based on current technologies, and over time new technologies may become more efficient or new technologies may emerge.

⁸⁹ Values for cadmium, gallium and indium reserves and resources; selenium, silver and tellurium resources and all rare earth values are from Watari, T., B. McLellan, S. Ogata and T. Tezuka, 2018. Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios. *Minerals* 8(4): 156. All other values are from U.S. Geological Survey (USGS), 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

⁹¹ U.S. Geological Survey (USGS), 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

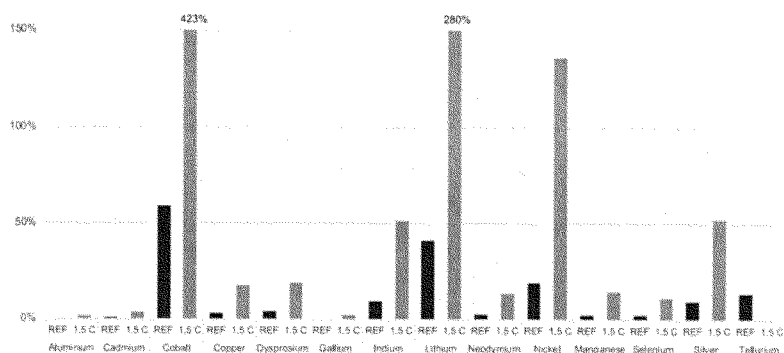
⁹² Speirs, J., Gross, R., Contestabile, M., Candelise, C., Houari, Y. and Gross, B., 2014. Materials availability for low-carbon technologies: An assessment of the evidence. *UK Energy Research Centre, London*. Available at: <http://www.ukerc.ac.uk/asset/34D2BFC5-9C0D-4C07-BA6CD6D16BDE549A/>

3.2 Key results

Metals with high cumulative demand in 2050 compared to reserves and resources

The cumulative demand from renewable energy and storage technologies could exceed current reserves for cobalt, lithium and nickel in the 1.5 degree scenario, and demand could reach over 50% of reserves for indium, silver and tellurium. In the reference scenario, cumulative demand for cobalt is 60% of reserves and lithium is 40% of reserves, as shown in Figure 6.

Figure 6: Cumulative total demand from renewable energy and storage by 2050 compared to reserves in the 1.5 degree and Reference scenarios



Cumulative demand from the total demand scenario and the scenario with the lowest demand is shown in Table 11 and compared to reserves and resources (for the 1.5 degree scenario). Aluminium has the highest cumulative demand by 2050, followed by copper, nickel and manganese.

Table 11: Cumulative demand from renewable energy and storage by 2050 in the 1.5 degree scenario

	tonnes		% of reserves		% of resources	
	Total demand	Lowest scenario	Total demand	Lowest scenario	Total demand	Lowest scenario
Aluminium	513,866,476	443,140,185	2%	1%	1%	1%
Cadmium	18,105	11,317	4%	2%	0%	0%
Cobalt	30,067,291	9,585,532	423%	135%	120%	38%
Copper	139,539,959	101,093,179	18%	13%	4%	3%
Dysprosium	1,073,070	210,142	19%	12%	11%	7%
Gallium	2,462	1,332	2%	1%	0%	0%
Indium	7,660	4,243	51%	28%	16%	9%
Lithium	44,861,515	13,811,115	280%	86%	85%	26%
Manganese	98,446,129	31,384,886	14%	5%	0%	0%
Neodymium	92,338	1,704,713	13%	8%	7%	5%
Nickel	100,628,432	32,080,611	136%	43%	77%	25%
Selenium	11,216	7,081	11%	7%	7%	4%
Silver	276,917	152,974	52%	29%	21%	12%
Tellurium	23,181	13,074	75%	42%	48%	27%

Metals with large projected increases in demand compared to current production

Annual demand from renewable energy and storage technologies exceeds current production levels for nearly half of the metals: cobalt, dysprosium, lithium, neodymium, nickel and tellurium (as shown in Table 12). Metals that have a high projected annual demand compared to current production levels will need to rapidly increase supply. Note that these results compare peak demand to current production (2017 data) and do not account for likely increases in production that may already be planned. Lithium has the highest peak annual demand compared to current production levels, followed by cobalt.

Demand for lithium, cobalt and rare earths from renewable energy exceeds current production rates by 2022. The rapid increase for these metals is owing to the predicted rapid electrification of the transport system, which has only begun to accelerate in the last few years. This is in comparison to the more established technologies of solar PV and wind, which have already been rolling out at rapid rates.

Table 12: Peak annual demand from renewable energy and storage compared to current production (2017 data) in the 1.5 degree scenario

	tonnes		% of annual production		Year of peak demand	
	Total demand	Lowest scenario	Total demand	Lowest scenario	Total demand	Lowest scenario
Aluminium	18,852,177	17,822,832	3%	3%	2036	2033
Cadmium	700	479	3%	2%	2035	2028
Cobalt	1,966,469	747,427	1788%	679%	2050	2031
Copper	5,626,579	4,493,216	29%	23%	2050	2033
Dysprosium	11,524	7,299	640%	406%	2050	2031
Gallium	89	57	28%	18%	2035	2028
Indium	276	181	38%	25%	2035	2028
Lithium	4,112,867	727,682	8845%	1565%	2050	2033
Manganese	6,438,599	2,447,220	40%	15%	2050	2031
Neodymium	94,687	59,118	592%	369%	2050	2031
Nickel	6,581,326	2,501,469	313%	119%	2050	2031
Selenium	404	289	12%	9%	2035	2028
Silver	9,926	6,646	40%	27%	2035	2027
Tellurium	834	555	199%	132%	2035	2028

The year at which demand for each metal peaks is shown in Table 12. For metals for which solar is the main source of demand, peak demand is around 2035/36, whereas for all other metals peak annual demand occurs in 2050. In the lowest demand scenario for each metal, peak annual demand occurs earlier (between 2027-2033), as the effects of recycling or shifting technology take effect.

Potential to offset demand

The potential to offset primary demand for each metal depends on the technology which is the dominant driver of demand.

For metals in batteries, the scenarios show that recycling has the biggest impact on reducing primary demand. This is shown in Figure 7, where the cumulative demand in the "potential recycling" scenario is significantly lower than the total demand scenario. Shifting away from Lithium-ion batteries which use cobalt and nickel also has a large impact on reducing demand for these metals, which is even greater when combined with recycling (as shown in the "new technology & potential recycling scenario"). However, this increases the demand for lithium which is used in greater amounts in Li-S batteries under the scenario. These results are based on recycling at end-of-life of the technologies in this study, and using recycled metals from other sources could further reduce primary demand.

Figure 7: Cumulative demand from EVs and battery storage by 2050 relative to reserves in three scenarios

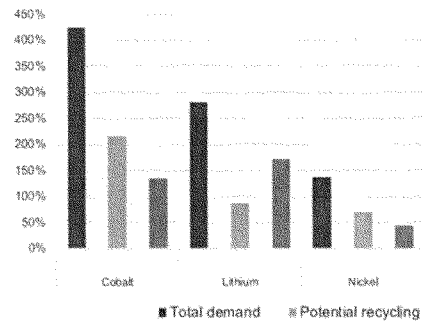
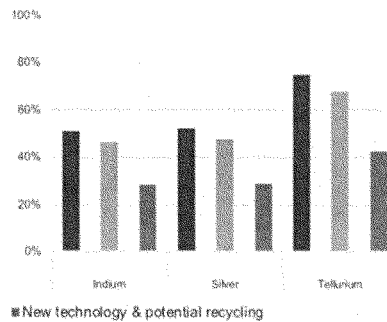


Figure 8: Cumulative demand from solar PV relative to reserves in three scenarios



Material efficiency has the most potential to offset primary demand for solar PV metals, rather than recycling. This is because the long lifetime of PV panels creates a lag for when the materials in PV panels become available for recycling. This is represented in Figure 8, where the "new technology & potential recycling" scenario has a much larger impact on cumulative demand compared to the "potential recycling" scenario.

Share of demand between technologies

Solar PV is the main driver of demand for aluminium across the entire period (Figure 9). Solar PV is also the main consumer of copper until 2035, and after this batteries dominate the consumption (Figure 10). In considering battery demand, EVs are the main source of demand for lithium, cobalt and other battery metals, rather than stationary storage. EVs, rather than wind power, are projected to drive demand for rare earths neodymium and dysprosium (Figure 11). The share of demand in the total demand (red) and potential recycling (orange) scenarios is shown below.

Figure 9: Share of primary demand for aluminium from wind, solar PV and batteries

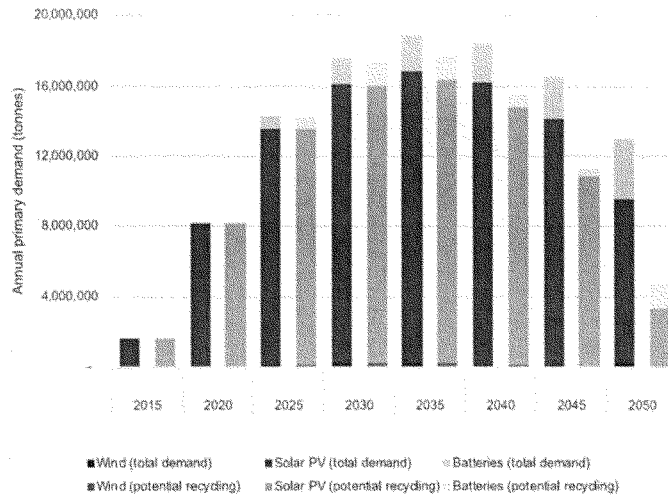
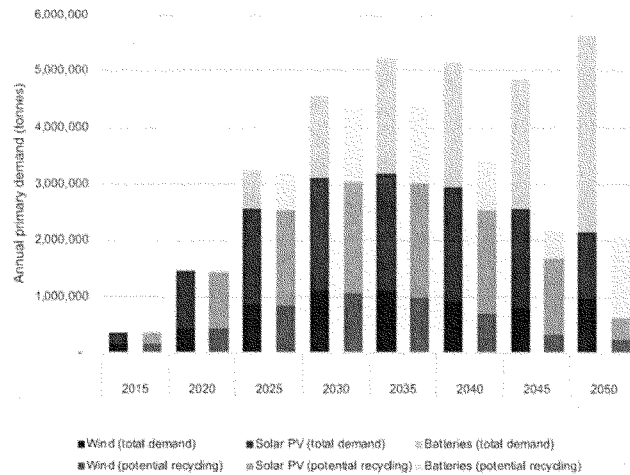
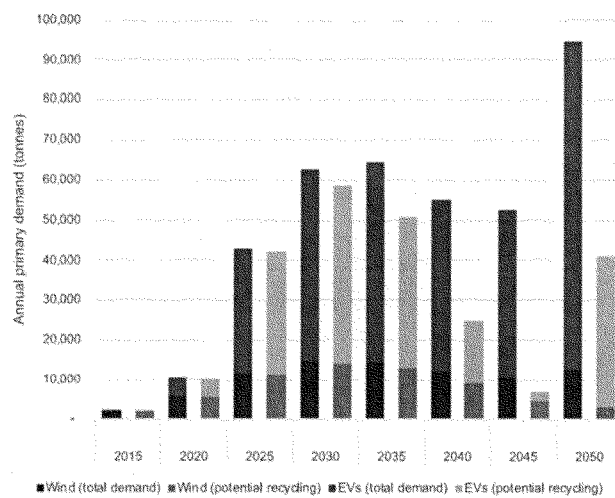


Figure 10: Share of primary demand for copper from wind, solar PV and batteries

Figure 11: Share of primary demand for neodymium from wind and EVs⁹³

Demand from solar PV for aluminium and copper peaks in 2035, as this period is assumed to have the largest increase in installations, as shown in Figure 10 and 11. Similarly, demand from wind for aluminium, copper and neodymium peaks in 2030, but then begins to increase again to replace end-of-life turbines. The deployment of batteries (mainly in EVs) increases over the period, but the annual demand varies with the replacement of end-of-life batteries. The effect of recycling EVs and batteries in the "potential recycling" scenario results in an earlier peak demand for copper and neodymium than in the "total demand" scenario. Overall batteries and solar PV have the greatest impact on demand, and detailed results for key metals for these technologies are shown in the following sections.

⁹³ The share of demand for dysprosium is similar to neodymium, as they are found in similar proportions in the two technologies

3.3 Batteries for EVs and stationary storage

Cobalt and lithium have an annual demand from batteries for EVs and storage that far exceeds current rates of production. Annual demand for cobalt and lithium could exceed current production rates by around 2023, in all scenarios.

Shifting to Li-S instead of LIB decreases demand for cobalt (shown in the “future technology” scenario). However, unless this shift happens alongside high recycling rates this has less impact on reducing primary demand than continuing with the current technology and recycling rates (the “current recycling” scenario). In the scenario of “future technology & potential recycling” the demand for cobalt could actually drop below current annual production by 2042 (Figure 12).

The shift to Li-S batteries increases demand for lithium, as these batteries have around three times the amount of lithium compared to LIB. Increasing recycling from current minimal levels (assumed 10%) has the most potential to offset primary demand for lithium (Figure 13).

Figure 12: Annual primary demand from EVs and battery storage for cobalt

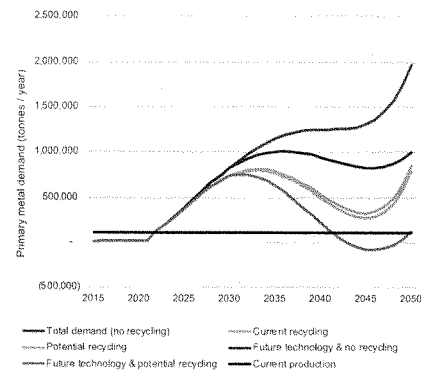
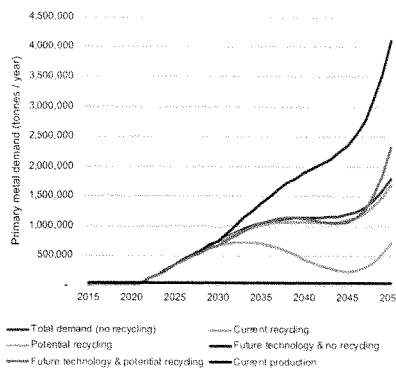


Figure 13: Annual primary demand from EVs and battery storage for lithium



Cumulative demand for cobalt from batteries for EVs and storage exceeds current reserves in all scenarios (Figure 14), and for lithium it is exceeded in all scenarios except for the “potential recycling” scenario” (Figure 15).

Figure 14: Cumulative primary demand by 2050 from EVs and battery storage for cobalt

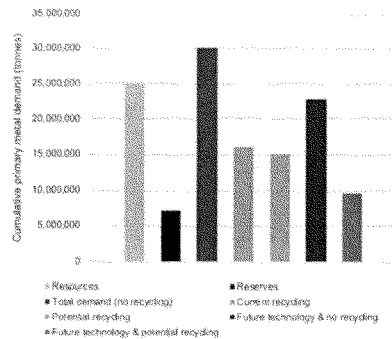
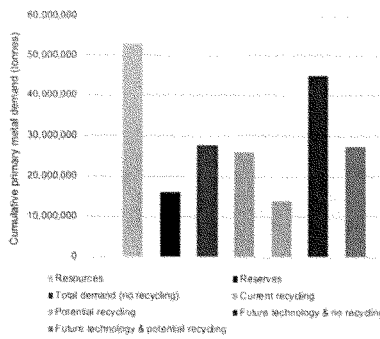


Figure 15: Cumulative primary demand by 2050 from EVs and battery storage for lithium



3.4 Solar PV

The annual demand from solar PV for silver could reach more than 40% of current production rates by 2050 in the "total demand" scenario (assuming no recycling and materials efficiency does not change) (Figure 16). Annual demand for tellurium could exceed current production rates by 2020, and demand could peak at 200% of current production in around 2035 (Figure 17). The point at which demand exceeds current production happens a few years later in the future technology scenario because of improved materials efficiency.

Figure 16: Annual primary demand from solar PV for silver

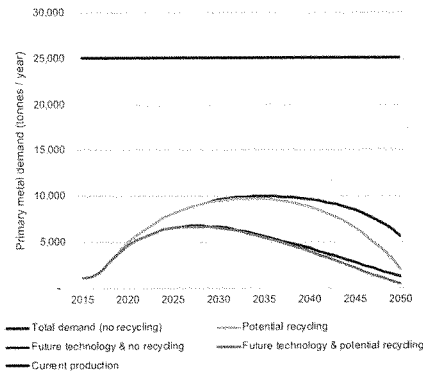
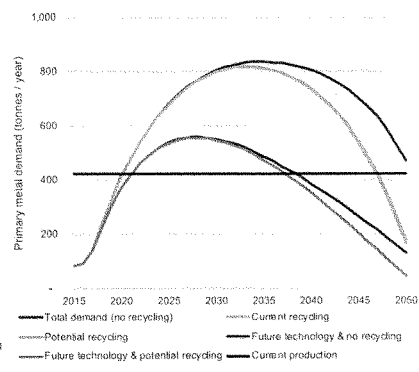


Figure 17: Annual primary demand from solar PV for tellurium



Cumulative demand for silver by 2050 could reach around half of current reserves in the "total demand" scenario, and around one-quarter if there is improved technology (Figure 18). For tellurium, cumulative demand by 2050 could reach two-thirds of current reserves with current technology, and around one-third if there is improved technology (Figure 19).

Figure 18: Cumulative primary demand by 2050 from solar PV for silver

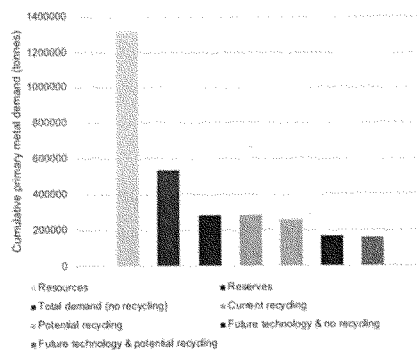
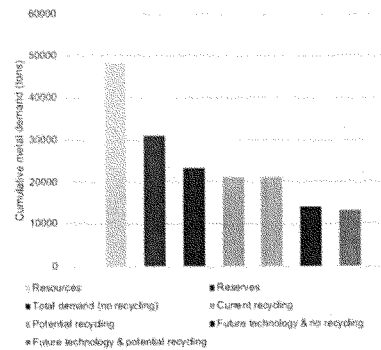


Figure 19: Cumulative primary demand by 2050 from solar PV for tellurium



For both metals, the reduction of material intensity in the "future technology" scenario has the greatest potential to reduce demand compared to the "total demand" scenario, and this is reduced further if recycling is included.

3.5 Summary of projected metal demand

Cobalt and lithium are the metals of highest concern for future demand, as they have a high cumulative demand compared to reserves and resources, as well as high annual demand compared to current production.

For all metals the cumulative demand was compared against reserves and resources to determine if there could be long-term issues with the availability of supply. Cobalt, lithium and nickel all exceed reserves; demand for indium, silver and tellurium could reach over 50% of reserves. For other metals, including rare earths, neodymium and dysprosium, there will be projected large increases in demand compared to current annual production, but no issues with long-term supply. The summary of risks from the demand projections is shown in Table 13.⁹⁴

The metals with high cumulative demand compared to reserves are the metals where marginal or unconventional resources are likely to be accessed, as easily accessible reserves will be exhausted soonest. These are often in more remote or biodiverse places, such as conservation areas or the ocean floor.⁹⁵ These metals are most likely to face volatile prices and issues with security of supply, as has already been observed for cobalt and lithium. A rapid increase in demand compared to production indicates the likelihood of the expansion or development of new mines in the near future, which is discussed for cobalt, lithium and rare earths in the next chapter.

Table 13: Summary of risks from future demand projections

	 Annual demand in 2050 compared to current production	 Cumulative demand compared to reserves & resources
Aluminium	 < 5% of production in all scenarios	 < 5% of reserves in all scenarios
Cadmium	 < 5% of production in all scenarios	 < 5% of reserves in all scenarios
Cobalt	 > 500% of production in all scenarios	 > 100% of reserves in all scenarios and resources in total demand scenario
Copper	 < 50% of production in all scenarios	 < 20% of reserves in all scenarios
Dysprosium	 > 500% of production in all scenarios	 < 20% of reserves in all scenarios
Gallium	 < 50% of production in all scenarios	 < 5% of reserves in all scenarios
Indium	 < 50% of production in all scenarios	 > 50% of reserves in highest scenario
Lithium	 > 100% of production in all scenarios	 > 100% of reserves in most scenarios
Manganese	 < 50% of production in all scenarios	 < 20% of reserves in all scenarios
Neodymium	 > 500% of production in all scenarios	 < 20% of reserves in all scenarios
Nickel	 > 100% of production in all scenarios	 > 100% of reserves in highest scenarios
Silver	 < 50% of production in all scenarios	 > 50% of reserves in highest scenario
Selenium	 < 20% of production in all scenarios	 < 20% of reserves in all scenarios
Tellurium	 > 100% of production in all scenarios	 > 50% of reserves in highest scenario

⁹⁴ For ranking the risk from annual demand in 2050 compared to production, red represents metals have demand more than 500% of current production in all scenarios, orange represents metals where demand is greater than 100% and yellow for metals that are less than 50% in all scenarios. For ranking cumulative demand, red represents metals that exceed reserves in any scenario, orange represents metals where demand is greater than 50% of reserves in any scenario and yellow for metals that are less than 50% of reserves in all scenarios.

⁹⁵ WWF, n.d. Responsible oil, gas and mining. Available at: <https://www.wwf.org.uk/what-we-do/area-of-work/responsible-oil-gas-and-mining>

4 Supply risks

4.1 Concentration of production and reserves

Mining to supply renewable energy technologies occurs in a large number of countries, but a smaller number of countries dominate production. China is the largest producer of metals used in solar PV and wind technologies, with the largest share of production for aluminium, cadmium, gallium, indium, rare earths, selenium and tellurium. In addition, China also has a large influence over the market for cobalt and lithium for batteries. While Australia is the largest producer of lithium, the majority of this is shipped to China for processing. The largest lithium mine, Greenbushes in Western Australia, is majority owned by a Chinese company. Similarly, while DR Congo mines more than half of the world's cobalt, China is the leading producer of refined cobalt, 90% of which is sourced from DR Congo through the many Chinese mining companies and trading houses in the region.⁹⁶ With a large share of the manufacturing of solar PV and lithium-ion batteries, China is also a large end-market for many of the metals, as well as the largest market for the technologies.

Australia, Chile, DR Congo and South Africa have large shares of the production of metals for lithium-ion batteries. Japan, Korea, Canada and Russia have significant production levels of metals for PV, in addition to China (shown in Figure 20). The countries with the highest share of current production and proven reserves for each of the metals are presented in Table 14.⁹⁷ The data presented below highlights reserves, which is the subset of total resources that can be economically mined, which are dependent on a multitude of factors and can change over time.

Table 14: Share of current supply and reserves (2017)⁹⁸

	Share of current production	Share of reserves
Aluminium	Aluminium smelter production: China 54%, Russia 6%, Canada 5%, India 5%	Bauxite and alumina reserves: Australia 20%, Vietnam 12%, Brazil 9%, Jamaica 7%
Cadmium	China 36%, Korea 16%, Japan 10%	Share of reserves unknown
Cobalt	DR Congo 58%, Russia 5%, Australia 5%, Canada 4%, Cuba 4%	DR Congo 49%, Australia 17%, Cuba 7%, Zambia 4%, Canada 4%, Russia 4%
Copper	Chile 27%, Peru 12%, China 9%, United States 6%	Chile 22%, Peru 12%, China 9%, United States 6%, Australia 5%
Gallium	China, Japan, Slovakia, United Kingdom, United States (high grade, share unknown)	Share of reserves unknown
Indium	China 43%, Korea 30%, Japan 10%, Canada 10%	Share of reserves unknown
Lithium	Australia 40%, Chile 30%, Argentina 12%, United States 8%, China 7%	Reserves: Chile 47%, Australia 17% Resources: Argentina 18%, Bolivia 17%, Chile 16%, United States 13%, Australia 9%, Canada 4%
Manganese	South Africa 33%, China 16%, Australia 14%, Gabon 10%	South Africa 29%, Ukraine 21%, Brazil 18%, Australia 14%
Nickel	Indonesia 19%, Philippines 11%, New Caledonia 10%, Canada 10%	Brazil 16%, Cuba 7%, Indonesia 6%, Philippines 6%
Rare Earths ⁹⁹	China 81%, Australia 15%, Russia & Brazil 2%	Brazil 18%, Vietnam 18%, Russia 15%, India 6%
Silver	Mexico 22%, Peru 18%, China 10%	Peru 18%, Poland 17%, Australia 17%, Russia 10%
Selenium	China 28%, Japan 23%, Germany 22%	China 26%, Russia 20%, Peru 15%
Tellurium	China 67%, Sweden 10%, Russia 8%	China 21%, Peru 12%, United States 11%, Canada 3%

⁹⁶ Frankel, T.C., 2016. The Cobalt pipeline. *Washington Post*. Available at:

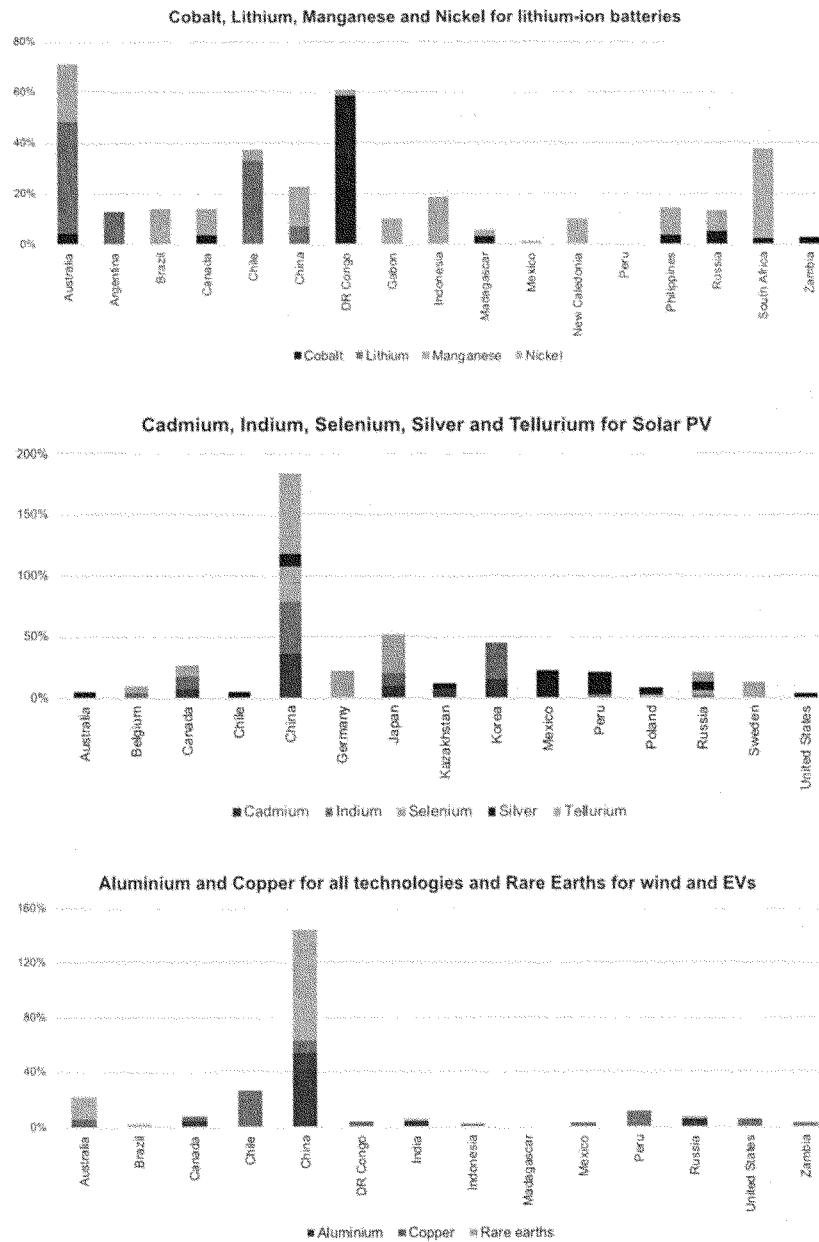
<https://www.washingtonpost.com/business/batteries/congo-cobalt-mining-for-lithium-ion-battery/?hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Abatteriesbottom&hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Abatteriesbottom>

⁹⁷ Both Table 14 and Figure 27 present the share of total production, it is not known which countries are producing for use in clean technologies compared to other uses, particularly for metals which clean energy technologies are not a major consumer.

⁹⁸ Data for 2017 from U.S. Geological Survey (USGS), 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

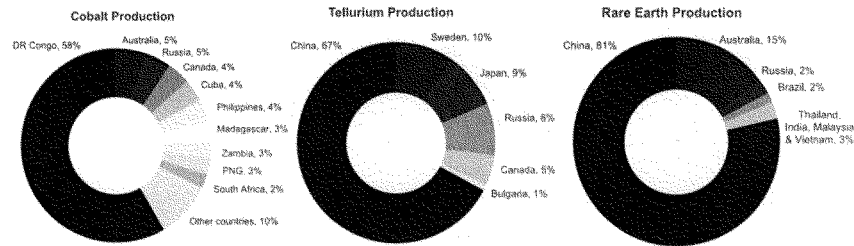
⁹⁹ Includes Dysprosium and Neodymium

Figure 20: Share of production for renewable energy technologies by country (2017)



The metals where production is most dominated by a single country are Rare Earths and Tellurium (China) and Cobalt (DR Congo). These are shown in Figure 21.17. In addition, DR Congo also has around half of current reserves of cobalt, but there are large global resources. The metals with the most concentrated production and reserves are also highlighted in Table 16 at the end of this section.

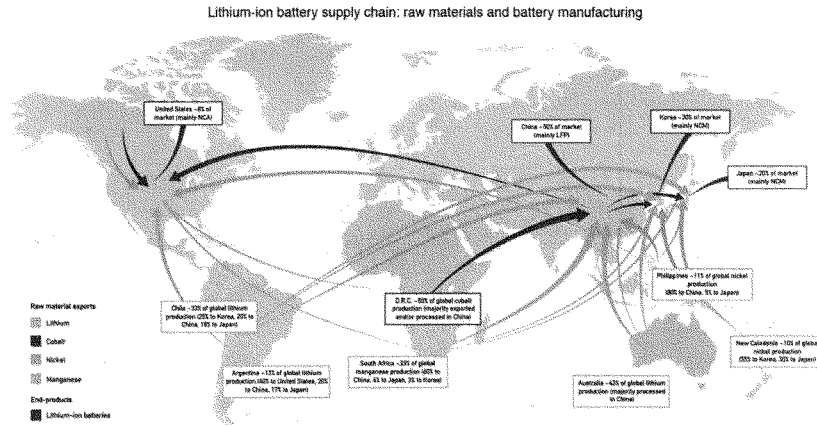
Figure 21: Production by country for cobalt, rare earths and tellurium (2017)



Generally, countries that have a large share of current production have the most potential to be able to increase supply in the short term, as they have existing resources in place required to bring a new mine in to operation. In addition, countries with existing mining are more likely to have the technological knowledge, infrastructure in place and social licence to operate. However, this does not always mean that they have the largest reserves or resources available.

Considering long term supply, for many metals there are countries that have a large share of global reserves or resources, but do not currently mine or have only a small amount of production (as shown in Table 14). Looking again at Rare Earths, Brazil (18%), Vietnam (18%) and Russia (15%) have a significant share of global reserves, but currently only have a very small share of production (less than 2% each). Other examples include Ukraine and Brazil, each with around 20% of manganese reserves, but currently only contribute 1% of world production each. Similarly, Brazil and Cuba may be long term sources for nickel, alongside existing producers.

Countries that have large reserves of several metals for which they only mine a small share of global production include Australia (cobalt and silver), Brazil (manganese, nickel and rare earths), Peru (selenium, tellurium and copper). Bolivia has the second largest share of the world's lithium resources but does not currently mine lithium. These countries have potential to be long term sources for these metals, alongside existing producers. However, there are many other considerations that will affect where mining expands or new mining takes place, including social, economic, technological and environmental factors.

Figure 22: Overview of lithium-ion battery supply chain¹⁹¹⁹ Based on Comtrade data available at <https://comtrade.un.org/Data/>

4.2 Where mining is likely to expand

Under a 100% renewable energy scenario metal requirements are projected to rise dramatically. Although secondary can sources significantly reduce primary demand, especially for batteries, there is a time delay for when recycling can reduce demand the metals. New mining is likely to take place to meet demand, and new mines are already under development.

The uptake of electric vehicles has already increased the demand of cobalt and lithium for lithium-ion batteries, and is the main driver of new demand for these metals. There is also increased demand for rare earths, including neodymium and dysprosium used for electric motors (as well as other rare earths used in a range of technologies). A large number of mines to create new supply for these metals are in development or exploration stages. In this section we review the expansion of mining for the key metals for electric vehicles, as this is the market that is expected to rapidly increase in the next decade, whereas PV and wind turbines are more mature technologies so the increase in demand will likely be steadier. The existing main sources for battery materials are shown in Figure 2218.

Cobalt

Cobalt is often produced as a by-product alongside nickel, copper or gold, however several new projects are solely targeting cobalt rather than as a by-product, reflecting the predicted high future demand. Notable new cobalt developments are underway in Australia, Canada and the United States, and further mines are proposed in the DR Congo. There are plans for the expansion and development of nickel mines in Indonesia and Vietnam, and a copper project in Panama, which plan to produce cobalt as a by-product, although the development of these mines is less certain.

Lithium

Lithium can be sourced from hard-rock ore (spodumene), from the evaporation of salt brines and from seawater. Lithium sourced from salt brines dominated the market in the 1990s due to lower production costs, however the current market share for brine and spodumene is roughly equal.¹⁰¹

Chile is the major producer of lithium from salt brines, in the form of lithium carbonate (Li_2CO_3), alongside Argentina who began commercial production from a new mine in 2015. Australia is the leading producer of lithium from spodumene and produces a concentrate containing lithium oxide (Li_2O).¹⁰² Historically, lithium carbonate from South America has been the main material for battery manufacture, whereas lithium oxide from hard rock was mainly used in the glass and ceramics industries.¹⁰³ However, the global supply chain is interlinked, and China processes lithium carbonate for use in battery manufacture from spodumene from Australia, as well as domestic mining of both spodumene and brines.¹⁰⁴

Expansion and development of new brine operations is underway in Argentina, Chile and the United States, as well as hard rock operations in Australia, Canada, China and Finland. While Bolivia has the largest resources of lithium, estimated at 9 million tonnes, there has been slow development of mining due to mining policies that restrict foreign investment and resistance from indigenous groups.¹⁰⁵ The country is currently looking to ramp up production from the Uyuni mine site, which is producing only 10 tonnes per month, but foreign companies are hesitant to invest.¹⁰⁶ Bolivia also faces economic challenges compared to neighbouring Argentina and Chile, including higher levels of

¹⁰¹ Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., 2017, Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, 797 Available at: <http://doi.org/10.3133/pp1802>

¹⁰² Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., 2017, Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, 797 Available at: <http://doi.org/10.3133/pp1802>

¹⁰³ Dunn, J.B. et al., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ. Sci.*, 8(1), pp.158–168. Available at: <http://dx.doi.org/10.1039/C4EE03029J> <http://xlink.rsc.org/?DOI=C4EE03029J>

¹⁰⁴ Prior, T. et al., 2013. Sustainable governance of scarce metals: The case of lithium. *Science of the Total Environment*, 461–462, pp.785–791. Available at: <http://dx.doi.org/10.1016/j.scitotenv.2013.05.042>

¹⁰⁵ Romero, S., 2009. In Bolivia, untapped bounty meets nationalism. *New York Times*. Available at: <http://www.nytimes.com/2009/02/03/world/americas/03lithium.html>

¹⁰⁶ Alper, A. 2017., Bolivia seeks investors to power up lagging lithium output. *Reuters* <https://www.reuters.com/article/us-bolivia-lithium-analysis/bolivia-seeks-investors-to-power-up-lagging-lithium-output-idUSKBN1EL1JB>

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magnesium in the brine which makes it more difficult to refine, poor infrastructure, and relatively high transport costs to get to markets in Asia and North America as it is a landlocked country.¹⁰⁷

Rare Earths

Rare earths are found in many regions of the globe, however they are often not found in economically viable concentrations and are difficult to extract.¹⁰⁸

The United States was the main producer of rare earths until the 1990s until the closure of the major US mine, which was unable to compete with Chinese production and faced environmental issues. China was able to gain an economic advantage in rare earth production, particularly as the biggest rare earth mine also produces iron ore which makes the mine more profitable. Chinese production soared following the closure of the US mine, and in 2002 China was producing 97% of the world's rare earths. A major mine at Mt Weld in Western Australia and associated processing facility in Malaysia and new investments in the United States in 2013 have somewhat reduced China's domination of the market.¹⁰⁹

There are major new mines under development in Australia, Canada, Greenland and South Africa, as well as interests in Malawi and Uganda.¹¹⁰

A list of the mines set to come into production in the next two years is shown in Table 15, with those likely to create significant supply in the short term in bold. This table also includes several existing mines that have started to expand their operations.

Table 15: New supply for key metals (at development stage or set to come online in next two years)¹¹¹

Cobalt	
Australia	• Clean TeQ Sunrise in New South Wales owned by Clean TeQ Holdings (China's Pengxin International Mining holds 16.5% stake) • Niwest owned by GME Resources • Kalgoorlie Nickel owned by Ardea Resources
Canada	• NICO in Northwest territories owned by Forture Minerals corp
DR Congo	• KCC material assets owned by Katanga Mining Ltd (KML) (75%) and Kamoto Copper Company (KCC) (25%) • Kipoi Central 60% owned by Tiger Resources
Indonesia	• Weda Bay jointly owned by Eramet and Tsingshan group
United States	• Idaho Cobalt owned by eCobalt • Northmet in Minnesota owned by Polymet Mining Corp.
Panama	• Cobre Panama owned by First Quantum Minerals
Vietnam	• Extension of Ban Phuc owned by Asian Mineral Resources (90%)
Nickel	
Zambia	• Restart of the Munal Nickel Project, owned by Consolidated Nickel Mines (CNM) (UK company). The mine ceased operations in 2011 due to low nickel prices and operational problems by previous owners.

¹⁰⁷ Mazumdaru, S. 2017, Bolivia's Evo Morales plans lithium mining offensive DW <https://www.dw.com/en/bolivia-s-evo-morales-plans-lithium-mining-offensive/a-39727810>

¹⁰⁸ Kuan, S.H., Saw, L.H. and Ghorbani, Y., 2016., A review of rare earths processing in Malaysia. Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management (UMTAS2016)

¹⁰⁹ Gholz, E., 2014., Rare Earth Elements and National Security. Council on Foreign Relations. Available at: https://cfrrd8-files.cfr.org/sites/default/files/pdf/2014/10/Energy%20Report_Gholz.pdf

¹¹⁰ Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

¹¹¹ Data for cobalt, lithium and nickel compiled from Ali A., Toledano, P., Maennling, N., Hoffman, N. Aganga, L., 2018. Resourcing Green Technologies through Smart Mineral Enterprise Development: A Case Analysis of Cobalt. *Columbia Center on Sustainable Investment at Columbia University and The Assay Group Mining Magazine*, The Battery Materials Edition, February 2018. Available at: <http://neometals.com.au/reports/the-assay-the-assay-battery-materials.pdf>

Data for rare earths from Hoenderdaal, S., Espinoza, L.T., Marscheider-Weidemann, F. and Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies?. *Energy*, 49, pp.344-355.

Lithium

Argentina	• Cauchari-Olaroz jointly owned by Lithium Americas and SQM • Salar de Centenario owned by Eramet • Sal de Vida owned by Galaxy Resources Ltd (Australian company) • Sal de Los Angeles owned by Lithium X Energy Corp. • Tres Quebradas owned by Neo Lithium Corp. (Canadian company)
Australia	• Expansion of Greenbushes jointly owned by Tianqi Lithium (51%) and Albermarle (49%) via Talison Lithium • Pilgangoora by Altura Mining • Mt Marion owned by Mineral Resources Limited (43.1%), Jiangxi Ganfeng Lithium Co., Ltd (43.1%) and Neometals Ltd (13.8%)
Bolivia	• Salar de Uyuni owned by Comibol
Chile	• Planta Salar owned by Rockwood Lithium
Canada	• Whabouchi owned by Nemaska Lithium • Authier owned by Sayona Mining
Mexico	• Sonora Lithium owned by Bacanora Minerals (70%) and Cadence Minerals (30%)
Serbia	• Jadar owned by Rio Tinto
United States	• Expansion of Silver Peak owned by Albermarle

Rare Earths

Australia	• Expansion of Mount Weld in Western Australia owned by Lynas Corporation Ltd and processed at the Lynas Advanced Material Plant (LAMP) near Kuantan, Malaysia¹¹² • Nolans in Northern Territory, owned by Arafura Resources¹¹³ • Dubbo Project in New South Wales, owned by Australian Strategic Materials Limited (ASM), a wholly owned subsidiary of Alkane Resources Ltd.¹¹⁴ • Browns Range in Western Australia, owned by Northern Minerals¹¹⁵
Canada	• Thor Lake owned by Avalon Advanced Materials Inc.¹¹⁶ • Hoidas Lake in Northern Saskatchewan owned by Navis Resources¹¹⁷ • Alces Lake in Northern Saskatchewan owned by Appia Energy Corp.¹¹⁸ • Port Hope Simpson CREE District, Henley Harbour Area and Red Wine Complex Labrador, owned by Search Minerals Inc.¹¹⁹
Greenland	• Kvanefjeld, Sørensen, and Zone 3 owned by Greenland Minerals Ltd (Australian company)¹²⁰
Malawi	• Songwe Hill in Southwestern Malawi, owned by Mkango (Canadian company)¹²¹
South Africa	• Steenkampskraal Mine in Western Cape owned by Steenkampskraal Holdings Ltd.¹²² • Zandkopsdrift owned by Frontier Rare Earths
Uganda	• Mukuutu project owned by Rwenzori Rare Metals Limited, a private Ugandan company that is 85% owned by the private investor Rare Earth Elements Africa (Pty) Ltd (South African company)¹²³

¹¹² Lynas Corporation, 2018., Mt Weld, Western Australia. Available at: <https://www.lynascorp.com/Pages/Mt-Weld-Concentration-Plant.aspx>

¹¹³ Arafura Resources, 2018., Nolans. Available at: <https://www.arulid.com/projects/nolans.html>

¹¹⁴ Alkane Resources, 2018., Dubbo project. Available at: <http://www.alkane.com.au/operations/dubbo-project/>

¹¹⁵ Northern Minerals, 2018, Browns Range. Available at: <http://northernminerals.com.au/future-prospects/browns-range/>

¹¹⁶ Avalon Advanced Materials Inc., 2018. Available at: <http://avalonadvancedmaterials.com/nechalacho/>

¹¹⁷ Navis Resources, 2018, Hoidas Lake. Available at: <http://naviscorp.com/properties/hoidas-lake>

¹¹⁸ Appia Energy Corp, 2018, News Release: Appia Provides Update on the Critical Rare Earth Element Exploration Program on Its Alces Lake Property. Available at: http://www.appiaenergy.ca/resources/news/nr_20180802.pdf

¹¹⁹ Search Minerals Inc., 2018, Projects. <http://www.searchminerals.ca/projects>

¹²⁰ Greenland Minerals Ltd, 2018, The Ilimaussaq Complex. Available at: <http://www.ggg.gl/project/geology-and-resource/>

¹²¹ Mkango, 2018, Songwe Hill. Available at: <http://www.mkango.ca/s/songwe.asp>

¹²² Steenkampskraal Holdings Ltd., 2018. Available at: <http://www.steenkampskraal.com/the-mine/>

¹²³ Rwenzori Rare Metals, 2018. Available at: <https://rwnzoriraremetals.com/>

4.3 Renewable energy share of consumption

The share of consumption of a metal by renewable energy technologies will affect growth in demand and supply risks. Metals for which renewable energy is a high share of total demand will have more need to increase supply. It also means that changes or potential restrictions in the supply of these metals will have a large impact on the renewable energy industry.

It is difficult to estimate the demand for renewable energy technologies for metals used in lithium-ion batteries for electric vehicles and storage, as lithium-ion batteries are also used in many other applications. Lithium-ion batteries for all uses make up a large share of the demand for key materials, consuming 40% of cobalt and 37% of lithium in 2016. Nickel demand for batteries is currently only a small share (~3%) of class 1 nickel demand.¹²⁴

Electric vehicles and battery storage are only about 10% of the end-use for lithium-ion batteries in 2018, the remaining 90% of battery demand is for electronics and machinery. However, it is renewable energy technologies that are driving growth in battery production, and the demand from electric vehicles and storage could be 80% of the battery market by 2020, and more than 90% by 2025.¹²⁵

Currently 80% of the cobalt that is used in batteries is used by lithium cobalt oxide (LCO) batteries, which are used in small electronics such as mobile phones and laptops. 17.5% is used in NMC batteries and 2.5% in NCA, both of which are used for electric vehicles and storage, as well as other applications.¹²⁶

Based on this, batteries for renewable energy are likely to have a current share of between 4 and 8% of total cobalt demand, and similar for lithium¹²⁷. With the current fast growth in battery production for electric vehicles and storage, it is predicted that lithium-ion batteries could reach 54% of cobalt end-use by 2020 and 63% of lithium end-use. If batteries for EVs and storage are 80% of the lithium-ion battery market by 2020, this could mean up to 43% of demand for cobalt in 2020 is for renewable energy. For lithium this could be even higher, with renewable energy technologies using 50% of lithium in 2020.¹²⁸

PV panels use approximately 9% of the total global demand for silver, and 15.7% of industrial demand (excluding coins, bars, jewellery and silverware). PV is one of the largest drivers of demand for silver, and there was a large growth in demand for PV of 19% from 2016 to 2017.¹²⁹

Thin-film panels are a major end-use for tellurium, with approximately 40% of consumption used in CdTe panels. CIGS panels are also a significant share of the consumption of gallium (17%) and indium (8%).¹³⁰ The share of cadmium and selenium for thin-film PV is unknown.¹³¹

For neodymium and dysprosium, it is estimated that approximately 32% of each metal is used in wind turbines and vehicles, split evenly between the two technologies.¹³²

For the remaining metals, aluminium, copper and manganese, renewable energy technologies are a very small share of end-use.¹³³ An overview of the differences between metals is shown in Table 16.

¹²⁴ Energy Insights by McKinsey, 2018, Metal mining constraints on the electric mobility horizon. Available at: <https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/>

¹²⁵ Energy Insights by McKinsey, 2018.

¹²⁶ Castellano, R., 2017. How to minimise Tesla's cobalt supply chain risk, Seeking Alpha. Available at: <https://seekingalpha.com/article/4113417-minimize-teslas-cobalt-supply-chain-risk>

¹²⁷ Note it is difficult to estimate total share of cobalt and lithium for renewable energy technologies as all data is either for electric vehicle and storage share of total lithium-ion batteries or the metal share of total lithium-ion batteries, and there is a range of chemistries used with different amounts of lithium and cobalt for the various technologies.

¹²⁸ Energy Insights by McKinsey, 2018.

¹²⁹ The Silver Institute and Thomson Reuters, 2018, World Silver Survey 2018. Available at: <https://www.silverinstitute.org/wp-content/uploads/2018/04/WSS-2018.pdf>

¹³⁰ Redlinger, M., Eggert, R. and Woodhouse, M., 2015. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. *Solar Energy Materials and Solar Cells*, 138, pp.58-71.

¹³¹ U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

¹³² Du, X. and Graedel, T.E., 2011. Global rare earth in-use stocks in NdFeB permanent magnets. *Journal of Industrial Ecology*, 15(6), pp.836-843.

¹³³ U.S. Geological Survey (USGS), 2018, Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

4.4 Supply chain criticality

The criticality of a metal is a measure of the security of its supply chain, including supply risks and likelihood of supply restriction. In this section we review the criticality of the key metals for all end-uses, not specifically for renewable energy technologies. This is an important consideration as metals that have a high level of criticality for all uses are vulnerable for possible supply restrictions or risks, even if renewable energy and storage technologies are not a main consumer of the metal.

Criticality also considers the importance and substitutability of metals. If metals are of high importance, or not able to be substituted, this will make it harder to shift supply for clean technologies from other end uses. Criticality is dynamic over time in response to changes in technology and geopolitics. The degree of criticality is not static between corporations or nations, but varies depending on who it is assessed for, and changes over time in response to technology and geopolitics.¹³⁴

Criticality can be measured in various ways, and in Table 16 we have shown the ratings of criticality based on two established methodologies from Yale University¹³⁵ and the European Commission.¹³⁶

Based on these methods, Indium is considered critical by both methodologies, Cobalt, Gallium, Rare Earths in the EU methodology and Silver in the Yale methodology.

Table 16: Summary of supply-side risks

	 Concentration of producers	 Concentration of reserves	 Supply chain criticality	 Renewable energy share of use
Aluminium	 China 54%	 Australia 20%	 Low criticality	 unknown
Cadmium	 China 36%	 unknown	 Medium criticality	 unknown
Cobalt	 DR Congo 58%	 DR Congo 49%	 Critical (EU)	 43% (2020)
Copper	 Chile 27%	 Chile 22%	 Low criticality	 unknown
Gallium	 unknown	 unknown	 Critical (EU)	 17%
Indium	 China 43%	 unknown	 Critical (Yale & EU)	 8%
Lithium	 Australia 43%	 Argentina 18% (resources)	 Low criticality	 50% (2020)
Manganese	 South Africa 33%	 South Africa 29%	 Low criticality	 unknown
Nickel	 Indonesia 19%	 Brazil 16%	 Low criticality	 3%
Rare earths	 China 81%	 Russia/Vietnam 18%	 Critical (EU)	 32%
Silver	 Mexico 22%	 Peru 18%	 Critical (Yale)	 9%
Selenium	 China 28%	 China 26%	 Medium criticality	 unknown
Tellurium	 China 67%	 China 21%	 Medium criticality	 40%

¹³⁴ Ciacchi, L. et al., 2016a. Metal Criticality Determination for Australia, the US, and the Planet—Comparing 2008 and 2012 Results. *Resources*, 5(4), p.29. Available at: <http://www.mdpi.com/2079-9276/5/4/29>.

¹³⁵ Graedel, T.E. et al., 2015. Criticality of Metals and Metalloids. *Proceedings of the National Academy of Sciences*, 112(14), pp.4257–4262. Based on ratings for supply risk and risk of supply restriction.

¹³⁶ European Commission, 2017. Study on the review of the list of critical raw materials. Available at: <https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en>

Aside from quantitative measures of criticality discussed above, we have also reviewed qualitative aspects of the supply chain, and the potential for supply disruptions.

Several metals are mined as a by-product, including cobalt (with the exception of artisanal mining in DR Congo), gallium and indium. These make these metals more vulnerable to price changes in these markets, as typically only a small percentage of the revenues of the companies which mine these metals come from the by-product.

There are known examples of supply restrictions for key metals in the supply chain of renewable energy technologies. Global cobalt markets have been impacted by supply restriction in DR Congo during civil unrest. In particular the "cobalt crisis" had a short but significant impact on manufacturing during 1978, and at that time DR Congo (then called Zaire) controlled a similar high proportion of current supply as it does now (around 50%).¹³⁷

There is also the well-known example of China cutting the exports of rare earths to Japan in 2010 in response to a territorial dispute. This led to global prices soaring in the short term and investment in new mining companies, however supply was not as restricted as thought and prices then plunged leaving many new market entrants in financial trouble. Although real supply was only minimally impacted, as there were difficulties enforcing the export cuts, it had economic costs. The market also adjusted and new mines in development prior to the 2010 export cuts in the US and Australia began to supply the market. This action undermined China's leverage in the market, and it is likely that China's domination of the rare earth market will continue to steadily decline.¹³⁸

While lithium is not considered critical due to the high resources, the market is relatively opaque for lithium as most lithium is sold in private transactions and there is no benchmark price or futures' market (unlike other key battery materials). As such the security of lithium supply has become a top priority for global battery and EV manufacturers, leading to the establishment of alliances and joint ventures between manufacturers and mining companies.

¹³⁷ Alonso, E. et al., 2012. Evaluating Rare Earth Element Availability: a Case with Revolutionary Demand from Clean Technologies. *Environmental Science & Technology*, 46, pp.3406–3414.

¹³⁸ Gholz, E., 2014., Rare Earth Elements and National Security. Council on Foreign Relations. Available at: https://cfrd8-files.cfr.org/sites/default/files/pdf/2014/10/Energy%20Report_Gholz.pdf

5 Environmental and social impacts of supply

The most significant environmental, health and human rights impacts that have been observed in the mining of key metals are outlined below. However, it is important to note that these metals have complex supply chains and many end-uses, so it is difficult to determine direct links to specific industries or companies.

Aluminium

Aluminium metal is predominantly produced from bauxite ores, which are abundant in many regions of the globe. Most bauxite deposits are found close to the surface and are extracted through open-cut mining (also called surface or strip mining), which involves the clearing and removal of large areas of land. The process of excavation, removal of soil and vegetation and transportation can impact ecosystems and lead to air, water and soil pollution.¹³⁹ Of particular concern is the release of fine dust particles, which can lead to respiratory and cardiovascular health problems.¹⁴⁰

The impacts of bauxite mining have been reported in Indonesia, Malaysia, India and Guinea. Indonesia was one of the largest producers of bauxite and China's largest supplier, until production dramatically reduced in 2014 following a ban on the export of unprocessed bauxite. Many Indonesia companies then shifted into Malaysia and mining rapidly increased in the Kuantan region, including many unlicensed mines.¹⁴¹ The mining occurs close to villages and agricultural land, which have been affected by dust and water pollution.¹⁴² Bauxite mining grew from 200,000 tonnes in 2013 to 35 million tonnes in 2015, until the government banned exports in early 2016 due to environmental concerns.¹⁴³

In the Boké region of Guinea, where bauxite mine has tripled since 2015, communities also face issues from dust in villages and crop fields. Farmlands have been appropriated without adequate compensation and mining has reduce community access to water.¹⁴⁴

In eastern India, bauxite mining has been controversial for many decades, with many projects delayed or cancelled because of potential environmental impacts and protests. For example, the proposed mine in the Niyamgiri Hills in southern Orissa has been rejected by the government on multiple occasions, including in 2010 and 2014, because of the impacts on the livelihoods of the Dongria Kondh tribe which consider the hill sacred, but disputes with the mining company continue.¹⁴⁵

Bauxite is processed into alumina and then into aluminium. The production of aluminium is highly energy intensive compared to other common metals such as steel, copper and nickel. Recycling of aluminium can create an energy saving of 95%.¹⁴⁶ However, if wastes are not disposed without treatment they can alter the pH of water bodies, making it toxic to aquatic organisms.¹⁴⁷

¹³⁹ Lee, K.Y., Ho, L.Y., Tan, K.H., Tham, Y.Y., Ling, S.P., Qureshi, A.M., Ponnudurai, T. and Nordin, R., 2017. Environmental and Occupational Health Impact of Bauxite Mining in Malaysia: A Review. *International Medical Journal Malaysia*, 16(2).

¹⁴⁰ Abdullah, N.H., Mohamed, N., Sulaiman, L.H., Zakaria, T.A. and Rahim, D.A., 2016. Potential health impacts of bauxite mining in Kuantan. *The Malaysian journal of medical sciences: MJMS*, 23(3), p.1.

¹⁴¹ Head, J. 2016 Bauxite in Malaysia: The environmental cost of mining. BBC News. Available at: <https://www.bbc.com/news/world-asia-35340528>

¹⁴² Abdullah, N.H., Mohamed, N., Sulaiman, L.H., Zakaria, T.A. and Rahim, D.A., 2016. Potential health impacts of bauxite mining in Kuantan. *The Malaysian journal of medical sciences: MJMS*, 23(3), p.1.

¹⁴³ U.S. Geological Survey (USGS), 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

¹⁴⁴ Human Rights Watch, 2018. "What do we get out of it?" The Human Rights Impact of Bauxite Mining in Guinea <https://www.hrw.org/report/2018/10/04/what-do-we-get-out-of-it/human-rights-impact-bauxite-mining-guinea>

¹⁴⁵ Oskarsson, P., 2017. Diverging discourses on bauxite mining in Eastern India: Life-supporting hills for adivasis or national treasure chests on barren lands?. *Society & Natural Resources*, 30(8), pp.994-1008.

¹⁴⁶ Norgate, T. and Haque, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*, 18(3), pp.266-274.

¹⁴⁷ Shinzato, M.C. and Hypolito, R., 2016. Effect of disposal of aluminum recycling waste in soil and water bodies. *Environmental Earth Sciences*, 75(7), p.628.

Cobalt

The mining of cobalt in DR Congo impacts the local environment and the health of miners and residents in the surrounding communities. The border between Zambia and the DR Congo, known as the African Copperbelt, is considered one of the top ten most polluted areas in the world.¹⁴⁸ The full extent of environmental impacts is unknown, however the discharge of pollutants from mines and smelters has led to heavy metal contamination of air, water, soil and plants with heavy metals, resulting in severe health impacts.¹⁴⁹

Cobalt is primarily produced as a co-product of nickel or copper mining. In the DR Congo it occurs alongside copper mining, and the copper-cobalt oxides are particularly suited for lithium-ion battery manufacturing.¹⁵⁰ Cobalt is mined in industrial large-scale mines (LSM), owned by local, Canadian, Australian, European and Chinese companies, as well as artisanal and small-scale mines (ASM). Both types of mines, as well as local smelters, contribute to environmental pollution.¹⁵¹

There are approximately 110,000 to 150,000 artisanal cobalt miners in DR Congo.¹⁵² Previous estimates of suggested 60-90% of cobalt exported from the DR Congo was from ASM,¹⁵³ but newer estimates suggest 15-20%.¹⁵⁴ Artisanal miners are particularly exposed to heavy metals including cadmium, cobalt, arsenic, lead and uranium, and the concentrations of cobalt found in people living in the area are the highest reported.¹⁵⁵ The local community are also exposed through pollution of soil and water in the food chain and dust inhalation.¹⁵⁶ The long-term consequences are not known but a recent study has found DNA damage in children¹⁵⁷, and a high prevalence of rare birth defects have been reported in regions with heavy mining.¹⁵⁸

The human rights impacts of cobalt mining include poor working conditions in LSM and ASM mines, and extensive child labour. Artisanal miners work in hand-dug tunnels deep underground without adequate safety equipment, and face a constant risk of cave-ins or landslides, particularly in the rainy season, and suffocation or drowning.¹⁵⁹ Artisanal miners often illegally mine in concessions owned by large companies, or from tailings, as the areas that they previously mined were granted to foreign mining companies in the early 2000s.¹⁶⁰

Child labour is widespread and it is estimated that there are around 40,000 children under 15 years of age working in artisanal cobalt mines, often doing tasks including sorting, washing and transporting ores.¹⁶¹ This work is particularly dangerous to children, and they are at risk of physical abuse and financial exploitation. Artisanal miners sell their cobalt to local trading houses, and usually are not able to negotiate a fair price. Despite this, artisanal workers earn higher wages than average, and artisanal cobalt mining provides income to a significant share of the population in the region.¹⁶²

¹⁴⁸ Narendrula, R., Nkongolo, K.K. & Beckett, P., 2012. Comparative soil metal analyses in Sudbury (Ontario, Canada) and Lubumbashi (Katanga, DR-Congo). *Bulletin of Environmental Contamination and Toxicology*, 88(2), pp.187–192.

¹⁴⁹ Dunn, J.B. et al., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ. Sci.*, 8(1), pp.158–168. Available at:

<http://dx.doi.org/10.1039/C4EE03029J> <http://xlink.rsc.org/?DOI=C4EE03029J>

¹⁵⁰ Schmidt, T., Buchert, M. & Schebek, L., 2016. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. *Resources, Conservation and Recycling*, 112, pp.107–122. Available at:

<http://dx.doi.org/10.1016/j.resconrec.2016.04.017>

¹⁵¹ Goethals, S., Okenda, J.-P. & Mbaya, R., 2009. *Chinese Mining Operations in Katanga*. Available at: <http://www.raid-uk.org/sites/default/files/drc-china-report.pdf>

¹⁵² Amnesty International, 2017. Time to recharge: corporate action and inaction to tackle abuses in the cobalt supply chain. Available at: <https://www.amnesty.org/download/Documents/AFR6273952017ENGLISH.PDF>

¹⁵³ Tsurukawa, N., Prakash, S. & Manhart, A., 2011. Social impacts of artisanal cobalt mining in Katanga, Democratic Republic of Congo. *Öko-Institut eV - Institute for Applied Ecology, Freiburg*, 49(0), p.65. Available at:

http://resourcefever.com/publications/reports/OEKO_2011_cobalt_mining_congo.pdf

¹⁵⁴ Clowes, W. and Wilson, T., 2018. Never Mind the Mines. In Congo, There's Cobalt Under the House. *Bloomberg*, 28 March 2018. Available at: <https://www.bloomberg.com/news/features/2018-03-28/never-mind-the-mines-in-congo-there-s-cobalt-under-the-house>

¹⁵⁵ Banza, C.L.N. et al., 2009. High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environmental Research*, 109(6), pp.745–752.

¹⁵⁶ Cheyns, K. et al., 2014. Pathways of human exposure to cobalt in Katanga, a mining area of the D.R. Congo. *Science of the Total Environment*, 490, pp.313–321. Available at: <http://dx.doi.org/10.1016/j.scitotenv.2014.05.014>

¹⁵⁷ Celestin Banza Lubaba Nkulu et al., 2018. Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability*

¹⁵⁸ Frankel, T.C., 2016. The Cobalt pipeline. *Washington Post*. Available at:

<https://www.washingtonpost.com/graphics/business/batteries/congo-cobalt-mining-for-lithium-ion-battery/?hpid=batteriesbottom>

¹⁵⁹ Tsurukawa, N., Prakash, S. & Manhart, A., 2011. Social impacts of artisanal cobalt mining in Katanga, Democratic Republic of Congo. *Öko-Institut eV - Institute for Applied Ecology, Freiburg*, 49(0), p.65. Available at:

http://resourcefever.com/publications/reports/OEKO_2011_cobalt_mining_congo.pdf

¹⁶⁰ Goethals, S., Okenda, J.-P. & Mbaya, R., 2009. *Chinese Mining Operations in Katanga*. Available at: <http://www.raid-uk.org/sites/default/files/drc-china-report.pdf>

¹⁶¹ Amnesty International, 2016. This is What We Die For: Human Rights Abuses in the Democratic Republic of the Congo Power the Global Trade in Cobalt. Available at: http://www.amnestyusa.org/sites/default/files/this_what_we_die_for_report.pdf

¹⁶² Tsurukawa, N., Prakash, S. & Manhart, A., 2011. Social impacts of artisanal cobalt mining in Katanga, Democratic Republic of Congo. *Öko-Institut eV - Institute for Applied Ecology, Freiburg*, 49(0), p.65. Available at:

http://resourcefever.com/publications/reports/OEKO_2011_cobalt_mining_congo.pdf

Copper

The main environmental impacts of copper mining are the contamination of agricultural soils with heavy metals, including copper, lead, cadmium and zinc, and long-lasting water pollution. There is historical contamination of agricultural soils in Chile, the largest copper producer.¹⁶³

Residents in the major copper mining region of China in Jiangxi Province are exposed to copper contamination of agriculture soils and food,¹⁶⁴ and copper mining has led to heavy metal contamination of surface water in Tibet.¹⁶⁵ Risks of heavy metal contamination in agricultural soils have also been observed in India¹⁶⁶ and communities have been exposed to cadmium and arsenic in drinking water in Brazil.¹⁶⁷

Documented impacts on health of workers include pulmonary tuberculosis (PTB) among underground miners exposed to silica in Zambia¹⁶⁸ and exposure to arsenic for smelter workers in China.¹⁷⁰

Copper mining has also had significant impacts in North America. A review of 14 copper porphyry mines in the US (accounting for nearly 90% of US production) found the mines were often associated with water pollution from acid mine drainage and accidental releases of toxic materials.¹⁷¹ All of the mines reviewed had experienced at least one accidental failure, with most mines experiencing multiple failures, such as pipeline spills, tailings failures, or mine seepage. These resulted in a variety of environmental impacts, such as contamination of drinking water aquifers and loss of fish and wildlife. Impacts can be so severe that acid mine drainage can lead to long-term water pollution.

The proposed Pebble mine in southern Alaska would be the largest copper porphyry mine if constructed. The mine is opposed by more than 80% of the Native Alaskan population, as well as many commercial fishers, with fears that the mine could damage the world's largest salmon sockeye fishery.¹⁷² The US EPA tried to impose restrictions on the mine in 2014 because of these potential environmental impacts, but these have been put on hold.

The storage of tailings can help to reduce acid mine drainage, as has been proposed at the Pebble mine. However the breach of tailings dams, the most common source of mining accidents, can have catastrophic environmental effects. For example, the breach of a tailings dam at the Mount Polley gold and copper mine in British Colombia in Canada in 2014 led to the release of 4.5 million cubic metres of mine waste into nearby forest.¹⁷³

Lithium

Lithium production is widely considered to have lower adverse environmental impacts than other battery materials, such as cobalt and nickel. However, it is not without impacts, and mining of lithium from hard rock in Australia and China produces large quantities of waste rock and uses large amounts of water and energy.¹⁷⁴

Freshwater contamination and water shortages are the main environmental concerns in the 'lithium triangle' between Argentina, Bolivia and Chile.¹⁷⁵ Chemicals used in processing can harm the

¹⁶³ Stowhas, T., Verdejo, J., Yáñez, C., Celis-Diez, J.L., Martínez, C.E. and Neaman, A., 2018. Zinc alleviates copper toxicity to symbiotic nitrogen fixation in agricultural soil affected by copper mining in central Chile. *Chemosphere*, 209, pp.960-963.

¹⁶⁴ Yu, Y., Wang, H., Li, Q., Wang, B., Yan, Z. and Ding, A., 2016. Exposure risk of rural residents to copper in the Le'an River Basin, Jiangxi Province, China. *Science of the Total Environment*, 548, pp.402-407.

¹⁶⁵ Huang, X., Sillanpää, M., Gjessing, E.T., Peräniemi, S. and Vogt, R.D., 2010. Environmental impact of mining activities on the surface water quality in Tibet: Gyama valley. *Science of the total environment*, 408(19), pp.4177-4184.

¹⁶⁶ Giri, S. and Singh, A.K., 2017. Ecological and human health risk assessment of agricultural soils based on heavy metals in mining areas of Singhbhum copper belt, India. *Human and Ecological Risk Assessment: An International Journal*, 23(5), pp.1008-1027.

¹⁶⁷ Bidone, E.D., Laybauer, L., Castilhos, Z.C. and Maddock, J.L., 2001. Environmental risk increase due to heavy metal contamination caused by a copper mining activity in Southern Brazil. *Anais da Academia Brasileira de Ciencias*, 73(2), pp.277-286.

¹⁶⁸ Ngosa, K. and Naidoo, R.N., 2016. The risk of pulmonary tuberculosis in underground copper miners in Zambia exposed to respirable silica: a cross-sectional study. *BMC public health*, 16(1), p.855.

¹⁷⁰ Sun, Q., Song, Y., Liu, S., Wang, F., Zhang, L., Xi, S. and Sun, G., 2015. Arsenic exposure levels in relation to different working departments in a copper mining and smelting plant. *Atmospheric Environment*, 118, pp.1-6.

¹⁷¹ Gestring, B., 2012., U.S. COPPER PORPHYRY MINES: The track record of water quality impacts resulting from pipeline spills, tailings failures and water collection and treatment failures. *Earthworks*. Available at: https://earthworks.org/cms/assets/uploads/2012/08/porphyry_copper_mines_track_record_-_8-2012.pdf

¹⁷² Rosen, J., 2017. The World Needs Copper. Does It Need This Controversial Mine? *National Geographic*. Available at: <https://news.nationalgeographic.com/2017/11/pebble-mine-alaska-copper-epa-trump-environment/>

¹⁷³ Moskowitz, P., 2014. Mount Polley mine spill: a hazard of Canada's industry-friendly attitude? *The Guardian*, 13 August 2014. Available at: <https://www.theguardian.com/environment/2014/aug/13/mount-polley-mine-spill-british-columbia-canada>

¹⁷⁴ Prior, T. et al., 2013. Sustainable governance of scarce metals: The case of lithium. *Science of the Total Environment*, 461-462, pp.785-791. Available at: <http://dx.doi.org/10.1016/j.scitotenv.2013.05.042>.

¹⁷⁵ Wanger, T.C., 2011. The Lithium future - resources, recycling, and the environment. *Conservation Letters*, 4(3), pp.202-206.

environment if released through leaching, spills or emissions into the air.¹⁷⁶ Mining companies in Chile have been accused of violating rules on the use of water, and companies in Argentina have been fined by the government for environmental offences.¹⁷⁷

There are also reports of conflicts arising between local communities and mining companies, particularly over water.¹⁷⁸ There are concerns over lack of adequate compensation for affected local communities, with many people remaining in poverty despite decades of lithium mining in Chile, and recently in Argentina.¹⁷⁹

In the US, several companies are investigating mining lithium in the ecologically damaged Salton Sea in southern California.¹⁸⁰

Nickel

High purity Class 1 Nickel is most suitable for lithium-ion battery manufacturing, which usually comes from sulphide mines.¹⁸¹ Mining and smelting of nickel sulphides in Canada and Russia has had lasting environmental impacts, although practices have improved over time in Canada. Environmental impacts include acid rain from the release of sulfur dioxide emissions, heavy metal soil contamination and damage of lakes and wetlands.¹⁸²

Open-cut mining of laterites – which is predominant in the Philippines, Indonesia and New Caledonia – releases large amounts of dust into the atmosphere that can lead to respiratory illnesses and cancer.¹⁸³ As some of the highest production from nickel is from these small island nations, there is a risk of toxicity to tropical marine species.¹⁸⁴ Nickel mining in Indonesia has been linked to river pollution¹⁸⁵ and there is conflict with high biodiversity and tourism areas.¹⁸⁶ Nickel mining has been controversial with indigenous Kanak communities in New Caledonia¹⁸⁷ and damaged lagoon ecosystems.¹⁸⁸

A recently closed nickel refinery in Australia (which processed nickel and cobalt-bearing laterite ores purchased from third party mines in New Caledonia, Indonesia and the Philippines) came under scrutiny for illegally dumping wastewater contaminated with tailings into the Great Barrier Reef World Heritage area.¹⁸⁹ The refinery is set to reopen, based on increased nickel prices due to increased demand, particularly from EV manufacturers.¹⁹⁰

¹⁷⁶ Friends of the Earth, 2012. Less is more: Resource Efficiency through waste collection, recycling and reuse. Available at: http://www.foeeurope.org/sites/default/files/publications/foee_report_-_less_is_more_0.pdf

¹⁷⁷ Frankel, T.C. & Whoriskey, P., 2016. Tossed aside in the "White Gold" rush. *Washington Post*. Available at: <https://www.washingtonpost.com/graphics/business/batteries/tossed-aside-in-the-lithium-rush/?hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Awhite-gold-rush&hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Awhite-gold-rush>

¹⁷⁸ Dunn, J.B. et al., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ. Sci.*, 8(1), pp.158–168. Available at: <http://dx.doi.org/10.1039/C4EE03029J>

¹⁷⁹ Frankel, T.C. & Whoriskey, P., 2016. Tossed aside in the "White Gold" rush. *Washington Post*. Available at: <https://www.washingtonpost.com/graphics/business/batteries/tossed-aside-in-the-lithium-rush/?hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Awhite-gold-rush&hpid=hp-business-news%3Abatteries%3Ahomepage%2Ft%3Awhite-gold-rush>

¹⁸⁰ Roth, S., 2016. A Salton Sea geothermal company thinks it's solved the lithium puzzle. Will this time be different? *The Desert Sun*. Available at: <https://www.desertsun.com/story/tech/science/energy/2016/10/25/salton-sea-geothermal-company-thinks-s-solved-lithium-puzzle-time-different/92703692/>

¹⁸¹ Energy Insights by McKinsey, 2018. Metal mining constraints on the electric mobility horizon. Available at: <https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/>

¹⁸² Mudd, G.M., 2010. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, 38(1–2), pp.9–26.

¹⁸³ Pasquet, C., Le Monier, P., Monna, F., Durllet, C., Brigaud, B., Losno, R., Chateau, C., Laporte-Magoni, C. and Gunkel-Grillon, P., 2016. Impact of nickel mining in New Caledonia assessed by compositional data analysis of lichens. *SpringerPlus*, 5(1), p.2022.

¹⁸⁴ Gissi, F., Stauber, J.L., Binet, M.T., Golding, L.A., Adams, M.S., Schiekat, C.E., Garman, E.R. and Jolley, D.F., 2016. A review of nickel toxicity to marine and estuarine tropical biota with particular reference to the South East Asian and Melanesian region. *Environmental pollution*, 218, pp.1308–1323.

¹⁸⁵ Hartono, D.M., Suganda, E. and Nurdin, M., 2017. Metal Distribution at River Water of Mining and Nickel Industrial Area in Pomalaa Southeast Sulawesi Province, Indonesia. *Oriental Journal of Chemistry*, 33(5), pp.2599–2607.

¹⁸⁶ Mudd, G.M., 2010. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, 38(1–2), pp.9–26.

¹⁸⁷ Mudd, G.M., 2010. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, 38(1–2), pp.9–26.

¹⁸⁸ Pasquet, C., Le Monier, P., Monna, F., Durllet, C., Brigaud, B., Losno, R., Chateau, C., Laporte-Magoni, C. and Gunkel-Grillon, P., 2016. Impact of nickel mining in New Caledonia assessed by compositional data analysis of lichens. *SpringerPlus*, 5(1), p.2022.

¹⁸⁹ Milman, O. 2014. Clive Palmer's nickel refinery pumped toxic waste into Great Barrier Reef park. *The Guardian*, 12 February 2014. Available at: <https://www.theguardian.com/environment/2014/feb/12/clive-palmer-nickel-refinery-pumped-toxic-waste-great-barrier-reef-park>

¹⁹⁰ Bavas, J. 2018. Clive Palmer says Queensland Nickel refinery in Townsville set to reopen. ABC News, 6 June 2018. Available at: <https://www.abc.net.au/news/2018-06-06/clive-palmer-says-queensland-nickel-refinery-townsville-to-reopen/9839966>

Deep sea mining

Deep-sea mining (DSM) generally refers to three types of mining: seafloor massive sulphide deposits around hydrothermal vents, polymetallic nodules (potato sized nodules on the sea floor) and ferromanganese crusts on the seabed surface.¹⁹⁷ These contain a wide range of metals, including silver, gold, copper, nickel, aluminium, manganese, zinc, lithium, cobalt, platinum and rare earths, which in some cases can be found in higher concentrations than on land.¹⁹⁸ For example, more than 120 million tonnes of cobalt have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans and extensive nickel resources.¹⁹⁹

Mining companies have been interested in deep-sea mining for decades, but it has remained technologically difficult and economically unviable. In addition, environmental concerns and legal uncertainties have slowed development, as well as technical challenges. The growing demand for these metals, including for the renewable energy sector, has led to renewed interest in deep sea mining.

Little is known about the biodiversity and ecosystems of the deep sea, which contains thousands of unknown species that are not found anywhere else on the planet. This makes it difficult to assess the potential impacts of deep-sea mining and put in place adequate safeguards. The potential environmental impacts, including disturbance of the sea floor, the release of sediments and pollution from noise and vibrations, or potential leaks or spills.²⁰⁰ Sulphide deposits from hydrothermal vents play an important role in climate regulation as a sink sequestering carbon and methane, and there is emerging research which suggests their destruction could lead to the release of sequestered methane with global climate impacts.²⁰¹ Deep sea mining is likely to disproportionately impact indigenous people, particularly in the Pacific Islands, and the exploratory phase has already impacted communities in Tonga and Papua New Guinea (PNG).²⁰²

The Solwara 1 project in PNG, which was to be the first seafloor massive sulphide mine, recovering copper, gold, silver and zinc, has been delayed for many years due to financial difficulties.²⁰³ It is being challenged in court by local communities, who are taking legal action over the consultation process and environmental impacts.²⁰⁴ Environmental concerns include destruction of seafloor ecosystems, the impact of noise on whales, dolphins, sharks, turtles and tuna, potential for pollution, including on beaches and the seafloor. There are concerns it will pose a risk to customary use, prevent access to fisheries, and lead to a reduction in fish stocks and contamination of seafood. The mine will generate limited revenue and opportunities for employment, and local communities will not receive the same benefits or royalties as a land based mine.²⁰⁵

The International Seabed Authority (ISA) has issued 29 exploration contracts in the Pacific, Atlantic and Indian oceans beyond any national jurisdiction,²⁰⁶ covering an area of more than 1.4 million square kilometres.²⁰⁷ The regulatory regime requires reform to reflect the latest scientific findings on the importance of the deep sea for biodiversity and climate, and protect local communities.²⁰⁸

¹⁹⁷ Cuyvers, L., Berry, W., Gjerde, K., Thiele, T. and Wilhem, C. (2018). Deep seabed mining: a rising environmental challenge. Gland, Switzerland: IUCN and Gallifrey Foundation. x + 74pp. Available at: <https://portals.iucn.org/library/sites/library/files/documents/2018-029-En.pdf>

¹⁹⁸ Miller, K.A., Thompson, K.F., Johnston, P. and Santillo, D., 2018. An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. *Frontiers in Marine Science*, 4, p.418.

¹⁹⁹ U.S. Geological Survey (USGS). 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

²⁰⁰ International Union for the Conservation of Nature (IUCN), 2018. Deep-sea mining. Available at: https://www.iucn.org/sites/dev/files/deep-sea_mining_issues_brief.pdf

²⁰¹ Levin, L.A., Baco, A.R., Bowden, D.A., Colaco, A., Cordes, E.E., Cunha, M.R., Demopoulos, A.W., Gobin, J., Grupe, B.M., Le, J. and Metaxas, A., 2016. Hydrothermal vents and methane seeps: rethinking the sphere of influence. *Frontiers in Marine Science*, 3, 72.

²⁰² Hunter, J. Singh, P. & Aguon, J. 2018 Broadening Common Heritage: Addressing Gaps in the Deep Sea Mining Regulatory Regime. *Harvard Environmental Law Review*. Available at: http://harvardelr.com/2018/04/16/broadening-common-heritage/#_ftn61

²⁰³ Maritime Executive, 2018. Anglo-American Exits Deep-Sea Mining Project. *Maritime Executive*, 4 May 2018. Available at: <https://www.maritime-executive.com/article/anglo-american-exits-deep-sea-mining-project>

²⁰⁴ Davidson, H. & Doherty, B. 2017 Troubled Papua New Guinea deep-sea mine faces environmental challenge. *The Guardian*, 12 December 2017. Available at:

<https://www.theguardian.com/world/2017/dec/12/troubled-papua-new-guinea-deep-sea-mine-faces-environmental-challenge>

²⁰⁵ Rosenbaum, H. 2018. The socio-political and regulatory context for sea bed mining in Papua New Guinea. Available at: <http://www.deepseaminingoutofourdepth.org/wp-content/uploads/DSMC-PNG-Report-on-Deep-Sea-Mining.pdf>

²⁰⁶ International Seabed Authority, 2019. Deep Seabed Minerals Contractors. Available at: <https://www.isa.org/im/deep-seabed-minerals-contractors>

²⁰⁷ Miller, K.A., Thompson, K.F., Johnston, P. and Santillo, D., 2018. An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. *Frontiers in Marine Science*, 4, p.418.

²⁰⁸ Hunter, J. Singh, P. & Aguon, J. 2018 Broadening Common Heritage: Addressing Gaps in the Deep Sea Mining Regulatory Regime. *Harvard Environmental Law Review*. Available at: http://harvardelr.com/2018/04/16/broadening-common-heritage/#_ftn61

Rare earths

Rare earths are a group of 15 lanthanides that are found in the same ore deposits, usually at low concentrations, which makes them difficult to extract.²⁰⁹ The mining and processing of rare earths is complicated and costly, and can create environmental hazards if not managed appropriately.²¹⁰ The initial mining stage involves thermal, chemical and physical processes to create a lanthanide concentrate, before mineral extraction processes to separate the rare earth minerals.

Rare earth ores often contain radioactive materials such as thorium (though not as radioactive as uranium mining), and requires large amounts of chemicals to extract the metals.²¹¹ These chemicals, including ammonium bicarbonate and oxalic acid, are potentially harmful if not managed appropriately. The processing of rare earths produces large amounts of waste. For every tonne of rare earth metal, approximately 9,600 to 12,000 cubic metres of waste gas (containing dust, hydrofluoric acid, sulfur dioxide, and sulfuric acid), 75 cubic meters of wastewater, and a tonne of radioactive waste are produced.²¹²

Although not well documented, there have been ongoing negative social environmental impacts in China, which at one point was producing 97% of the world's supply. The town of Baotou, in Inner Mongolia, processes rare earths from the Bayan Obo mine, a 48 square kilometre open-pit mine that is the largest source of rare earths in China, as well as producing iron ore. Here wastewater from the tailings dams has polluted groundwater, which has led to crop failures and the displacement of farming communities.²¹³

Issues around the cost of environmental compliance also led to the closure of the Mountain Pass mine in California in the 1990s, when the mine was sued by the district for wastewater spills. Most recently there have been conflicts over environmental pollution at the Lynas Advanced Materials Plant (LAMP) in Kuantan, Malaysia, which processes concentrate from the Mt Weld mine in Western Australia.²¹⁴

Silver

Silver is primarily mined as a by-product from lead-zinc mines, copper mines or gold mines, rather than as the principal metal at a mine. There are examples of silver mining linked to ongoing water pollution. The Red Dog lead, zinc and silver mine in a remote area of Alaska has been listed as the most "toxics-releasing" facility in the US by the EPA Toxics Release Inventory. The contamination of lead and cadmium in treated mine wastewater flowing into the Red Dog river is a concern for residents of the Native village of Kivalina downstream of the mine.²³³ A study of the nearby National Park found elevated concentrations of zinc, lead and cadmium, although this has improved with a large investment in infrastructure to control dust from the mine sites and transport.²³⁴ The largest primary silver mine in the US is the Greens Creek silver mine in Alaska, which is located in an environmentally sensitive area, and is ranked second after Red Dog in the Toxics Release Inventory.²³⁵

²⁰⁹ Kuan, S.H., Saw, L.H. and Ghorbani, Y., 2016., A review of rare earths processing in Malaysia. Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management (UMTAS2016)

²¹⁰ Hurst, C. 2010, China's Rare Earth Elements Industry: What Can the West Learn? Institute for the Analysis of Global Security (IAGS)

²¹¹ Kaiman, J. 2014, Rare earth mining in China: the bleak social and environmental costs. The Guardian, 21 March 2014. Available at: <https://www.theguardian.com/sustainable-business/rare-earth-mining-china-social-environmental-costs>

²¹² NASA, n.d. Rare Earth in Bayan Obo. Available at: <https://earthobservatory.nasa.gov/images/77723/rare-earth-in-bayan-obo>

²¹³ Bontron, C., 2012. Rare-earth Mining in China Comes at a Heavy Cost for Local Villages. *The Guardian*, 7 August 2012. Available at: <http://www.theguardian.com/environment/2012/aug/07/china-rare-earth-village-pollution>

²¹⁴ Ali, S.H., 2014. Social and environmental impact of the rare earth industries. *Resources*, 3(1), pp. 123-134.

²³³ Nobel, J. 2018, America's Most 'Toxics-Releasing' Facility Is Not Where You'd Think, *National Geographic*, 21 February 2018. Available at: <https://news.nationalgeographic.com/2018/02/most-toxic-town-us-kotzebue-alaska-red-dog-mine/>

²³⁴ Nettlich, P.N., Ver Hoef, J.M., Berryman, S.D., Mines, A., Geiser, L.H., Hasselbach, L.M. and Shiel, A.E., 2017. Trends in spatial patterns of heavy metal deposition on national park service lands along the Red Dog Mine haul road, Alaska, 2001–2006. *PLoS one*, 12(5), p.e0177936.

²³⁵ United States Environmental Protection Agency, 2018, 2016 TRI Factsheets: State – Alaska. Available at: https://iaspub.epa.gov/triexplorer/tri_factsheet_factsheet_forstate?&pstate=AK&pyear=2016&pParent=NAT

Mercury was previously used in silver production, which has led to historical contamination of soils in Mexico, Peru and Bolivia. Communities in Peru are exposed to some of the highest levels of mercury contamination worldwide.²³⁶ Concerning levels of mercury has been found in children's blood in Mexico²³⁷ and contamination of groundwater with arsenic and other heavy metals.²³⁸

The world's second-largest silver mine (Escobal) in Guatemala is currently closed following the constitutional court ruling that the Xinka Indigenous peoples had not been adequately consulted before a mine licence was granted.²³⁹

Specialty PV metals

For many of the elements used in small amounts in solar PV, little is known about the environmental or human health impacts. However, indium and gallium are known to be hazardous and there are reports of potentially fatal lung disease from exposure to indium particles in manufacturing.²⁴⁰ Selenium, cadmium and tellurium, which are usually recovered as by-products from other mining processes, are also known to be harmful to human health.²⁴¹ These metals are unlikely to cause harm once embedded in the technology, and as they are usually by-products, if they were not extracted in the mining process they would likely remain in tailings.

Impacts of recycling

Recycling is also not without social and environmental impacts. In particular, the recycling of PV panels requires environmentally sensitive chemical processes to extract the metals. The recycling of rare earths from end-of-life products involves similar chemical techniques as are used for raw material processing.²⁴²

The informal recycling of e-waste occurs in many developing countries, with health risks to workers and environmental pollution. E-waste is considered hazardous waste, and is therefore illegal to export under the Basel Convention.²⁴³ However e-waste is brought in as second-hand devices through legal channels, or illegally imported, as well as collected domestically. Informal workers are involved in all parts of the supply chain, including collection, dismantling and metal extraction.²⁴⁴

The working conditions are extremely hazardous, and workers extract valuable metals by hand, using acids and burning off plastics. These processes may not recover the same amount of materials that could otherwise be recovered, and can emit dangerous toxins, heavy metals and acid fumes into the surrounding environment. Workers usually come from marginalised groups, including minorities and migrants, and are not able to negotiate fair pay.

²³⁶ Robins, N.A., Hagan, N., Halabi, S., Hsu-Kim, H., Gonzales, R.D.E., Morris, M., Woodall, G., Heine, P., Zhang, T., Bacon, A. and Vandenberg, J., 2012. Estimations of historical atmospheric mercury concentrations from mercury refining and present-day soil concentrations of total mercury in Huancavelica, Peru. *Science of the Total Environment*, 426, pp.146-154.

²³⁷ Morton-Bermea, O., Jiménez-Galicia, R.G., Castro-Larragoitia, J., Hernández-Álvarez, E., Pérez-Rodríguez, R., García-Arreola, M.E., Gavilán-García, I. and Segovia, N., 2015. Anthropogenic impact of the use of Hg in mining activities in Cedral SLP Mexico. *Environmental Earth Sciences*, 74(2), pp.1161-1168.

²³⁸ Esteller, M.V., Domínguez-Mariani, E., Garrido, S.E. and Avilés, M., 2015. Groundwater pollution by arsenic and other toxic elements in an abandoned silver mine, Mexico. *Environmental Earth Sciences*, 74(4), pp.2893-2906.

²³⁹ Jamasmie, C. 2018. Guatemala delays ruling on Tahoe's Escobal mine reopening. *Mining.com* <http://www.mining.com/guatemala-delays-ruling-tahoes-escobal-mine-reopening/>

²⁴⁰ White, S.J.O. and Shine, J.P., 2016. Exposure potential and health impacts of indium and gallium, metals critical to emerging electronics and energy technologies. *Current environmental health reports*, 3(4), pp.459-467.

²⁴¹ U.S. Geological Survey (USGS), 2018. Mineral commodity summaries 2018: U.S. Geological Survey. Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/>

²⁴² McLellan, B. C., Corder, G. D. and Ali, S. H., 2013. Sustainability of rare earths—an overview of the state of knowledge. *Minerals* 3(3): 304-317.

²⁴³ See more details at: www.basel.int

²⁴⁴ International Labour Office (ILO) 2014, The informal economy of e-waste: The potential of cooperative enterprises in the management of e-waste. International Labour Office, Sectoral Activities Department (SECTOR), Cooperatives Unit (COOP), Geneva

Impacts of metal recycling compared to mining

Mining is a large consumer of energy, and the extraction and primary processing of metals is responsible for 10% of global climate change impacts.²⁴⁵ The mining of lower-grade ores as metals become scarcer could have a significant influence on energy consumption. Recycling has significant energy and greenhouse gas (GHG) emissions savings compared to primary metals. For example, producing 100,000 tonnes of recycled aluminium, nickel or copper saves 92% 90% and 65% of CO₂ emissions respectively. Recycling avoids the creation of waste and potential environmental impacts. It also avoids the large volumes of waste associated with primary extraction; for example, 3.2 tonnes of mud is produced for every tonne of aluminium.²⁴⁶

Recycling rates remain low for many metals, as primary metals are often low cost and relatively abundant. The material value and cost of collection must be high enough to justify the cost of recycling, or appropriate policy and industry incentives in place.²⁴⁷

Summary of environmental and social impacts

If not managed appropriately, there are significant environmental and social impacts associated with the mining and processing of metals used for renewable energy and technologies. These include pollution of water and agricultural soils through the release of wastewater and dust, the risk of tailings dam failures and health impacts from workers and surrounding communities.

It should also be noted that mining can bring positive economic benefits, for example nickel mining is the largest employer in New Caledonia and makes a significant contribution to the country's GDP.²⁴⁸ Increased renewable energy may lead to less impacts from coal mining, which is responsible for the greatest number of fatalities, health and environmental issues, including damage of lungs from exposure to coal dust²⁴⁹ and kidney disease from the contamination of groundwater.²⁵⁰

With the growing demand for these metals from renewable energy, responsible mining and recycling practices are necessary to avoid negative environmental impacts and ensure the respect human rights and guarantee an equitable sharing of benefits.

²⁴⁵ IRP, 2019, Global Resources Outlook 2019: Natural Resources for the Future We Want (Factsheet), Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., and Cabernard, L., Che, N., Chen, D., Droz-Georget, H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt, A., Geschke, A., Haupt, M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr, J., Miatto, A., Newth, D., Oberschelp, C., Obersteiner, M., Pfister, S., Piccoli, E., Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z., Zhu, B., A Report of the International Resource Panel, United Nations Environment Programme, Nairobi, Kenya. Available at: <http://www.resourcepanel.org/reports/global-resources-outlook>

²⁴⁶ Grimes, S., Donaldson & J. Gomez, GC. 2008, Report on the Environmental Benefits of Recycling, Bureau of International Recycling (BIR). Available at: http://www.mgg-recycling.com/wp-content/uploads/2013/06/BIR_CO2_report.pdf

²⁴⁷ Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F. and Sonnemann, G., 2011. *Recycling rates of metals: A status report*. United Nations Environment Programme. Available at: http://www.resourcepanel.org/file/381/download?token=he_rldvr

²⁴⁸ Pasquet, C., Le Monier, P., Monna, F., Durlot, C., Brigaud, B., Losno, R., Chateau, C., Laporte-Magoni, C. and Gunkel-Grillon, P., 2016. Impact of nickel mining in New Caledonia assessed by compositional data analysis of lichens. *SpringerPlus*, 5(1), p.2022.

²⁴⁹ Castleden, W., Shearman, D., Crisp, G. & Finch, P. 2011. The mining and burning of coal: effects on health and the environment. *The Medical Journal of Australia*, 19 September 2011, Vol.195(6), pp.333-5

²⁵⁰ Finkelman, R.B., Orem, W., Castranova, V., Tatu, C.A., Belkin, H.E., Zheng, B., Lerch, H.E., Maharaj, S.V. and Bates, A.L., 2002. Health impacts of coal and coal use: possible solutions. *International Journal of Coal Geology*, 50(1-4), pp.425-443.

6 Industry responses and awareness

The following section highlights the current levels of industry awareness and responses. It is based on interviews with seven industry experts, including manufacturers, researchers and NGOs engaged in solar PV, batteries and EVs, mining and recycling, as well as a review of the literature.

The renewable energy industry is very aware of issues around supply risks for key metals. The main concern of the industry is the ability to guarantee long-term supply of key metals at a stable price, rather than a concern over supply restrictions or long-term sufficiency of supply. The industry experts interviewed for this project noted that the solar PV industry are concerned about the price for silver, and that the battery and EV industry see cobalt and nickel as difficult to obtain but are not concerned with long-term supply compared to reserves, especially for lithium.

6.1 Reducing demand through efficiency, substitution and recycling

Current industry responses:

The renewable energy industry has made significant improvements to the efficiency of technologies, to improve performance, minimise demand for materials and reduce production costs. This has a benefit to reducing supply risks, although in most cases this is not the main driver.

The battery industry has been focused on improving the material efficiency of lithium-ion batteries which have significantly improved in efficiency and reduced in cost, dropping 24% in cost from 2016 to 2017.²⁵¹ Battery manufacturers have reduced the amount of cobalt in batteries, however the low-cobalt chemistry has a higher nickel content that has increased nickel demand, and a further shift towards cobalt-free lithium-sulfur batteries would increase lithium demand.²⁵² EV manufacturers are also developing motor technologies that replace neodymium and dysprosium with lower cost rare earths or different materials altogether.²⁵³

The industry experts interviewed noted that secondary supply would be an important source for manufacturing in addition to primary supply. At this early stage of deployment there is not yet a large volume of these technologies that have reached “end-of-life” and current recycling infrastructure remains underdeveloped and/or not optimised for high value metal recovery. The wider application of lithium-ion batteries is driving advances in recycling and the industry is very aware of the looming volumes from EV. Recycling of lower-value metals from wind turbines relies on existing scrap recycling so it is comparatively mature (excluding rare earth permanent magnets). PV recycling is demonstrated but not optimised for high value metal recovery. These are either industry-led schemes (such as EV battery take-back schemes) or part of regulatory requirements in major markets (such as the EU).

The main driver for industry-led take-back and recycling schemes is corporate responsibility and capturing the economic value of materials, whereas ensuring supply of materials appears to be a secondary motivation, according to interviewees. In the EU, the regulations are also driven by a motive to ensure security of resources for European industry. Safety concerns around fire risk has also provided a driver for managing end-of-life batteries that are used in a broader range of applications than EVs and stationary storage.

Producer responsibility is emphasised in the EU where PV panels have recently been incorporated under the existing Directive for WEEE, and all end of life EV and stationary batteries must be taken-back by the producer under the EU Battery Directive.

²⁵¹ Chediak, M., 2017, The Latest Bull Case for Electric Cars: the Cheapest Batteries Ever, Bloomberg, 6 December 2017 <https://www.bloomberg.com/news/articles/2017-12-05/latest-bull-case-for-electric-cars-the-cheapest-batteries-ever>

²⁵² Energy Insights by McKinsey, 2018, Metal mining constraints on the electric mobility horizon. Available at: <https://www.mckinseyenergyinsights.com/insights/metal-mining-constraints-on-the-electric-mobility-horizon/>

²⁵³ Widmer, J.D., Martin, R. and Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies*, 3, pp.7-13.

PV stewardship in the European Union and United States

In the EU, where much of the early deployment was located, PV manufacturers founded PV CYCLE in 2007 as a voluntary scheme focussed on end-of-life management of panels. In partnership with European regulators and contracted service providers, this initiative established 300 collection locations, waste transport and recycling services for panels. PV CYCLE has subsequently been restructured with emergence of new regulations under the EU WEEE Directive. As of December 2017, PV CYCLE had collected and treated 17,000 tonnes of panels and is developing approaches for refurbishment and is currently working to establish activities outside of Europe with interests in USA, China, India and Australia.²⁵⁴

In 2012, the EU Waste Electrical & Electronic Equipment (WEEE) Directive was revised to specifically include end-of-life management of PV panels.²⁵⁵ The approach taken in the WEEE Directive is one based on the Extended Producer Responsibility (EPR) principle that means that producers are liable for the costs of collection, treatment and monitoring. The WEEE Directive sets minimum requirements that member states can adjust (up) when they transpose the requirements into their own legislation. From 2018 onwards the WEEE Directive sets an annual collection target of 65% (by mass) of all equipment put on the market, or 85% of waste generated and an annual recycling and recovery target of 85% recovered, with 80% prepared for reuse or recycling.

Washington State passed legislation in July 2017 to promote sustainable, local renewable energy industries, through modifications to renewable energy system tax incentives and new requirements for PV module recycling²⁵⁶. As part of this legislation, the Solar Module Stewardship and Takeback Program was announced, which aims to ensure the recycling of PV modules in a convenient and environmentally sound way. Guidance developed by the State will stipulate how manufacturers placing PV modules on the market must prepare and submit a stewardship plan. The plan will specify the funding mechanism to cover costs of collection, management and recycling, and guarantee that PV modules can be delivered to take-back locations without cost to the owner. Enforcement will begin in January 2021 and applies to all modules purchased after July 1 2017. From this point only manufactures with approved stewardship plans will be permitted to sell PV modules in the State. Non-complying manufactures may be required to pay a penalty of \$10,000 for each sale after receipt of a written warning. Washington State is the first US state to have developed this policy approach.

Challenges to recycling:

Whilst recycling can help to offset primary material demand through recycled sources, there are technological, social and environmental challenges to increase recycling rates. In many places collection systems and infrastructure is not well established.

Collection remains a challenge for distributed rooftop PV and storage systems. Installations of solar PV and wind at utility scale are the easiest to facilitate recycling at end-of-life, and auto-manufacturers also have established networks to return batteries through auto-dealerships.

Across all technologies there is a trend for recycling to prioritise the recovery of valuable or problematic materials, and not all metals are being recovered in the process. The main focus of recycling for PV is glass, aluminium, steel and copper, while silver and other specialty metals are not recovered.²⁵⁷ For lithium-ion batteries cobalt and nickel are the main driver of recovery, and lithium and manganese are not generally recovered.²⁵⁸ As demand increases the economic drive to recover these metals may justify recovery.

The value of cobalt and nickel drive lithium-ion battery recovery, and recycling is undertaken by manufacturers as well as third-party businesses. However, in many cases the costs associated with collection, sorting and transport make it unviable at current low collection volumes. For solar PV third-party businesses are not usually economic without regulations in place that require recycling,

²⁵⁴ More details available here: <http://www.pvcycle.org/>

²⁵⁵ Directive 2012/19/EU. More details available here: http://ec.europa.eu/environment/waste/weee/index_en.htm

²⁵⁶ More details available here: <https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Solar-panels>

²⁵⁷ Weckend, S.; Wade, A.; Heath, G. End-of-Life Management Solar Photovoltaic Panels; International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems: Paris, France, 20

²⁵⁸ King S. Boxall NJ, Bhatt AI (2018) Australian Status and Opportunities for Lithium Battery Recycling. CSIRO, Australia

such as in the EU. This highlights the importance of regulation and product stewardship schemes for batteries and solar PV.

The business model is challenging for solar PV, owing to technological difficulties in recycling with low environmental impact and low cost and the long lifetime of solar PV panels. PV and ancillaries (inverters and batteries) are expected to represent a very large fraction of total e-waste in the coming decades when early installations reach end-of-life.

This highlights the importance of regulations, including standards for high-value recycling. The EU is currently developing technical treatment standards with the aim of promoting 'high-value' recycling. These standards will focus on avoiding potentially harmful substances, capturing rare materials (e.g. silver, tellurium and indium) and the quality of recycled material.²⁵⁹

Leasing of batteries for EVs

Renault is applying circular economy principles to extend the life of their EV batteries – customers can purchase new EVs and hire the battery. In theory, this novel business model, whereby Renault maintains ownership of the battery provides an incentive to extend the life of the battery and maximise recovery at the end of the EV battery service life. Customers pay a monthly fee based on their requirements and Renault guarantees battery performance to at least 75% otherwise they will repair or replace it. Renault, in partnership with Connected Energy and Power Vault, is also involved in a number of projects demonstrating the potential to reuse vehicle batteries for stationary energy applications when the charge capacity falls below an acceptable level (75 %) for transport applications.²⁶⁰

Closed-loop recycling integrated into manufacturing

There is an advantage for manufacturers in establishing take-back and recycling schemes as they can be integrated with the manufacturing process in a closed-loop system. First Solar, the leading manufacturer of CdTe panels, have an in-house recycling process, which also recycles scrap from manufacturing line and any breakages. The company mainly focuses on developing and supplying panels for large utility-scale projects. These projects are an advantage for recycling as they are installed with a decommissioning plan in place, with requirements for recycling.²⁶¹

In Tesla's recycling program, working components (including case and electronic components) are extracted for reuse or remanufacturing, and the rest of the battery is recycled.²⁶² Tesla are aiming to create a closed-loop system where batteries can be recycled in the same factory where the materials can be reused in new battery manufacture.²⁶³

²⁵⁹ See more details at: http://ec.europa.eu/environment/waste/weee/standards_en.htm

²⁶⁰ See more details at: <https://www.renault.co.uk/renault-finance/battery-hire.html> and <https://group.renault.com/en/news/blog-renault/renault-optimizes-the-lifecycle-of-its-electric-vehicle-batteries/>

²⁶¹ See more details at: <http://www.firstsolar.com/en-AU/Modules/Recycling>

²⁶² See more details at: https://www.tesla.com/en_AU/blog/teslas-closed-loop-battery-recycling-program

²⁶³ Forfar, J. 2018. Tesla's Approach to Recycling is the Way of the Future for Sustainable Production, Medium, 7 August 2018 <https://medium.com/tradr/teslas-approach-to-recycling-is-the-way-of-the-future-for-sustainable-production-5af99b62aa0e>

6.2 Securing responsible sources of supply

Current industry responses:

The security of supply of cobalt and lithium supply has become a top priority for global battery and EV manufacturers. This has led to the establishment of alliances and joint ventures between manufacturers and mining companies. The battery and EV industry are signing long-term contracts with miners, often at a price below current market rates.²⁶⁴ In looking to secure supply of cobalt, many manufacturers are looking to areas of "low sovereign risk" such as Canada or Australia, rather than trying to source responsibly from the DR Congo.

The industry experts interviewed noted that reducing the environmental and social impacts of supply is not a major focus of the renewable energy industry. However, the impacts of cobalt mining in DR Congo are well known to the battery and EV industry.

Amnesty International has undertaken an assessment of 29 companies to assess the extent to which companies have put in place human rights due diligence measures for their cobalt supply chain, to know where their cobalt comes from, and the conditions it was extracted in. They assessed Zhejiang Huayou Cobalt Co., Ltd (Huayou Cobalt), whose wholly owned subsidiary in the DR Congo, Congo Dongfang International Mining SARL (CDM), is known to be major buyer from traders of artisanal cobalt. They also assessed companies that have possible supply chain links to Huayou Cobalt, directly or indirectly, including cathode and battery cell manufactures, electronics companies and EV manufacturers.²⁶⁵

The Amnesty International report identified that although some companies have made progress, more action is needed to address human rights risks. The best performing EV manufacturers were BMW Group and Tesla, and the two Korean battery cell manufacturers Samsung SDI and LG Chem have also made progress. However, cathode material manufacturers (based in China and South Korea) are failing to take action, and are a crucial part of the supply chain.

The Amnesty International assessment found that EV companies have taken less action than consumer electronics companies to undertake due diligence of their cobalt supply chains. The industry experts interviewed also felt that the electronics sector was more engaged in due diligence and responsible certification, but that parts of the renewable energy industry have recently shown interest in demonstrating that they are responsible. For the electronics industry, responsible certification has been applied not only apply to the most valuable or problematic metals (such as cobalt), but also to lower value metals, all the way through value chain. This is likely owing to the fact that consumer electronics companies have received greater public scrutiny over their supply chains, compared to the EV companies which are a comparatively new market for lithium-ion batteries.

Challenges to responsible sourcing:

Transparency in the supply chain remains a challenge, particularly for metals such as lithium that are sold in private transactions.

Although some EV are companies are beginning to engage in responsible sourcing and certification, the industry experts interviewed felt that they are more cautious as they are concerned about getting adequate volumes of supply from responsibly sourced mines. However, if the auto industry makes public commitments to responsible sourcing practices, it will encourage more mines to engage with responsible certification schemes. The benefits for mining companies include preferential purchasing contracts, which may also provide EV manufacturers with security of supply, as well as easier access to finance and avoided costs from litigation.

So far industry led-efforts are dominated by consumer-facing companies, who need to put pressure on their suppliers upstream, including mine operators, smelters, traders and component manufacturers to engage in responsible sourcing.²⁶⁶

²⁶⁴ Reuters, 2017. What Price Lithium, the Metal of the Future? <http://fortune.com/2016/06/06/lithium-price-tesla-metal-future/>

²⁶⁵ Amnesty International, 2017. Time to recharge: corporate action and inaction to tackle abuses in the cobalt supply chain. Available at: <https://www.amnesty.org/download/Documents/AFR6273952017ENGLISH.PDF>

²⁶⁶ Ibid

Responsible sourcing initiatives

IRMA Standard for Responsible Mining

The Initiative for Responsible Mining Assurance (IRMA) launched the *Standard for Responsible Mining* and certification scheme in 2018. The standard is a multi-minerals approach designed to meet four principles: business integrity, planning for positive legacies, social responsibility and environmental responsibility. The standard is for the certification of industrial-scale mines, and includes guidance on collaborating with initiatives for responsible small-scale and artisanal mining to ensure that the standard does not result in unintended consequences for ASM. The IRMA standard and certification scheme was developed through a multi-stakeholder process and in collaboration with existing standards and schemes, such as chain of custody standards for single-minerals (e.g. steel and aluminium) and product sectors.²⁶⁷

OECD Due Diligence Guidance

The Organisation for Economic Co-operation and Development (OECD) has developed the most widely accepted framework for operating or sourcing minerals from conflict-affected and high-risk areas. The *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD Guidance)* sets out a five-step due diligence process for all companies involved in the mineral supply chain. It is endorsed by states and is widely recognized as the international standard for responsible mineral supply chains.²⁶⁸ The document also provides guidance on sourcing from artisanal mines and aims to ensure that artisanal mining communities to continue to benefit from mining. The OECD Guidance forms the basis of many of the requirements of IRMA.

Responsible Minerals Initiative (RMI)

The Responsible Minerals Initiative (RMI) has over 350 members, and provides programs and resources to enable companies to conduct due diligence in line with the OECD guidance. The RMI has a specific focus on cobalt and is piloting a reporting tool for companies to map their downstream supply chain.²⁷⁰

Cobalt initiatives

There are various initiatives specific to cobalt. The China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters (CCCME) adopted the *Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains (CCCME Guidelines)*, which are aligned to due diligence framework in the OECD Guidance. These guidelines apply to all Chinese companies involved in upstream (extraction, trading, transport and processing) and downstream parts of the supply chain.²⁷¹ The CCCME launched the *Responsible Cobalt Initiative (RCI)* in November 2016, which aims to promote corporate supply chain due diligence. It has 16 corporate members, mainly battery cathode and cell manufacturers and downstream electronics companies, but also includes Huayou Cobalt.

The *Cobalt Institute (CI)* is a cobalt industry association which plans to establish industry wide guidance on responsible sourcing.²⁷² *Drive Sustainability*, which is a group of European auto-manufacturers, have developed a coordinated approach to responsible sourcing. They are working with their suppliers and sub-suppliers to map their cobalt supply chains.²⁷³

There are a number of other single-mineral certification schemes focused on chain-of-custody along the supply chain. This includes the *Aluminium Stewardship Initiative*, with members including Audi, BMW and Jaguar Land Rover, which has developed a third-party certification program for sustainability and human rights principles in production, use and recycling. *ResponsibleSteel* are currently developing a multi-stakeholder standard and certification initiative for the steel industry.²⁷⁴

²⁶⁷ See more details at: <https://responsiblemining.net/>

²⁶⁸ OECD, 2016, *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas*, Available at: <http://www.oecd.org/corporate/mines/mining.htm>

²⁷⁰ See more details at: <http://www.responsiblemineralsinitiative.org/media/docs/RMI/RMI-Cobalt2.pdf>

²⁷¹ China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters (CCCME), 2015, *Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains (CCCME Guidelines)*, Available at: <http://www.cccmc.org.cn/docs/2016-05/20160503161408153738.pdf>

²⁷² See more details at: <https://www.cobaltinstitute.org/responsible-sourcing.html>

²⁷³ See more details at: <http://drivesustainability.org/>

²⁷⁴ See more details at: <https://www.responsiblesteel.org/draft-standard/>

There are a large number of responsible sourcing initiatives, most of which are voluntary and industry-led. If these initiatives are widely adopted, it may lead to more responsible supply chains. However very few jurisdictions have regulations for due diligence of supply chains.

The EU Mineral Due Diligence Regulation and the US Dodd-Frank Act require due diligence and public reporting for tantalum, tin, tungsten or gold supply chains (known as 3TG and often referred to as "conflict minerals") originating from the DR Congo or neighbouring countries.²⁷⁵ However these are the only metals which they are required to report on. For cobalt specifically, Amnesty International recommend that the Congolese government include cobalt as a "designated mineral", which would mean companies are required to undertake due diligence in the same way as they are required for 3TG metals.

Responsible sourcing initiatives need to ensure that they do not lead to unintended negative consequences, such as increasing poverty, by avoiding sourcing from countries with poorer governance, as has been a criticism of the Dodd-Frank act.²⁷⁶ Focusing on supporting responsible operations has a better long-term impact than avoiding supply from these countries.

Responsible sourcing will be most effective through verified high-bar standards or certification schemes (such as IRMA) and not solely reliant on industry self-monitoring. The renewable energy transition and associated resource requirements could provide an opportunity for promoting new frameworks for resource governance at the international level.²⁷⁷

²⁷⁵ See more details at: <https://www.cftc.gov/LawRegulation/DoddFrankAct/index.htm> and https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.130.01.0001.01.ENG&toc=OJ.L.2017.130:TOC

²⁷⁶ Raghavan, S., 2014. How a well-intentioned U. S. law left Congolese miners jobless. *The Washington Post*.

²⁷⁷ Ali, S. H., D. Giurco, N. Arndt, E. Nickless, G. Brown, A. Demetriades, R. Durrheim, M. A. Enriquez, J. Kinnaird, A. Littleboy, L. D. Meinert, R. Oberhänsli, J. Salem, R. Schodde, G. Schneider, O. Vidal and N. Yakovleva, 2017. Mineral supply for sustainable development requires resource governance. *Nature* 543: 367.

6.3 Key intervention points going forward

Under a 100% renewable energy scenario metal requirements could rise dramatically. It is expected that with the renewable energy transition, renewable energy technologies will consume a growing share of the metals discussed in this report. This growth in demand will have significant influence on overall market dynamics, including influencing prices, which may feedback to efforts to reduce material intensity and invest in reuse and recycling infrastructure, or promote responsible sourcing.

Importance of recycling to reduce demand

This study found that cobalt, lithium and rare earths have the highest projected demand and supply risks, and batteries for EVs are the main driver of demand for these metals. Modelling the potential to reduce primary demand found that recycling is the most important strategy to reduce demand for battery metals, and materials efficiency has the most potential to reduce demand for solar PV metals. However, as renewable energy and battery manufacturers are already focused on improving the efficiency of material use, overall recycling is the most important strategy going forward for these industries to reduce primary demand.

Need for responsible sourcing

Recycling can reduce demand for primary metals, but as shown in this study, recycled sources from renewable energy and battery technologies cannot meet all demand, and there is a time delay for when recycled metals become available. New mining is likely to take place to meet demand in the short term, and new mines are already under development linked to renewable energy (e.g. cobalt, copper, lithium, rare earths, nickel). When supply cannot be met by recycled sources, responsible sourcing is needed to promote environmental stewardship and the respect of human rights.

Key intervention points along the supply chain to promote recycling and responsible sourcing include:

- **Design:** It is important to consider lifecycle impacts in the design of renewable energy technologies and systems, through consideration of functionality and supply chain impacts of material selection. For example, batteries can be designed for recycling supported through closer collaboration between recyclers and cathode manufacturers. At the system level, transport systems should be designed to minimise the need for batteries, through promoting public/active transport and car-pooling. Alternative technologies such as pumped hydro can be considered for stationary storage.²⁷⁸
- **Manufacturing:** The renewable energy and battery industries need to engage publicly with mining and chain of custody standards, to show they are committed to sourcing responsibly and to encourage more mines to engage in responsible certification. There are significant opportunities for sector-based commitments to responsible procurement and supply chain due diligence. As consumer facing brands, which are most likely to face pressure from consumers to act responsibly, EV manufacturers are more likely to be able to create change along the supply chain and influence their suppliers upstream.
- **Purchasing:** Large purchasers of renewable energy and storage technologies, such as energy utilities or governments, have an opportunity to require responsible sourcing and plan for take-back and recycling at end-of-life in their procurement contracts.
- **Use:** Changes in consumption patterns of organisations and consumers, such as shifts towards public transport over private vehicles and increased energy efficiency, is also an opportunity to reduce demand.
- **End-of-life:** Manufacturers, third party businesses, and even some mining companies are involved with the recycling or reuse of technologies at end-of-life. However, policy to ensure take-back and recycling at end-of-life of batteries and solar PV will be needed if the industry does not establish effective voluntary schemes.

The renewable energy transition is an opportunity to promote the stewardship of both primary sources and technologies at end-of-life. As renewable energy technologies become the major driver of demand for key metals examined in this report, this has the potential to improve the sustainability of the supply chain for these metals more broadly.

²⁷⁸ Florin, N. and Dominish, E., 2017. Sustainability evaluation of energy storage technologies. Report prepared by the Institute for Sustainable Futures for the Australian Council of Learned Academies. Available at: https://acola.org.au/wp/wp-content/uploads/WP3_UTS_full.pdf

Appendices

Energy scenario

Table 17: Reference Scenario

Electricity generation (TWh/ year)	2015	2020	2025	2030	2035	2040	2045	2050
Hard coal (& non-renewable waste)	7,662	8,334	8,942	10,237	11,389	12,495	13,083	13,589
Lignite	1,780	1,767	1,773	1,803	1,832	1,901	1,962	1,982
Gas	5,743	6,179	6,998	8,159	9,294	10,428	11,422	12,285
Oil	877	739	633	512	446	382	330	287
Diesel	122	122	125	131	137	141	148	153
Nuclear	2,545	2,991	3,218	3,452	3,638	3,825	4,018	4,218
Hydrogen	0	0	0	0	1	1	1	1
Renewable H2	0	0	0	0	0	0	0	0
Hydro	3,888	4,299	4,684	5,202	5,583	5,964	6,320	6,667
Biomass (& renewable waste)	471	649	785	953	1,082	1,211	1,354	1,514
Geothermal	80	104	130	178	230	281	344	426
Solar thermal power plants	9	25	38	58	94	130	183	260
Ocean energy	1	2	4	7	16	25	37	53
Wind	838	1,394	1,948	2,431	2,894	3,358	3,856	4,389
PV	247	662	1,057	1,460	1,826	2,192	2,645	3,209
Total renewables	5,534	7,133	8,645	10,290	11,725	13,160	14,740	16,517
Total generation	24,262	27,266	30,333	34,584	38,461	42,332	45,702	49,032
Share of renewables	23%	26%	29%	30%	30%	31%	32%	34%

No of vehicles (thousand vehicles)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	1,074	5,596	12,952	27,619	47,396	72,691	144,325	218,591
Plug-in Hybrid Electric Vehicles (PHEV)	56	441	1,377	3,759	8,326	16,070	28,221	46,683
Commercial Vehicles (CV)	102	432	1,209	3,001	4,800	6,004	7,016	7,480
Buses	184	368	1,061	2,429	4,283	5,991	7,067	7,914
Total electric vehicles	1,416	6,837	16,600	36,807	64,805	100,756	186,628	280,668

Battery capacity (GWh)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	41	224	557	1,326	2,465	4,143	8,659	13,553
Plug-in Hybrid Electric Vehicles (PHEV)	0	3	11	38	100	209	395	700
Commercial Vehicles (CV)	26	130	423	1,200	2,160	3,002	3,859	4,488
Buses	9	22	61	128	227	311	382	453
Total battery capacity	76	378	1,053	2,691	4,951	7,665	13,295	19,194

Table 18: 1.5 Degree Scenario

Electricity generation (TWh/ year)	2015	2020	2025	2030	2035	2040	2045	2050
Hard coal (& non-renewable waste)	7,638	7,323	4,931	2,164	439	20	0	0
Lignite	1,780	1,609	445	182	80	0	0	0
Gas	5,743	6,245	6,636	5,896	4,879	3,056	1,234	0
Oil	877	737	502	269	43	5	0	0
Diesel	122	103	68	22	0	0	0	0
Nuclear	2,545	2,921	2,250	1,515	841	182	12	0
Hydrogen	0	0	34	278	754	1,719	2,620	3,127
Renewable H2	0	0	16	210	643	1,596	2,547	3,127
Hydro	3,888	4,299	4,495	4,625	4,743	4,823	4,909	4,988
Biomass (& renewable waste)	471	823	1,683	2,395	2,660	2,933	3,156	3,286
Geothermal	80	113	314	908	1,568	2,266	2,848	3,324
Solar thermal power plants	9	32	329	1,834	3,772	5,709	7,211	8,147
Ocean energy	1	2	41	168	414	705	991	1,178
Wind	838	1,545	4,536	9,075	13,677	17,622	20,300	21,567
PV	247	918	3,917	7,483	11,396	15,633	18,439	19,695
Total renewables	5,534	7,732	15,331	26,699	38,873	51,286	60,402	65,311
Total generation	24,237	26,670	30,180	36,816	45,265	54,672	61,720	65,311
Share of renewables	23%	29%	51%	73%	86%	94%	98%	100%

No of vehicles (thousand vehicles)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	1,345	10,158	102,132	284,926	495,630	677,357	772,588	916,469
Plug-in Hybrid Electric Vehicles (PHEV)	85	2,889	55,147	129,023	183,240	158,563	92,885	56,932
Commercial Vehicles (CV)	102	1,333	10,673	40,600	81,416	87,430	90,078	91,248
Buses	184	368	1,061	2,429	4,283	5,991	7,067	7,914
Total electric vehicles	1,716	14,748	169,014	456,978	764,570	929,341	962,618	1,072,563

Battery capacity (GWh)	2015	2020	2025	2030	2035	2040	2045	2050
Battery Electric Vehicles (BEV)	51	406	4,392	13,676	25,773	38,609	46,355	56,821
Plug-in Hybrid Electric Vehicles (PHEV)	0	17	441	1,290	2,199	2,061	1,300	854
Commercial Vehicles (CV)	26	400	3,736	16,240	36,637	43,715	49,543	54,749
Buses	9	29	229	782	1,148	1,354	1,497	1,595
Total battery capacity	87	852	8,797	31,989	65,757	85,740	98,695	114,019

Senator CARPER. I would also add that I appreciate very much our Chairman's concern for human rights in the context of mining conduct overseas. As we know, issues related to labor practices and the treatment of workers go well beyond just the extraction of minerals currently needed to produce electric vehicle batteries. I am confident that our Chairman's comments—and I hope mine as well—mean that we will join together in crafting, with our colleagues, and passing legislation that makes major investments in all electric waste recycling infrastructure to recover critical minerals, but also provide real investments in research, development, and deployment of the next generation batteries that don't need any of the mined materials that are causing the concern that he has spoken to.

As the Chairman knows, my colleagues may know, I have been eager for our Committee to foster meaningful dialogue about the importance of recycling. I want to thank him for holding today's hearing. It is what I hope will be the first of any number of conversations about what our country can do to improve recycling education and infrastructure, and producer responsibility.

I have said in this Committee many, many times, in adversity lies opportunity. There is plenty of adversity here on this front, but there is also a lot of opportunity.

Today, we get to focus on a couple of my favorite issues, that is electric vehicles and recycling. I expect we will learn more today about how investments in each of these areas can support the other.

Our country's transportation sector is currently the single largest source of greenhouse gas emissions in America. It wasn't always that way, but it is today.

We know that promoting zero-emission vehicles, such as electric vehicles—including them, but also, I would add hydrogen powered vehicles using fuel cells and others as well—it is one of the best ways we can modernize and clean up our transportation sector. More electric vehicles on our roads means easier air, a better climate, and less reliance on foreign oil.

We also know that while electric vehicles are already one of the cleanest vehicles available today, over time, they are only going to get cleaner as the power sector that charges the electric vehicles gets cleaner. I am certainly not the only one who sees the vast environmental and economic benefits of cleaner cars. Cities across the country and countries like China and Norway are investing significantly to transition to electric vehicles. I have seen it with my own eyes in my visits to those countries.

Today, you could ask almost every car manufacturer where the global vehicle market is heading, and they will tell us that electric vehicles are the future. That doesn't mean we are going to have every car, truck, and van on the roads in 10 years to be an electric vehicle; that is not true, or a hydrogen powered, or powered by natural gas. But a lot of them will be. We will still have vehicles powered by diesel, still have vehicles powered by gasoline as well. But given the challenges we face on climate change, it is important that we move away from those over time. I think we will.

But as the global market for electric vehicles grows, so will the demand for the raw materials needed to make the batteries that

power them. Production of electric vehicle batteries, just like the production of smart phone batteries, requires critical minerals, such as lithium and cobalt, many of which are not mined in the USA.

Some of our colleagues believe we must eliminate or lower mining and environmental standards to keep up with the increasing demand. I just don't agree with that. I would remind us that the damage we have seen incurred by cutting corners in hard rock mining regulations; local communities pay the price in many cases, in environmental and health effects, sometimes for generations.

I am confident that the critical mineral mining industry can meet the new demands of the market forces and produce more here at home without endangering human health and our environment. It is important that we do that.

Some of our colleagues will also say that we need to wait to make real investments in electric vehicles until we have made investments in domestic critical mineral mining. I think that is a little bit like saying, we need every American to use a rotary phone until we mine more for cell phone batteries. It is what is called a logical fallacy. I don't know that it is realistic.

For automakers to be competitive in the global market, we can no longer delay investments in electric vehicles in this country. Fortunately, more mining isn't the only solution. Manufacturers are hard at work to create a more sustainable electric vehicle battery, one that needs fewer critical minerals.

And of course, technology is rapidly evolving. Just as the cell phones used 5 years ago are significantly different than the ones we use now, the kind of vehicle batteries we use today will not be the same batteries we used 5, 10, or 15 years ago.

We don't, however, need to wait for better battery technology to have a more sustainable electric vehicle battery. Using today's technology, we can recycle critical minerals and other materials found in electric batteries that fuel our vehicles and our gadgets. Electric waste, or e-waste, was once destined for the landfill, but now can live a new life as another product, if recycled properly.

In fact, critical minerals can be infinitely recycled without losing any of their properties. Imagine that. Battery recycling also reduces our need for new critical minerals, reduces the carbon footprint of an electric battery, and creates economic opportunities through good paying recycling jobs.

China and the European Union have, or will soon have, laws in place that require automakers to take on the responsibility of recycling spent batteries. This incentivizes automakers to find a new purpose for these batteries and recover the minerals in them.

Clearly, other countries are stepping up to the plate when it comes to investments in electric vehicle battery recycling. It is time for the U.S. to get into the game.

The last thing I would say is, I read in the media this past week that Ford Motor Company has joined with a major European auto company to develop a new generation of electric vehicles. Does anybody know who the partner is in Europe?

Mr. SANDERS. Volkswagen.

Senator CARPER. Volkswagen, there you go. That is an interesting partnership, but frankly, I think, a very encouraging devel-

opment. We look forward to hearing more about what the U.S. can do to ensure that we reap the environmental and economic benefits of e-waste recycling and how we can help enhance recycling infrastructure and technologies.

We are delighted that you are here. Thank you so much for joining us.

Mr. Chairman, thank you so much for calling this hearing.

Senator BARRASSO. Thank you, Senator Carper.

I now look forward to welcoming our distinguished panel of witnesses and experts.

The Committee today welcomes Michael Sanders, who is the Senior Advisor of Avicenne Energy.

Additionally, James Greenberger, who is the Executive Director of the National Alliance for Advanced Technology Batteries International, known as NAATBatt, and Ajay Chawan, who is the Associate Director of Navigant Consulting.

We welcome all of you.

I would like to remind the witnesses that your full written testimony will be made part of the official record, so I ask that you try to keep your statements to 5 minutes, so we will have plenty of time for questions.

Senator CARPER. Could we ask our third witness to introduce the family member that is the audience?

Senator BARRASSO. We will do that when we get to him.

Let me start first with Michael Sanders.

Thank you.

**STATEMENT OF MICHAEL SANDERS,
SENIOR ADVISOR, AVICENNE ENERGY US**

Mr. SANDERS. Chairman Barrasso, Ranking Member Carper, and members of the Committee, thank you for the opportunity to provide testimony concerning the environmental issues and opportunities in the use of electric batteries.

I am a senior analyst at Avicenne Energy, which is a premier market research and consulting firm, focused on rechargeable battery markets and their opportunities. I have nearly 16 years' experience in the battery market, and I am now advising many companies in this space.

Electric vehicle demand is growing very rapidly, being led by China, both for full electric vehicles and buses. China led with clear direction, along with substantial support and vehicle subsidies. But most of these are expiring. However, the mandates for electrification remain in place.

Many of the EU countries and cities have also established dates for full conversion to electric vehicles. A large group of U.S. mayors recently released a target to purchase a large number of electric buses, and the charts in the deck basically highlight a lot of the data that is behind the testimony. You see in the charts the growth of electric vehicles worldwide.

From a U.S. perspective, the number of electric vehicles that are forecast are for a half-million vehicles in 2020, a million-five by 2025, and 3.7 million vehicles by 2030. This demand projection is based on current global regulations, supply chain development,

known vehicle launches, expected cost improvements reaching cost parity, and the growth in transit and utility vehicles.

The second market that you all asked questions on was the energy storage system market. Demands are much lower in that market, but it is starting to grow fairly rapidly.

The cell production is continuing to expand in China. Many announcements and constructions have begun in the EU, and the U.S. only has one major announcement for additional manufacturing.

In the EU, the plants are mainly by the current industry leaders. Some OEMs have done investment with some of the start ups, and there are two pending government consortiums, one in Germany and one in France.

Lithium ions are made up of many different types of components to produce the cell. The value chain map starts basically with the main components of the battery and ends with the OEMs. This is a very well established value chain, and cell plants have been established in the U.S. But most of the raw materials still come from Asia. We are seeing major expansion in cell plants in the EU, and that is leading to raw material suppliers also expanding in the EU.

The industry is very risk averse, which provides only limited opportunities for new companies to enter this space. The U.S. has industry leaders that produce metals raw materials in many different areas. They go into cathode and salt such as lithium.

There have been many announcements on lithium investments in the U.S., but for these investments to become a supplier, these companies will need to demonstrate products that meet the quality requirements for batteries and also are cost competitive.

In cathodes, cobalt is a major component, and the U.S. does not have a significant position. Significant development has been progressing for low cobalt or no cobalt containing cathode systems. OEMs have gone to significant efforts for materials traceability to ensure that the supply is responsibly sourced.

Nickel is much more abundant. The U.S. is in better position to provide nickel precursors and the advanced types of nickel that are required for batteries. Aluminum is also used in cathodes, current collectors, cell casing, and structural components.

The U.S. is in a very good position in aluminum, with major producers like Alcoa, Novelis, and Granges.

Recycling of lithium ion batteries and establishing a complex value chain is being led by China. They began with guidance documents in the 1990s, moved to requirements for recycling for electric vehicles and consumer electronics. Substantial development has been completed in spent battery collection centers to prepare batteries for recycling and transportation hubs.

The industry leaders have established recycling processes that can recover metal precursors. The piloting facilities have not reached profitability yet, but with larger scale facilities we are projecting them to become profitable shortly. Korea is gaining ground rapidly on China to support their large cell producers. The EU has established battery recycling mandates that require 50 percent of the materials to be recycled into—and there is a major meeting this week in the EU to discuss raising that to a normal level.

The U.S. could play an ever increasing role in the value chain. The first major change is for additional cell plants to be built locally and also materials demand. Second is for local components manufacturing, and finally to establish meaningful recycling. This should offer significant opportunities for the U.S. to become more relevant while managing the environmental and safety concerns. I think the “China-like” model of starting the process by establishing targets, assisting facilities for collecting and recycling could go a long way in demonstrating commitment and getting results.

I thank you for the opportunity today to provide my testimony. I look forward to answering additional questions and supporting the Committee’s work in the future.

[The prepared statement of Mr. Sanders follows:]



Michael Sanders
Senior Advisor, Battery and Raw Materials Expert
AVICENNE Energy

Michael Sanders joined the Avicenne team in May of 2016 as a Senior Advisor after a long career with DuPont in multiple roles. Avicenne is a team of Advisors and Consulting professionals for providing market understanding, research and consulting for the energy storage market. The focus of the activity is to support clients with their efforts in battery materials and providing market

context for companies to establish their growth and development plans. Mike is the US leader in Batteries and Materials and is responsible for proprietary projects supporting customers' growth efforts, completing the interviews, writing the reports and mainly solicited for his knowledge on the US market. Recent projects have been conference presentations and tutorials, strategy workshops for various levels of the energy storage value chain, market analysis for various types of rechargeable batteries, market connections and validation of opportunities for battery and materials companies and supporting merger & acquisition programs, along with business development based on the Avicenne network.

Mike has significant energy storage materials value chain understanding with an emphasis on lithium ion batteries and systems with 10 years of market knowledge and relationships.

Successful program leadership experience with significant business growth in ventures and existing businesses with a proven track record leading mergers and acquisition team to enter the lithium ion battery materials market.

His most recent role with DuPont was the Global Marketing Director – Energy Storage Venture. He developed significant understanding and insights for the energy storage materials market, device manufacturing and systems while leading global marketing and customer interface efforts to establish programs to enter the \$20B energy storage materials market. Mr. Sanders executed strategic and market planning for opportunity evaluation, research, and choices for entry into rapidly growing new market.

Mr. Sanders received a Bachelor's degree in Chemistry from the University of Delaware in Newark. He has affiliations with the Society of Automobile Engineers and the Electrochemical Society. Additionally, Mr. Sanders has been awarded DuPont's Marketing Excellence Award, Sustainable Excellence and Advocates for Highway and Highway Safety Award, and the Highway Safety Hero Award.

Testimony of Michael L. Sanders
Avicenne Energy
Environmental issues and opportunities in the use of electric batteries in transportation and energy storage.

Statement of Michael L. Sanders

Senior Advisor,
Avicenne Energy, US Leader

at the

Dirksen Building - 406

before the

Senate Committee on Environment and Public Works

concerning

Environmental issues and opportunities linked to an increase in the use of electric
batteries in transportation and energy storage.

July 17, 2019

Testimony of Michael L. Sanders
 Avicenne Energy
 Environmental issues and opportunities in the use of electric batteries in transportation and energy storage.

Introduction

Chairman Barrasso. Ranking Member Carper and Members of the Committee, thank you for the opportunity to provide testimony concerning environmental issues and opportunities in the use of electric batteries. I am a Senior Advisor with Avicenne Energy, who is a premier market research and consulting firm focused on the rechargeable battery markets. I have nearly 16 years' experience in the battery market and I am now advising companies in this market.

Testimony

My testimony will cover the following topics: Electric Vehicle and Energy Storage System Demand; Cell Supply Chain; Raw Materials Supply and Demand; Global Recycling and Mandates; and Meaningful areas for the US to participate.

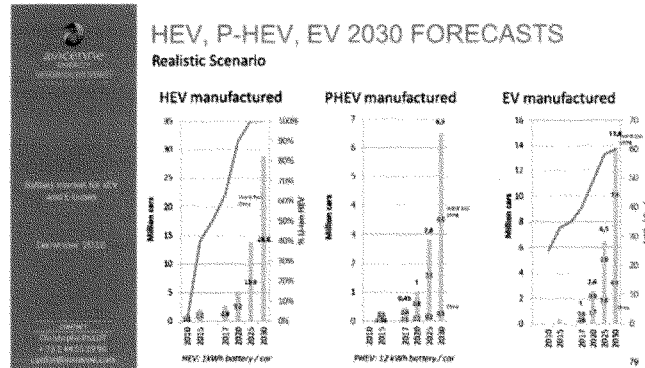
Electric Vehicle and Energy Storage Demand

Electric vehicle demand is growing very rapidly, being led by China for both full electric vehicles and buses. China led with clear direction, along with substantial support, vehicle subsidies, most of these are expiring, however mandates for electrification remain. Many EU countries and cities have also established dates for full conversion to electric vehicles. A large group of US mayors released a target to purchase a very large number of electric buses. The chart highlights the growth in all electric vehicles worldwide:

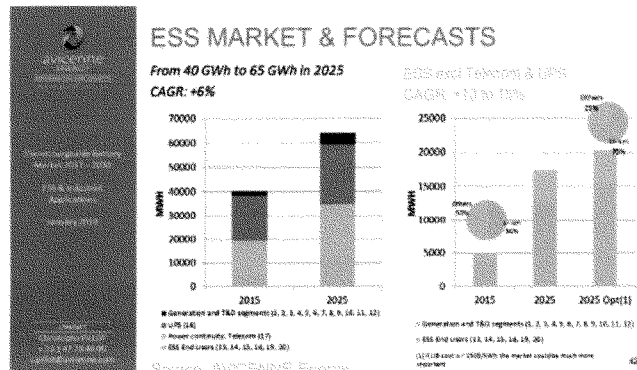
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The forecast of US electric vehicles sold for 2020 is 0.5M, 1.5M vehicles in 2025 and 3.7M vehicles by 2030. The demand prediction is based on current global regulations, supply chain development, known vehicle launches, expected cost improvements reaching cost parity and the growth in transit and utility vehicles. Energy Storage System demands are much lower.



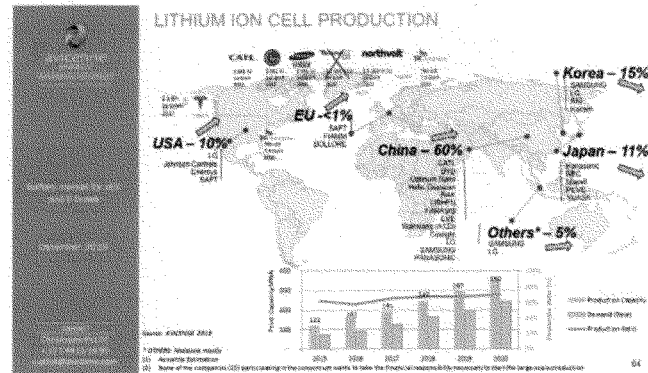
Cell Supply Chain

The cell production is continuing to expand in China, many announcements and construction has begun in the EU and the US has only one major announcement.

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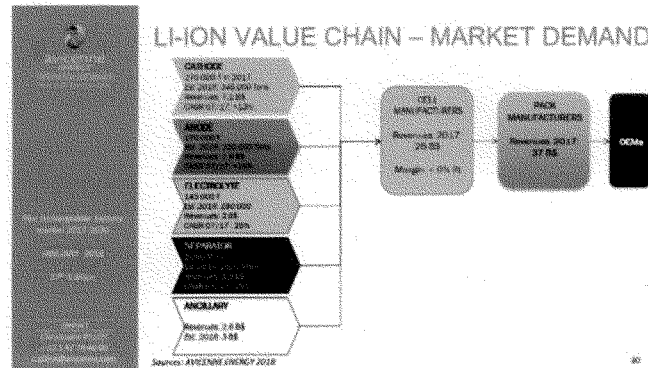
Environmental issues and opportunities in the use of electric batteries in transportation and energy storage.



In the EU the plants are mainly by industry leaders, some OEM investments with start-ups and two pending government consortiums in Germany and France.

Raw Materials Supply and Demand

Lithium Ion Cells are made from many different components to produce a cell. The value chain map starts with the main components of the battery and ends with the OEMs



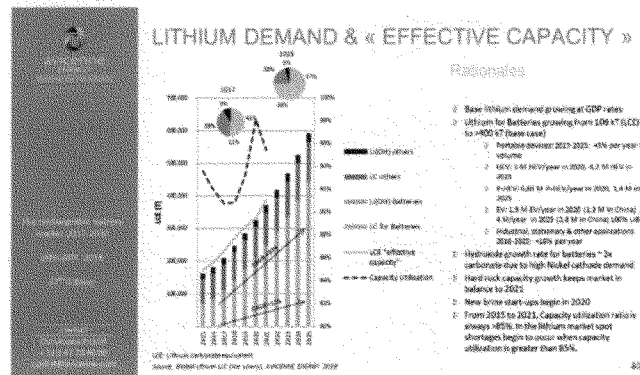
There is a well-established value chain and as cell plants have been established in the US most of the raw materials come from Asia. We are seeing expansions in the EU that leading raw

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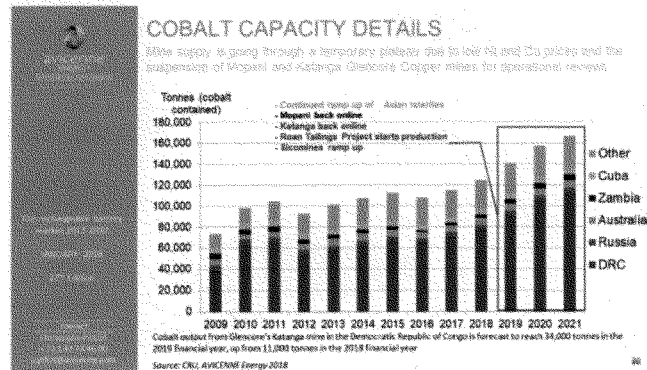
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materials suppliers are expanding in the EU. The industry is very risk averse providing only limited opportunity of new entrants. The US has industry leaders that produce metals raw materials that go into cathode and salt such as Lithium (Albemarle and Livent).



There have been announcements in Lithium investments in the US: American Lithium, Nemaska, Piedmont and others as examples. To become a supplier these companies will need to demonstrate products that meet quality requirements and have costs that are competitive.



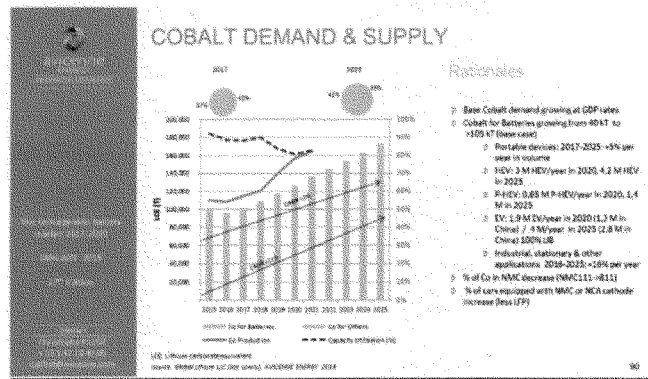
In cathodes Cobalt is a major component and the US does not have a significant position.

Testimony of Michael L. Sanders

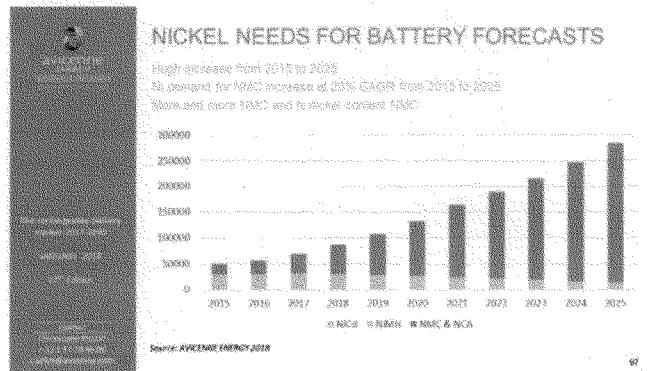
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Environmental issues and opportunities in the use of electric batteries in transportation and energy storage.

Significant development has been progressing well for low Cobalt or no Cobalt systems. OEMs have gone to significant efforts for materials traceability to ensure that the supply is responsibly sourced.



Nickel is much more abundant, and the US is in a better position to provide Nickel precursors.



Aluminum is used in cathodes, current collectors, cell casing and structural components. The US is in a very good position in Aluminum with major producers like Alcoa, Novelis and Granges.

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Global Recycling Challenges and Mandates

Recycling of lithium ion batteries and establishing the complex value chain is being led by China. They began with guidance documents in the late 1990s and moved to requirements for recycling for electric vehicles and consumer electronics. Substantial development has been completed in spent battery collection, centers to prepare batteries for recycling facilities and transportation hubs. The industry leaders in recycling have established processes that can recover the metal precursors. The piloting facilities have not reached profitability, but with larger scale facilities we have projected them becoming profitable. Korea is rapidly gaining ground on China to support their very large cell producers. The EU has established battery recycling mandates requiring 50% of the materials to be recycled before significant growth in auto. The EU has auto mandates for 90% of the materials be recycled. The EU is reviewing the battery mandate and there is a major meeting in the EU this week.

Meaningful areas for US to participate

The US could play an ever-increasing role throughout the value chain: the first major change is for additional cell plants to be built for local supply and materials demand; second is for local components manufacturing and finally to establish meaningful recycling of spent batteries. This should offer significant opportunities for the US to become more relevant in this market while managing the environmental and supply concerns. I think a “China-like” model of starting the process by establishing targets, assisting pilot facilities for collection and recycling could go a long way in demonstrating commitment and the focus on getting results.

Closing

Testimony of Michael L Sanders

Avicenne Energy

Environmental issues and opportunities in the use of electric batteries in transportation and energy storage.

Chairman Barrasso. Ranking Member Carper and Members of the Committee, again thank you for the opportunity. I look forward to answering any additional questions and supporting the committee's work in the future.

Senator BARRASSO. Thank you very much, Mr. Sanders.
Mr. Greenberger.

STATEMENT OF JAMES J. GREENBERGER, EXECUTIVE DIRECTOR, NATIONAL ALLIANCE FOR ADVANCED TECHNOLOGY BATTERIES INTERNATIONAL

Mr. GREENBERGER. Good morning Chairman Barrasso, Ranking Member Carper, and members of the Committee.

My name is James Greenberger. I am the Executive Director of NAATBatt International, a trade association of about 120 corporations and research institutions working to promote advanced battery technology and the industries it will power in North America.

The subject of my testimony is the important role that recycling of lithium ion batteries can play in developing new industry and supporting reduction of greenhouse gas emissions.

Advanced battery technology will be one of the most important technologies of the 21st century. Lithium ion battery chemistry, which was invented in the United States, represents the most powerful new battery technology widely used in commerce today.

Lithium ion batteries not only power but enable electric vehicles, wearable and implantable medical devices, mobile robotics, consumer electronic devices, drones, the Internet of Things, high energy weapons, and a variety of other new electric devices. Several new technologies will shape human society in the 21st century. Advanced battery technology will be but one of them.

But advanced battery technology is unique in that it will enable many of those other technologies. Nations wanting leadership in those technologies will need a vibrant, advanced battery industry within their borders.

For the United States to have a vibrant lithium ion battery industry, it needs to ensure that U.S. based manufacturers have access to the energy materials and compounds needed to manufacture batteries. Few of those energy materials, such as lithium, nickel, and cobalt, are found in great quantities in the United States, and almost none of the chemicals into which those energy materials must be processed to make batteries are manufactured here currently.

Recycling lithium ion batteries used in the United States offers a partial solution to this supply chain problem. Recycling batteries can create a strategic reserve of battery materials which can provide supply and some assurance of price stability to domestic manufacturers.

Building a strong lithium ion industry in the United States is critically important. Few other industries have the potential to create more jobs—both upstream and downstream of their immediate products—than advanced battery manufacturing. As we have long pointed out at NAATBatt, who makes the batteries will one day make the cars.

Recycling high voltage lithium ion batteries is also important for the environment and for public safety. Making lithium ion battery cathode materials from recycled batteries can use as little as 18 percent as much energy, 23 percent as much water, and produce only 9 percent as much SO_x emissions as producing those compounds from virgin materials.

Recycling high voltage lithium ion batteries at the end of their useful lives also removes them from potential contact with incautious adults and curious children. A high voltage battery, no longer powerful enough to power a car, is still powerful enough to electrocute a human being.

Recycling lithium ion batteries is a matter of public safety, as well as good environmental stewardship. But recycling lithium ion batteries in the United States is a major problem. It is impossible, using current recycling technology, to make money from recycling most lithium ion batteries.

The cost of shipping, storing, and recycling those batteries is simply greater than the revenues to be made from selling the recycled materials. As a consequence, fewer than 5 percent of lithium ion batteries reaching the end of useful life are recycled in the United States today.

New recycling technology, such as the direct recycling technology being developed at the Department of Energy's new ReCell Center, may in time change this dynamic. But unless and until it does, the only way to recycle lithium ion batteries will be to require consumers, directly or indirectly, to pay for the cost of that recycling.

Electric vehicles and stationary energy storage of renewably generated electricity are powerful tools in the fight against greenhouse gas emissions. Imposing recycling costs on consumers on top of the still expensive cost of lithium ion batteries will inevitably impact market demand and greenhouse gas mitigation efforts. It is essential that recycling costs be kept as low as possible.

I would respectfully recommend that the Committee consider four actions to protect U.S. economic competitiveness and greenhouse gas reduction efforts. First, ensure that any program requiring the recycling of high voltage lithium ion batteries be implemented on a consistent, nationwide basis.

Second, encourage environmental and transportation regulations that differentiate between sophisticated, high voltage lithium ion batteries, the kind used in electric vehicles, and the smaller, far less consistent lithium ion batteries used in consumer devices.

Third, limit the export of used lithium ion batteries in order to ensure a steady supply of battery materials to U.S. battery manufacturers.

And fourth, fund more research into next generation technologies that may make recycling lithium ion batteries safer, cheaper, and in time, hopefully profitable.

Thank you very much for your attention.

[The prepared statement of Mr. Greenberger follows:]



James J. Greenberger
Executive Director
NAATBatt International

Jim Greenberger is the Executive Director of NAATBatt International, a not-for-profit trade association of advanced battery manufacturers and their supply chain partners doing business in North America and around the world. Mr. Greenberger co-founded NAATBatt in 2007 as part of a national initiative to promote the manufacturing of large format lithium-ion batteries for electric vehicles in the United States. Today NAATBatt International has about 120 corporate members including major automobile manufacturers, electric utilities, equipment manufacturers, battery cell and pack manufacturers, energy materials producers, research institutions and professional service firms. NAATBatt's organizational mission is to support developments in the science of and markets for advanced electrochemical energy storage technology in North America consistent with the goals of enhancing energy efficiency, reducing petroleum dependence and enabling carbon-free electricity generation.

Mr. Greenberger currently serves on the Board of Directors of the International Battery Materials Association, the Board of Advisors to the U.S. Department of Energy's Battery500 Consortium, the UCSD Strategic Energy Initiatives Advisory Council, the Executive Committee of the Center for Renewable Energy at Illinois State University, and the Board of Directors of Spiers New Technologies Inc. and Braille Energy Systems Inc. Before entering the battery industry, Mr. Greenberger practiced corporate law in Chicago, Illinois for more than 30 years, most recent as a partner at Reed Smith LLP. He is a former Chair of the Commercial Finance & Transactions Committee of the Chicago Bar Association and a former board member of the Association for Corporate Growth in Chicago, Illinois. He currently resides in Longboat Key, Florida with his wife of 31 years, Ellen.

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STATEMENT OF JAMES J. GREENBERGER

EXECUTIVE DIRECTOR

of

NAATBATT INTERNATIONAL

before the

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

concerning

“RECYCLING LITHIUM-ION BATTERIES TO PROMOTE U.S. BATTERY
MANUFACTURING AND GREENHOUSE GAS REDUCTION”

July 17, 2019

Testimony

Good morning Chairman Barrasso, Ranking Member Carper, and members of the Committee. Thank you for the opportunity to speak with you today. My name is James Greenberger. I am the Executive Director of NAATBatt International, a trade association of approximately 120 corporations and research institutions working to promote advanced battery technology and the industries it will power in North America.

The subject of my testimony this morning is the important role that recycling of lithium-ion batteries can play in developing new industry that can provide high paying jobs to American workers and supporting reduction of greenhouse gas emissions.

The Importance of Lithium-Ion Battery Technology

Advanced battery technology, or more precisely the technology that enables deliver of electric power to devices not connected to the grid, will be one of the most important technologies of the 21st Century. Lithium-ion battery chemistry, which was invented in the United States and first brought to market in 1991, represents the most powerful new battery technology widely used in commerce today. Lithium-ion batteries not only power but enable electric vehicles, wearable and implantable medical devices, mobile robotics, consumer electronic devices, drones, the Internet of Things, high energy weapons, such as railguns and lasers, and a variety of other power applications.

Several new technologies will shape human society and the wealth of nations in the 21st Century. Advanced battery technology will be one of them. But advanced battery technology is unique in that it will enable and provide added value to the large majority of those other technologies. Nations wanting to gain or maintain leadership in those other technologies need to have a vibrant advanced battery industry within their borders and, if possible, hold a leadership position in advanced battery technology worldwide.

The competition for leadership in lithium battery technology is well underway. Japan and South Korea grabbed an early lead in the last decade, spending billions of dollars to support their companies working in the industry as part of a planned industrial strategy. Today in South Korea industrial technical personnel working in battery factories are exempt from otherwise compulsory active military service. Just this year France and Germany announced and funded a €1.7 billion consortium to manufacture lithium-ion battery cells of the latest generation, with a view to ensuring that 30% of all lithium-ion batteries are made in the EU by 2030.

But to date China has bested them all. Starting from virtually nothing 10 years ago, China today manufactures about 75% of all lithium-ion batteries made worldwide. Two Chinese companies, CATL and BYD, are now the largest companies in the industry. The number of scientists and engineers working to develop new battery technology in China today probably substantially exceeds the number of scientists and engineers working on the same technology in Europe and North America combined.

By comparison, in the United States where lithium-ion battery technology was invented, U.S. companies manufacture only about 3% of lithium-ion batteries made worldwide. The shift in manufacturing capacity and technology development from the United States to Asia, and perhaps soon to Europe, has been dramatic. It is impossible to tell what long term impact this shift will have, not just on the battery industry, but also on the auto industry, the medical device industry, robotics, drones, high-energy weapons, consumer electronics, electric aircraft and the Internet of Things. But the Chinese, Japanese, Koreans and Europeans have all considered that question and come to the same conclusion. It is only America that still needs convincing.

Energy Materials and the Lithium-Ion Battery Supply Chain

If the United States decides to get serious about advanced battery manufacturing and lithium battery technology, one of the principal barriers we will face is limited access to the materials needed to make lithium-ion batteries. Although many different materials go into making lithium-ion batteries, supply chain concerns tend to center on three elements: cobalt, Class I nickel and lithium.

It is important to start any discussion of potential supply chain disruption by distinguishing between the physical scarcity of certain elements in nature and the institutional inefficiencies that are more commonly the cause of supply chain problems and price spikes. Cobalt, nickel and lithium once extracted from the ground must go through a series of processing and refinement, often done in different parts of the world, to be put into the state that they can be used in the cathode of a lithium-ion battery cell. Each step of the process is necessary and each step of the process holds the potential for disruption and supply-demand imbalance.

The fact that about half of the world's reserves of cobalt are located in the Democratic Republic of the Congo is an act of God. The fact that more than 80% of the cobalt sulfate used in batteries is processed in China is an act of government policy.

While North America enjoys modest natural reserves of lithium and nickel, almost none of the processing of energy materials into the cathode and anode compounds used in lithium-ion batteries takes place in the United States. This fact poses a supply risk for any manufacturer wanting to produce lithium-ion battery cells in the United States. The effect is circular: Without robust demand for battery materials by cell manufacturers in North America, there is little incentive to process energy materials here. Without robust demand for lithium-ion batteries in North America (relative to the rest of the world), there is little incentive to make battery cells here, and so on.

The Potential Role of Recycling in the Lithium-Ion Battery Supply Chain

What drives much of the interest in lithium-ion battery recycling in the United States today is that it offers a potential way out of the otherwise self-reinforcing lithium-ion battery supply chain problem. That is because the lithium-ion batteries that we import today into the United States contain the very energy materials and battery compounds that we do not and might be challenged to manufacture domestically.

Recycling those batteries at the end of their original lives can provide a reliable source of energy materials supplies for battery manufacturers that might wish to establish operations in the

United States. More interestingly, certain innovative direct recycling technologies, such as those being developed at the Department of Energy's new ReCell Center, may be able to preserve and reuse higher level cathode and anode compounds from batteries being recycled than has been the case with more traditional pyro- and hydro-processing recycling technologies. The impact of this new recycling-driven supply chain could be significant. A recent NREL report suggests that by 2040 a full 65% of the cobalt needed to supply electric vehicle demand in the United States could be provided by recycling.

The Barriers to Lithium-Ion Battery Recycling Today

Today, however, only a small fraction of lithium-ion batteries are recycled in the United States. The reason is economics. It simply costs more to recycle a lithium-ion battery than the market value of the energy materials a recycler can recover. The economics of lithium-ion battery recycling today stand in stark contrast to the economics of lead acid battery recycling, where recyclers can recover their costs and make a profit from the sale of recovered lead. Today about 98% of automotive lead-acid batteries are recycled. It is estimated that less than 5% of lithium-ion automotive batteries are recycled.

The high cost of recycling lithium-ion batteries is a threat to vehicle electrification and to storing renewable energy on the grid. According to the EPA the transportation sector is the largest emitter of greenhouse gases, accounting for about 29% of all greenhouse gas emissions in the United States. Vehicle electrification is one of the most powerful tools we have for reducing greenhouse gas emissions. Any program that mandates the recycling lithium-ion batteries, however structured, will end up burdening consumers with the cost of that recycling. That cost will diminish demand for electric vehicles and, in turn, diminish greenhouse gas mitigation efforts.

It is critical that any program which mandates the recycling of lithium-ion batteries do so in a way that minimizes the cost of recycling to consumers and, perhaps one day through use of next generation recycling technologies, eliminates that cost altogether.

Recycling Lithium-Ion Batteries is Important

There are two other reasons why recycling lithium-ion batteries is important, in addition to the need to recover strategic energy materials. The first is good environmental stewardship. Much of what drives consumer and government interest in electric vehicles is their positive environmental attributes. Those perceived positive attributes will be fundamentally undermined if one of the consequences of vehicle electrification is that millions of tons of used lithium-ion batteries end up in landfills or by the side of the road.

Also, there are significant environmental benefits to replacing the mining and processing of virgin energy materials with recycled energy materials. A recent report produced by the ReCell Center suggests that direct recycling of lithium-ion battery cathode materials will use only 18% as much energy, 23% as much water, and produce only 9% as much Sulphur oxide emissions as producing those compounds from virgin materials.

The other reason why lithium-ion batteries need to be recycled is because of the environmental threat that they pose. To be clear, used lithium-ion batteries are, in the traditional sense, relatively environmentally benign when compared to older batteries based on lead-acid or

nickel-cadmium chemistries. The principal environmental danger that lithium-ion batteries pose relates to the high voltage electricity that they can potentially contain. A used lithium-ion automotive battery laying in a junkyard or by the side of a road poses a direct threat to human health and safety from high voltage electric current. We call this the “stranded energy” problem. First responders, second responders, junk yard operators, hobbyists, and curious adults and children are all at risk from the stranded energy that used lithium-ion batteries may contain.

If we do not properly dispose of high voltage lithium-ion batteries, it is not a question of if a child wandering through a field or junk yard will be electrocuted, but how many--and how long will it be before we decide to do something about it.

The good news is that we have a little time to decide what to do about it. The electric vehicle and stationary energy storage markets are still in their infancy. It will be several years before used high voltage lithium-ion batteries start reaching the end their useful lives in significant quantities.

Proposed Approaches to the Lithium-Ion Battery Recycling Challenge

But it is not too early to start thinking about the problem and to start putting in place a program that will ensure U.S. manufacturer’s access to a stable supply of energy materials, protect public safety, and keep the cost of lithium-ion battery recycling to consumers as low as possible. I would respectfully suggest that any such program should include the following elements:

1. A Single, Consistent Nationwide Program. Any mandatory program to recycle lithium-ion batteries should be managed on a national basis, and probably try to include Canada. Nothing will increase the cost of recycling to consumers more than to have individual states enact unique and potentially inconsistent requirements for batteries sold or recycled within their jurisdictions. Keeping the cost of electric vehicles as low as possible is critical to the national goal of greenhouse gas reduction. Congress should immediately pre-empt the field of lithium-ion battery recycling to federal jurisdiction.

2. Differentiate Between High Voltage and Consumer Batteries. There is a significant difference in strategic materials content, manufacturing quality and safety hazards between the high voltage lithium-ion batteries used in automotive, stationary energy storage and many industrial applications, on the one hand, and the lower voltage batteries used in consumer electronic devices, on the other. Defining the difference between these two types of batteries and regulating them differently, for purposes of recycling, transport and storage, would better protect public safety and lower the cost of electric vehicles and renewably generated electricity to consumers.

3. Prohibit the Export of Used Lithium-Ion Batteries. Energy materials and compounds contained in used lithium-ion batteries are strategic commodities. Foreign manufacturers should be prohibited from requiring their U.S. customers to return used batteries and battery materials to the foreign manufacturer at the end of the original battery life. The general export of used lithium-ion batteries and used battery materials and compounds should also be restricted or prohibited.

4. Support for New Battery Recycling Technology. Congress should continue to support scientific research into new recycling technologies that have the potential to reduce or eliminate the negative cost of lithium-ion battery recycling. Programs such as the U.S. Department of Energy's ReCell Center can indirectly do much to help lower greenhouse gas emissions and help U.S. industry regain its leadership in lithium-ion battery technology.

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Senator BARRASSO. Thank you very much, Mr. Greenberger.
And now, Mr. Chawan, and if you would, introduce your son as well.

**STATEMENT OF AJAY CHAWAN,
ASSOCIATE DIRECTOR, NAVIGANT CONSULTING, INC.**

Mr. CHAWAN. Thank you very much for having me here today. Good morning, Chairman Barrasso, Ranking Member Carper, members of the committee.

My name is Ajay Chawan, and I will introduce my 10-year-old son, J.D. Chawan, who is here to cheer me on.

I am glad you recognized him, as he is growing up in a world where plugging in an EV is as natural as plugging in an iPad. When I would come home from work, when he was 3 years old, he would come in to put the plugger in the car. Now for people like him and his cohort, an EV is just another thing you plug in.

I really appreciate the opportunity to be here with you today to provide testimony regarding the benefits, challenges, and opportunities associated with electrified transportation. I have worked in the EV space since 2012, and have led the effort to bring three electrified vehicles to market, with two different automakers. Currently, I am a member of the Transportation and Grid Team at Navigant Consulting, where I help organizations, including municipalities and utilities, transition to using electric vehicles.

The movement toward the development and production of electric vehicles represents a revolution in how goods and people will move, and has the potential to impact numerous portions of our lives. Three areas I would like to touch on today include energy security, jobs, and health.

Electric vehicles provide a significant opportunity to reduce our dependence on foreign oil. The U.S. is a net importer of about 854 million barrels of oil annually. For each consumer EV that gets put on the road, we can reduce our oil consumption by 25 barrels per year. The same EVs can be powered by electricity produced by a variety of domestic energy sources that employ American workers.

The transportation sector is a significant source of employment in America. The consumer automotive segment alone directly employs over 7 million people and indirectly impacts millions of others who live in those communities. As the transportation technology advances, the nature of these jobs will continue to evolve. The need for workers who are skilled in computer programming, advanced manufacturing, and chemistry will continue to increase. American students who have benefited from emphasis on science, technology, engineering, and math, or STEM curriculums, will be well equipped to enter these technology focused spaces.

Finally, eliminating the tailpipes on cars and trucks will result in cleaner air due to a reduction in particulates, including carbon monoxide and nitrogen oxide, from engine exhaust. These and other exhaust components are known to contribute to costly diseases, including asthma, heart disease, and cancer. One 2010 study found that if clean air standards were met in California, 30,000 emergency room visits would have been avoided, saving \$193 million in hospital expenses for that State alone. EVs will help achieve those clean air standards nationally.

EVs have been growing in popularity since they entered the market on a mass scale at the beginning of this decade. In 2012, there were approximately 14,000 EVs sold across six models. In 2018, more than 225,000 vehicles were sold across 16 models, an increase of 1,500 percentage points. Next year, consumers will have at least 40 models of EVs to choose from.

For reference, total annual vehicle sales in the U.S. is somewhere between \$15 million and \$17 million, depending on how the economy is doing. That is across 500 units. In 2030, Navigant projects that there will be about 3 million EVs sold that year, and that 13 million EVs will be on the road in that year as well.

One of the key opportunities to address with the increase in EV proliferation is what to do when the vehicle goes off the road, what do you do with that battery? I think my fellow panelists have addressed that point. The average life of a car or truck in the U.S. is about 11 years. After this time, the EV battery still has about 70 percent of its storage capacity left.

One option receiving significant consideration today is using these batteries to provide backup power at critical locations, such as military facilities, hospitals, and data centers. Finding uses to give second life batteries a new home is an area my team is very much focused on today.

As research and development dollars continue to flow into the EV battery space, their characteristics will continue to evolve. This includes the very elements used to make batteries and the methods by which they can be redeployed and later recycled. Our research and data shows that there are social, domestic energy security, economic, and societal benefits from electric transportation that are poised to increase in the coming years.

Again, I would like to thank you for the opportunity to be here today. I look forward to our discussion.

[The prepared statement of Mr. Chawan follows:]



Ajay Chawan
Associate Director
Navigant

Ajay Chawan is an Associate Director in Navigant's Global Energy Practice where he is a member of the firm's Transportation-to-Grid (T2G) Team.

Over the past eight years, Ajay has led efforts to bring new electric vehicles (EVs) to market and has helped to shape strategies for future mobility options made possible through the development of autonomous, connected, electric, and shared (ACES) technologies. From 2012 to 2013, he led the effort to localize production of the Nissan LEAF in the U.S. Ajay then joined Audi of America and led its launch efforts for its first plug-in vehicle, the A3 e-tron, its first full electric SUV due to launch in 2019, and new business models made possible by ACES technologies. Ajay has developed relationships with many of the key players across the charging infrastructure landscape, including hardware manufacturers and network providers.

In addition to his mobility experience, Ajay has worked as a research associate at the National Aeronautics and Space Administration (NASA), a product development engineer at Ford Motor Company, and founded two businesses in the food industry. Ajay holds a Bachelor of Science in Aerospace Engineering degree from Syracuse University, a Master of Science in Mechanical Engineering degree from the University of Michigan, a Master of Engineering Management degree from Northwestern University, and a Master of Business Administration (MBA) degree from the Kellogg School of Management.

Areas of expertise: electric mobility, future mobility, automotive industry fundamentals, new venture formation



Written Statement of Ajay Chawan

**Prepared for the United States Senate Committee on
Environment and Public Works**

17 July 2019

Submitted by:
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**Written Statement of Ajay Chawan, Associate Director, Navigant Consulting, Inc.
Before the United States Senate Committee on Environment and Public Works
17 July 2019**

Good morning, Chairman Barrasso, Ranking Member Carper, and members of the committee. Thank you for the opportunity to be here with you today. My name is Ajay Chawan and I am here to provide the Committee testimony regarding the benefits, challenges, and opportunities associated with electrified transportation.

I have worked in the electric vehicle field since 2012 and have led efforts to bring three electrified vehicles to market. Currently, I am a member of the transportation-to-grid team at Navigant Consulting where I help organizations, including municipalities and utilities, transition to using electric vehicles.

The movement toward the development and production of electric vehicles (EVs) represents a revolution in how people and goods will move and has the potential to impact numerous portions of our lives. Three areas I would like to touch on today include energy security, jobs, and health.

Electric vehicles provide a significant opportunity to reduce our dependence on foreign oil. The U.S. is a net importer of about 854 million barrels of oil annually.¹ For each consumer EV that gets put on the road, we can reduce our oil consumption by 25 barrels per year.² Those same EVs can be powered by electricity produced from a variety of domestic energy sources that employ American workers.

The transportation sector is a significant source of employment in America. The consumer automotive segment alone directly employs more than 7 million people, and indirectly impacts millions of others who live in these communities.³ As transportation technology advances, the nature of these jobs will continue to evolve. The need for workers who are skilled in computer programming, advanced manufacturing, and chemistry will continue to increase. American students who have benefitted from an emphasis on Science, Technology, Engineering, and Math, or STEM, curriculums will be well-equipped to enter these technology-focused spaces.

¹ U.S. Energy Information Administration, <https://www.eia.gov/tools/faqs/faq.php?id=727&t=6>

² Alternate Fuels Data Center <https://afdc.energy.gov/data/>, U.S. Department of Transportation Bureau of Transportation Statistics <https://www.bts.gov/content/average-fuel-efficiency-us-light-duty-vehicles>, U.S. Energy Information Administration <https://www.eia.gov/tools/faqs/faq.php?id=327&t=9>, Internal analysis.

³ Alliance of Automobile Manufacturers, <https://autoalliance.org/>

Finally, eliminating the tailpipes on cars and trucks will result in cleaner air due to a reduction in particulates, including carbon monoxide and nitrogen oxide, from engine exhaust. These and other exhaust components are known to contribute to costly diseases including asthma, heart disease, and cancer. One 2010 study found that, if clean air standards were met in California, 30,000 emergency room visits would have been avoided, saving \$193 million in hospital expenses for that state alone⁴. EVs will help achieve those clean air standards.

EVs have been growing in popularity since they entered the market on a mass scale in the beginning of this decade. In 2012, there were approximately 14,000 units sold across six models. In 2018, more than 225,000 vehicles were sold across 16 models – an increase of 1500%.⁵ Next year, consumers will have at least 40 EV models to choose from. For reference, total annual vehicles sales in the U.S. is about 15 to 16 million units over about 500 models. In 2030, Navigant projects there will be about 3 million EVs purchased that year and 13 million EVs will be on the road in the U.S.⁶

Figure 1 below illustrates the growth of EVs globally during the period 2010 to 2018. It is important to note that, while the sales of EVs in the U.S. grew by 1,500% between 2012 and 2018, EV sales in China increased by almost 8,000% during this same period. According to Navigant Research, EV sales are expected to continue growing globally at a compounded annual growth rate (CAGR) of 26.1%; this growth is illustrated below in Figure 2.

⁴ Romley, John. "The Impact of Air Quality on Hospital Spending." *Rand Corporation*.
https://www.rand.org/pubs/technical_reports/TR777.html

⁵ InsideEVs <https://insideevs.com/news/344007/monthly-plug-in-ev-sales-scorecard-historical-charts/>, Internal analysis.

⁶ *Market Data: Global EV Market Forecasts; Global Forecasts for Light Duty Plug-In Hybrid and Battery EV Sales and Populations: 2018 – 2030*. Published 1Q 2019. Navigant Research.

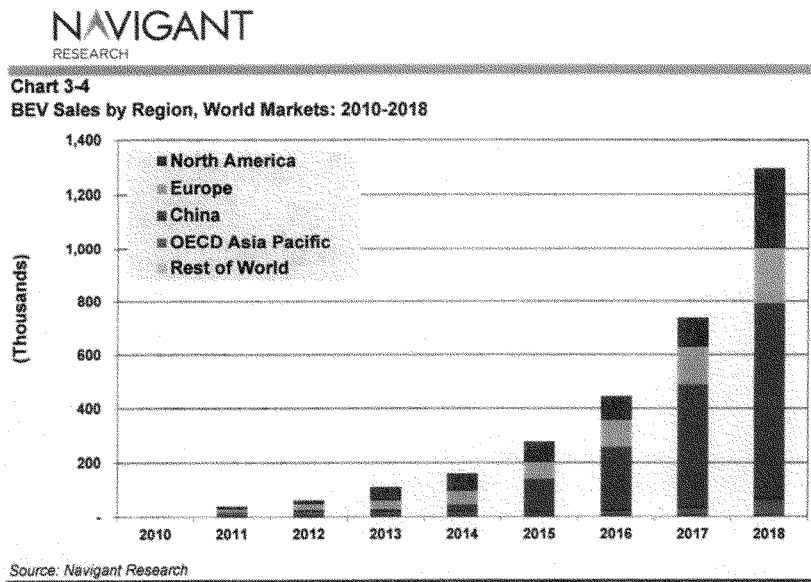
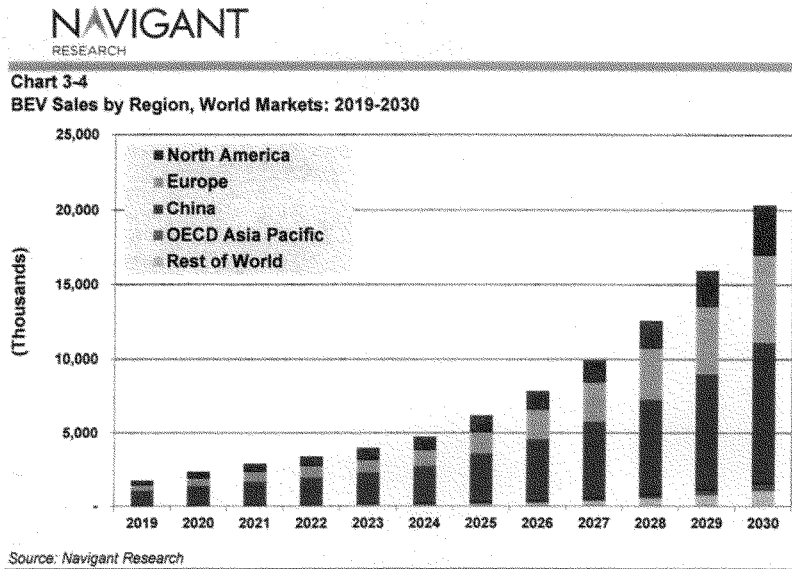
Figure 1: Global EV sales 2010 – 2018

Figure 2: Projected Global EV sales, 2019 – 2030



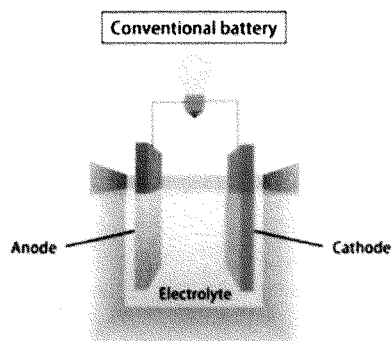
Given this projected strong growth in the EV market globally, automakers are making significant investments in electric vehicle technology firms. Between 2014 and today, private investment in the automotive and transportation sector has attracted \$18.47 billion in private investment. It is worth noting that only about 13% of this investment came from traditional transportation companies. The rest of the investment has come from organizations from outside the industry. Outside investors include technology firms such as Alphabet and venture capital/private equity firms.⁷

One of the major areas of investment in the EV space is in battery technology. The batteries used in EVs today primarily use a combination of lithium, cobalt, and nickel (for the anode). Figure 3 below illustrates the common composition of a lithium-ion battery that is commonly used in EVs.⁸

⁷ CB Insights, analyst interviews.

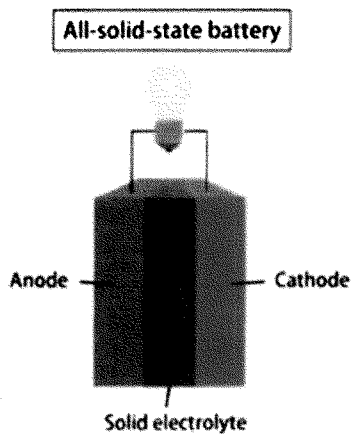
⁸ Spring8. http://www.spring8.or.jp/en/news_publications/research_highlights/no_49/

Figure 3: Conventional EV battery configuration



One focus of battery research today is to replace the liquid electrolyte (which is commonly made from lithium salt), with a solid electrolyte. This revised configuration is shown below in Figure 4.⁹

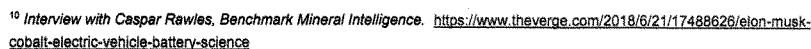
Figure 4: Solid-state battery configuration



⁹ Spring8. http://www.spring8.or.jp/en/news_publications/research_highlights/no_49/

Given numerous benefits offered by and projected growth of EVs, automakers are investing heavily in outside firms who are developing EV technology. Where automakers are making investments is illustrated below in Figure 5.

E Where automakers are investing in electric vehicle technology
2014 - 2019 YTD (3/6/2019)



¹¹ U.S. Geologic Survey, <https://www.usgs.gov/centers/nmic/lithium-statistics-and-information>, <https://www.usgs.gov/centers/nmic/cobalt-statistics-and-information>, <https://www.usgs.gov/centers/nmic/nickel-statistics-and-information>

Page 7

One automaker absent from Figure 5 is Toyota. Toyota has stated that it intends to introduce a solid-state battery by 2022, possibly sooner¹². Amongst the firms pursuing solid-state technology, Toyota leads them all with 25 patent applications. Toyota is followed by Fujifilm Holding Corporation (18 patent applications), QuantumScape (10 patent applications), and Hyundai Motor Company (10 patent applications).¹³

One of the key opportunities to harness with the increase of EV proliferation is what to do with the battery when the vehicle comes off the road. The average life of a car or truck in the U.S. is about 11 years.¹⁴ After this time, an EV's battery still has about 70% of its storage capacity left.¹⁵ One option receiving significant consideration today is to use these batteries to provide backup power at critical locations, such as military facilities, hospitals, and data centers. Finding uses to give a second life to batteries is an area my team is very focused on.

As research and investment dollars continue to flow into the EV battery space, their characteristics will continue to evolve. This includes the very elements used to make batteries and methods by which they can be redeployed and later recycled. Our research and data have shown there are social, domestic energy security, economic, and societal benefits from electric transportation that are poised to increase in the coming years.

Thank you for the opportunity to share this testimony and for this Committee's important work.

¹² "Toyota pushes ahead with solid-state batteries for future electric cars." *Digital Trends*. <https://www.digitaltrends.com/cars/toyota-may-introduce-solid-state-batteries-for-electric-cars-by-2020/>

¹³ CB Insights, analyst interviews.

¹⁴ U.S. Department of Transportation, Bureau of Transportation Statistics, <https://www.bts.gov/content/average-age-automobiles-and-trucks-operation-united-states>. Internal analysis

¹⁵ Internal analysis

TECHNICAL ASSISTANCE AS REQUESTED

This technical assistance is provided in response to a Congressional request and is not intended to reflect the viewpoint or policies of any element of the Department of Transportation or the Administration.

Senate Legislative Counsel
Draft Copy of MAZ19390

SEC. . STORMWATER MANAGEMENT GUIDANCE.

(a) **Definitions.**—In this section:

(1) ADMINISTRATOR.—The term "Administrator" means the Administrator of the Federal Highway Administration.

(2) GUIDANCE DOCUMENT.—

(A) IN GENERAL.—The term “guidance document” means a document issued by the Administrator [that—]

(i) [provides an interpretation of a regulation of the Administrator; or]

(ii) [includes an enforcement policy of the Administrator that is made available to the public.]

(B) INCLUSION.—The term “guidance document” includes—

(i) an analysis of a state-of-the-practice;

(ii) a report on the community of practice;

(iii) a planning-level review document:

(iv) a quick references guide; and

(v) a handbook.

(b) Reissuance.—Not later than 1 year after the date of enactment of this Act, the Administrator shall update and reissue each guidance document relating to stormwater management issued before January 1, 2015.

(c) Updates.—Not less frequently than once every 5 years after the date on which the Administrator reissues a guidance document described in subsection (b), the Administrator shall update and reissue the guidance document until the earlier of the date on which—

(1) the guidance document is [removed/withdrawn]; and/or

(2) the contents of the guidance document are incorporated into applicable regulations of the Administrator.

Commented [A1]: "Guidance document" is defined by OMB Bulletin 07-02 ("Agency Good Guidance Practices") and a DOT General Counsel memo, "Review and Clearance of Guidance Documents" (Dec. 20, 2018) for Executive Branch/DOY purposes. This bill appears to create a different definition.

Commented [A2]: The FHWA has adopted the AASHTO Highway Drainage Guidelines (last updated in 2014) as guidelines to be followed on all construction projects funded under title 23, United States Code. See 23 CFR 650.211(a). These guidelines relate to stormwater management; however, only AASHTO can update them.

Commented [A3]: See earlier comment. There is an existing Executive Branch wide definition of guidance document.

Commented [A4]: it may be challenging to update all guidance documents covered by this provision within 1 year, particularly if some guidance documents are "significant" and subject to further review procedures per Executive Branch guidance.

Commented [A5]: The purpose of updating and reissuing guidance documents under paragraph (c) is unclear (e.g., to reflect any new information?).

Updating the guidance documents described in subsection (b) every 5 years could be challenging and resource-intensive.

Commented [A6]: The term "withdrawn" is often used to refer to an agency action where a guidance document is no longer meant to be in effect.

Commented [A7]: As drafted to refer to "the earlier of" two dates, this "and" should be "or" to refer to (1) or (2).

Senator BARRASSO. Thank you very much to all three of you. You can tell how much interest there is in this topic by the number of Senators who have already arrived to listen to you.

Mr. Sanders, relatively little critical mineral mining occurs in the United States, even though we do have some mineral resources. Just last week, CNBC had an article out, and it discussed opportunities for Wyoming to increase our domestic supply of minerals. I am going to enter this article into the record, without objection.

[The referenced information follows:]

Wyoming may hold key to the rare earth minerals trade war with China

[cnbc.com/2019/07/10/wyoming-may-hold-key-to-the-rare-earth-minerals-trade-war-with-china.html](https://www.cnbc.com/2019/07/10/wyoming-may-hold-key-to-the-rare-earth-minerals-trade-war-with-china.html)

July 9,
2019

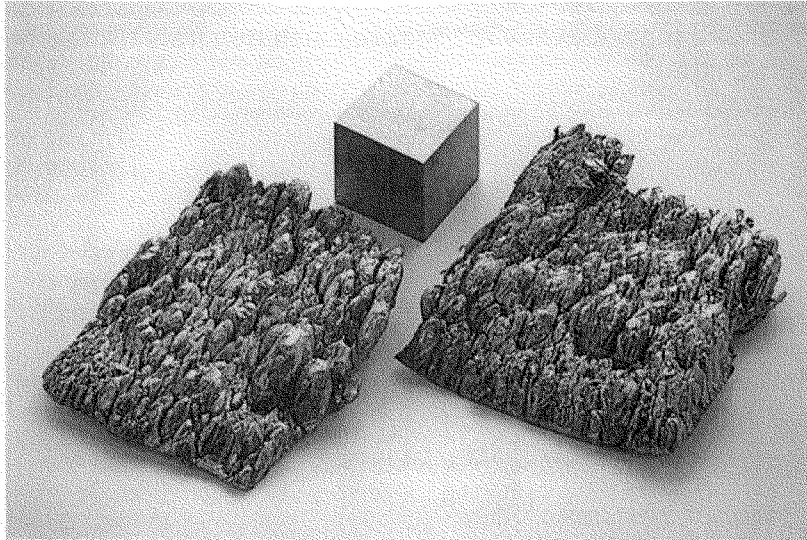
America's
TOP STATES
FOR BUSINESS

Wyoming may hold the key to the rare earth minerals trade war with China

Published Wed, Jul 10 2019 8:00 AM EDT Updated Wed, Jul 10 2019 10:30 AM EDT

[Bryan Borzykowski@bborzyko](mailto:Bryan.Borzykowski@bborzyko)

- In May, China threatened to cut off supply to the U.S. as part of the U.S.-China trade war.
- America depends on China for 80% of its rare earth imports.
- The global rare earth market will grow in value from \$8.1 billion in 2018 to more than \$14.4 billion by 2025 as demand for electric vehicles, cellphones and other products rise.
- Wyoming could play a key role in making the U.S. more rare-earth independent.



Rare earth metals are used in cellphones, electric-vehicle batteries, fluorescent lights, defense, clean energy and much more. The global rare earth market is expected to grow in value from \$8.1 billion in 2018 to more than \$14.4 billion by 2025.

Photo: Heinrich Pniok

Wyoming is best known for its picturesque views and towering mountain ranges, but if Randy Scott has his way, it'll become famous for something else: rare earth minerals. These resources have been in the spotlight since China, the country that dominates global supply, threatened in May to cut off supply to the U.S. as part of the U.S.-China trade war.

Since 2011, when Scott became the president and CEO of Littleton, Colorado-based Rare Earth Resources, the veteran mining executive and metallurgical engineer has been trying to get a massive stash of rare earth — a metallic element that's used in cellphones, electric vehicle batteries, fluorescent lights, defense, clean energy and much more — out of Bear Lodge, a small mountain range tucked away in the northeast corner of the state, about 40 miles from South Dakota's border.

According to mining experts, Bear Lodge is home to one of the richest and highest-grade rare earth deposits in the U.S., with an estimated 18 million tons of rare earth inside. Scott thinks there could be more than that. "It's an enormous, and enormously important, deposit," he says.

But despite efforts to get the metal out of the ground — Rare Earth Resources has been exploring the area since 2004, while others have tried here and there to mine it since the metal was first discovered in the area in 1949 — it remains stuck in the mountain. “It’s a great resource,” says Scott. “But we keep hitting a brick wall.”

The quest for rare-earth independence

Many people, especially in the mining community, are excited about Bear Lodge because, other than at the massive, high-grade deposit in Mountain Pass, California, no one’s mining rare earth in America. According to the U.S. Geological Survey, China produces about 70% of rare earth in the world, while 80% of America’s rare earth imports come from the Red Giant. In 2018 China produced 120,000 metric tons of rare earth, while the U.S. produced just 15,000 metric tons, up from zero in 2017, [according to Investingnews.com](#).

The open pit mine at Molycorp’s rare earths mining and processing facility in Mountain Pass, California

Jacob Kepler | Bloomberg | Getty Images

Rare earth isn’t actually rare — there’s an estimated 99 million tons of it in the Earth’s crust — though it is hard to find large quantities of the metal in one spot. Before about 1995, barely anyone paid attention to the mineral, but demand has skyrocketed since. Why? Because each mineral contains one or more rare earth elements, many of which are now used in everyday products. For instance, neodymium, when combined with iron and boron, makes a powerful magnet that’s used in cellphones, headphones, electric-vehicle motors and more. Lanthanum is used in lighting and camera lenses; cerium is used in self-cleaning ovens.

As more cellphones get made and as more electric vehicles hit the roads, demand for rare earth will only rise. According to [Zion Market Research](#), the global rare earth market will grow in value from \$8.1 billion in 2018 to more than \$14.4 billion by 2025. “They’re literally the building blocks of all modern technologies and electronics,” says Ann Bridges, the Silicon Valley-based co-author of “Groundbreaking!: America’s New Quest for Mineral Independence.”

More from America’s Top States for Business:

[These are the states offering \\$10,000 or more to live there](#)

[The top 10 states in America to land your dream job in 2019](#)

[Antiwar candidate Bernie Sanders faces backlash over the \\$1.2 trillion war machine he brought to Vermont](#)

Naturally, many Americans are worried about the outsized impact China has on this market. In 2010, China temporarily banned rare earth exports to Japan during a diplomatic dispute,

and some think they could do the same here if the U.S.–China trade war escalates. “Laser-guided missiles, sophisticated weaponry, car batteries — all these components come from China,” says Bridges.

Wyoming, ranked No. 26 on CNBC's 2019 America's Top States for Business list, has a key role in making the U.S. more rare-earth independent, she says. “We won’t have all the minerals we’ll need, but the issue now is that we’re depending on China for our military and 21st-century lifestyle,” she says. “We need to get America mineral-independent.”

Regulatory delays

With a rare earth deposit that’s ready to be mined and a growing demand for these elements, you’d think that everyone would be itching to pull these metals out of the ground. Yet Rare Earth Resources hasn’t been able to move forward despite locating deposits in Bear Lodge and providing environmental assessments.

One issue is regulation — it takes a while to get the proper permits, says Scott. From 2010 to 2014, the company collected all sorts of environmental data, which it then showed to the U.S. Forest Service. In January 2016 it received a draft environmental impact statement from the government agency, which recommended that the project go ahead. Before it could receive the final impact statement, though, rare earth prices cratered — neodymium fell from about \$85/kg to about \$46 in 2016 (it’s now at \$75/kg) — and the project had to be put on hold.

The Bear Lodge property is situated east of the crest of the Bear Lodge Mountains, a relatively small northwesterly trending range. The project area is flanked to the west by the Powder River Basin, famous for its extensive coal mines, and is surrounded by the Great Plains.

Source: Rare Element Resources

In addition to regulation, Bridges blames environmental litigation as reasons for more delays. While Bear Lodge hasn’t seen any lawsuits, other mines have. “We have a real problem in this country where even though there’s a defined process under environmental protection acts that have been passed, lawsuits can halt a project in its tracks,” she says.

More mining ahead?

Over the last couple of years, the prospects for rare earth mining in Wyoming has started to improve. In December 2017, President Donald Trump signed an executive order to create a federal critical minerals strategy, which would cut red tape and boost resources for exploration. In June the government released its **Federal Strategy to Ensure a Reliable Supply of Critical Minerals** document, which, according to a press release, “directs the U.S.

Department of the Interior to locate domestic supplies of those minerals, ensure access to information necessary for the study and production of minerals, and expedite permitting for minerals projects.”

In April, U.S. Senators Joe Manchin, Shelley Moore Capito and Lisa Murkowski introduced the Rare Earth Element Advanced Coal Technologies Act, which would allocate \$23 million a year to the Department of Energy and its National Energy Technology Laboratory (NETL) through 2027 to help develop technologies that could extract rare earth elements from coal and coal by-products in U.S. mines.

VIDEO04:41

China's control of rare earth minerals explained

That could help Scott Quillinan, director of research at the University of Wyoming's School of Energy resources. He's found high rare earth element content in coal seams — coal deposits that can be seen inside of rocks — and coal ash. This is important because Wyoming is the largest producer of coal in the U.S. It produces two-fifths of all coal mined annually.

If Quillinan can figure out a way to extract rare earth from coal — that's the next step in his research — then Wyoming could produce a lot more rare earth than originally thought. “This is significant,” he says. “Coal seams here are much thicker than they are in the East, and if you start to develop this unconventional source of rare earth, then there's a lot of potential here.”

While the bill has yet to be passed, and it's still unclear as to whether you can mine rare earth from coal in a clean way, Quillinan is hopeful that additional funding will push this part of the industry forward. “Thanks to the financial support made available through NETL, creating new industries and markets for coal looks quite promising,” he says.

Despite Trump's executive order and an increase in attention on the importance of rare earth independence, Bear Lodge remains idle. However, Rare Earth Elements secured a new investor in 2017, which allowed it to kickstart the project again. It's updated its environmental assessment and has the permits it needs to move forward. Now it needs approval, which it's still waiting on. It's also developing a technology that will allow it to process rare earth at the mine site, a key component for getting the metal out of the ground and into products.

Naturally, Scott is anxious to get started, and he thinks the state of Wyoming is, too. “I know the people of Wyoming are looking to diversify its economic base and move away from carbon-based products,” he says. “This will happen at some point, because if the U.S. doesn't do something, then we are going to find ourselves in big trouble.”

VIDEO09:11

Senator BARRASSO. In your testimony, you highlighted interest in producing critical minerals domestically. Could you discuss what is driving the interest, and how can we do more of these activities in the U.S. in an environmentally responsible way?

Mr. SANDERS. The interest comes from really a couple of different areas. Most of these materials have extremely long supply chains.

Take cobalt, for instance. Most of it is mined in the Congo. It then goes to Asia for production of cathodes, and then back to wherever the country is that the battery is being produced.

So it would be a much more efficient supply chain, if a cell is being produced here in the U.S., if the minerals and raw materials also came from the U.S. So that is the easiest one. That is a tremendous cost to the industry, of relocating these materials from these various areas.

The second thing is, just from an environmental perspective, if the U.S. can become competitive in supplying these materials, it then reduces our reliance on China and other areas basically being the leaders in this space.

Your article on Wyoming was focused in on rare earth type materials. Those are very critical to electric vehicles, mostly in the motor and the magnet side of the equation, a little bit in lithium ion. But there has also been reports of lithium reserves in western States, Wyoming and Nevada and others.

So there is the potential of the U.S. becoming competitive and supplying the critical material.

Senator BARRASSO. Can we do it in an environmentally responsible way?

Mr. SANDERS. I think all of these materials and mining can be done in a responsible way, as long as it has the right guidance and establishment of processes. My prior career was with DuPont, and we had lots of chemical processes and so forth that could be operated in a lot of different areas. So that type of thing can be set up responsibly, it just needs to have the right systems put in place.

Senator BARRASSO. Mr. Greenberger, in your testimony, you talk about the need to manage spent batteries because of the public safety concerns. You said if we do not properly dispose of high voltage lithium ion batteries, it is not a question of if a child wandering through a field or a junk yard would be electrocuted, but how many, and long it would be before we decide to do something about it.

How do spent batteries pose electrocution or fire risks, and what should we do about it?

Mr. GREENBERGER. As spent batteries are high voltage electric equipment, just like any high voltage electric equipment, someone who opens one up and touches the wrong part of it is likely to have a very bad outcome. So we have to do something to make sure that at the end of useful life, those batteries are removed from the environment, are decommissioned, disassembled, and hopefully recycled.

There is a real public need to make sure that that happens. I know members of my organization very much look forward to working with this Committee and the Congress in trying to figure out exactly how best to do that.

Senator BARRASSO. Mr. Sanders, you may know about how much it would cost to recycle a lithium ion battery from an electric vehicle. Do we see that cost decreasing through new and innovative recycling techniques?

Mr. SANDERS. The best place to look for economics on recycling today is looking at what China did. They basically established collection facilities to basically collect the battery packs into a reasonable location, prepare those for recycling, and ship those then to a recycling center. The processes that have been established in China, though they are only at piloting level, appear to be able to, once they get to full commercial scale, to recover enough metals to basically recover the cost of the recycling piece.

The piece that still remains a cost to the overall system is that collection piece. Those batteries that are collected and then sold in China to the recycling centers are done at the metals cost. So that cost piece still has to be managed in the value chain. That is still something that has to be worked out as to how exactly that manages to go forward.

Somebody mentioned earlier the lead acid being 99 percent here in the U.S. That is true. But the processes established and the procedure there that basically got to where there were collection facilities in place, and also as we buy, as consumers, batteries in the marketplace, we also pay a recycling fee when we buy a battery at the local supply chain. So there are ways of managing those types of things, they just have to be figured out, what is the best way to manage that economically.

Senator BARRASSO. Do you have an estimate of the current cost to recycle a lithium ion battery from an electric vehicle?

Mr. SANDERS. From raw material all the way, or from basically collecting it from the spent vehicle, to the total reproduction, probably in the neighborhood of \$5,000, depending on size of vehicle and so forth. The metals value is probably in the \$3,500 range. So a substantial portion of that can be recovered from the metals piece of it.

Senator BARRASSO. Senator Carper.

Senator CARPER. Again, thank you all. This is fascinating and I believe encouraging.

Some of our colleagues arrived mercifully after the Chairman and I gave our opening statements, but I just want to go back and reiterate one of the things I said.

It was just announced last week, a joint venture between Ford and Volkswagen, to develop the next generation electric vehicle. These vehicles are coming, and there are going to be a lot more of them on the road, which I think is a good thing. Hopefully a lot of those vehicles are going to be made here in America, with components, including batteries, that are American.

I have reminded my colleagues a time or two in the past that the Detroit Auto Show—which I go to just about every year—11 or 12 years ago, the car of the year was Chevrolet Volt, V-O-L-T, an electric hybrid, 38 miles on a charge. A year or 2 ago, the Chevrolet Bolt, B-O-L-T, all electric, 240 miles on a charge. Next year at the Detroit Auto Show, we will see Tesla vehicles and others getting 300 miles on a charge. This is coming.

We can either be part of it and be very much invested and en-joined in the creation of these manufacturing jobs, the research and manufacturing, recycling, or not, or let somebody else do it. We have to be smart enough to take full advantage of it. As we say in Delaware, *Carper diem*, also known as *carpe diem*.

I would ask this question, if I can, I want to make sure I pronounce your name right. Is it Chawan?

Mr. CHAWAN. Chawan, yes, sir.

Senator CARPER. Thank you. In your written testimony, you mentioned that between 2012 and 2018, electric vehicle sales in our country grew by 1,500 percent. You go on to say that during the same time period, electric vehicle sales in China increased by almost 8,000 percent. The growth trend isn't expected to slow down any time soon.

It is my understanding that if current trends continue, China could account for half of the global electric vehicle market share by 2025. Other countries are also adopting electric vehicles at a faster rate than the U.S.

Should the elected Government support the deployment of electric vehicles in the U.S. to ensure that China and the rest of the world do not dominate the future of transportation electrification? In your answer would you discuss how Federal investments in electric vehicle charging infrastructure in this country would help our car manufacturers to be competitive?

Mr. CHAWAN. Thank you for your question, sir. In order to promote EV adoption in the U.S., there are three pillars that we typically look at. We look at infrastructure, we look at the product cost, and we look at awareness. So awareness generation has been taking place through many activities, including activities by the automakers, by other third parties such as network operators.

The network operators are also building infrastructure. There are several national network operators out there today. There are also network infrastructures being built by electric utilities, which is an area that we spend a lot of time focusing on as well.

Last is the cost piece. As the proliferation of EVs continues, the cost per unit will continue to go down. We are kind of in the \$6,000 per flat panel TV stage of the technology development curve. As more and more volume comes online, the economies of scale will kick in, and new manufacturing techniques and advances in production will enable us to bring the cost per unit down. That will help with the affordability factor of electric vehicles.

Senator CARPER. Good, thanks. Just one follow up question to that, if I could. Based on what you know today, do we have sufficient critical minerals available to be able to produce enough batteries to support the projected electric vehicle growth in our country?

Mr. CHAWAN. In our country? I do not have that information, sir. The last—the only reference point I have is from a USGS report on some of the critical elements that were talked about today for battery production. USGS shows that the U.S. has less than 1 percent of global reserves of nickel, cobalt, and lithium.

Senator CARPER. All right. A follow up question to you, Mr. Chawan. In your testimony, you stated that battery research is happening today that if successful, would dramatically reduce the

quantity of critical minerals needed to build and run an electric vehicle battery.

My question is, how far along is this research in the U.S.? Do you see automakers switching from a more traditional lithium ion battery to a more sustainable battery? Do you agree with what I said in my statement that the electric vehicle batteries we are using today are most likely not the battery technologies we are going to be using 5 or 10 years from now?

Mr. CHAWAN. I think there are three answers to each point individually. Question one was about how far battery research is coming along. There are numerous reports out there for what is the next generation of batteries commonly referred to as solid state, where the liquid portion of the battery is changed to a solid material.

Toyota has stated it is going to have that out by 2022, and some reports say it could be even sooner than that. That would represent a major shift in battery technology.

The question about what our batteries will look like several years from now versus today, the chemistry will very likely be different. As far as what that chemistry looks like, I don't know for sure.

And I am sorry, could you repeat the other question?

Senator CARPER. Do you agree with what I said earlier in my statement, that the electric vehicle batteries that we are going to be using in 5 or 10 years are going to be different? That was my last part, I think you responded to that.

Mr. CHAWAN. Thank you.

Senator CARPER. I am going to slip out for a little bit. We all have other committees that are meeting right now. In the Homeland Security committee, we are having an important roundtable discussion on push and pull factors leading to all the surge of people coming to our borders. So I will be going to that, and I will be back. I am very much interested in everything you have to say.

Mr. Chairman, I am delighted that we are having this hearing. Thank you.

Senator BARRASSO. Thank you, Senator Carper.

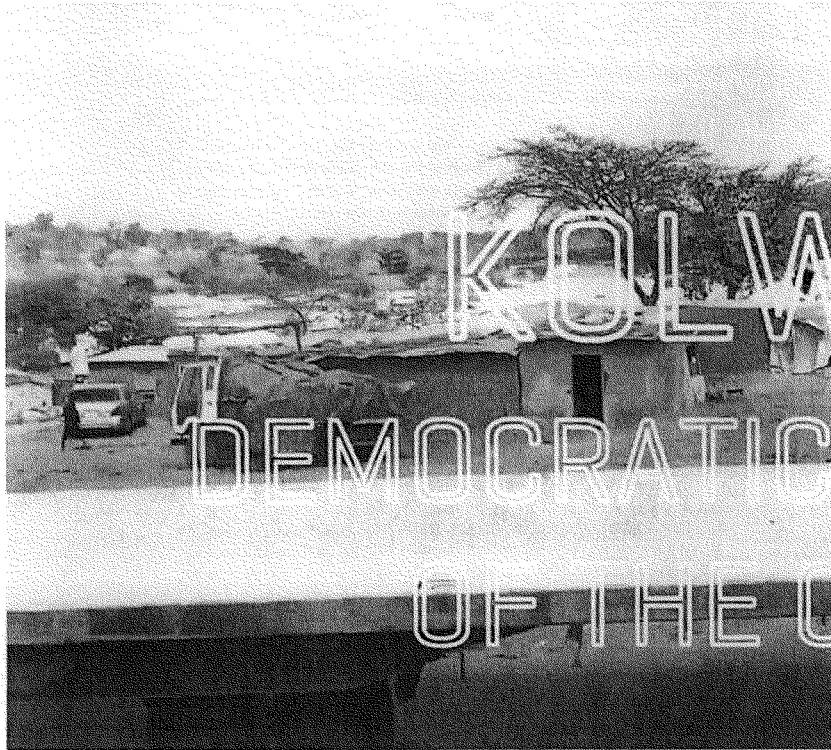
Senator Inhofe.

Senator INHOFE. Thank you, Mr. Chairman.

First, I want to get into the record this article in Fortune Magazine; it talks about some of the child labor problems.

Senator BARRASSO. Without objection.

[The referenced information follows:]



Blood, Sweat, and Batteries

Two-thirds of the world's cobalt, an essential ingredient in our smartphones and electric cars, comes from one of the planet's poorest countries. All too often it is mined by children.

This story was produced with support from the Pulitzer Center on Crisis Reporting.

MOST OF HIS NEIGHBORS are still sound asleep at 5 a.m., when Lukasa rises to begin his 12-hour workday. The slender 15-year-old, with an oval face and piercing stare, slips out of his family's mud-brick home before dawn six days a week. Then he makes the two-hour walk from his tiny village in the southern region of the Democratic Republic of the Congo to a government-owned mining site. (*Fortune* is withholding the name of the village in order to protect Lukasa and other children.) Once at the mine, Lukasa spends eight hours hacking away in a hole to accumulate chunks of a mineral that is crucial to keeping our modern lives moving: cobalt.

By about 3 p.m., Lukasa has filled a sack with his day's haul. He hoists the load, which can weigh up to 22 pounds, on his back and lugs it for an hour by foot to a trading depot. "I sell it to Chinese people," he says, referring to the buyers from Chinese commodity trading companies who dominate the market in the area. Lukasa is wearing a T-shirt with "Prada" written on the front and sitting under a shade tree in his village on a recent Sunday, his one day off, as he explains his routine. With a hint of pride he says, "On good days I can earn 15,000 francs." That adds up to about \$9.

From his vantage point in one of the poorest countries in the world, Lukasa has little awareness that a multibillion-dollar scramble is underway for the grayish metal he digs out of the ground some 300 days a year. Lukasa has, he says, recently begun to grasp that his cobalt mining earnings are a pittance compared with the sums that traders make selling it on the world market. But that business is hard to fathom for those living near Kolwezi, the hardscrabble center of the cobalt industry in Congo. It's more difficult still for diggers living in poverty, like Lukasa, to understand a surge in demand for the mineral that has sent the price of cobalt on commodities markets rocketing up some 400%, from about \$10 a pound in 2016 to a peak of about \$44 in April.

That soaring appetite for cobalt is a product of today's device-driven tech economy: The metal is a key component in the lithium-ion batteries that power countless millions of smartphones, computers, and tablets. Cobalt provides a stability and high energy density that allows batteries to operate safely and for longer periods. Without it, our digital lives—at least for the moment—would be unable to function as they do.

And yet, as valuable as cobalt is today, its crucial role is only now coming into focus. The global transition to renewables—the biggest energy shift in a century—could depend in good measure on how readily cobalt will be available over the next several years, and how expensive it will be to produce and refine. As many governments around the world—if not the one in Washington, D.C.—begin rolling out their climate-change targets to curb carbon emissions, so automakers are hugely ramping up production of electric vehicles. General Motors, for example, says it is planning for



Miners pulling up a bag of cobalt inside the Kasulo mine near Kolwezi in the Democratic Republic of the Congo. Sebastian Meyer for Fortune Magazine

Absent a breakthrough invention in battery technology, each electric-vehicle battery will need about 18 pounds of cobalt—over 1,000 times as much as the quarter-ounce of cobalt in a smartphone. Volkswagen, for example, expects it will need to build six giant battery factories within a decade simply to supply its electric-car plants.

That means the spike in cobalt may have only just begun. Demand for cobalt for lithium-ion batteries alone could triple by 2025, and then double again, reaching about 357,000 tons a year by 2030—nearly seven times the current level, according to the London-based cobalt-trading company Darton Commodities. On the ground in Congo, the pressure to produce cobalt has reached a fever pitch. "If you want to be king of the world in the next 10 years, you have to have cobalt," says Jean-Luc Kahamba Kukenge, deputy general manager of the Congolese mine Commus Global, which is owned by the China's Zijin Mining Group, when I meet him in Kolwezi. "In the next 10 years, it will be everything."

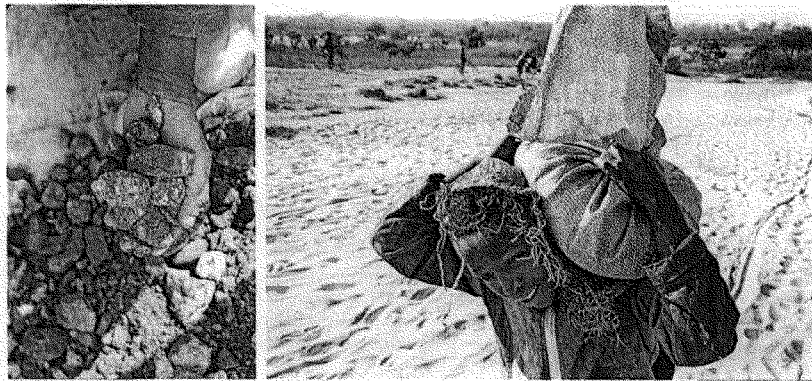
The reliance on a single raw material is nothing new, of course: The auto industry owes its very existence to pumping crude oil out of the earth. But there is a key difference between the car revolution that began a century ago and the electric-vehicle revolution that is just beginning. Oil reserves are tapped in dozens of countries and under every ocean. By contrast, cobalt has until now been heavily concentrated in one sliver of territory. Worse still, that territory is within a country



ethical conundrums for the technology, automotive, and mining companies that need cobalt—problems that, if not resolved, could threaten the very ability of those companies to win over millions of consumers to cleaner energy.

ROUGHLY TWO-THIRDS of the world's cobalt is produced in the DRC's southeastern province of Lualaba, near the border with Zambia. The region sits atop a dizzyingly rich mineral vein known as the Copperbelt—and cobalt is mostly a by-product of copper and nickel extraction. Mining accounts for about 80% of the DRC's earnings. Stretching across Africa's broad midsection, the DRC has for decades epitomized the term "resource curse." Despite giant riches of tin, gold, nickel, copper, and now cobalt, the average person there earns just \$700 a year.

Life is grindingly difficult for the millions of Congolese who have no running water or electricity at home; the average life expectancy is about 60. The DRC ranked near the bottom on the UN's Human Development Index in 2015, at 176th out of 188 countries. And it fares little better on the anti-corruption index of the NGO Transparency International, which cites rampant patronage among a small elite, headed by President Joseph Kabila, who has held power for nearly 18 years. Kabila has picked a close ally to succeed him, in December elections, which could spark violence.



Left: A miner holds chunks of cobalt he has dug out at the Kasulo mine near Kolwezi in the DRC. Right: An 11-year-old mine worker named Daniel carries a bag of cobalt from a dig site to a depot to be sold, Sebastian Meyer for Fortune Magazine

When our small plane bumps to a halt one wintry afternoon in mid-July on the airstrip in Kolwezi, the small provincial capital of Lualaba, there is nothing to suggest we have landed in the epicenter of the world's cobalt wealth. A small cinder-block

In 2016, I had landed in the same spot, on assignment for *Fortune*, traveling in an eight-seater aircraft leased by the Switzerland-based commodities giant Glencore. On that trip, the company's representatives whisked me off to the bright-lit, air-conditioned complex of Mutanda Mining, the world's biggest cobalt production facility, with state-of-the-art technology and a meticulous corporate management system that felt like an alien planet amid the chaotic galaxy beyond the gates. Mutanda's CEO Pedro Quinteros, a seasoned Peruvian engineer, told me then that the mineral concentration in Congo's Copperbelt was so high that he had "never seen anything like it in my career."

Now I was back to see the other side of the story. Glencore still mines and exports more cobalt than any company in the world, and it says it is planning to double its production over the next two years in expectation of a looming global shortfall in supply.

See Fortune's Change the World list.

That industrial-scale output dwarfs the production of the more than 100,000 so-called artisanal cobalt miners around Kolwezi—traditional, independent diggers who have converged on the area to search for cobalt, often with primitive tools. The diggers include an unknown number of children like 15-year-old Lukasa, who support their families by digging small quantities of cobalt by hand, then selling them to middlemen, virtually all Chinese; children in a small village near Kolwezi greet us in Chinese with "Ni hao!" since the only non-Africans most have ever seen are from China.

While it is impossible to know how many underage miners there are, Congolese activists working to end child labor say poverty has driven up the numbers. "Because of the economic crisis, there are about 10,000 of them," says Hélène Kayekeza Mutshaka, who coordinates a monitoring program in Kolwezi that the government began last year, to try to stop children from mining cobalt. Mutshaka says she faces strong resistance from poor families, who have long sent their children to dig for minerals in order to supplement their meager earnings. "They believe they can try to make it into the middle class if they work as artisanal miners," Mutshaka says.

Around Kolwezi, that seems an almost impossible dream.

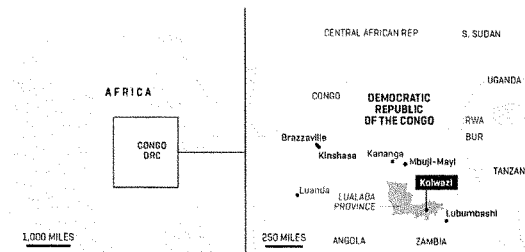
One morning in July, on the edge of an artisanal mine called Kingiamiyambo, about eight miles outside of Kolwezi, we meet 11-year-old Daniel, a small boy walking up the hill from the digging site, caked in dust and carrying a load of cobalt on his back, on his way to sell it to Chinese traders; he tells us he has never attended school. Children like Daniel toil at the very bottom of the global cobalt market. For their families, many of whom depend on the tiny sums their children bring home, there seems little hope of actual life improvement. Yet asking them to stop mining seems equally difficult, so long as cobalt appears a ready source of income. "What do they do



Dynamics, which monitors the mining sector. "They will seek survival. And what is survival here?" he says. "It is obvious: a mine next door."

PLAGUED BY POVERTY BUT RICH IN RESOURCES

The Democratic Republic of the Congo is one of the world's poorest nations despite its mining wealth. Two-thirds of global cobalt supply comes from the DRC's Lualaba province, which sits astride a mineral vein called the Copperbelt.



Despite the grueling conditions, the temptation for children to keep working is strong. Many earn just \$2 per day, often acting as human mules for cobalt diggers. "When kids are not in school, they all go work in the mines," says Franck Mande, who oversees a project funded by Apple that aims to teach child miners new skills. "They work from 14, 15, 16 years—even from 10 years old," Mande says.

Congolese authorities say that they are trying hard to stop children from mining cobalt, but that it is almost impossible to end child labor completely. And they point out that artisanal miners—the vast majority of them adults—account for just 20% of the country's cobalt output.

But for companies sourcing cobalt from the DRC, the existence of artisanal miners creates another headache: It is virtually impossible to assure consumers of iPads, smartphones, or electric vehicles that no children have dug, crushed, washed, or transported the cobalt inside their devices. For some companies, it has seemed simpler, in fact, to end all business with artisanal miners—a decision that NGOs and Congolese officials say devastates millions of people who depend on the work.

CORPORATE CONCERNS have risen sharply since 2016, when Amnesty International issued a deeply researched report naming more than two dozen electronics and automotive companies that, Amnesty concluded, had failed to do enough due diligence to ensure that their supply chains didn't include cobalt produced with child labor at artisanal mines. The report caused a firestorm—and set some companies scrambling to find ways to avoid the DRC altogether. As the debate over Congo's cobalt rages on, the question is whether the country can overhaul its



reaching, rapid change seems hard to imagine.

Congolese officials are not the only ones at fault, however. Amnesty blasted Western tech giants for blithely ignoring the problems surrounding child labor and corruption—in large part because consumers had rushed to buy tech devices, without asking questions about the industry's darker side. "Millions of people enjoy the benefits of new technologies, but rarely ask how they are made," the organization said at the time.

But that is finally changing. The shift has come after recent TV reports have depicted child miners like Daniel and Lukasa, digging for cobalt under tough conditions. "We have reached a tipping point where it's become more expensive not to abide by good standards," says Tyler Gillard, senior legal adviser to the Organization for Economic Cooperation and Development, or OECD, in Paris, who helped draft due-diligence guidelines for corporations on mineral supply chains. "Companies see this as a major threat to brand value," he says. "Are consumers going to demand child-labor-free, corruption-free electric vehicles? I think it is coming."



Inside the Kasulo mine, which is owned by the DRC government and run by China's Congo Dongfang International Mining, or CDM. Sebastian Meyer for Fortune Magazine



some outward hostility from DRC officials in reporting this story.

Despite obtaining media accreditation in advance from the central government in the national capital of Kinshasa, once photographer and filmmaker Sebastian Meyer and I arrived in Kolwezi, we had to seek permission from Lualaba's provincial governor, Richard Muyej, to conduct interviews without being detained or ordered out of the country. Sitting in Muyej's office, we listed sites we wanted to visit. In response, the governor told us several times, in French, "*On a rien à cacher*"—we have nothing to hide.

But our experience during one week in Kolwezi suggested a very different picture. The provincial Ministry of Mines and the police refused us entry into all but one mine site, telling us that we were forbidden to do any independent reporting without their permission. Some of our interviews were conducted under surveillance by police.

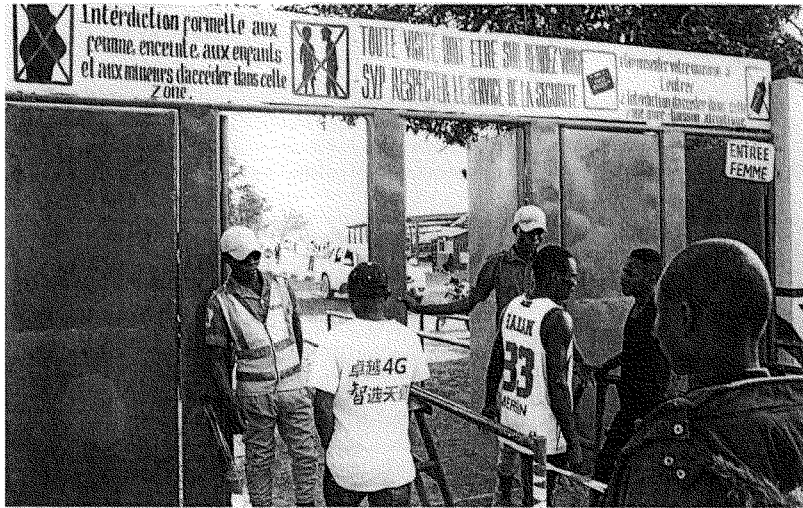
At the only cobalt mine to which we were granted official access—Kasulo, owned by the government—provincial mining officials rushed us around the site under the escort of armed police, telling us that the security presence was to protect us from harassment by miners. They refused our request to return to Kasulo a second time, despite the fact that we had an appointment there with Pact, the Washington, D.C.-based NGO working in Kasulo, with government approval, to end child labor in the mines.

On our last morning in the country, I asked Governor Muyej why his police and local officials had blocked us at virtually every turn. "People come with prejudices," he said, citing journalists who have recently described child cobalt miners in Kolwezi. "They see all the bad, not the good."

SINCE AMNESTY'S DAMNING REPORT in 2016, the government has indeed made attempts to clean up cobalt production—a task that is dauntingly difficult, if not paradoxical, given that top officials have benefited for years from opaque mining deals.

As an example of its new efforts, Lualaba's mining authorities point to its "model mine" of Kasulo. The sprawling 420-acre site sits north of Kolwezi and began in 2012, when locals living on the land struck reserves containing cobalt with an extraordinary 14% mineral concentration; thousands of people poured in, sparking a free-for-all hunt for cobalt.

In response to the human-rights outcry, the provincial authorities last year fenced off Kasulo, creating a single entrance and exit to the site, at which it posted armed security guards. Next to the entrance are now hand-painted signs proclaiming in French and Swahili that children under 18 and pregnant women are banned from entering, as is anyone with alcohol.



Signs in French at the entry gate to the Kasulo mine say pregnant women and children under 18 are not allowed inside. Sebastian Meyer for Fortune Magazine

Now, about 14,000 diggers converge on Kasulo every day to find cobalt, organizing themselves into small teams, then dividing their day's earnings at sundown. The mine accounts for one-quarter of the cobalt from the DRC's artisanal mines, and the exclusive rights to the ore are held by China's Congo Dongfang International Mining, or CDM, a wholly owned subsidiary of Huayou Cobalt, which Amnesty's 2016 report assailed for purchasing artisanal cobalt with little knowledge of labor conditions; Huayou says it has since implemented programs for Kasulo's miners, run by Pact, to teach safety and explain why children should not mine. It remains unclear how people's ages or pregnancy status are checked. "Do you see any child? No, none," says Erick Tshisola Kahilu, director general of the province's Ministry of Mines, standing amid hundreds of miners digging in the ground, as he guides us around the site. "And no babies either."

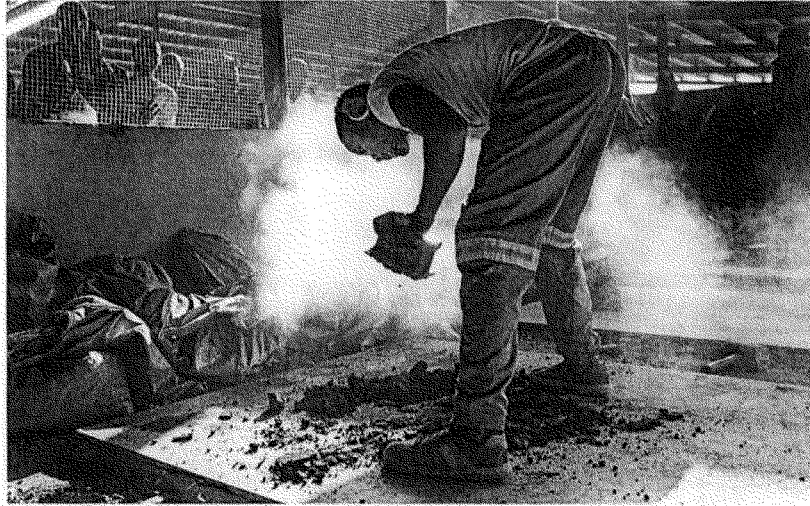
Three months before I landed in Kolwezi, I had listened to DRC mining officials espouse their efforts in Kasulo, at a conference on mineral supply chains in Paris, hosted by the OECD. Congolese officials distributed a glossy 10-page brochure, proclaiming Kasulo as a "*merveille émergente*," or emerging wonder. But the wonder inside Kasulo's gates more closely resembles a frenzied scene from the California gold rush of the 1850s, rather than a current-day mining enterprise. Several hundred men chip away in deep holes and open pits without overalls, helmets, or any other protective gear, using basic hand tools like lengths of rebar to hack away at the surface, and hauling up rocks with handmade lengths of rope.



open-air hangar inside the gates of Kasulo. The buyers check the cobalt concentration of the rocks, which determines the price they will pay, using a small digital instrument called a Metorex. The prices are marked on handwritten lists tacked to the walls of the hangar. Inside caged areas, Chinese traders pass wads of Congolese francs to weary miners. Despite the digital measurements, several miners told us they suspected that the buyers routinely lowered the cobalt concentration figures in order to decrease the pay. There is no proof their suspicions are correct. But the free-for-all atmosphere seems primed for conflict. As the digging day in Kasulo ended, I witnessed a fierce argument among six miners standing on one rutted path amid the pits over how to split the day's proceeds. The group's total sum: 60,000 francs, or just \$37.

For thousands of diggers working outside the more formal structure of Kasulo, the main trading hub is Musompo cobalt market, a cluster of about 50 open-air depots stretching a half-mile or so along the main east-west road out of Kolwezi. Musompo looks like the kind of village market that typically sells food or housewares. But for many tons of cobalt, this is a key gateway to the huge export market. Chinese middlemen, who speak rudimentary Swahili, test the concentration of cobalt brought in by diggers, and for about eight hours each day conduct a brisk trade in the metal. "I arrived recently from Nigeria," says Xu Bin Liu, 30, from Hebei province, China, who runs the "Boss Liu" depot on the edge of the Musompo market. Seated at a small wooden table knocked together with nails and covered in burlap, Xu says the job involves tough haggling over prices.

Officially, Huayou's CDM no longer buys cobalt from the Musompo market. But when we asked a Chinese buyer in Musompo for an interview, he said he needed the approval of his "boss," a CDM official in Kolwezi. Tech companies like Apple, Samsung, and others have said that it is exceedingly difficult to prove that Musompo's cobalt is free of child labor, and that the battery manufacturers that supply them—largely in South Korea and China—source the metal from child-labor-free mines.



A miner crushes cobalt that will be tested for purity at the Kasulo mine depot. Sebastian Meyer for Fortune Magazine

The situation has prompted companies to make some tough choices: cut all artisanal miners out of their supply chain, for example, or halt purchases of DRC cobalt—either option potentially an economic disaster for the country. “If everybody simply runs, that can put children and families in a more vulnerable position,” says Ben Katz of the NGO Pact. “That is not reducing harm. It’s causing more harm.”

Among companies, a race is underway to decrease the cobalt in electric-vehicle batteries, from the current 10% or so to 5% or less. Under current technology, cobalt is essential in making high-performing batteries. But Tesla CEO Elon Musk has said he intends to produce non-cobalt batteries for the next generation of Tesla vehicles. Likewise, Volkswagen has partnered with QuantumScape, a startup in San Jose, to invent a cobalt-free, solidstate battery to replace the lithium-ion version—but they do not expect quick results. “We are at a very early research stage,” VW’s research director Axel Heinrich says. “I cannot tell you which year we will have batteries with no cobalt.”

Shaken by the possibility that children might be mining cobalt used in iPads and iPhones, Apple says that it has identified every smelter providing cobalt in its supply chain, and that they are regularly audited by independent third parties. Last year, the company announced that it would stop sourcing all cobalt from informal mines in the DRC, but that it did not agree with those pushing to pull out of Congo altogether.

“There are real challenges with artisanal mining of cobalt in the Democratic Republic

environment."



Cobalt buyer Xu Bin Liu, 30, from Hebei province in China, tests the purity of cobalt he's buying at the Musompo market on the outskirts of Kolwezi. Sebastian Meyer for Fortune Magazine

In an effort to lessen their dependence on the DRC, some companies are instead investing to develop new cobalt reserves; exploration projects are underway in Australia, Papua New Guinea, Canada, and Montana and Idaho in the U.S. That is partly because of rising anxiety that China is locking up most of the world's cobalt supplies; in March, Glencore agreed to dedicate one-third of its entire cobalt production during the next three years to GEM, the Shenzhen-based battery recycling company. China produces a whopping 80% of the world's cobalt sulfate—the compound used in lithium-ion batteries. And by 2020, China will likely produce 56% of those batteries, according to Benchmark Mineral Intelligence in London.

Yet leaving the DRC entirely is hard to manage so long as cobalt demand keeps soaring. Cobalt-free batteries are likely years away from mass production, and new mines outside Congo could take years to come on line. "The DRC is absolutely critical to the production of lithium-ion batteries," says Caspar Rawles, Benchmark's analyst on battery technology. "Without the DRC, we are not going to have enough cobalt. There is no question about that."



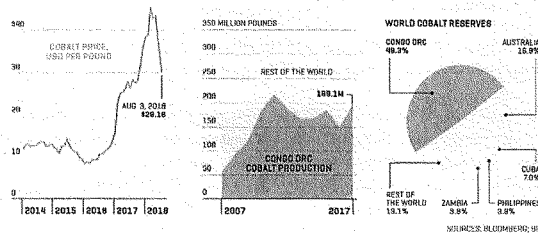
NORTH OF KOLWEZI IS THE TINY VILLAGE known as UCK (pronounced "oo-say-kah" for the French acronym of its original copper mine). There, amid the dirt paths where children kick battered soccer balls, is one sign of how Silicon Valley is trying to grapple with child labor without alienating consumers.

In the backyard of a small house down a side lane in the village one morning in July, three teenage boys were bent over a van, learning how to repair it. They were participants in an Apple-funded program that began late last year, operated by Pact with the approval of Congolese authorities. The idea is to switch children from mining to new moneymaking skills. Today, about 100 teenagers are being taught sewing, cell phone repair, hairdressing, carpentry, catering, and other skills in villages around Kolwezi.

Not all families have welcomed Apple's efforts, however. Some fear they will lose the income they desperately need to survive. "My parents asked me why I would abandon the mine," says Thomas Muyamba, a soft-spoken 16-year-old helping to fix the vehicle in UCK village. He says he began digging for cobalt at age 12, and earned between \$3.50 and \$9 a day—crucial support for his family. Attending school is not an option, he says, since his family cannot afford school fees. So he convinced his mother that being an auto mechanic would ultimately serve the family best. "I tell them it will guarantee my future," he says.

FEEDING A GLOBAL HUNGER FOR BATTERIES

Cobalt is a key component in lithium-ion batteries, helping to provide high energy density and stability. Soaring demand for smartphones, tablets, and now electric vehicles has caused the price of cobalt to spike. The DRC remains the biggest source of the mineral. But concerns about the country's labor conditions are pushing companies to explore elsewhere for the commodity.



The family has the same hope for Thomas's sister Rachel, 15, whose bushy pigtails frame her round cheeks like antennae. Rachel is one of about 10 girls who, until joining an Apple-funded project a few months ago, washed cobalt in the tailings in the river in Kolwezi—low-paid work that NGOs believe is particularly toxic for young lungs. Now, as part of the training program, the girls are seated at Singer sewing machines in a shed about five miles from Kolwezi, taking orders for clothes from clients and working on commission.

But the Apple program is not the only one trying to root out labor abuses in cobalt mining. Last year, China's Chamber of Commerce of Metals, Minerals & Chemicals



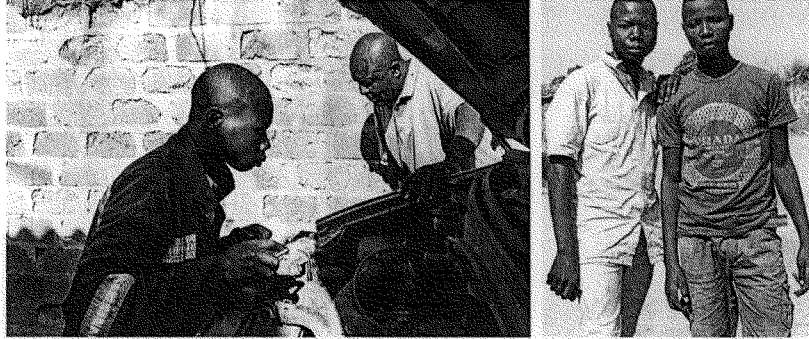
child labor from their supply chains. The group includes Apple, Samsung SDI, HP, and Sony. In a separate program, Huayou and other refiners, miners, and carmakers have joined the Better Cobalt project, launched in March by RCS Global, a London-based organization that tracks and audits supply chains of natural resources. The group claims it will be able to identify cobalt that meets "the highest global standards," focusing on child labor and human rights abuses. And the large commodities trader Trafigura has begun registering some 12,000 artisanal cobalt miners at the large Chemaf mine in Kolwezi, implementing health and safety standards and organizing them into cooperatives. Trafigura claims miners are earning dramatically more money as a result.

Besides the threat of a consumer backlash, companies also increasingly worry about potential legal liabilities, perhaps from an investor lawsuit, should they violate human rights. In July, the London Metal Exchange said that starting in January it would require every company that sources more than a quarter of its metals from Congo's artisanal mines to be audited independently. Those that fail to meet human-rights standards risk being banned from trading on the LME. And in April, an informal WhatsApp group began among major investors, to share information with locals about abuses in the DRC's cobalt industry. "If there are violations and there are lawsuits on a local level, the claims can be brought back to an international level, to a company traded on London Stock Exchange," says Christine Chow, director of Hermes Investment Management in London. "I do not want to use a phone that has been put together by a 4-year-old."

FOR ALL THE EFFORTS of companies and investors, the projects nonetheless have strong limitations—so long as grinding poverty persists for millions of Congolese.

That much is clear when you travel just a few miles away from the digging sites in Kolwezi. The day after meeting the teenagers Thomas and Rachel Muyamba, we meet them again, by happenstance, in their home village. (Again, *Fortune* has not named the community, for fear authorities might target those children in the village still mining cobalt for talking to journalists without permission.)

Sitting outside the tiny, mud-brick dwelling where Thomas and Rachel live with their family, it is clear that their mother and grandfather's decision to allow them to join Apple's training programs, and stop mining cobalt, has been difficult. The teenagers still earn just a fraction of what they made in the mines, putting a squeeze on the family.



Left: Thomas Muyamba, 16, works on a car engine with Vincent Kalangi, his teacher. Muyamba used to mine cobalt but is now in an Apple-funded apprenticeship program. Right: Muyamba, in button-down shirt, with his friend Lukasa, 15, who rises before dawn six days a week to work in the cobalt mines. Sebastian Meyer for Fortune Magazine

As a crowd gathers around us while we talk, I ask which children are still digging for cobalt. Several hands shoot up—including that of 15-year-old Lukasa, the boy whose 12-hour day begins at 5 a.m. in this village.

For these child miners, the daily task of digging for cobalt still seems worth the backbreaking work—despite the growing number of business-backed programs urging them to quit. Lukasa's earnings—\$9 on good days—are far higher than Thomas's pay from his Apple-funded job as a trainee auto mechanic, and match what Rachel makes for an entire week of sewing. Rachel says she expects to earn a solid living as a seamstress after a few years. "I will have my own shop," she says.

If Rachel succeeds in her plans, it will be a rare chance indeed for one of Congo's child miners to rise above the bare-bones survival gleaned from cobalt. Tech and auto companies are hoping thousands of other children find their way out of the mines too—allowing the technology industry to ward off consumer anger even as it continues tapping Congo's giant wealth to give us the batteries we demand.

This article originally appeared in the September 1, 2018 issue of Fortune.



Senator INHOFE. Mr. Chawan, I have spent a lot of time in Africa. I know some of the problems that are there. We know that most of this mining we are talking about is in Congo. We know of some of the problems that were pointed out by the Chairman, the picture up here of some of the problems that I am very familiar with.

We know that children are used in cobalt mining, primarily in the Congo, and some of the companies are taking initiatives to better ensure that batteries are ethically mined. What is your thought about that? What have we accomplished, and what can we do that we are not doing now?

Mr. CHAWAN. The traceability of materials I think would be potentially another way to describe what you are referring to. It is definitely possible. It is done in other industries today. For example, the food industry does that very well. The auto industry does that very well for manufacturing, so we know precisely—

Senator INHOFE. So you would be doing it just as well as it is being done right now?

Mr. CHAWAN. It is being done in these other industries for sure. I do not have familiarity with the mining industry, so I cannot speak to the traceability there. I can simply state that there are best practices from other industries that could potentially be adopted for the mining industry.

I think one of the challenges that we would see is what happens when you mix raw materials from multiple sources at a processing facility.

Senator INHOFE. OK, it sounds like if you have any problems, just consult your son.

[Laughter.]

Senator INHOFE. Well, I actually do that. I have 20 kids and grandkids. I fly airplanes, and every time I get a new instrument for an airplane, I have my grandkids read the manual and explain it to me. So I am serious when I make that suggestion.

[Laughter.]

Mr. CHAWAN. I am happy to chat separately about this with your office.

Senator INHOFE. All right. I have another article, Daily Caller article, to be made part of the record.

Senator BARRASSO. Without objection.

[The referenced information follows:]

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Daily Caller - <https://dailycaller.com>

OPINION

GUNASEKARA: California's Electric Vehicle Craze Is Fueling Child Labor



COURTESY

MANDY GUNASEKARA
CONTRIBUTOR

May 22, 2019
3:30 PM ET

Many of today's conscious consumers try use their pocketbook to effectuate good by purchasing products that have a positive impact on the planet and the people in it. One can buy shoes that help clothe the world, coffee that helps protect the world and fashionable totes that help feed the world. When it comes to purchasing cars marketed as "saving the world" it gets complicated. ,

11/10/2019

GUNASEKARAN, California's Electric Vehicle Craze Is Fueling Child Labor | The Daily Caller

High-dollar marketing campaigns have convinced the environmentally conscious that driving around in a zero-emission vehicle can make one look and feel good. While the consumer's desire is often genuine and laudable, electric vehicle makers, marketers and some of the environmental NGOs that support them are hoping the Zen of an environmentally-sound purchase is enough to outweigh any other concern, including the heartbreaking fact that the growth of the electric vehicle market is exacerbating the problem of child labor in African cobalt mines.

A few weeks ago, this very issue took center stage before the California General Assembly Committee on Transportation in the form of AB-735. The bill would require the local permitting authority — the California Air Resources Board — to certify that vehicles subject to the state's "zero emission vehicle" mandate are free of any material made using child labor. As the committee report explains, the bill was aimed at ensuring California's "lofty environmental goals" are not inadvertently exacerbating well-documented and much criticized child labor practices prevalent in the cobalt mines of the Democratic Republic of the Congo (DRC).

Cobalt is an essential part of lithium-ion batteries that power electric vehicles. Other products such as cell phones, laptops and "smart" luggage use these batteries as well. However, the much larger quantities required for electric vehicle batteries and the projected growth of the industry has been a key driver of rising cobalt demand. In 2018, investors referred to cobalt as the "hottest metal on the planet" after demand had nearly tripled and many analysts project demand to double again by 2020.

While cobalt is mined all over the world, close to 60 percent of the global supply comes from the DRC. According to UNICEF and Amnesty International, around 40,000 children are involved in cobalt mining in the DRC where they make a few dollars a day. An investigative look found that work in the African mining operations begins as early as four-years old where children can pick cobalt out of a pile. At 10, hard labor begins when children are forced to carry heavy sacks of cobalt on their backs to rivers for washing.

11/13/2019

GUNASEKARA: CALIFORNIA'S ELECTRIC VEHICLE CRAZE IS FUELING CHILD LABOR | THE DAILY CALLER

Californians purchase and drive more electric vehicles than any other state. Taking a lead to ensure that the state's environmental progress is not being built on the backs of impoverished African children makes a lot of sense. Unfortunately, AB-735 failed. Eleven members of the Transportation Committee relied on a bevy of arguments to ensure the bill did not pass.

According to the bill's analysis, the crux of the arguments raised during the debate were as follows: the bill could imperil California's climate goals; it would be really hard; making cars is a long-term process; the regulatory body assigned the responsibility of certification is not appropriate; it would require a lot of work; lots of other industries use child labor too; and it would not effectively address the issue.

Notably missing from the arguments was any claim that the problem the bill seeks to address was not true. In legalese this is referred to as an admission by omission. Instead of figuring out a way to constructively address the issue, legislators stood behind a series of seemingly logical arguments to wash their hands of it.

The hard truth is that the electric vehicle market is exacerbating child labor atrocities abroad. As a country, we are at a critical juncture where we can either continue to find justifications to turn a blind eye to this inconvenient truth or do something about it. While California proved uninterested, every other state could propose a similar bill. Congress could also consider how to ensure the taxpayer-funded electric vehicle tax credit is not a part of the problem either.

In a world of conscious consumers and a prevailing woke mentality to take injustices head-on, this presents the perfect opportunity to ensure environmental progress is not at the behest of other virtuous causes. If we can source a coffee bean to its exact longitude and latitude to ensure it is harvested by sustainable practices, then there is no reason we cannot do the same for a critical mineral to ensure its not mined by children.

Mandy Gunasekara is the founder of the Energy 45 Fund. She previously served as a senior official in President Trump's EPA and was a former counsel to the U.S. Senate

7/13/2019

GUNASEKARA: California's Electric Vehicle Craze is Fueling Child Labor | The Daily Caller

Environment and Public Works Committee.

The views and opinions expressed in this commentary are those of the author and do not reflect the official position of The Daily Caller.

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Senator INHOFE. This covers some of the problems with the labor problems that are in there.

I would like to—Mr. Sanders, this article talks about how California is contributing to the increased demand on cobalt. We know that is the case. Environmentalists claim that electric cars are the solution to many of the problems that we have. I would also suggest that maybe they are the problem than other solutions.

For example, what is happening with the Highway Trust Fund right now, the reason it is in trouble, is primarily due to electric cars. Then we have the human rights concerns. Earlier this year, the State of California debated a bill that would require the State to ensure zero-emissions vehicles that they are free from materials using child labor. Now, that bill failed, and the reason is very simple: a prohibition of this kind would get in the way of maintaining the radical electric vehicle mandate.

Unfortunately, California turned a blind eye to the human rights abuses.

Mr. Sanders, could you talk about these human rights concerns in the remaining time?

Mr. SANDERS. Well, I think the human rights concerns are real. The traceability is also becoming real. Multiple OEMs, global OEMs have established traceability programs from the mines in the Congo, all the way through their supply chain. So it is something that can be executed. And it is being executed by some of the major OEMs.

The other point that is starting to happen—Senator Carper pointed it out and asked, are batteries today going to be the same as they 5 years and 10 years from now. There are substantial programs to reduce the amount of cobalt that is contained in batteries, and potentially to go to zero-cobalt batteries in the very near future. Lots of universities and OEMs have claimed significant breakthroughs. So I think the percentage of cobalt per battery is likely to go down dramatically, which will also further improve the situation.

Senator INHOFE. Thank you, Mr. Sanders.

Thank you, Mr. Chairman.

Senator BARRASSO. Thanks, Senator Inhofe.

Senator Cardin.

Senator CARDIN. Thank you, Mr. Chairman. I very much appreciate your leadership, and Senator Carper's leadership, on this issue.

It is clear that consumer choice for electric vehicles is there. We have seen the increase in demand. Consumers like it. It is an imperative on our environment to reduce carbon emissions.

So this is clearly not only the future, it is the present. And we need to encourage this.

The supply chain issues are real. I just really want to underscore the concerns that have been raised by my colleagues. We cannot allow that vulnerability for our consumers rewarding labor practices which are totally unacceptable, and the security issues of our own supply chain. So that is an issue that I fully support the leadership of this Committee, to look at alternative ways. You have mentioned legislation, Mr. Chairman, I think we all need to look at ways to be more secure in that regard.

I want to get to the recycling issue for one moment. To me, that seems like low hanging fruit. As I understand it, we are very dependent on recycling outside the United States. We do not have the domestic industries here to handle the demand that is clearly here today, and will grow tomorrow. That reduces the need for a lot of these critical materials. It also is much friendlier toward our environment generally. And it economically makes sense.

Mr. Greenberger, let me start with you. What do we do as Congress to encourage the robust development of domestic recycling for these batteries?

Mr. GREENBERGER. Ultimately, what you need to do, what we need to do as a Nation is really encourage the development of a market for these products in the United States. Just to go back to the human rights issue that was earlier talked about, it really is a problem, that human rights abuses are going on in the Congo, and there is really nothing we can do about it, if China is buying 80 percent of cobalt, which is what is going on today. Because the Chinese don't have the same concerns that we do about human rights issues.

If we built a vibrant battery industry in the United States, by building a vibrant industry for electric vehicles, suddenly we have some control over our future, or over human rights violations abroad, over how we recycle batteries and use the materials here in the United States.

So it really does come down, for me, to the issue of, if we are going to be serious about competing in this new technology, we have to do essentially what China did, and that is build a domestic demand for the products. It is really important, and not just for cars and not even just for greenhouse gas emission issues, it is really important because it is the technology of the future, and it is going to impact a number of industries that are important to this country and that are going to be the source of jobs.

Senator CARDIN. I agree with that point. I am proud of Maryland; we have companies that are on the cutting edge of battery technology. You are right, it is well beyond just transportation. But it is an area where the United States should excel, and we are not as competitive as we need to be. So I completely agree with you.

This Committee, of course, needs to look at the transportation infrastructure. It seems to me that by recycling, we not only are doing things that are smart economically, but we are reducing our demand on the supply chain. I couldn't agree with you more, we should be able to have control of our supply chain, and we don't. China right now is the dominant player on it.

So we need to develop an entire industry. But it seems to me, low hanging fruit is the recycling of the batteries. What do we need to do to get that moving?

Mr. Sanders.

Mr. SANDERS. One of the biggest areas that is probably the first challenge that we are facing is, how do we get these used batteries back into the supply chain. If you look at how China set up their model to begin with, the first step that they took was establishing a mandate that basically a certain percentage needed to be recycled. Then they established basically a protocol to get these things to collection centers.

We all have probably a dozen of these things sitting in our house that are waste batteries and waste electronics that have value. If we got to having a robust collection facility approach, that then goes a long way. Because then you have a supply chain of materials that then can go into recycling, can go into the value chain.

But until you get these things collected, they are scattered throughout the U.S. and around the world, and that is a huge challenge for everybody. The EU is meeting this week regarding these and how many of these are used in each different country. So they actually have data to then go, how big is the problem, or how big is the opportunity.

I think that is the first step, is kind of understanding where these challenges are, and putting together a directive that basically says, here is where we are going. We may not know all the answers of how to get there. But until we basically say, we are going in this direction, it is really hard to get everybody motivated into one organized direction.

Senator CARDIN. I would just conclude by saying, I agree with you. The supply today is huge, just in order to get this started. But think about where we are going to be tomorrow. I mean, it is just going to continue to grow. And you can't put these policies into effect overnight. It is going to take time. We are already well behind where we need to be, and when we look at the future, it is imperative that we act quickly.

Thank you, Mr. Chairman.

Senator BARRASSO. Thank you, Senator Cardin.

Senator CAPITO.

Senator CAPITO. Thank you, Mr. Chairman, and thank all of you.

We talked a lot about the core materials that are needed for the batteries. But we do have rare earth elements that are essential to some of that. You all have alluded to some of this in some of your testimony. It is a particular source of interest to me, because of what we see happening in our State of West Virginia. We know that the last rare earth mine closed, but then reopened, but they are having difficulty with their profitability.

Even though they were able to mine some of the materials, they had to send it, my understanding is, to China to have it refined. That is an issue and an expense at the same time.

So I think we need to guard ourselves against the shocks, the global supplies, of these rare earth elements. At West Virginia University, led by—I am going to call him Dr. Z, because that is what we call him, has been exploring technology to clean up the waste and generate concentrated rare earth elements in our coal, our fly ash, and our acid mine drainage. So for me, this holds great promise to solve a domestic supply problem for us in rare earth, but also has the environmental benefit of going into prior acid mine damage or fly ash, to be able to get some benefit out of this and clean it up at the same time.

They are working with a Pennsylvania company called InnoH2O Solutions, and I have a letter for the record that I would like to submit, without objection, Mr. Chairman.

Senator WHITEHOUSE. Without objection, so ordered.

[The referenced information follows:]



July 17, 2019

The Honorable John Barrasso
Chairman
Committee on Environment and Public Works
United States Senate
Washington, DC 20510

The Honorable Tom Carper
Ranking Member
Committee on Environment and Public Works
United States Senate
Washington, DC 20510

RE: Hearing on Electric Battery Production and Waste: Opportunities and Challenges

Dear Chairman Barrasso and Ranking Member Carper:

Thank you for focusing on this important issue and for considering this letter's inclusion in the record.

Please take a moment to think about the Appalachian Region...its grandeur...its many resources, and its unequivocal contribution to the industrial foundation of our great country. This region is indeed special, and was built by innovative, gritty pioneers who valued hard work. Passed down through generations, this invaluable work ethic still runs through the veins of more than 25 million people from New York to Alabama. Following in the footsteps of their ancestors, the men and women of Appalachia are pioneering an energy revolution as we create the first US-based raw material supply chain of technology metals.

A well-known pollutant, acid mine drainage (AMD) is a widespread problem across most of Appalachian coal country. InnoH2O Solutions, LLC (hereto, InnoH2O), a company based in Somerset County, PA, has developed in conjunction with our team a chemical-free AMD treatment system that transforms this polluting AMD waste stream into a perpetual natural resource. Technology metals such as Cobalt, Nickel, Lithium, Aluminum, Manganese, (collectively Critical Materials, or CMs) and Rare Earth Elements (REEs) are now able to be recovered in an environmentally benign process pioneered by our technology. As both the renewable energy sector and the United States Department of Defense (US DoD) scrambles to secure a conflict-free, consistent, and environmentally benign CM and REE material supply

chain, Appalachian Coal Country is poised to turn the green revolution on its head and become the world-leader in the clean recovery of technology metals.

The US DoD currently requires the supply of some 800 tons of REEs every year – with over 80% of that supply coming from the Peoples Republic of China. This poses a significant national security threat on the defense of the nation. In addition to that, the typical mining process of CM and REE operations destroy the environment every day, by releasing the harmful byproducts of CM and REE production into the environment of the countries and regions that currently satiate the world's supply of these metals. There is no better demonstration of this than the fact that the only remaining REE mine in the United States ships their ore to China for extraction because of the lax human and environmental regulations there. This is true for all regions that are currently supplying the vast majority of CMs and REEs to the market – the environment has been destroyed, it may never recover from the current mining methods and people are affected both socially and medically by the process of mining.

InnoH2O's CM and REE recovery process from AMD, by comparison, does two really incredible things: 1) it eliminates existing AMD pollution by cleaning the water during the extraction process; and 2) does not create any new pollution. Unlike other methods, we are still able to recover CMs and REEs from AMD without the extreme environmental implications of current processing methods. The data point that offers the most relevance, though, is that the entire US DoD demand for REEs (800 tons per year) could be satisfied by the concentrations of REEs found in Appalachian AMD discharges. In addition, even greater amounts of CMs (more than 800 tons per year) can be extracted from the AMD. This offers not only a significant enhancement to national security but strengthens the US position as a whole against the whims of potential supply-chain disruptions – and protects domestic manufacturers from foreign interference in their supply chains.

Imagine an Appalachia where Tesla Gigafactory's replace abandoned mine lands, where raw materials are mined, refined, and processed into market-ready batteries, fuel cells, solar panels, and wind turbines in an area of the country desperate for new technology jobs. Imagine an Appalachia where despair is replaced with hope, substance abuse replaced with engineering textbooks, and poverty replaced with prosperity. InnoH2O believes in Appalachia and we're committed to rebuilding it through innovation, collaboration, and grit.

InnoH2O stands at the ready to work with this committee, The Appalachian Regional Commission, The Department of Energy, The Department of Defense, and all private-sector companies in the development of a real, viable and environmentally neutral supply chain of CMs and REEs.

Sincerely,
The InnoH2O Team

Cc: The Honorable Shelley Moore Capito

Senator CAPITO. Thank you, thank you, Mr. Chairman——

Senator BARRASSO. In waiting.

[Laughter.]

Senator CAPITO. That is a good one.

So anyway, I have three questions around this in particular. I am interested in the recycling issue as well, but I am going to concentrate on the rare earth.

Can you speak to the importance of rare earth elements in building EVs, batteries, and drive trains? Are the costs of these rare earth elements disproportionate to the small volume that they're used in? Put another way, are they expensive inputs? How vulnerable do you think we are as Americans to have access to rare earth elements to be able to threaten this industry?

I will just start with you, Mr. Sanders.

Mr. SANDERS. They are very expensive. That is probably the easiest one of the questions. We are very vulnerable to the supply chains of these materials. As you said, most of the refining of these, and most of the mining of these is done in China.

Senator CAPITO. Right.

Mr. SANDERS. So that creates a significant challenge. Where they are really critical is in the motors and the drive train side of this. In the battery side, less so.

A significant opportunity that we have not talked about today for the U.S. would also be natural graphite, the anode side of the equation here. For those States that produce coal, that could be an option to basically get to a natural graphite solution. So there are opportunities for the U.S. to participate here in both the battery and the EV space.

Senator CAPITO. Mr. Greenberger.

Mr. GREENBERGER. Again, I believe the problem with the rare earths and our production of rare earths in the United States is that the market for rare earths in the United States is relatively small. So we have not been willing—businesses can't make investments in those types of projects and hope for a reasonable rate of return.

The Chinese, because they have done so much to promote their markets for vehicle electrification and for the other types of technologies that use rare earths materials, are really in the catbird seat when it comes to producing and supporting their own domestic industries. So there is no reason why we cannot produce rare earths in the United States, and we should. But the best, fastest, and most direct way to do that is to build up demand for products that actually will require rare earth materials and stand back and see what American businesses will do.

Senator CAPITO. Right. And that seems to be sort of a universal thing, certainly with you, but with the panel as well. The market needs to develop to catch up. But for this particular—my particular interest on the environmental side, I think, is the Department of Energy has been very helpful in terms of helping us to develop that technology.

Mr. Chawan.

Mr. CHAWAN. Yes, I think I would echo everything the panelists have said.

The other topic I would add is, as technology develops, the demand for rare earths is declining. So there is a new technology called asynchronous motors; it is a motor that in short, allows for better current flow into the battery for better torque control on your motor which provides better driving dynamics. It will also reduce the need for these materials.

Senator CAPITO. But are the materials—as far as my knowledge is here, the materials are used in a vast other array. It is just creating a bigger market, better market in this country. Because if China has cornered the market, there is obviously something there, yes.

Thank you.

Senator BARRASSO. Senator Markey.

Senator MARKEY. Thank you, Mr. Chairman. Thank you for this hearing.

Some members of the Committee have expressed concerns about the sources of raw materials used to make electric vehicle batteries. As has been pointed out today, mining practices associated with some of the raw materials in batteries, particularly cobalt, raise legitimate reason for concern. Exploiting child labor and using unregulated mining practices is unacceptable. We must work to avoid these sources.

Mr. Chawan, do all electric vehicle batteries require the use of cobalt?

Mr. CHAWAN. For most of the technologies that are popular today, yes.

Senator MARKEY. New alternatives, however, are being developed?

Mr. CHAWAN. Yes, sir, they are being developed. Tesla, for example, has already done a great job of reducing the amount of cobalt that it requires. I believe it is called an 8-1-1 configuration. I can follow up with your office with more details on that.

A lot of research has been put into reducing the need for cobalt in EV batteries today. It was simply found that that was an effective solution in the beginning of this decade, when we were trying to develop EV batteries for the market.

Senator MARKEY. So these new alternatives are very important, because we could focus, perhaps, on the ethical sourcing?

Mr. CHAWAN. Precisely. If we can take away the economic demand for these problematically sourced materials, we can definitely have a positive impact that way.

Senator MARKEY. So a coalition of major car manufacturers has committed to source cobalt ethically; Ford, LG Chem, IBM, Huayou Cobalt, have undertaken a blockchain project to address the problem in the Democratic Republic of the Congo. Potential applications like this are why I think we should try to promote the use of blockchain technology. I am the co-sponsor of a bill which has already passed out of the Commerce committee last week. We have to find solutions here, because they will encourage avoiding mining in vulnerable, marginalized communities, not only around the world, but even here in the United States.

So it is important for us to ensure that the notion that the only choice we have is to trade one child harmed in the world for a child harmed here, it is just not acceptable.

Yes, sir, Mr. Sanders.

Mr. SANDERS. In addition to block chain, standard traceability techniques that have been used in the food industry and other areas are being put in place in the Congo. Only about 20 percent of the mining in the Congo has the concern of child labor and those issues. The three major producers in the Congo have responsibly produced cobalt for quite some time.

Multiple OEMs have established relationships with their mining partners and their supply chain to basically put traceability in place. So blockchain is an option. But standard traceability of shipments and understanding where it is coming from and ensuring that it is coming through that value chain has also been put in place by both U.S. OEMs and some German OEMs that I am aware of.

Mr. MARKEY. And I want to highlight one other issue, which is, instead of expanding mining, we should be looking to other solutions, like recycling. The minerals used in these EV batteries are used in many electronic products, in military applications. I am glad to hear today from our witnesses that recycling can be a bipartisan solution, and would look forward to working together with all of us on a bipartisan basis in order to expand efforts in that direction.

When Congress was faced with the environmental impacts of disposing of lead acid batteries, we took action to create the necessary incentives to recycle. We should do the same for the recycling of electric vehicle batteries and all of the materials that would be central to advancing that goal.

Researchers in my home State of Massachusetts are advancing the state of lithium ion battery recycling. Companies like Battery Resources are finding ways to process and re-use these materials.

Can you give us your insight on that issue as well?

Mr. Chawan.

Mr. CHAWAN. Yes, on the recycling?

Senator MARKEY. Yes.

Mr. CHAWAN. I think what we are really focusing on is extending the life of the battery. Once it is built, we want to use that battery for as long as it is humanly possible. So what we are doing is focusing on, what can we do when the battery comes out of the vehicle, and finding homes for it in other applications, for demand response.

So if you can provide backup power for important facilities such as medical centers and data centers, you can use that battery for a longer period of time and delay the time that you need to spend time, energy, and money to break down the battery into its constituent components. We are hopeful, as more vehicles come into the market, more batteries come into the market, we will build up a larger bank of vehicles or batteries that you will hopefully start to get the economies of scale better needed to have a robust recycling program.

Senator MARKEY. Thank you.

Mr. Chairman, thank you.

Senator BARRASSO. Thank you very much.

Senator Braun.

Senator BRAUN. Thank you, Mr. Chair.

I am interested in the carbon footprint. Reading that, to produce an electric vehicle currently, give or take, it produces maybe twice the carbon impact versus an internal combustion engine vehicle. I want to know if that is true or not, or if that is roughly the dynamic. Then it begs the question of what the useful life is, and of course, the battery and so forth.

Has there been any study—and anyone can answer this—to where you look at what the CAFE standards would have to go to in terms of miles per gallon before it would make the whole argument of an electric vehicle more of a moot point? Normally, that would seem to be something, especially if I was making a regular vehicle, I would want to know, well, how good would we need to make the mileage before it would make the whole argument for electric vehicles maybe less relevant, and addressing the fact that to produce one, it has twice the carbon footprint, just to get it on the road.

Mr. GREENBERGER. I will try that. I have heard this statistic, about twice the amount of greenhouse emissions.

Senator BRAUN. Yes.

Mr. GREENBERGER. I have no idea where that comes from. That seems a little bit odd to me.

I think certainly recycling is one of the ways that we can reduce the carbon footprint that it takes to produce an electric vehicle. But I think that we are also—it is important to pay attention to another issue in terms of what is really driving the move to vehicle electrification. Part of it is greenhouse gas emissions. But part of it is also is that everything is just electrifying. When we start putting automatic locks and heated seats in cars, you are moving to things like autonomous drive, which are huge draws of electricity on the vehicle, our vehicles are going to become electric regardless of what fuel prices do. That is just the way that technology is going. We are going to be riding around in computers on wheels. And computers don't tend to run on gasoline very well.

So I think the vehicle electrification is coming for a number of different reasons. I don't know that just increases in fuel economy in the internal combustion engine are really going to, in the long term, significantly slow down that trend.

Senator BRAUN. Fair point.

Mr. Sanders, you had mentioned earlier roughly \$5,000, was that the cost to rehabilitate a worn battery, or what is the cost of a new battery in the average EV currently, and what does it cost to recycle one? Is its life as long as the original battery once it is recycled?

Mr. SANDERS. The \$5,000 was a typical battery that is in China now that is basically for an electric vehicle, so what would be here a mid-size type vehicle. There is such a range on each one of those pieces of data that it is hard to quote a given number. But the bottom line in China is, they have put together a collection organization, basically, that allows the folks doing collection and collecting the battery and readying for recycling to make money. Then it appears now that the companies that are doing the recycling, because of the metals value that they can recover out of the recycling process, once they get to commercial scale, which we are projecting at about 20,000 units, which is not terribly big, they should be able to make money themselves.

So there appears to be financially viable ways of doing this. But it is going to take basically that same type of commitment that China did to basically establish that directive, establish the collection process and drive it through the value chain. Whether it ends up being a hybrid of something like we did for lead acid, where there was support for the recycling through the value chain, or whether it is totally done in a different economic model here, I think is still to be determined.

Senator BRAUN. And is the projected cost of that recycled battery, once you got to economy of scale, going to be less than the original cost of a new one? Is there any data on that? Because I think that would be a strong case for not only building the infrastructure for recycling, but it would be a cost savings, as long as the life of the recycled battery is close to what the new one would be.

Mr. SANDERS. There certainly is that opportunity for profitability, basically, beyond where they are taking recycling today. Where they are taking recycling today is to the metals precursors only. But there is the conversion, then, to the cathode, there is the conversion into the battery itself that basically can be done at a profitable level through the value chain.

But there is also significant companies, an IP that has been established for conversion of those precursors into a battery material and into the batteries themselves. So I am not exactly sure how that is going to play out. That is still to be determined.

But there are large organizations that have been established, that are battery manufacturers, that have established themselves as the leaders in establishing that value chain and establishing the recycling. So they certainly think that there is the opportunity there to make money through this value chain, and to improve profitability and sustainability by doing it themselves.

Senator BRAUN. Thank you.

Senator BARRASSO. Senator Whitehouse.

Senator WHITEHOUSE. Thank you, Chairman, and thank you for this hearing.

The electric vehicle battery recycling problem falls into a larger context of electronics recycling generally. As you all know, the United Nations found that out of 45 million metric tons of e-waste generated globally, 20 percent gets properly recycled, and the rest just goes off into whatever kind of junk operation there is.

A lot of that junk operation is overseas. Do any of you have anything nice to say about the quality, capability, integrity, cleanliness, effectiveness of a lot of these off the books overseas electronic waste disposal operations?

Mr. GREENBERGER. If I may, yes. Let's make sure that doesn't happen.

Senator WHITEHOUSE. It is pretty poisonous.

Mr. GREENBERGER. It is bad stuff.

Senator WHITEHOUSE. And it is badly handled in most of these overseas operations.

Mr. GREENBERGER. And the good news is, if we can keep our waste here and turn it into products that we can use in domestic manufacturing, it is a double win.

Senator WHITEHOUSE. So let me tell you one quick story, which is that I have a bill just on the electronic waste that comes out of

these things, our consumer electronics, not refrigerators and washing machines. And there is a group called the Institute of Scrap Recycling Industries, which is the trade association for this group. My bill would do exactly what you have proposed, require it to stay here, so that Americans get the jobs in the recycling and disassembly, so that it does not contribute to the poisoning of wherever this is done on the cheap overseas.

ISRI has been opposing the legislation because ISRI members—guess what?—are invested in overseas operations. So they have a big conflict of interest on this. We are still working with them. But we have a real problem with the fact that some of the groups that are active in Congress on this subject actually are invested in some of these overseas operations.

So if we are going to do this, we are going to have to address that fact head on. I am with you, and I hope we can do this.

What is each of your best estimates on how many EVs will be on the road by 2040? By that, I mean cars, trucks, and buses.

Mr. Sanders.

Mr. SANDERS. Twenty-four is a long way out there, but we are projecting 3.7 million by 2030. If you stay on that same ballpark curve of where that is by 2030, that should put it somewhere in the range of 6 million.

Senator WHITEHOUSE. OK.

Mr. SANDERS. So at that point we would be at 6 million vehicles per year sold. So in addition, basically if you look at that—

Senator WHITEHOUSE. So you stack it up year over year.

Mr. SANDERS. Yes, if you stack that up basically from today, you would be sitting probably in the range of 50 million vehicles.

Mr. GREENBERGER. So I am going to defer to my two witnesses that are in the business of collecting this data.

Mr. CHAWAN. Senator Whitehouse, I have data through 2030 in front of me from our latest forecast. U.S. EV sales in 2030 are about 3 million. And the U.S. EV population in that same year, so total light duty vehicles on the road is about 14 million.

Senator WHITEHOUSE. U.S.?

Mr. CHAWAN. U.S.

Senator WHITEHOUSE. How about globally?

Mr. CHAWAN. Globally I don't have those figures. I can follow up with you.

Senator WHITEHOUSE. I will do a request for the record, a QFR, so you can follow up.

Mr. SANDERS. Globally, you have through 2030 in my testimony. There is one chart. And basically by 2030, we are projecting, I think it is around 11 million vehicles to be sold in 2030. So the cumulative, basically, if you looked at that from a 2040 basis, in addition to the 50 here, there would probably be close to 50 in Europe, and probably close to 100 million in Asia. So 200 million vehicles, roughly.

Senator WHITEHOUSE. And as people who look at this market, I think there was an expectation that when electric vehicles came into the market, they would be basically glorified golf carts and kind of cheesy, and people would laugh at them. In fact, they are coming in through Audi, Jaguar, Mercedes, Bentley has even started displaying its concept EV.

Mr. SANDERS. Porsche.

Senator WHITEHOUSE. Porsche has a huge car that is actually coming to market right now. They are coming in, not at the bottom of the market like glorified golf carts, they are coming in at the top of the market as vehicles that compete on performance with Lamborghinis and cost a quarter, or a third, or a tenth as much. What does it say to you about adoption, that these vehicles are coming in at the top of the market as market leading, aspirational purchases, rather than as glorified golf carts creeping into the bottom of the market?

Mr. SANDERS. I don't know whether you all have had the opportunity or the fun driving experience of driving an electric vehicle.

Senator WHITEHOUSE. We have two Bolts, which is probably the cheapest and least exciting of all these electric vehicles. And it is great, it is amazing, it is a wonderful vehicle.

Mr. SANDERS. Right. The torque is incredible. The amount of noise is just next to nothing. And the only cost of maintenance, basically, that is demonstrating that it is going up versus going down, is tires. That is because we are all going a little too fast in the electric vehicles. But they are a hoot.

And the breadth of vehicles that are starting to be offered now, you are right, there are certainly the premier vehicles and so forth. But if you look at some of the launches now by General Motors and by Volkswagen and some of the others, they are hitting the midstream, main focus of vehicles. We are projecting cost parity now for electric vehicles to happen by 2023 to 2025.

So when these things actually start costing equal to or less than internal combustion engine vehicles, that is when we really start hitting the curve for these things taking off.

Senator WHITEHOUSE. And I have overdone my time, so let me just ask unanimous consent to put into the record a report on electric vehicles being cleaner from cradle to grave.

Senator BARRASSO. Without objection.

[The referenced information follows:]

[Union of
Concerned Scientists]

EXECUTIVE SUMMARY

Cleaner Cars from Cradle to Grave

How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions

HIGHLIGHTS

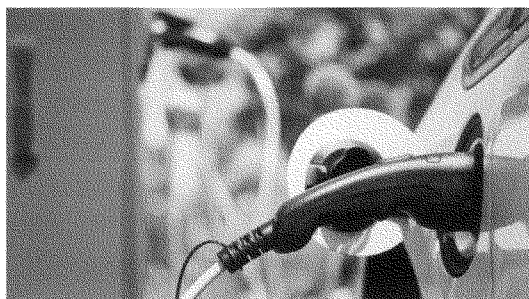
Electric vehicles (EVs) are a critical part of the American transportation future, given their potential to dramatically cut oil use and global warming emissions—especially when charged by low-carbon renewable electricity. New UCS analysis finds that, over its lifetime—from manufacturing to operation to disposal—a battery electric vehicle generates about 50 percent fewer global warming emissions than a comparable gasoline car. Based on the most recently available data on power plant emissions and EV sales, driving an EV produces global warming emissions similar to a gasoline vehicle that gets 68 miles per gallon, on average. To reach their full potential as a global warming solution, EVs must account for a larger share of vehicle sales, and the electricity grid must continue to shift from coal to more renewable resources.

Electric vehicles (EVs) are a critical part of the American transportation future, given their potential to dramatically cut global warming emissions—especially when charged by a clean electricity grid. Together with other oil-saving approaches, such as more efficient vehicles and advanced biofuels, EVs can help cut projected U.S. oil use in half over the next 20 years. EVs will also be essential to achieving the deep emissions reductions by mid-century needed to avoid the worst impacts of climate change.

This report compares battery-electric vehicles (BEVs) with similar gasoline vehicles by examining their global warming emissions over their “life cycles”—from the raw materials to make the car through manufacturing, driving, and disposal or recycling. Toward that end, we performed up-to-date assessments of the carbon footprints of BEVs, taking into account the latest information about electricity generation and BEV models. The two BEVs we modeled, midsize and full-size, are not specific to any particular manufacturer but are based on the two most popular BEV models sold in the United States today: the Nissan LEAF and the Tesla Model S. Our analysis reflects the BEVs available to American consumers and comparable gasoline vehicles.

Our analysis revealed that:

- **From cradle to grave, BEVs are cleaner.** On average, BEVs representative of those sold today produce less than half the global warming emissions of comparable gasoline-powered vehicles, even when the higher emissions associated with BEV manufacturing are taken into consideration. Based on modeling of the two most popular BEVs available today and the regions where they are currently being sold, excess manufacturing emissions are offset within 6 to 16 months of driving.



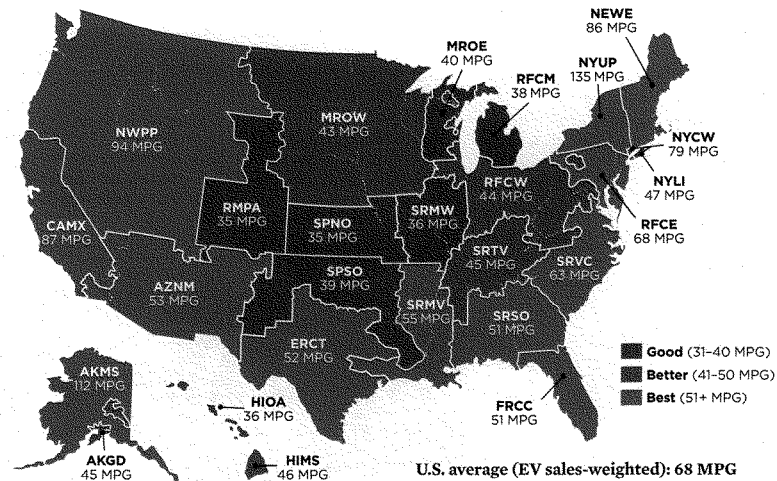
On average, battery-electric vehicles produce less than half the global warming emissions of comparable gasoline-powered vehicles; these emissions savings increase in regions of the country that get more of their electricity from renewable resources.

- ## Global Warming Emissions from Driving Electric Vehicles

Although a BEV has no tailpipe emissions, the total global warming emissions from operating it are not insignificant; they depend on the sources of the electricity that charge the vehicle's batteries and on the efficiency of the vehicle. We estimated the global warming emissions from electricity consumption in the 26 "grid regions" of the United States (see Figure ES-1)—representing the group of power plants that together serve as each region's primary source of electricity—and we rated each region based on how charging and using an EV there compares with driving a gasoline vehicle. We also estimated, based on recent sales data, the average efficiency of new EVs (battery-electric and plug-in electric vehicles combined) sold in the United States in 2015.

Note: The MPG (miles per gallon) valued for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions equivalent to driving an EV. Regional global warming emissions ratings are based on 2012 power plant data in the EPA's eGRID 2015 database (the most recent version). Comparisons include gasoline and electricity fuel production emissions. The 68 MPG U.S. average is a sales-weighted average based on where EVs were sold in 2014.

SOURCE: EPA 2015C; IHS 2015.



We found that: (1) driving the average electric vehicle in any region of the country produces lower global warming emissions than the average new gasoline car achieving 29 MPG; (2) our ratings in 20 out of 26 regions have improved since our 2012 report; and (3) more than 66 percent of Americans—up from 45 percent just three years ago—live in regions where powering an EV on the regional electricity grid produces lower global warming emissions than a 50 MPG gasoline car.

Comparisons between electric vehicles and gasoline cars look even more attractive when one considers that many EVs are currently being sold and driven in areas where the electricity grid is cleaner than the U.S. mean. As a result, based on calculations that weighted where EVs were sold in 2014, driving an EV in the United States produced global warming emissions equal to a gasoline vehicle with 68 MPG during operation.

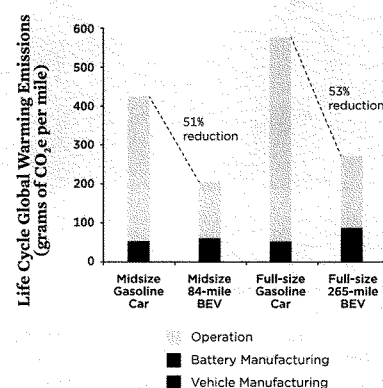
Emissions from operating electric vehicles are likely to keep falling, as national data from 2013 to 2015 show a declining percentage of electricity generated by coal power and an increase in renewable resources such as wind and solar. Additionally, the Clean Power Plan finalized by the U.S. Environmental Protection Agency (EPA) in 2015 offers opportunities for even greater progress, as states must collectively cut their 2005 power-sector carbon emissions 32 percent by 2030. Meanwhile, many EV owners are pairing electric vehicle purchases with home investments in solar energy. With increasing levels of renewable electricity coming onto the grid, with carbon standards for fossil-fuel power plants beginning to be implemented, and with continued improvements in vehicle technologies, the emissions-reduction benefits of EVs will continue to grow.

Global Warming Emissions from Manufacturing Battery-Electric Vehicles

Global warming emissions occur when manufacturing any vehicle, regardless of its power source, but BEV production results in higher emissions than the making of gasoline cars—mostly due to the materials and fabrication of the BEV lithium-ion battery. Under the average U.S. electricity grid mix, we found that producing a midsize, midrange (84 miles per charge) BEV typically adds a little over 1 ton of emissions to the total manufacturing emissions, resulting in 15 percent greater emissions than in manufacturing a similar gasoline vehicle. However, replacing gasoline use with electricity reduces overall emissions by 51 percent over the life of the car.

A full-size long-range (265 miles per charge) BEV, with its larger battery, adds about six tons of emissions, which increases manufacturing emissions by 68 percent over the gasoline version. But this electric vehicle results in 53 percent

FIGURE ES-2. Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles

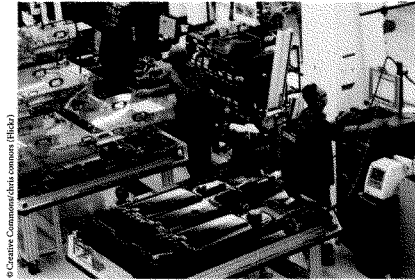


Notes: We assume that the midsize vehicles are driven 125,000 miles over their lifetimes and the full-size vehicles 175,000 miles. The difference in the two mileages derives from the dissimilar uses of 84-mile-range and 265-mile-range battery-electric cars, as described in Chapter 2. We further assume that a consumer buying a BEV would drive it the same total of miles as a corresponding gasoline vehicle. We use U.S. average electricity grid emissions to estimate manufacturing emissions, while the average electricity grid emissions intensity during vehicle operation are based on a sales-weighted average of where EVs are being sold today.

lower overall emissions compared with a similar gasoline vehicle (see Figure ES-2).

In other words, the extra emissions associated with electric vehicle production are rapidly negated by reduced emissions from driving. Comparing an average midsize midrange BEV with an average midsize gasoline-powered car, it takes just 4,900 miles of driving to “pay back”—i.e., offset—the extra global warming emissions from producing the BEV. Similarly, it takes 19,000 miles with the full-size long-range BEV compared with a similar gasoline car. Based on typical usages of these vehicles, this amounts to about six months’ driving for the midsize midrange BEV and 16 months for the full-size long-range BEV.

Meanwhile, the global warming emissions of manufacturing BEVs are falling as automakers gain experience and improve production efficiency. With a focus on clean manufacturing, emissions could fall even more. There are many ways in which the EV industry might reduce these manufacturing-related emissions, including:



Technicians test the performance of EV battery packs during vehicle manufacturing and assembly. Batteries increase EVs' manufacturing-related emissions compared with gasoline vehicles, but the excess manufacturing emissions can be offset in 6 to 16 months of average driving.

- Advances in manufacturing efficiency and in the recycling or reuse of lithium-ion batteries;
- The use of alternative battery chemistries that require less energy-intensive materials; and
- The use of renewable energy to power manufacturers' and suppliers' facilities.

Recommendations

To accelerate the U.S. transition to a low-carbon future, we recommend the following:

- Under the EPA's Clean Power Plan, states should develop and implement strong compliance plans that prioritize renewable energy and energy efficiency in meeting their emissions-reduction targets.
- Policy makers at all levels of government should adopt new or strengthened policies and programs for increasing energy

efficiency and the deployment of renewable energy. These options include renewable electricity standards, energy-efficiency resource standards, carbon-pricing mechanisms, tax incentives and other financial incentives, and improvements in grid operation, transmission, and resource planning.

- Government and the private sector should support more research aimed at decreasing the global warming emissions associated with making electric vehicles' batteries, increasing the efficiency of their operation, and improving the processes for battery recycling or reuse. By supporting this emerging sector, we can help encourage manufacturers not only to reduce manufacturing emissions but also to lower the batteries' costs.
- To increase the benefits of electric vehicles—especially those in regions where global warming emissions from electricity generation are higher than the U.S. average—policies should support consumers who consider investing in cleaner sources of electricity, such as by installing rooftop solar photovoltaic systems or purchasing renewable energy credits.
- Electric vehicle makers and their suppliers should raise the percentage of renewable electricity they use to build these cars. The Union of Concerned Scientists estimates that, with a future 80 percent renewable electricity grid, manufacturing emissions alone could decrease by more than 25 percent compared with manufacturing BEVs today.

Electric vehicles provide benefits both in carbon emissions and oil savings, with the greatest emissions benefits occurring in regions with the lowest-carbon electricity sources. To reach their full potential, EVs must account for a larger share of vehicle sales while the electricity grid shifts from coal to low-carbon renewable sources. Moving forward with both of these transitions constitutes a critical strategy for cutting projected oil use in half over the next 20 years and putting the United States on a trajectory toward net-zero climate emissions by mid-century.

Union of Concerned Scientists

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The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with citizens across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

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Senator BARRASSO. Senator Van Hollen.

Senator VAN HOLLEN. Thank you, Mr. Chairman.

Thank all of you for your testimony.

I want to thank the Chairman and the Ranking Member for having this hearing. I think it is a really important and timely hearing.

I was listening in by TV before I came here. Mr. Greenberger, I thought I heard you say he who makes the battery will ultimately make the car. Is that right?

Mr. GREENBERGER. That is correct.

Senator VAN HOLLEN. And we also know just by looking at where we are today in the United States compared to China, for example, we are way behind. We just have a couple recent headlines: China is building the batteries of the future; electric cars, China powers the battery supply. We had mentioned the fact that they have a lot of natural resources in China.

But they also are doing the recycling. They are doing a major recycling program. They have also been much more strategic about overseas supply operations.

So my question is this, because we are talking about the future market for electric cars, we are also talking about the fact that China has a huge head start. If you look at their investment in clean energy overall from 2005 to 2018, it has gone up like a rocket ship. We were essentially a little bit ahead of them in 2005, the United States, if you looked at both public and private investment in clean energy. They are now way ahead of us, and it has been a steady incline.

So what does that mean to all of you in terms of who is going to be making the cars around the world when it comes to the electric car industry? What would you do, if you were czar, if you were king for a day here in the United States, what are the three things that you would do, that we could do, to help change this?

Mr. Greenberger, you talked about how we need to juice the market, you need more demand, get more people to invest. But it is a little bit of a chicken and egg situation, right? So Senator Markey and I and others have bills that would create more of a financing authority, kind of a green bank, a climate bank, to help more U.S. investment go into clean energy.

But what are the three things each of you would do, here for the United States, to address the challenge that we see before us? If you could just give me the top three. I am looking for anything that also requires congressional action.

Mr. GREENBERGER. Sure, first of all, I think we should look at history to some extent. We have seen this movie before. Ten years ago, we wanted the United States to get into the electric vehicle business, and the ARA devoted \$2 billion to battery manufacturing in the United States and to promote electric vehicles.

Those investments were not particularly successful, because it was sort of build it and they will come type investment. It didn't really pan out. Most of those projects turned out not to be commercially successful, and many ended up being bought by Chinese companies.

China took a somewhat different approach. They decided to incent demand. There are 400,000 electric buses in China; there

are 2,000 electric buses, about, in the United States. There were huge incentives put into electric vehicles. There was a market created for vehicle electrification. If you take a look at a lot of the things we hear about China, that we don't like about China, about them promoting a technology transfer, it is all by companies trying to access this consumer market in China.

So the lesson to be learned from the last 10 years, from my perspective, is pay attention to market demand rather than technology push. That is really where the Chinese have gained their leverage. If you can create that market demand, however you are going to do it, whether that is by additional vehicle subsidies, whether that is by purchasing electric buses or heavy duty trucks for municipalities or government organizations, however you want to do it, if you can do that, you are going to be far better along than you will be of just trying to build a supply chain for a demand that doesn't yet exist on a real basis.

Senator VAN HOLLEN. Got it, thank you.

Mr. SANDERS. I guess the guidance that I would give us, don't invent the process. There are multiple examples today by China of establishing very clear direction and sticking with it. We have a tendency here of wandering in direction. And when you wander in direction, you get poor results. Jim mentioned the facilities that were built in 2008. Great intentions at the time.

But the market wasn't there. And then we didn't stay with the program. We then went off to some other different direction.

If you look at how China established clear guidance that we are going to electrify, now their problem for pollution was substantially worse than ours. So they had to do something. They had no choice.

But if you look at what is happening in Europe now, you are getting very clear direction. Norway set deadlines, England set deadlines, Germany has set deadlines for when they are going to convert from internal combustion engines to electrified vehicles.

And now the overall business infrastructure is getting behind that. And it gives them a clear path to basically then execute to do what business does well, see the opportunity and say, OK, the game is going to change, how am I going to participate in that game and win. We have the opportunity to win here. It is just a matter of, it has to be a clear direction in where we are going.

Senator VAN HOLLEN. Got it. Thank you.

Mr. CHAWAN. What I will add to this is, continuing to support legislation that promotes electric vehicles, so the Drive American Forward Act that Senators Stabenow and Alexander have co-sponsored, which includes increasing the Federal tax credit for electric vehicles from \$200,000 to \$600,000 per manufacturer. That allows consumers to help make up that difference in true cost between an EV and a conventional vehicle, and other tax credits to that effect.

That is what you need when you have a nascent market. As I said earlier in my testimony, we are still in the age of \$6,000 flat panels, we are at that early stage of the technology curve.

The second thing I would do from a congressional level is to continue to support advanced research. So the advanced battery research technology that is being done is done by many of our national labs, including Oak Ridge and NREL. That work will help to create these new battery technologies that will have different

chemistries than they have today, and that will enable us to bring down the overall price of the vehicle. And the battery is the largest component of that price today.

Senator VAN HOLLEN. I appreciate that.

Mr. Chairman, I think all three have indicated you need national incentives and push and guidance, if I was able to get unanimous agreement on that.

I do worry, we have to make sure that the politics doesn't get in our way up here. Because right now we are, in my view, losing this importance race. We got behind on 5G, and we are getting behind really fast. We are already behind; we have to catch up on this.

Thank you.

Senator BARRASSO. Senator Carper.

Senator CARPER. Again, thank you all for your testimony. It has been enormously encouraging and important.

Senator Inhofe mentioned earlier in his questioning that electric vehicles—I have two unanimous consent requests. But I think Jim in his question mentioned that vehicles are the primary reason, electric vehicles are the primary reason we face a shortfall in our Highway Trust Fund.

While I believe we must find—I know the Chairman agrees—we must find a way for electric vehicles to pay their fair share for using the roads, I would ask unanimous consent to insert into the record a Business Journal article on the purchasing power of the Highway Trust Fund. It states basically the 18 cent gas tax provides about 90 percent of the funds we need that we are using in the Trust Fund.

That tax was set in 1993. If it had been modified for inflation over the last X number of years, it would be not 18 cents, but 32 cents.

Senator BARRASSO. Without objection.

[The referenced information follows:]

7/18/2019

Electric cars challenge funding for road repairs - The Business Journals

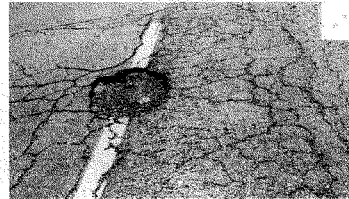
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GOVERNMENT & REGULATIONS

How electric cars could make America's crumbling roads even worse



The federal government rates more than one-quarter of all urban interstates as being in fair or poor condition and one-third of U.S. bridges needing repair.

PAUL COWAN

By Jay L. Zagorsky - Contributing Writer
Feb 25, 2019, 12:11pm EST

U.S. roads and bridges are in abysmal shape - and that was before the recent winter storms made things even worse.

In fact, the government rates over one-quarter of all urban interstates as in fair or poor condition and one-third of U.S. bridges need repair.

To fix the potholes and crumbling roads, federal, state and local governments rely on fuel taxes, which raise more than US\$80 billion a year and pay for around three-quarters of what the U.S. spends on building new roads and maintaining them.

I recently purchased an electric car, the Tesla Model 3. While swerving down a particularly rutted highway in New York the economist in me began to wonder what will happen to

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<https://www.bizjournals.com/bizjournals/news/2019/02/25/how-electric-cars-could-make-america-s-crumbling.html>

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FILE — Tesla Model 3 cars are stored at the Tesla Service Center in Scottsdale, Ariz., Sept. 13, 2018. (Caitlin O'Hara/The New York Times)
CAITLIN O'HARA

Fuel taxes 101

Every time you go to the pump, each gallon of fuel you purchase puts money into a variety of pockets.

About half goes to the drillers that extract oil from the earth. Just under a quarter pays the refineries to turn crude into gasoline. And around 6 percent goes to distributors.

The rest, or typically about 20 percent of every gallon of gas, goes to various governments to maintain and enhance the U.S. transportation's infrastructure.

Currently, the federal government charges 18.4 cents per gallon of gasoline, which provides 85 percent to 90 percent of the Highway Trust Fund that finances most federal spending on highways and mass transit.

State and local government charge their own taxes that vary widely. Combined with the national levy, fuel taxes range from over 70 cents per gallon in high-tax states like California and Pennsylvania to just over 30 cents in states like Alaska and Arizona. The difference is a key reason the price of gasoline changes so dramatically when you cross state lines.

While people often complain when their fuel prices go up, the real burden of gasoline taxes has been falling for decades. The federal government's 18.4 cent tax, for example, was set way back in 1993. The tax would have to be 70 percent higher, or 31 cents, to have the same

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On top of that, today's vehicles get better mileage, which means fewer gallons of gas and less money collected in taxes.

And electric vehicles, of course, don't need gasoline, so their drivers don't pay a dime in fuel taxes.

A crisis in the making

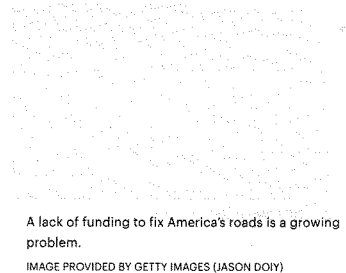
At the moment, this doesn't present a crisis because electric vehicles represent only a small proportion of the U.S. fleet.

Slightly more than 1 million plug-in vehicles have been sold since 2012 when the first mass market models hit the roads. While impressive, that figure is just a fraction of the over 250 million vehicles currently registered and legally drivable on U.S. highways.

But sales of electric cars are growing rapidly. Dealers sold a record 360,000 electric vehicles last year, up 80 percent from 2017.

If sales continue at this breakneck pace, electric cars will become mainstream in no time. In addition, governments in Europe and China are actively steering consumers away from fossil fuels and toward their electric counterparts.

In other words, the time will come very soon when the U.S. and individual states will no longer be able to rely on fuel taxes to mend American roads.



A lack of funding to fix America's roads is a growing problem.

IMAGE PROVIDED BY GETTY IMAGES (JASON DOY)

What states are doing about it

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One involves charging owners of electric cars a fixed fee. So far, 17 states have done just that, with annual taxes ranging from \$100 to \$200 per car.

There are a few problems with a fixed fee approach. For example, the proceeds only go to state coffers, even though the driver also uses out-of-state roads and national highways.

Another is that it's regressive. Since a fixed fee hits all owners equally, regardless of income or how much they drive, it hurts poorer consumers most. During debate in Maine over a proposed \$250 annual EV fee, opponents noted that the average person currently pays just a third of that - \$82 - in state fuel taxes.

Oregon is testing another solution. Instead of paying fuel taxes, drivers are able to volunteer for a program that lets them pay based on miles driven rather than how many gallons they consume. The state installs tracking devices in their cars - whether electric or conventional - and drivers get a refund for the gas tax they pay at the pump.

The program raises privacy and fairness concerns especially for rural residents who have few other transportation options.



Tesla Superchargers are quickly proliferating.
IMAGE PROVIDED BY GETTY IMAGES (SJOERD VAN DER WAL)

Another way forward

I believe there's another solution.

Currently, carmakers and others are deploying large networks of charging stations throughout the country. Examples include Tesla's Superchargers, Chargepoint, EVgo and Volkswagen's proposed mobile chargers.

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They operate just like gas pumps, only they provide kilowatts of electricity instead of gallons of fuel. While electric vehicle owners are free to use their own power outlets, anyone traveling long distances has to use these stations. And because charging at home is a hassle - requiring eight to 20 hours - I believe most drivers will increasingly choose the convenience and speed of the charging stations, which can fill up an EV in as little as 30 minutes.

So one option could be for governments to tack on their taxes to the bill, charging a few extra cents per kilowatt "pumped into the tank." Furthermore, I would argue that the tax - whether on fuel or power - shouldn't be a fixed amount but a percentage, which makes it less likely to be eroded by inflation over time.

It is in everyone's interest to ensure there are funds to maintain the nation's roads. A small percentage tax on EV charging stations will help maintain U.S. roads without hurting electric vehicles' chances of becoming a mass market product.

Jay L. Zagorsky is a senior lecturer at Boston University. This article originally appeared in The Conversation.

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Senator CARPER. Finally, I would just ask unanimous consent to submit for the record, Mr. Chairman, other materials relevant to today's discussion.

Thank you.

Senator BARRASSO. Without objection.
[The referenced information follows:]



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SUMMARY

R45350

June 7, 2019

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Funding and Financing Highways and Public Transportation

For many years, federal surface transportation programs were funded almost entirely from taxes on motor fuels deposited in the Highway Trust Fund. The tax rates, which are fixed in terms of cents per gallon, have not been increased at the federal level since 1993. Meanwhile, motor fuel consumption is projected to decline due to improved fuel efficiency, increased use of electric vehicles, and slow growth in vehicle miles traveled. In consequence, revenue flowing into the Highway Trust Fund has been insufficient to support the surface transportation program authorized by Congress since 2008.

Congress has yet to address the surface transportation program's fundamental revenue issues, and has given limited consideration to raising fuel taxes in recent years. Instead, since 2008 Congress has supported the federal surface transportation program by supplementing fuel tax revenues with transfers from the U.S. Treasury general fund. The most recent reauthorization act, the Fixing America's Surface Transportation Act (FAST Act; P.L. 114-94), authorized spending on federal highway and public transportation programs through September 30, 2020. The act provided \$70 billion in general fund transfers to the Highway Trust Fund from FY2016 through FY2020. This use of general fund transfers to supplement the Highway Trust Fund will have been the de facto funding policy for 12 years when the FAST Act expires. Congressional Budget Office (CBO) projections indicate that the Highway Trust Fund insufficiency relative to spending will reemerge following expiration of the FAST Act. The projections indicate a shortfall of \$74.5 billion over the first five years following the FAST Act, and \$97 billion over the first six years.

As the September 2020 expiration of the FAST Act approaches, Congress may again examine adjustments to the funding and financing of the federal role in surface transportation.

- Raising motor fuel taxes could provide the Highway Trust Fund with sufficient revenue to fully fund the program in the near term, but may not be a viable long-term solution due to expected declines in fuel consumption. It would also not address the equity issue arising from the increasing number of personal and commercial vehicles that are powered electrically and therefore do not pay motor fuel taxes.
- Replacing motor fuel taxes with a mileage-based road user charge would need to overcome a variety of financial, administrative, and privacy barriers, but could be a solution in the longer term.
- Treasury general fund transfers could continue to be used to make up for the Highway Trust Fund's projected shortfalls but could require budget offsets of an equal amount.

The political difficulty of adequately funding the Highway Trust Fund could lead Congress to consider altering the trust fund system or eliminating it altogether. This might involve a reallocation of responsibilities and obligations among federal, state, and local governments.

Some surface transportation needs can be met by private investment, including public-private partnerships, and federal loans from the Transportation Infrastructure Finance and Innovation Act (TIFIA) program. If it desires to promote private investment in transportation infrastructure, Congress could consider asset recycling incentive grants to state and local governments for the sale or lease of government-owned infrastructure if the proceeds are committed to new infrastructure.

Tolling may be an effective way to finance specific roads, bridges, or tunnels that are likely to have heavy use and are located such that the tolls are difficult to evade. All revenue from tolls flows to the state or local agencies or private entities that operate tolled facilities; the federal government does not collect any revenue from tolls. However, a major expansion of tolling might reduce the need for federal expenditures on roads. Tolling and private investment are unlikely to provide broad financial support for surface transportation needs, and many projects are not well suited to alternative financing.

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Introduction

Almost every conversation about surface transportation finance begins with a two-part question: What are the “needs” of the national transportation system, and how does the nation pay for them? This report is aimed almost entirely at discussing the “how to pay for them” question. Since 1956, federal surface transportation programs have been funded largely by taxes on motor fuels that flow into the Highway Trust Fund (HTF). A steady increase in the revenues flowing into the HTF due to increased motor vehicle use and occasional increases in fuel tax rates accommodated growth in surface transportation spending over several decades. In 2001, though, trust fund revenues stopped growing faster than spending. In 2008 Congress began providing Treasury general fund transfers to keep the HTF solvent.¹

Every year since 2008, there has been a gap between the dedicated tax revenues flowing into the HTF and the cost of the surface transportation spending Congress has authorized. Congress has filled these shortfalls by transfers, largely from the general fund, that have shifted a total of \$143.6 billion to the HTF (roughly 22% of outlays).² The last \$70 billion of these transfers were authorized in the Fixing America’s Surface Transportation Act (FAST Act; P.L. 114-94), which was signed by President Barack Obama on December 4, 2015.³ The FAST Act funds federal surface transportation programs from FY2016 through FY2020. When the act expires the de facto policy of relying on general fund transfers to sustain the HTF will be 12 years old.

Congressional Budget Office (CBO) projections indicate that the imbalance between motor fuel tax receipts and HTF expenditures will persist beyond FY2020. In consequence, funding and financing surface transportation is expected to continue to be a major issue for Congress.

The Highway Trust Fund Revenue Dilemma

The HTF has two separate accounts—highways and mass transit. The primary revenue sources for these accounts are an 18.3-cent-per-gallon federal tax on gasoline and a 24.3-cent-per-gallon federal tax on diesel fuel. Although the HTF has other sources of revenue, such as truck registration fees and a truck tire tax, and is also credited with interest paid on the fund balances held by the Treasury, fuel taxes in most years provide 85% to 90% of the amounts paid into the fund by highway users. The transit account receives 2.86 cents per gallon of fuel taxes, with the remainder of the tax revenue flowing into the highway account. An additional 0.1-cent-per-gallon fuel tax is reserved for the Leaking Underground Storage Tank (LUST) Fund, which is not part of the transportation program.

Since the trust fund was created in 1956, Congress has increased federal motor fuel taxes four times: in 1959, 1982, 1990, and 1993. Since the 1993 increase, additional changes to the taxation structure have modestly boosted trust fund revenues. However, since 2001, revenue flowing into the HTF has not met expectations in most years.⁴ The American Jobs Creation Act of 2004 (P.L.

¹ Based on Federal Highway Administration (FHWA) data. Balances in the HTF accrued in previous years were large enough to keep the fund sufficient until FY2008.

² Based on actual and projected outlays FY2009 through late FY2021, when the HTF is projected to approach a zero balance.

³ CRS Report R44388, *Surface Transportation Funding and Programs Under the Fixing America’s Surface Transportation Act (FAST Act; P.L. 114-94)*, coordinated by Robert S. Kirk.

⁴ See Congressional Budget Office (CBO), *How Would Proposed Fuel Economy Standards Affect the Highway Trust Fund?* May 2012, p. 3. A drop in outlays in FY2006 helped bring the HTF briefly into balance in FY2006 and FY2007.

108-357), for example, provided the trust fund with increased future income by changing elements of federal “gasohol” taxation. In 2005, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (P.L. 109-59; SAFETEA) sought to bolster the trust fund by addressing tax fraud. SAFETEA also provided for the transfer of some general fund revenue associated with transportation-related activities to the trust fund. It was believed at the time of SAFETEA’s passage that the tax changes, a \$12.5 billion unexpended balance in the trust fund, and higher fuel tax revenue due to expected economic growth would be sufficient to finance the surface transportation program through FY2009.⁵ This prediction proved to be incorrect. Trust fund revenue has generally lagged inflation since FY2007. The shortfalls resulting from the overly optimistic forecasts associated with SAFETEA were rectified by Treasury general fund contributions. In September 2008, Congress enacted a bill that transferred \$8 billion from the general fund to shore up the HTF. Other transfers followed (see **Table 1**).

When the HTF was conceived, annual vehicle miles traveled (VMT), and therefore motor fuel tax revenue, were rising rapidly. That is no longer the case. The Federal Highway Administration (FHWA) projects that VMT will grow at an average of roughly 1.2% per year over the next 20 years.⁶ Meanwhile, other policy changes are weakening the link between driving activity and motor fuel tax revenues. Under rules issued in 2012, new passenger cars and light trucks are expected to attain an average fuel economy of 41.0 miles per gallon in model year 2021 and 49.7 miles per gallon in model year 2025.⁷ Improved fuel economy is slowly reducing the average amount of fuel used per mile of travel. The expanding fleets of hybrid and electric vehicles, respectively, pay less or nothing by way of fuel taxes, raising equity issues that are likely to become more prominent as the electric/hybrid vehicle fleet expands.⁸ On April 2, 2018, the Trump Administration announced its intent to revise the Corporate Average Fuel Economy (CAFE) standards for the model years 2022-2025.⁹ This change could slow the increase in the average fuel economy of the motor vehicle fleet.

An increase in the existing fuel tax rates would provide immediate relief to the trust fund. As a rule of thumb, adding a penny to federal motor fuel taxes provides the trust fund with roughly \$1.7 billion to \$1.8 billion per year.¹⁰ The prospect of reduced motor fuel consumption, however, casts doubt on the ability of the motor fuel taxes to support increased surface transportation spending beyond the next decade, even with significant increases in tax rates.

⁵ Jeff Davis, “Ten Years of Highway Trust Fund Bankruptcy: Why Did It Happen, and What Have We Learned?,” *Eno Transportation Weekly*, August 27, 2018, pp. 8-12.

⁶ Federal Highway Administration, *FHWA Forecasts of Vehicle Miles Traveled (VMT): Spring 2018*, Washington, DC, May 2018, https://www.fhwa.dot.gov/policyinformation/tables/vmt/vmt_forecast_sum.pdf.

⁷ CRS Report R45204, *Vehicle Fuel Economy and Greenhouse Gas Standards: Frequently Asked Questions*, by Richard K. Lattanzio, Linda Tsang, and Bill Canis.

⁸ Congressional Budget Office, *How Would Proposed Fuel Economy Standards Affect the Highway Trust Fund?*, May 2012, http://cbo.gov/sites/default/files/cbofiles/attachments/05-02-CAFE_brief.pdf. Because of the gradual turnover in the car and truck fleet and because the new standards were not to take effect until model year 2017, CBO estimated at the time that the standards would reduce “gasoline tax revenues between 2012 and 2022 by less than 1 percent.”

⁹ CRS In Focus IF10871, *Vehicle Fuel Economy and Greenhouse Gas Standards*, by Richard K. Lattanzio, Linda Tsang, and Bill Canis.

¹⁰ Congressional Budget Office, *Budget and Economic Outlook: 2019 to 2029*, Washington, DC, January 29, 2019, <https://www.cbo.gov/publication/54918>. See revenue projections.

Table 1. Transfers to the Highway Trust Fund
(in billions of dollars; reflects sequestration for FY2013 and FY2014)

Public Law	Effective Date	Highway Account	Mass Transit Account	Highway Trust Fund Total
P.L. 110-318	Sept. 15, 2008	8.017	0	8.017
P.L. 111-46	Aug. 7, 2009	7.000	0	7.000
P.L. 111-147	Mar. 18, 2010	14.700	4.800	19.500
P.L. 112-141	July 6, 2012			
From LUST	For FY2012	2.400	0	2.400
From general fund	For FY2013	5.884	0	5.884
From general fund	For FY2014	9.651	2.042	11.693
P.L. 113-159	Aug. 8, 2014	7.765	2.000	9.765
From LUST	Aug. 8, 2014	1.000	0	1.000
P.L. 114-41	July 31, 2015	6.068	2.000	8.068
P.L. 114-94				
From general fund	Dec. 4, 2015	51.900	18.100	70.000
From LUST	Dec. 4, 2015	0.100	0	0.100
From LUST	Oct. 1, 2016	0.100	0	0.100
From LUST	Oct. 1, 2017	0.100	0	0.100
General fund total		110.985	28.942	139.927
LUST fund total		3.700	0	3.700
Total transfers		114.685	28.942	143.627

Sources: Public laws as indicated. Sequestration amounts from FHWA.

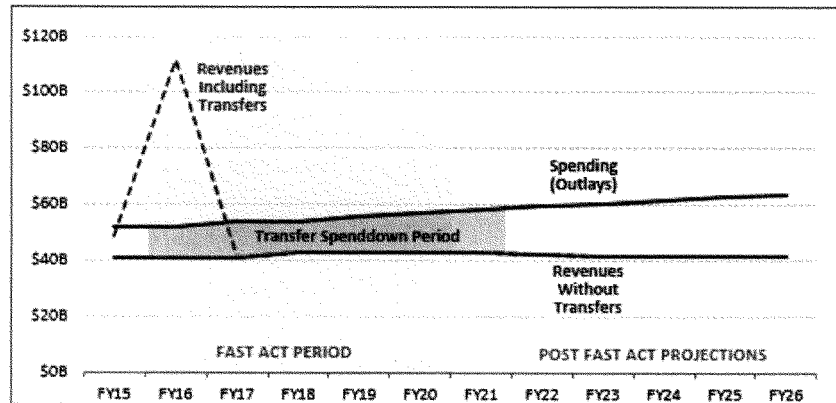
Notes: Transfers are from the Treasury's general fund unless indicated. LUST refers to the Leaking Underground Storage Tank Trust Fund administered by the Environmental Protection Agency.

What Congress Faces

CBO projects that from FY2021 to FY2026 the gap between dedicated surface transportation revenues and spending will average roughly \$19 billion annually (**Table 2**).¹¹ In 2020, as Congress considers surface transportation reauthorization, it could again face a choice between finding new sources of income for the surface transportation program and settling for a smaller program, which might look very different from the one currently in place. **Figure 1** shows the impact of the general fund transfers within the context of the underlying imbalance between HTF revenues and projected spending for FY2018-FY2026.

¹¹ Congressional Budget Office, *Projections of Highway Trust Fund Accounts Under CBO's May 2019 Baseline*, May 2019, https://www.cbo.gov/system/files/2019-05/51300-2019-05-highwaytrustfund_1.pdf. The \$19 billion figure represents the average annual gap between projected receipts from the motor fuel and other excise taxes that flow into the Highway Trust Fund and the anticipated cost of maintaining the surface transportation program at its current "baseline" level. Because of beginning of year (BOY) HTF balances for FY2021, a five-year surface transportation bill (FY2021-FY2025) could be funded with roughly \$74.5 billion in transfers or increased revenues.

Figure 1. Highway Trust Fund Funding Gap



Source: CRS, based on CBO, *Highway Trust Fund Projections: May 2019 HTF Baseline 2018-2029*. FY2016-FY2018 revenues and outlays are actual.

Notes: Includes highway account and mass transit accounts combined. Revenues include interest on HTF balances. The shading between spending and revenues indicates the period that the HTF balance is maintained by the FAST Act transfers from the general fund and the LUST fund.

The Underlying Problem: HTF Spending Exceeds Revenues

Table 2 provides projections of the gap between HTF receipts and outlays following the expiration of the FAST Act at the end of FY2020. In recent decades, Congress has typically sought to reauthorize surface transportation programs for periods of five or six years. As the table indicates, a five-year reauthorization beginning in FY2021 faces a projected gap between revenues and outlays of almost \$93 billion. A six-year reauthorization would face a gap of \$115 billion.¹² These projections assume that spending on federal highway and public transportation programs would remain as it is today, adjusted for anticipated inflation.

¹² Since the early 1990s Congress has begun the reauthorization debates with a goal of a six-year bill. The most recent bill, the FAST Act, however, provided five years of funding.

Table 2. Projected HTF Revenue and Spending (Outlays) Imbalance
(in billions of dollars)

Fiscal Year	HTF Revenue	HTF Outlays	Difference
2021	42.6	58.4	-15.8
2022	42.1	59.4	-17.3
2023	41.9	60.5	-18.7
2024	41.7	61.5	-19.8
2025	41.6	62.8	-21.2
2026	41.4	63.9	-22.5
5-YR: FY2021-2025 total	209.9	302.6	-92.8
5-YR: FY2021-2025 average	42.0	60.5	-18.6
6-YR: FY2021-2026 total	251.2	366.5	-115.3
6-YR: FY2021-2026 average	41.9	61.1	-19.2

Source: CRS calculations based on CBO, *Highway Trust Fund Projections: May 2019 HTF Baseline 2018-2029*.

Notes: Includes combined figures from both the highway account and the mass transit account. The "HTF Revenue" column includes interest on the HTF balances. Numbers may not add due to rounding.

The Resulting Funding Shortfalls

When the FAST Act expires at the end of FY2020, the balance in the HTF is expected to be \$18.4 billion—an amount equal to almost four months of outlays. CBO projects that this balance, plus incoming revenue, will allow the Federal Highway Administration (FHWA) and the Federal Transit Administration (FTA) to pay their obligations to states and transit agencies until late summer in FY2021. However, without a reduction in the size of the surface transportation programs, an increase in revenues, or further general fund transfers, the balance in the HTF is projected to be close to zero near the end of FY2021 (see **Table 3**). At that point, both FHWA and FTA would likely have to delay payments for completed work.¹³

Table 3. Projected Negative Cash Flow and HTF Cumulative Shortfalls
(in billions of dollars)

	2021	2022	2023	2024	2025	2026
Start-of-year HTF balance ^a	18.4	+2.6	-14.8	-33.4	-53.2	-74.5
Revenues minus outlays	-15.8	-17.3	-18.7	-19.8	-21.2	-22.5
End-of-year HTF shortfall	+2.6	-14.8	-33.4	-53.2	-74.5	-97.0

Source: CBO, *Highway Trust Fund Projections: May 2019 HTF Baseline 2018-2029*.

Notes: Includes combined figures from both the highway account and the mass transit account. Numbers may not add due to rounding of the underlying data.

a. Under current law, the HTF cannot incur negative balances.

¹³ Federal Highway Administration, *Action: Procedures for Reimbursements During a Cash Shortfall*, July 1, 2014, <https://www.transportation.gov/sites/dot.gov/files/docs/Guidance-Memo-Cash-Allocation-Final-3.pdf>.

Based strictly on projected income and expenses, the HTF would move from a positive balance of \$18.4 billion at the start of FY2021 to a negative balance of \$74.5 billion at the end of FY2025. However, current law does not allow the HTF to incur negative balances. Unless this is changed, \$74.5 billion represents the minimum amount the House Ways and Means Committee and the Senate Committee on Finance would need to find over the FY2021-FY2025 period in some combination of additional revenue for general fund transfers, should Congress choose to continue funding surface transportation at the current, or “baseline,” level, adjusted for inflation.¹⁴ Because the HTF currently provides all but about \$2 billion of annual spending authorized for the highway and transit programs (the main exception being the FTA Capital Investment Grants Program), these numbers have implications for the size of the program Congress may approve to follow the FAST Act.

Highway and transit spending based solely on the revenue projected to flow into the HTF under current law would be limited to roughly \$42.6 billion in FY2021, significantly less than the “baseline” FY2021 outlays of roughly \$58.4 billion. The projected stagnation and eventual FY2026 decline in HTF revenue implies that once expected inflation is factored in, FHWA and FTA would have less contract authority in each year to spend on projects through FY2026.¹⁵

Reducing expenditures would not provide immediate relief from the demands on the HTF. Because transportation projects can take years to complete, both the highway and public transportation programs must make payments in future years pursuant to commitments that have already been incurred. As of FY2019, obligated but unspent contract authority for highway projects in progress is projected to be roughly \$63 billion. This does not count another \$23 billion in available but unobligated contract authority. For public transportation programs the equivalent figures for FY2019 are projected to be almost \$18 billion in unpaid obligations and another \$11 billion in unobligated contract authority.¹⁶ The obligated amounts represent legal obligations of the U.S. government and must be paid out of future years’ HTF receipts.

On February 9, 2018, President Trump signed the Bipartisan Budget Act of 2018 (P.L. 115-123), which raised the ceilings on non-defense discretionary spending for FY2018 and FY2019 by \$63.3 billion and \$67.5 billion, respectively. House and Senate leaders agreed to work with the appropriators to ensure that at least \$10 billion per year of these additional outlays would be provided for infrastructure, including surface transportation.¹⁷ The Consolidated Appropriations Act, 2018 (P.L. 115-141), provided additional infrastructure funding from the general fund in accordance with the Bipartisan Budget Act, including \$2.834 billion for programs normally funded from the HTF. The Consolidated Appropriations Act, 2019 (P.L. 116-6), provided an additional \$3.950 billion. These funds were not credited to the HTF, however, and have no impact on HTF solvency.

¹⁴ FHWA estimates that it must also maintain a working balance of \$5 billion. Maintaining this working balance increases the funding shortfall five-year total to \$79.5 billion.

¹⁵ Contract authority is a type of budget authority that is available for obligation even without an appropriation. However, appropriators must eventually provide liquidating appropriation authority, which is not recorded as budget authority, to permit the eventual outlays. Contract authority is the type of budget authority used by the HTF.

¹⁶ Office of Management and Budget, *Budget of the U.S. Government FY2020: Appendix* (Washington, DC: 2019), pp. 876, 901, <https://www.whitehouse.gov/wp-content/uploads/2019/03/dot-fy2020.pdf>.

¹⁷ “Bipartisan Budget Agreement: a Memorandum from the House and Senate Leaders,” February 8, 2018.

Existing Highway Fuel Taxes¹⁸

The first federal tax on gasoline (1 cent per gallon) was imposed in 1932, during the Hoover Administration, as a deficit-reduction measure following the depression-induced fall in general revenues. The rate was raised to help pay for World War II (to 1.5 cents per gallon) and raised again during the Korean War (to 2 cents per gallon). The Highway Revenue Act of 1956 (P.L. 84-627) established the HTF and raised the rate to 3 cents per gallon to pay for the construction of the Interstate Highway System. The Federal-Aid Highway Act of 1959 (P.L. 86-342) raised the rate to 4 cents per gallon. The gasoline tax remained at 4 cents from October 1, 1959, until March 31, 1983. During this period, revenues grew automatically from year to year as fuel consumption grew along with increases in vehicle miles traveled.

Since 1983 lawmakers have passed legislation raising the tax rates on highway fuel use three times. Although infrequent, these rate increases were quite large in a proportional sense. The gasoline tax was raised on April 1, 1983, from 4 to 9 cents per gallon, a 125% increase; on September 1, 1990, from 9 to 14 cents (not counting the additional 0.1 cent for LUST), or 55%; and on October 1, 1993, from 14 to 18.3 cents, or 31%.¹⁹

How the Rates Have Been Raised Since 1983

Increasing the rate of the fuel taxes has never been popular. The last three increases were accomplished with difficulty and were influenced by the broader budgetary environment and the politics of the time.²⁰

The “Great Compromise” and the Highway “User Fee”

The increase in the fuel tax rate under the Surface Transportation Assistance Act of 1982 (STAA; P.L. 97-424, Title V) occurred in the lame-duck session of the 97th Congress. In the “Great Compromise,” supporters of increased highway spending had come to an agreement with transit supporters (mostly from the Northeast) that a penny of a proposed 5-cents-per-gallon increase would be dedicated to a new mass transit account within the HTF. This meant that support for the bill during the lame-duck session was widespread and bipartisan. President Reagan’s opposition to an increase in the “gas tax” softened during the lame-duck session. On November 23, 1982, he announced that he would support passage of STAA because “Our country’s outstanding highway system was built on the user fee principle—that those who benefit from a use should share in its cost.”²¹ Nonetheless, the bill faced a series of filibusters in the Senate, which were eventually overcome by four cloture votes. The conference report was again filibustered, and President

¹⁸ This discussion tracks the changes in the rate of the gasoline tax. Over time other fuels such as diesel have been taxed at different rates. For instance, the current tax on diesel fuel is 6 cents per gallon higher than the gasoline tax. For a tabular history of the rates of the various federal fuel taxes, see Federal Highway Administration, *Highway Statistics: Table FE101-A*, <https://www.fhwa.dot.gov/policyinformation/statistics/2015/fe101a.cfm>.

¹⁹ CRS Report RL30304, *The Federal Excise Tax on Motor Fuels and the Highway Trust Fund: Current Law and Legislative History*, by Sean Lowry.

²⁰ Federal Highway Administration, *Funding Federal-aid Highways: Appendix K, Historical Federal Fuel Tax Rates*, last modified January 2017, <https://www.fhwa.dot.gov/policy/olsp/fundingfederalaid/k.cfm>.

²¹ U.S. President (Reagan), “Remarks to Reporters Announcing the Administration’s Proposal for a Highway and Bridge Repair Program: Nov. 23, 1982,” *The American Presidency Project: Public Papers*.

Reagan helped secure the votes needed for cloture. President Reagan signed STAA into law on January 6, 1983, more than doubling the highway fuel tax to 9 cents per gallon.²²

50/50 Share: Deficit Reduction/Highway Trust Fund

The Omnibus Budget Reconciliation Act of 1990 (OBRA90; P.L. 101-508), enacted November 5, 1990, was passed under the pressure of impending final FY1991 sequestration orders issued by President George H. W. Bush under Title II of P.L. 99-177, the Balanced Budget and Emergency Deficit Control Act of 1985, also known as the Gramm-Rudman-Hollings Act (GRH). OBRA90 included budget cuts, tax changes, and the Budget Enforcement Act (P.L. 101-508), which rescinded the FY1991 sequestration orders. OBRA90 also raised the tax on gasoline by 5 cents per gallon, to 14 cents. Half the increase went to the HTF (2 cents to the highway account and 0.5 cents to the mass transit account), with the other 2.5 cents per gallon to be deposited in the general fund for deficit reduction. This was the first time since 1957 the motor fuel tax had been used as a source of general revenue. Section 9001 expressed the sense of Congress that all motor fuel taxes should be directed to the HTF as soon as possible.

More for Deficit Reduction

The Omnibus Budget Reconciliation Act of 1993 (OBRA93; P.L. 103-66) Section 13241(a) made further changes in regard to fuel taxes

- The 2.5-cents-per-gallon fuel tax dedicated to deficit reduction in OBRA90 was redirected to the HTF beginning October 1, 1995, and its authorization was extended to September 30, 1999.
- The highway account received 2 cents per gallon and the mass transit account 0.5 cents per gallon of the rededicated amount.
- An additional permanent 4.3-cents-per-gallon fuel tax took effect in October 1993 and was dedicated to deficit reduction.

This brought the gasoline tax to 18.3 cents per gallon, although for two years (October 1, 1993, to October 1, 1995) 6.8 cents per gallon of this was deposited in the general fund. On October 1, 1995, the amount going to the general fund dropped to 4.3 cents per gallon, and the amount dedicated to the HTF increased to 14 cents per gallon. Subsequently, under the Taxpayer Relief Act of 1997 (P.L. 105-34), all motor fuel tax revenue was redirected to the HTF. (The LUST fund continues to receive the revenue from an additional 0.1 cents-per-gallon tax.)

Alternatives for HTF Revenue

The political difficulty of increasing motor fuel taxes has led to interest in alternative approaches for supporting the HTF. Among options that have been proposed are the following:

“Fixing” the Gas Tax

A differently designed gas tax might be indexed to both inflation (either inflation generally or highway construction cost inflation) and fuel-efficiency improvements.²³ This new design could

²² See Jeff Davis, *Reagan Devolution: The Real Story of the 1982 Gas Tax Increase*, Eno Center for Transportation, Washington, DC, 2015, pp. 1-40.

²³ There are many inflation indexes that could be used. Which one is most appropriate might become an issue of

be imposed after raising the current gas tax rate to compensate for the loss in purchasing power since the last rate increase in 1993.²⁴

If the motor fuel taxes for gasoline and diesel had been adjusted in 2018 to keep pace with the change in the Bureau of Labor Statistics' consumer price index since 1993, the 18.3-cents-per-gallon gasoline tax would now be 31.8 cents per gallon, and the 24.3-cents-per-gallon diesel tax would be 42.2 cents per gallon. Consequently, the first step in implementing this method of "fixing" the gas tax would be to raise the base tax rate for gasoline by roughly 13.5 cents per gallon and to raise the rate for diesel by roughly 17.9 cents per gallon. Future adjustments would depend on the inflation rate in future years.

Tax-rate adjustments to make up for revenue lost due to greater fuel efficiency could be determined by dividing miles driven by vehicle category by the total amount of fuel consumed by that category and comparing the quotient to the previous year. Although fuel-economy standards for new vehicles are to rise over the next few years, the average efficiency of the entire vehicle fleet will rise slowly because of the large number of older vehicles on the road.

Switching to Sales Taxes

Under the sales tax concept, the federal motor fuel taxes would be assessed as a percentage of the retail price of fuel rather than as a fixed amount per gallon. Some states already levy taxes on motor fuels in this way, either alongside or in place of fixed cents-per-gallon taxes on motor fuel purchases.

If fuel prices rise in the future, sales tax revenues could rise from year to year even if consumption does not increase. Conversely, however, a decline in motor fuel prices could lead to a drop in sales tax revenue. Many states that tied fuel taxes to prices after the price shocks of the 1970s encountered revenue shortfalls in the 1980s, when fuel prices fell dramatically. Over a 20-year period, most of these variable state fuel taxes disappeared.²⁵ In 2013, Virginia eliminated its cents-per-gallon fuel taxes in favor of a sales tax on fuel and a general sales tax increase that was dedicated to transportation purposes. The Virginia law mandates that the tax be imposed on the average wholesale price (calculated twice each year) but sets price floors; if prices of motor fuels fall beneath those floors, the amount of fuel tax charged per gallon is not reduced further.²⁶

A federal sales tax on motor fuel would likely be at best an interim solution to the long-term problem of financing transportation infrastructure because, as with the current motor fuel tax, it relies on fuel consumption to fund transportation programs. To the extent that improved vehicle

controversy. The most commonly used index is the U.S. Bureau of Labor Statistics' consumer price index (CPI), which, for example, is used to adjust certain aviation user fees. Other examples are the Bureau of Economic Analysis price indexes for gross government fixed investment and the Federal Highway Administration's National Highway Construction Cost Index (NHCCI).

²⁴ Institute on Taxation and Economic Policy, *A Federal Gas Tax for the Future*, Washington, DC, September 2013, pp. 1-13, <http://www.itep.org/pdf/fedgastax0913.pdf>.

²⁵ Jeffrey Ang-Olson, Martin Wachs, and Brian D. Taylor, *Variable-Rate State Gasoline Taxes*, Institute of Transportation Studies, University of California, Berkeley, Working Paper, UCB-ITS-WP-99-3, July 1999. See also, M. Madowitz and K. Novan, "Gasoline taxes and revenue volatility: An Application to California," *Energy Policy*, vol. 59, 2013, pp 663-673, <http://www.sciencedirect.com/science/article/pii/S0301421513002577>.

²⁶ Virginia House Bill 2313, 2013 session. As passed, the price floor was the wholesale price as of February 20, 2013. The taxes are paid when the fuel is removed from a refinery or tank farm terminal. This is often referred to as collecting at the "rack."

efficiency or adoption of hybrid or electric vehicles leads to long-term declines in fuel usage, a sales tax on fuel may not lead to increases in trust fund revenues.²⁷

Vehicle Miles Traveled Charges (VMT)

Economists have long favored mileage-based user charges as an alternative source of highway funding. Under the user charge concept, motorists would pay fees based on distance driven and, perhaps, on other costs of road use, such as wear and tear on roads, traffic congestion, and air pollution. The funds collected would be spent for surface transportation purposes.²⁸

The concept is not new: federal motor fuel taxes are a form of indirect road user charge insofar as road use is loosely related to fuel consumption. Some states have charged trucks by the mile for many years, and toll roads charge drivers based on miles traveled and the number of axles on a vehicle, which is used as a proxy for weight. Recent technological developments, as well as the evident shortcomings of motor fuel taxes, have led to renewed interest in the user charge concept, including funding for pilot programs included in the FAST Act.

VMT charges, also referred to as mileage-based road user charges, could range from a flat cent-per-mile charge based on a simple odometer reading to a variable charge based on vehicle movements tracked by Global Positioning System (GPS). Other proposals envision VMT charges that would mimic the way Americans now pay their fuel taxes by collecting the charge at the pump, but a different method would be required to obtain payment from electric vehicle users.

Implementation of a VMT charge would have to overcome a number of potential disadvantages relative to the motor fuel tax, including public concern about personal privacy; higher collection and enforcement costs (estimates range from 5% to 13% of collections); the administrative challenge of collecting the charge from roughly 268 million vehicles;²⁹ and the setting and adjusting of VMT rates, which would likely be as controversial as increasing motor fuel taxes. Another issue is how to collect the charge from drivers who have no bank accounts or credit/debit cards.

A nationwide VMT charge would be analogous to a national toll. This raises the prospect that vehicles using toll roads might be charged twice, although this effectively happens now in that toll-road users also pay tax on the motor fuel they consume while using the toll road. Technically, it would be possible for a VMT charge to replace an existing toll, but this could cause complications with respect to the servicing of bonds funded by toll-road revenue.

²⁷ A fuel price floor could be established, but its impact would depend on how high the floor is set and whether the floor is indexed to inflation. The outcome could still fail to meet revenue expectations.

²⁸ See CRS Report R44540, *Mileage-Based Road User Charges*, by Robert S. Kirk and Marc Levinson. For additional discussion of mileage-based charges, see Transportation Research Board, National Cooperative Highway Research Program, *Implementable Strategies for Shifting to Direct Usage-Based Charges for Transportation Funding*, NCHRP Project 20-24(69), Web-Only Document 143, October 2009, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w143.pdf. See also Paul Sorensen, Liisa Ecola, and Martin Wachs, *Mileage-Based User Fees for Transportation Funding: A Primer for State and Local Decisionmakers*, Rand Corporation, 2012, pp. 1-34, http://www.rand.org/content/dam/rand/pubs/tools/TL100/TL104/RAND_TL104.pdf. See also Asha Weinstein Agrawal, Hilary Nixon, and Ashley M. Hooper, *Public Perception of Mileage-based User Fees*, Washington, DC, Transportation Research Board, 2016, pp. 1-139, <https://www.nap.edu/download/23401>.

²⁹ Federal Highway Administration, *State Motor-vehicle Registrations: 2017*, Table MV-1, January 2019, <https://www.fhwa.dot.gov/policyinformation/statistics/2017/mv1.cfm>.

VMT Charges and Non-highway Programs

Since 1982, the HTF has financed most federal public transportation programs as well as highway programs. If a VMT charge were to be used strictly for highway purposes, it might reasonably be characterized as a user fee even if the amount paid by each individual driver does not correspond precisely to the social cost (such as pollution and traffic congestion costs) of that user's driving. A VMT charge that funded both highways and public transportation might arguably be seen more as a tax than a user fee. This distinction raises a number of legal issues.³⁰ Any legislation establishing a VMT charge would, at a minimum, have to clearly identify what the charge would be spent on. If the existing HTF were to be retained, legislation would have to specify what share of the revenue would be credited to the separate highway and mass transit accounts within the fund.

Carbon Taxes

A carbon tax would be assessed on emissions of carbon dioxide and other greenhouse gases. Its scope might include manufacturing facilities, power plants, and transportation.³¹ A share of revenues from a carbon tax could be dedicated to federal transportation programs, either directly or via existing transportation trust funds such as the HTF or the Airport and Airway Trust Fund. The revenues could either replace or supplement current transportation taxes such as the motor fuel taxes. In December 2016, CBO estimated that a carbon tax of \$25 per metric ton would increase federal revenues by \$977 billion between 2017 and 2026 after adjusting for tax revenue losses related to increased business costs. The projection assumed the tax would increase at an annual rate of 2%, indexed for inflation. CBO estimated that the tax would reduce cumulative emissions from the taxed sources by roughly 9%.³² The effect of a carbon tax on the HTF would depend on the design of the tax and the use of the revenue it generates.

Electric Vehicle Fees/Taxes

Since electric vehicles do not burn taxed motor fuels, their wider use could further weaken the sustainability of the HTF. In the near term, however, the impact of electric vehicles on HTF revenue is expected to be modest. In 2018 plug-in vehicles accounted for 2.1% of U.S. light vehicle sales,³³ and the roughly 1,196,000 plug-in vehicles sold in the United States since their 2010 introduction comprise roughly 1.1% of registered automobiles.³⁴ If each electric vehicle is

³⁰ There may be legal considerations depending on whether the VMT charge is structured as a fee or tax. See, for example, U.S. Const. Art. I, §8, cl. 1 ("all Duties, Imposts and Excises shall be uniform throughout the United States"). Legally, the two are distinguished by the relationship between the amount charged by the government and the services rendered to the payor. For example, the Supreme Court has explained that a tax may be administered "arbitrarily and [without regard to] benefits bestowed by the Government on a taxpayer and go solely on ability to pay, based on property or income," while a user fee is a specific charge imposed for a benefit that accrues only to the payors. *Nat'l Cable Television Ass'n v. United States*, 119 U.S. 336, 340-41 (1974).

³¹ CRS Report R42731, *Carbon Tax: Deficit Reduction and Other Considerations*, by Jonathan L. Ramseur, Jane A. Leggett, and Molly F. Sherlock.

³² Congressional Budget Office, *Options for Reducing the Deficit: 2017 to 2026*, Publication 52142, Washington, DC, December 2016, pp. 211-212, <https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/52142-budgetoptions2.pdf>.

³³ Electric Drive Transportation Association, *Electric Drive Sales Dashboard*, May 2019, <https://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952>. Sales since introduction are 1,195,810 through May 29, 2019.

³⁴ Federal Highway Administration, *State Motor-Vehicle Registrations—2017*, Table MV-1, Washington, DC, January 2019, <https://www.fhwa.dot.gov/policyinformation/statistics/2017/mv1.cfm>.

assumed to replace a light duty vehicle that consumes 474 gallons of petroleum-based fuel per year, roughly \$104 million in annual revenue is lost to the HTF.³⁵ Even if electric vehicle sales grow rapidly, a significant impact on annual HTF revenues is likely to be roughly eight to 10 years in the future.

As of 2019, 23 states had some form of tax or fee on electric vehicles.³⁶ In most cases, the revenue from such fees is dedicated to transportation. Although sales and mileage fees have been considered, the most common form of tax is a flat fee paid annually at registration. Congress could consider imposing a similar federal fee. However, if Congress structures a federal registration fee in a way that mandates the states to implement the federal program, unrelated to the provision of federal funds, the fee might be challenged in court on constitutional grounds.³⁷

Other Options to Preserve the Highway Trust Fund

A wide range of additional proposals has been suggested to generate revenue for the HTF. These proposals largely originated from the work of two commissions established pursuant to SAFETEA and of groups such as the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB).³⁸ For example, AASHTO's "Matrix of Illustrative Surface Transportation Revenue Options" lists 37 potential HTF revenue options with yield estimates in tabular form.³⁹ Many of these options involve taxes on freight movements or energy. It should be emphasized that the revenue estimates from these exercises are merely suggestive; the revenue obtained from any given measure would depend on changes in the price of motor fuels, growth in the number of annual auto registrations, and other factors.

The Future of the Trust Fund

The HTF was set up as a temporary device that was supposed to disappear when the Interstate System was finished. It has endured, and its breadth of financing has expanded well beyond the Interstates, most significantly with the 1982 creation of the mass transit account within the HTF to support public transportation spending. But the HTF is not essential to a federal role in transportation funding. Congress routinely funds large infrastructure projects, such as those constructed by the Army Corps of Engineers, from general fund appropriations. Before 1956, it funded highway projects using annual appropriations. As recently as the 1990s, significant

³⁵ Federal Highway Administration, *Annual Vehicle Distance Traveled in Miles and Related Data—2017*, Table VM-1, Washington, DC, March 2019, <https://www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm>.

³⁶ American Road & Transportation Builders Association, *State Electric Vehicle Fees*, Washington, DC, 2019, https://transportationinvestment.org/wp-content/uploads/2019/04/State-Electric-Vehicle-Fees_updated-20190405.pdf.

³⁷ CRS Report R45323, *Federalism-Based Limitations on Congressional Power: An Overview*, coordinated by Andrew Nolan and Kevin M. Lewis.

³⁸ The Transportation Research Board, through its research programs, has prepared several reports on future surface transportation finance that discuss VMT and other options, including National Cooperative Highway Research Program (NCHRP), *Future Financing Options to Meet Highway and Transit Needs*, NCHRP Project 20-24, Web-Only Document 102, December 2006, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w102.pdf; and Transportation Research Board, *The Fuel Tax and Alternatives for Transportation Funding*, Special Report 285, January 2006, <http://onlinepubs.trb.org/onlinepubs/sr/sr285.pdf>.

³⁹ American Association of State Highway and Transportation Officials, "Matrix of Illustrative Surface Transportation Revenue Options," January 2019, https://fundingfinance.transportation.org/wp-content/uploads/sites/16/2019/02/Matrix_of_Funding_Options.pdf.

highway programs such as the Appalachian Development Highway System were funded from the general fund.

If Congress chooses not to impose new taxes and fees dedicated to the HTF, it could still maintain or expand the surface transportation program with general fund monies. Any of the revenues from the HTF financing options discussed above could also be deposited into the general fund rather than the HTF if Congress considers alternatives to the trust fund financing model. Possible alternatives include the following:

Eliminate the Trust Fund. This would do away with the complicated budget framework of contract authority, obligations, and apportionments.⁴⁰ Surface transportation would be forced to compete with other federal programs for funding each year, possibly affecting the level of funding provided for transportation.

There could be advantages to moving away from trust fund financing of surface transportation. Until recently, one of the most intractable arguments in reauthorization debates concerned which states were “donors” to transportation programs and which were “donees.” Donor states were states whose highway users were estimated to pay more to the highway account of the HTF than they received. Donee states received more than they paid. The donor-donee dispute was unique to the federal highway program, and occurred largely because of the ability to track federal fuel tax revenues by state. This issue has faded as HTF shortfalls have been resolved with injections of general fund transfers to the fund. These general fund monies transferred into the HTF have nothing to do with highway tax revenues, but have made nearly all states donees. The donor-donee issue would likely disappear entirely if transportation-related taxes were deposited into the general fund instead of the trust fund. This would provide Congress with greater flexibility to allocate funding among various transportation modes and between transportation and nontransportation uses. However, treating fuel taxes as just another source of federal revenue would weaken the long-standing link between road user charges and program spending.

Most trust-fund outlays take the form of formula grants over which states have a great deal of spending discretion. While there are numerous federal requirements attached to trust fund expenditures, there have been until recently relatively few performance-oriented goals that the states are required to meet in selecting projects to be undertaken with federal monies. Performance measures might be easier to implement without formula programs that automatically apportion funding to the states. However, this may not be the case; performance measures in recent years have been imposed on the Federal-Aid highway programs as they are currently structured, although implementation has been slow.⁴¹

Eliminating the trust fund might also allow for creativity in thinking about the provision of transportation infrastructure across the modal boundaries that now define much of federal transportation spending. Historically, important parts of U.S. transportation infrastructure, such as the transcontinental railroads and the Panama Canal, were authorized by specific congressional enactments rather than grant programs. Reconsidering the trust fund structure might reopen discussion of this approach.

Devote HTF Revenues Exclusively to Highways. This option would leave transit and other surface transportation programs to be funded entirely by annual appropriations of general funds

⁴⁰ Joshua Schank, “Life and Death of the Highway Trust Fund: How We Pay for Transportation,” Eno Center for Transportation, December 2014, <https://www.enotrans.org/store/research-papers/the-life-and-death-of-the-highway-trust-fund-2>.

⁴¹ Jeff Davis, “Regulatory Freeze Continues as Agencies Extend Deadlines and Regroup,” *Eno Transportation Weekly*, February 8, 2017, pp. 1-3.

or devolved to the states. Such a change would have political implications. Since the early 1990s, public transportation and cycling advocates, environmentalists, and a wide range of other groups have become full-fledged supporters of the surface transportation program. They might be less enthusiastic about supporting a program that does not address their interests.

“Devolve” Surface Transportation Programs to the States. The federal government could devolve most federal responsibility for highways and public transportation to the states. Under devolution proposals, the federal taxes that now support surface transportation programs, mostly fuel taxes, would be reduced accordingly, leaving individual states to raise their own taxes to pay for highway and transit projects as they see fit. A small program, funded by much-reduced motor fuel taxes, would remain in place at the federal level to maintain roads on federal lands, fund highway safety efforts, and support other programs Congress decides not to devolve.⁴²

By enacting the FAST Act, Congress chose to support the current funding model by transferring funds into the HTF, mostly from the Treasury general fund. Whether such general fund support should continue is likely to become a major point of contention when Congress debates reauthorizing surface transportation programs beyond FY2020.

Making a General Fund Share Permanent

By FY2020, the last year of the FAST Act, federal highway programs will have been funded for 12 years under a de facto policy of providing a Treasury general fund share. Congress could address the inadequacy of motor fuel taxes to meet surface transportation needs by making the general fund share permanent.

The public transportation titles of surface transportation bills already fund the Capital Investment Grants program through appropriations from the general fund. The Federal Aviation Administration (FAA) budget is also supported by a combination of trust funds and general funds; the general fund amount is supposed to approximate the value of the airways system to military and other government users and to “societal” nonusers (people who do not fly but, for example, benefit from the delivery of freight via aircraft).⁴³ A similar argument could be made regarding the public good benefits of a well-functioning highway system to justify an annual general fund appropriation to support spending on roads.⁴⁴

Should Congress agree on a future policy of providing an annual general fund share for federal highway funding, the financing structure of the federal-aid highways program could change. Congress would have the choice of appropriating the general fund share to the HTF and maintaining the programmatic status quo, or it could fund some programs from the trust fund and fund others via appropriations. Congress could also consider a two-pronged approach to authorization. It could authorize the trust funded programs separately from the appropriated programs. This would give Congress the option of approving a very long authorization for trust-funded projects that typically take many years to plan and complete. The long-term authorization

⁴² CRS Report R44811, *Surface Transportation Devolution*, by Robert S. Kirk.

⁴³ The provision of a general fund share for the FAA is not required by statute but is the historical norm. When the Airport and Airway Trust Fund was running sufficient balances to do so, it was not uncommon for presidential budgets to propose funding the entire FAA budget with trust fund revenues. Since the 1971 creation of the Airport and Airway Trust Fund, however, this only occurred in FY2000.

⁴⁴ Joseph E. Stiglitz, *Economics of the Public Sector* (New York, NY: W. W. Norton Co., 1986), p. 599.

could be paired with a series of short-term bills funded with appropriated general funds for programs whose projects are more likely to be completed quickly.⁴⁵

Toll Financing of Federal-Aid System Highways

Toll roads have a long history in the United States, going back to the early days of the republic. During the 18th century, most were local roads or bridges that could not be built or improved with local government tax revenue alone. However, beginning with the Federal Aid Road Act of 1916 (39 Stat. 355), federal law has included a prohibition on the tolling of roads that benefited from federal funds.⁴⁶ During the late 1940s and early 1950s, the prospect of toll revenues allowed states to build thousands of miles of limited-access highways without federal aid and much sooner than would have been the case with traditional funding. Despite this, the tolling prohibition was reiterated in the Federal-Aid Highway Act and Highway Revenue Act of 1956 (70 Stat. 374), which authorized funds for the Interstate System, created the HTF, and raised the fuel taxes to pay for their construction. Over the last three decades the prohibition has been moderated so that exceptions to the general ban on tolling now cover the vast majority of federal-aid roads and bridges. There remains a ban on the tolling of existing Interstate System highway surface lane capacity. While new toll facilities have opened in several states, some of those projects have struggled financially.

Generally, there are several levels of restrictions on tolling of federal-aid highways. Non-Interstate System highways and bridges may be converted to toll roads but only after reconstruction or replacement. Existing Interstate System surface lane capacity may not be converted to toll roads except under the auspices of two small pilot programs. Interstate System bridges and tunnels may be converted if they are reconstructed or replaced. New capacity on the federal-aid highway system, including Interstate Highways, generally may be tolled. There are no federal restrictions on tolling of roads that are not part of the federal-aid system.

Options for Expanded Use of Tolling

Highway toll revenue nationwide came to \$14.457 billion in FY2016, according to FHWA. While the amount of toll revenue has grown significantly in recent years, toll revenue as a share of total spending on highways has been relatively steady for more than half a century, ranging from roughly 5% to 7%.⁴⁷ On average, facility owners collected \$2.41 million per mile of toll road or bridge in FY2016, but revenue per mile varies greatly among toll facilities.⁴⁸ All revenue from tolls flows to the state or local agencies or private entities that operate tolled facilities; the federal government does not collect any revenue from tolls. However, a major expansion of tolling might reduce the need for federal expenditures on roads. There are three possible means of increasing revenue from tolling:

⁴⁵ See Jeff Davis, *Why Not a Ten-Year Year Surface Transportation Bill? (Executive Summary)*, Eno Center for Transportation, February 26, 2015, p. 1.

⁴⁶ CRS Report R44910, *Tolling U.S. Highways and Bridges*, by Robert S. Kirk.

⁴⁷ Federal Highway Administration, *Highway Statistics: Summary to 1975*, Table HF-211, 1977, pp. 107-136. Also *Highway Statistics: Summary to 1995*, Table SF-210; *Highway Statistics*, various years, Tables SF-21, HF-10, and HF-10a; *Our Nation's Highways: 2010*, Figure 6-6: Toll Facility Revenue: 1993-2008, http://www.fhwa.dot.gov/policyinformation/pubs/pl10023/fig6_6.cfm.

⁴⁸ Federal Highway Administration, *Funding for Highways and Disposition of Highway-User Revenues, All Units of Government, 2015*, Table HF-10, May 2017.

- **Increase the Extent of Toll Roads.** FHWA statistics identify 6,001 tolled miles of roads, bridges, and tunnels as of January 1, 2017,⁴⁹ a net increase of 1,280 miles, or 27%, over 1990.⁵⁰ Toll-road mileage comprises 0.6% of the 1,027,849 miles of public roads eligible for federal highway aid.⁵¹ While there may be many existing roads on which tolling would be financially feasible, the vast majority of mileage on the federal-aid system probably has too little traffic to make toll collection economically viable.
- **Increase the Average Toll per Mile.** Raising tolls can be politically challenging, especially when revenue is used for purposes other than building and maintaining the toll facility. Trucking interests frequently raise opposition to rate changes that increase truck tolls relative to automobile tolls. Where roads are operated by private concessionaires, the operators' contracts with state governments typically specify the maximum rate at which tolls can rise. Additionally, large increases can encourage motorists to use competing nontolled routes, thereby reducing their revenue-raising potential.
- **Increase Toll-Road Usage.** To a great extent, increasing toll road usage is dependent on policies that effectively increase the number of miles tolled and establish toll rates that maximize revenues without discouraging use. However, toll road use is also determined by broad economic and social trends. The financing of many of the toll roads constructed in the 20th century was based on the assumption that the new roads would lead to increased vehicle usage. Although vehicle miles traveled declined in the wake of the recession that began in 2007, vehicle use has been rising again since 2014. If this trend continues it bodes well for toll revenues, which would rise with increasing traffic. On the other hand, if demographic trends and social changes eventually lead to slower growth in personal motor vehicle use, then toll revenues may be constrained in the longer term.

The constraints on these means of increasing revenue from tolling suggest that imposing tolls on individual transportation facilities is likely to be of only limited use in supporting the overall level of highway capital spending. Furthermore, some states, particularly those with low population densities, may have few or no facilities suitable for tolling.⁵² Toll collection itself can be costly; collection costs on many existing toll roads exceed 10% of revenues. For these reasons, while tolls may be an effective way of financing specific facilities—especially major roads, bridges, or tunnels that are likely to be used heavily and are located such that the tolls are difficult to evade—they would likely be less effective in providing broad financial support for surface transportation programs.

⁴⁹ Federal Highway Administration, *Toll Facilities in the United States: Toll Mileage Trends—2007 to 2017*, Washington, DC, April 4, 2018, <https://www.fhwa.dot.gov/policyinformation/tollpage/page05.cfm>.

⁵⁰ Federal Highway Administration, *Toll Facilities in the United States: Bridges-Roads-Tunnels-Ferries*, Publication No: FHWA-PL-91-009, 1991, p. v.

⁵¹ Federal Highway Administration, *Public Road Length-2017: Miles by Functional System and Federal-Aid Highways, National Summary*, Table HM-18, Washington, DC, August 23, 2018, <https://www.fhwa.dot.gov/policyinformation/statistics/2017/hm18.cfm>.

⁵² CRS Report R45250, *Rural Highways*, by Robert S. Kirk.

Value Capture

Value capture represents an attempt to cover part or all of the cost of transportation improvements from landowners or developers who benefit from the resulting increase in the value of real property. Value capture revenue mechanisms include tax increment financing, special assessments, development impact fees, negotiated exactions, and joint development.⁵³ The federal role in value capture strategies may be limited, as the Government Accountability Office (GAO) has noted,⁵⁴ but it is worth describing these strategies to provide a fuller picture of the ways in which they might supplement or supplant more commonly used funding and financing mechanisms.

Value capture is not a new idea. Land developers built and operated streetcar systems in the late 19th century as a way to sell houses on the urban fringe, for example. Much of the recent experience with value capture has been associated with public transit. GAO found that the most widely used mechanism is joint development, in which a real estate project at or near a transit station is pursued cooperatively between the public and private sectors. An example might involve a transit agency leasing the unused space over a station, its “air rights,” to a developer in exchange for a regular payment.

Joint development has generated relatively small amounts of money for transit agencies. For example, the Washington Metropolitan Area Transit Authority received about \$10 million from joint development in FY2016, about 1% of its operating revenue.⁵⁵ However, less widely used strategies, such as special assessment districts, are estimated to generate significant amounts of funding for specific projects. In a special assessment district, properties within a defined area are assessed a special tax for a specific purpose. A special assessment district in Seattle produced \$25 million of the \$53 million (47%) needed to fund the South Lake Union streetcar project.⁵⁶

There has been less use of value capture in highway projects, but this appears to be changing. Texas, for example, has authorized the use of tax increment financing through the creation of transportation reinvestment zones to help fund highway projects.⁵⁷ Special assessment districts also have been set up in several states, including Florida and Virginia, to fund highway projects. In Virginia a special assessment district was used to help fund the expansion of Route 28 near Washington Dulles International Airport beginning in the late 1980s.⁵⁸

⁵³ Adeel Lari, David Levinson, and Zhirong Zhao, et al., *Value Capture for Transportation Finance: Technical Research Report*, Center for Transportation Studies, University of Minnesota, June 2009, <http://www.cts.umn.edu/research/featured/value-capture>. Tax increment financing uses the increase in property tax revenue within a defined area resulting from an infrastructure improvement to cover the cost of the improvement.

⁵⁴ Government Accountability Office, *Public Transportation: Federal Role in Value Capture Strategies for Transit Is Limited, but Additional Guidance Could Help Clarify Policies*, GAO-10-781, July 2010, <http://www.gao.gov/new.items/d10781.pdf>.

⁵⁵ Washington Metropolitan Area Transit Authority, *FY2019 Proposed Budget*, p. 17, https://www.wmata.com/about/records/public_docs/upload/FY2019-Proposed-Budget-Book-12-12-2017-Final.pdf.

⁵⁶ Government Accountability Office, *Public Transportation: Federal Role in Value Capture Strategies for Transit Is Limited, but Additional Guidance Could Help Clarify Policies*, GAO-10-781, July 2010, pp. 16, 20, <http://www.gao.gov/new.items/d10781.pdf>.

⁵⁷ Sharada Vadali, Rafael Manuel-Aldrete, and Arturo Bujanda, et al., *Transportation Reinvestment Zone Handbook*, Texas Transportation Institute, College Station, TX, 2011, http://ntl.bts.gov/lib/37000/37800/37821/0-6538-P1_Handbook_resub_editjd_sv.pdf; Texas Department of Transportation, “Transportation Reinvestment Zone,” <http://www.txdot.gov/government/programs/trz.html>.

⁵⁸ For more information, see Route 28 Corridor Improvements LLC, “Route 28 Public/Private Partnership: Moving

Public-Private Partnerships (P3s)

Growing demands on the transportation system and constraints on public resources have led to calls for more private-sector involvement in the provision of highway and transit infrastructure through public-private partnerships (P3s), which can be designed to lessen demands on public-sector funding.⁵⁹ Private involvement can take a variety of forms, including design-build and design-build-finance-operate agreements. Typically, the “public” in public-private partnerships refers to a state government, local government, or transit agency. The federal government, nevertheless, exerts influence over the prevalence and structure of P3s through its transportation programs, funding, and regulatory oversight.⁶⁰

To be viable, P3s involving private financing typically require an anticipated project-related revenue stream from a source such as vehicle tolls, freight container fees, or, in the case of transit station development, building rents. Private-sector resources may come from an initial payment to lease an existing asset in exchange for future revenue, as with the Indiana Toll Road and Chicago Skyway, or they may arise from a newly developed asset that creates a new revenue stream. Either way, a facility user fee, such as a toll, is often the key to unlocking private-sector participation and resources.

In some cases, private-sector financing is backed by “availability payments,” regular payments made by government to the private entity based on negotiated quality and performance standards of the facility. Aversion in the private sector to the risk that too few users will be willing to pay for use of a new facility, known as demand risk, has made availability payment P3s more common over the past few years. As a result, state and local governments are retaining demand risk more often.⁶¹

It is frequently asserted that hundreds of billions of dollars of private funds are available globally for infrastructure investment.⁶² To date, however, the number of transportation P3s in the United States is relatively small, as is the amount of long-term private financing provided. According to one source, from 1993 through September 2017 there were 30 surface transportation P3s involving long-term financing, with total project costs totaling \$39 billion. This includes the 99-year lease of the Chicago Skyway; the I-595 managed lanes project in Florida; and the Purple Line light rail transit project in Maryland.⁶³ P3s and private investment in infrastructure, including surface transportation, are relatively larger in many other countries, including Canada, Australia, and the United Kingdom.⁶⁴

While private investment may grow in the future, many impediments remain. Some of the major ones include the relative attractiveness of the tax-exempt financing available to state and local government, political opposition to tolling and privatization, and difficulties associated with

Right Along,” <http://www.28freeway.com>.

⁵⁹ See, for example, Bipartisan Policy Center, *Bridging the Gap Together: A New Model to Modernize U.S. Infrastructure*, May 2016, <https://bipartisanpolicy.org/library/modernize-infrastructure/>.

⁶⁰ CRS Report R45010, *Public-Private Partnerships (P3s) in Transportation*, by William J. Mallett.

⁶¹ “Demand Risk P3s Are An Unhappy Family,” *Public Works Financing*, September 2014, p. 19.

⁶² Bipartisan Policy Center, *Bridging the Gap Together: A New Model to Modernize U.S. Infrastructure*, May 2016, p. 67, <https://bipartisanpolicy.org/library/modernize-infrastructure/>.

⁶³ “U.S./Canada Transportation P3 Market 1993-2017,” *Public Works Financing*, September 2017, pp. 9-12.

⁶⁴ EY, *Public-Private Partnerships and the Global Infrastructure Challenge*, 2015, figure 1, https://www.ey.com/Publication/vwLUAssets/Health%24FILE/EY_PPP_Thought_Leadership.pdf.

project development. Private-sector financing generated through P3s might best be seen as a supplement to traditional public-sector funding rather than as a substitute.

In addition to attracting private capital, P3s may generate new resources for highway and transit infrastructure in at least two ways. First, P3s may improve efficiency through better management and innovation in construction, maintenance, and operation—in effect providing more infrastructure for the same price. Private companies may be more able to examine the full life-cycle cost of investments, whereas public agency decisions are often tied to short-term budget cycles. Such cost reductions may not materialize, however, if the public sector has to spend a substantial amount of time on procurement, oversight, dispute resolution, and litigation.

Second, P3s may reduce government agencies' costs by transferring the financial risks of building, maintaining, and operating infrastructure to private investors. These risks include construction delays, unexpectedly high maintenance costs, and the possibility that demand will be less than forecast. There is a danger, however, that this transfer of risk may prove illusory if major miscalculations force the public agency to renegotiate contracts or provide financial guarantees.⁶⁵ Moreover, as GAO points out, not all the risks can or should be shifted to the private sector. For instance, private investors are unlikely to accept the risk of higher construction costs due to delays in the environmental review process.⁶⁶

Asset Recycling

Asset recycling is the sale or lease to the private sector of government-owned infrastructure assets and the investment of the proceeds in new infrastructure. For a few years, the national government of Australia had a policy of making 15% incentive payments to state and territory governments if they agreed to sell or lease assets to the private sector and then “recycle” these payments to other infrastructure projects. Over the roughly three-year period the asset recycling initiative was in effect, the national government entered into four agreements with incentive payments totaling A\$3.175 billion (approximately US\$2.4 billion). One of the agreements involved the lease of 49% of the electricity network businesses owned by the State of New South Wales and the investment of the proceeds in the Sydney Metro, Parramatta Light Rail, and several road projects.⁶⁷ A similar program for the United States was proposed in a draft bill on infrastructure investment circulated by House Transportation and Infrastructure Committee Chairman Bill Shuster in 2018. The draft bill proposed to provide a federal payment of 15% of the assessed value of a leased infrastructure asset to eligible project sponsors, allotting \$3 billion for this purpose from FY2019 through FY2023. No similar proposal has been introduced as legislation. Infrastructure assets that qualify for recycling in the draft bill include highways, public transit, airports, ports and port terminals, publicly owned railroads, intercity bus facilities, intermodal transportation facilities, and drinking and wastewater facilities.⁶⁸

⁶⁵ E. Engel, R. Fischer, and A. Galetovic, “Privatizing Highways in the United States,” *Review of Industrial Organization*, vol. 29, 2006, pp. 27-53.

⁶⁶ Government Accountability Office, *Highway Public-Private Partnerships*, February 2008.

⁶⁷ Honorable Paul Fletcher, Minister for Urban Infrastructure, “Building our Future: Strengthening Australia through Critical and Innovative Infrastructure Investment,” media release, May 3, 2016, http://minister.infrastructure.gov.au/pf/releases/2016/May/budget-infra_02-2016.aspx.

⁶⁸ “The Shuster Infrastructure Proposal,” https://transportation.house.gov/uploadedfiles/infra_001_xml.pdf.

Municipal Bonds

Municipal bonds, debt instruments used by states and all types of local government, are a major source of financing for transportation infrastructure. The interest on municipal bonds is generally exempt from federal income tax; consequently, an investor will usually accept a lower interest rate than on a non-tax-exempt bond, and the borrower can finance a project at a lower cost. The forgone tax revenue is the federal government's contribution to a project financed with municipal bonds. CBO estimates that the cost to the federal government of tax-exempt bonds in state and local transportation and water infrastructure investment is 26 cents per dollar financed.⁶⁹

Private activity bonds (PABs) are a type of municipal bond in which a state or local government acts as a financial intermediary for a business or individual.⁷⁰ PABs are not eligible for federal tax exemption unless Congress grants an exception for a certain purpose and other requirements are met. Congress has approved limited use of tax-exempt private activity bonds for airports, docks and wharves, mass commuting facilities, high-speed intercity rail facilities, and qualified highway or surface freight transfer facilities (26 U.S.C. §142). In the case of qualified highway or surface freight transfer facilities, the Secretary of Transportation must approve the issuance of PABs, and the aggregate amount allocated must not exceed \$15 billion (26 U.S.C. §142(m)(2)). The authorization for the sale of qualified highway or surface freight transfer facilities was a provision in SAFETEA, enacted in 2005. As of May 31, 2019, \$10.13 billion of the \$15 billion had been issued to finance 26 projects, and another \$2.33 billion had been allocated to five other projects.⁷¹ There have been proposals to increase the bond issuance cap so that PABs, which are seen as an important support for P3 deals, can continue to be issued in the future.

While municipal bonds are a popular financing method, there are a number of potential disadvantages to their use. Because they are issued by state and local governments, the federal government has less control over the types of projects supported and the amount of the federal contribution than it does with grant and loan programs. Tax-exempt bonds, moreover, can be an inefficient way to subsidize state and local debt because borrowing costs are reduced by less than the forgone federal revenue. As CBO notes, "the remainder of that tax expenditure accrues to bond buyers in the highest income tax brackets."⁷² Also, tax-exempt bonds are unattractive to investors that do not have a federal tax liability, such as pension funds and foreign individuals and organizations, shrinking the potential funds available to state and local governments.

Tax credit bonds, an alternative type of tax-preferred municipal bond, might help to overcome some of these limitations. Tax credit bonds typically do not pay interest. Instead, the investor receives a tax credit, an amount that is the same for investors in different tax brackets. Tax credit bonds, therefore, are more efficient than tax-exempt bonds because the revenue forgone by the federal government equals the reduction in borrowing costs that state and local governments receive. Unused tax credits may be carried forward to another year or sold to another entity with tax liability. With some types of tax credit bonds known as issuer credit or direct pay bonds, the credit is paid to the issuer (a state or local government) by the Treasury, and the investor gets

⁶⁹ Congressional Budget Office, *Federal Support for Financing State and Local Transportation and Water Infrastructure*, October 2018, p. 2, <https://www.cbo.gov/system/files?file=2018-10/54549-InfrastructureFinancing.pdf>.

⁷⁰ Joint Tax Committee, *Overview of Selected Provisions Relating to the Financing of Surface Transportation Infrastructure*, June 23, 2015, JCX-97-15, <https://www.jct.gov/publications.html?func=showdown&id=4796>.

⁷¹ Department of Transportation, Build America Bureau, "Private Activity Bonds: Current Status," June 7, 2019, <https://www.transportation.gov/buildamerica/programs-services/pab>.

⁷² Congressional Budget Office, "Answer to a Question for the Record Following a Hearing on the Long-Term Financing of the Highway Trust Fund Conducted by the House Committee on Ways and Means," July 24, 2015, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/50418-QFRs_HTF_1.pdf.

interest similar to taxable securities. Consequently, tax credit bonds can be attractive to investors with no federal tax liability.

Federal authority exists for state and local governments to issue some types of tax credit bonds, but under current authority none can be used to finance transportation projects. Tax credit bonds authorized by the American Recovery and Reinvestment Act of 2009 (P.L. 111-5), known as Build America Bonds, were used to finance a wide range of projects including transportation. The authorization to issue these bonds expired December 31, 2010.

Transportation Infrastructure Finance and Innovation Act (TIFIA)

An existing federal mechanism for providing credit assistance to relatively large transportation infrastructure projects is the Transportation Infrastructure Finance and Innovation Act (TIFIA) program, enacted in 1998.⁷³ TIFIA provides federal credit assistance in the form of secured loans, loan guarantees, and lines of credit.⁷⁴

Federal credit assistance reduces borrowers' costs and lowers project risk, thereby helping to secure other financing at rates lower than would otherwise be possible. Another purpose of TIFIA funding is to leverage nonfederal funding, including investment from the private sector. Loans must be repaid with a dedicated revenue stream, typically a project-related user fee, such as a toll, but sometimes dedicated tax revenue. As of June 7, 2019, according to DOT, TIFIA had provided assistance of about \$31 billion to more than 70 projects. The overall cost of the projects supported is estimated to be \$110 billion.⁷⁵

The FAST Act (P.L. 112-141) authorized \$275 million for TIFIA in both FY2016 and FY2017, \$285 million in FY2018, and \$300 million in both FY2019 and FY2020.⁷⁶ Because the government expects its loans to be repaid, an appropriation need cover only administrative costs and the subsidy cost of credit assistance. According to the Federal Credit Reform Act of 1990, the subsidy cost is "the estimated long-term cost to the government of a direct loan or a loan guarantee, calculated on a net present value basis, excluding administrative costs."⁷⁷ According to DOT, \$1 in TIFIA funding historically has provided about \$10 in credit assistance, a 10% subsidy cost, although in recent years each dollar has provided closer to \$16.⁷⁸

The FAST Act also allowed states to use funds they receive from two other highway programs to pay for the subsidy and administrative costs of credit assistance. These two programs are the Nationally Significant Freight and Highway Projects Program (NSFHPP), authorized at \$950 million in FY2019, and the National Highway Performance Program (NHPP), authorized at \$23.7

⁷³ 23 U.S.C. §601 et seq.

⁷⁴ CRS Report R45516, *The Transportation Infrastructure Finance and Innovation Act (TIFIA) Program*, by William J. Mallett.

⁷⁵ U.S. Department of Transportation, "Projects Financed by TIFIA," <http://www.dot.gov/tifia/projects-financed>.

⁷⁶ Highway and Transportation Funding Act of 2014 (P.L. 113-159); Highway and Transportation Funding Act (P.L. 114-21); Surface Transportation and Veterans Health Care Choice Improvement Act of 2015 (P.L. 114-41).

⁷⁷ Federal Credit Reform Act of 1990 (§502 5A), enacted as §13201 of Omnibus Budget Reconciliation Act of 1990 (P.L. 101-508).

⁷⁸ Based on the original subsidy rate for FY2015 through FY2020. Office of Management and Budget, *Budget of the U.S. Government, FY2020, Federal Credit Supplement*, Tables 1 and 7, https://www.whitehouse.gov/wp-content/uploads/2019/03/cr_supp-fy2020.pdf.

billion in FY2019. If states decide to use their formula funding in this way, the potential amount of loans and other credit assistance may be much greater than would be possible using the \$275 million direct authorization alone. The Better Utilizing Investments to Leverage Development (BUILD) Transportation Discretionary Grants program (formerly TIGER program), funded by general fund appropriations, also can be used by grant recipients to pay the subsidy and administrative costs of a TIFIA loan.⁷⁹

Several changes to the TIFIA program in the FAST Act were aimed at making it easier to finance smaller projects, particularly those in rural areas. These provisions included

- providing authority for a TIFIA loan to a state infrastructure bank (SIB) to capitalize a “rural project fund”;
- adding transit-oriented development (TOD) infrastructure as an eligible project (TOD infrastructure is a “project to improve or construct public infrastructure that is located within walking distance of, and accessible to, a fixed guideway transit facility,⁸⁰ passenger rail station, intercity bus station, or intermodal facility”),⁸¹
- allowing up to \$2 million of TIFIA budget authority each fiscal year to pay the application fees for projects costing \$75 million or less instead of requiring payment by the project sponsor;
- modifying or setting the minimum project cost thresholds for credit assistance at \$10 million for TOD projects, the capitalization of a rural project fund, and local government infrastructure projects; and
- providing for a streamlined application process for loans of \$100 million or less.

In addition, the FAST Act authorized the creation of a new National Surface Transportation and Innovative Finance Bureau within DOT to administer federal transportation financing programs, specifically the TIFIA program, the SIB program, the Railroad Rehabilitation and Improvement Financing (RRIF) Program, and the allocation of authority to issue private activity bonds for qualified highway or surface freight transfer facilities. To fulfill this mandate, DOT established the Build America Bureau in July 2016. The bureau also will be responsible for establishing and promoting best practices for innovative financing and P3s, and for providing advice and technical expertise in these areas. The bureau will administer the discretionary Nationally Significant Freight and Highway Projects grant program, known as INFRA grants, and will have responsibilities related to procurement and project environmental review and permitting.

National Infrastructure Bank

Congress has considered several proposals to create a national infrastructure bank to help finance infrastructure projects. One purported advantage of a national infrastructure bank over other loan programs, such as TIFIA, is that it would have more independence in its operation, such as in project selection, and have greater expertise at its disposal. Additionally, a national infrastructure bank would likely be set up to help a much wider range of infrastructure projects, including

⁷⁹ A maximum of 20% (\$300 million) of the funding appropriated in FY2018 was available to pay the subsidy and administrative costs of TIFIA credit assistance. Department of Transportation, “Notice of Funding Opportunity for the Department of Transportation’s National Infrastructure Investments Under the Consolidated Appropriations Act, 2018,” 83 *Federal Register* 18651-18661, April 27, 2018.

⁸⁰ Fixed guideway transit generally includes rail transit, passenger ferries, and bus rapid transit.

⁸¹ FAST Act, §2001.

water, energy, and telecommunications infrastructure. Proponents claim that the best projects, or at least those that are the most financially viable, would be selected from across these sectors.

In many formulations, capitalization of a national infrastructure bank comes from an appropriation, but in others the bank is authorized to raise its own capital through bond issuance. By issuing securities that are not tax exempt, it could tap pools of private capital that do not invest in tax-exempt bonds, such as pension funds and foreign citizens, the traditional source of much project finance. Tax-exempt municipal securities are unattractive to some investors, either because individual issues are too small to interest them or because the investors do not benefit from the tax preference. Taxable bonds with long maturities might be attractive to some of these investors.⁸² An infrastructure bank also might also choose to reduce the federal government's share of project costs, putting greater reliance on nonfederal capital and user fees.

Most infrastructure bank proposals assume the bank would improve the allocation of public resources by funding projects with the highest economic returns regardless of infrastructure system or type. Selection of the projects with the highest returns, however, might conflict with the traditional desire of Congress to ensure funding for various purposes. In the extreme case, major transportation projects might not be funded if the bank were to exhaust its lending authority on water or energy projects offering higher returns.

Limitations of a national infrastructure bank include its duplication of existing programs like TIFIA and the Wastewater and Drinking Water State Revolving Funds. An infrastructure bank may not be the lowest-cost means of increasing infrastructure spending. CBO has pointed out that a special entity that issues its own debt would not be able to match the lower interest and issuance costs of the U.S. Treasury.⁸³ In some formulations, a national infrastructure bank exposes the federal government to the risk of default.⁸⁴

State Infrastructure Banks

State infrastructure banks (SIBs) already exist in many states. In 32 states and Puerto Rico, SIBs were created pursuant to a federal program originally established in surface transportation law in 1995 (P.L. 104-59).⁸⁵ Several other states, among them California, Florida, Georgia, Kansas, Ohio, and Virginia, have state investment banks that are unconnected to the federal program.⁸⁶ Local governments have also begun to embrace the idea. The City of Chicago has established a nonprofit organization, the Chicago Infrastructure Trust, as a way to attract private investment for

⁸² U.S. Congress, Senate Committee on Banking, Housing, and Urban Affairs, Testimony of Felix Rohatyn, Co-Chair of the Commission on Public Infrastructure, *Hearing on Condition of Our Nation's Infrastructure and Proposals for Needed Improvement*, 110th Cong., 2nd Sess., March 11, 2008; U.S. Congress, House Committee on Transportation and Infrastructure, Testimony of Bernard Schwartz, President and CEO, BLS Investments, *Hearing on Financing Infrastructure Investments*, 110th Cong., 2nd Sess., June 10, 2008.

⁸³ U.S. Congress, House Committee of the Budget and Committee on Transportation and Infrastructure, Testimony of Peter R. Orszag, Director, Congressional Budget Office, *Hearing on Financing Infrastructure Investment*, 110th Cong., 2nd Sess., May 8, 2008.

⁸⁴ U.S. Congress, House Committee on Ways and Means, Subcommittee on Select Revenue Measures, Testimony of Samuel Staley, *Hearing on the National Infrastructure Banks*, 111th Cong., 2nd sess., May 13, 2010.

⁸⁵ Federal Highway Administration, "State Infrastructure Banks (SIBs)," http://www.fhwa.dot.gov/ipd/finance/tools_programs/federal_credit_assistance/sibs/.

⁸⁶ Robert Puentes and Jennifer Thompson, *Banking on Infrastructure: Enhancing State Revolving Funds for Transportation*, Brookings Institution, September 2012, <https://www.brookings.edu/wp-content/uploads/2016/06/12-state-infrastructure-investment-puentes.pdf>.

public works projects,⁸⁷ and Dauphin County, PA, has established an infrastructure bank funded from a state tax on liquid fuels to make loans to the 40 municipalities and private project sponsors within its borders.⁸⁸

One of the biggest stumbling blocks to federally authorized SIBs has been capitalization. States can capitalize the banks using some of their apportioned and allocated highway and transit funds, and any amount of rail program funds. Under the FAST Act, capitalization of a rural project fund may now be made by a loan from the TIFIA program. Federal funds have to be matched with state funds, generally on an 80% federal, 20% state basis.

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⁸⁷ Chicago Investment Trust, <http://chicagoinfrastructure.org/>.

⁸⁸ Jeff Frantz, "Dauphin County Creates Infrastructure Bank for Road Improvements," *PennLive*, March 1, 2013, http://www.pennlive.com/midstate/index.ssf/2013/03/dauphin_county_creates_infrast.html.

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Hardrock Mining on Federal Lands

Thousands of mining operators have extracted billions of dollars worth of hardrock mineral from land now managed by the Department of the Interior's Bureau of Land Management (BLM) without being required to pay a federal royalty. In addition, some operators have abandoned hardrock mining sites and did not reclaim BLM land disturbed by their exploration, mining, and mineral processing operations.

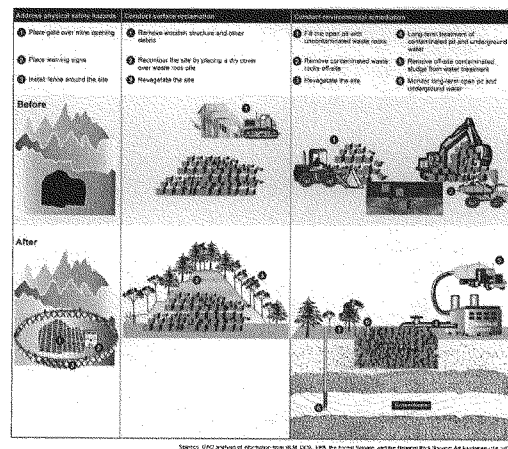
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The General Mining Act of 1872 helped open the West by allowing individuals to obtain exclusive rights to mine billions of dollars worth of hardrock minerals, including gold, silver, copper, uranium, and other valuable mineral deposits on land belonging to the United States without having to pay a federal royalty. Additional revenues could be generated by amending the General Mining Act of 1872 so that the federal government could collect federal royalties on minerals extracted from federal lands.

Regarding mine reclamation, BLM issued regulations effective in 1981 requiring all operators of hardrock mines to reclaim the land disturbed by mining when operations cease. BLM amended the regulations in 2001 to require all mining operations to provide bonds or other financial assurances before beginning exploration or mining operations on BLM land. Prior to these regulatory changes, some operators left BLM with many thousands of acres of unreclaimed land, some of which posed environmental and health and safety risks. Having adequate financial assurances to pay reclamation costs for BLM land disturbed by hardrock operations is critical to ensuring that the land is reclaimed if the mining operators fail to do so.

Figure 1: Examples of Cleanup Activities That Could Take Place at Abandoned Uranium Mine Sites



Sources: GAO analysis of information from BLM, DOE, EPA, the Forest Service, and the Department of the Interior. All landscape (top left).

Note: This figure is illustrative and does not include all possible activities that may take place based on site-specific conditions.

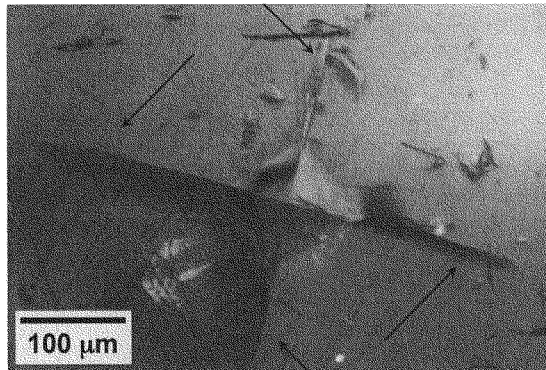
For more on GAO's reports and recommendations, see the key reports tab above.

7/18/2019

Toward all-solid lithium batteries | MIT News

MIT News

ON CAMPUS AND AROUND THE WORLD



Using specialized equipment, the MIT team did tests in which they used a pyramidal-tipped probe to indent the surface of a piece of the sulfide-based material. Surrounding the resulting indentation (seen at center), cracks were seen forming in the material (indicated by arrows), revealing details of its mechanical properties.

Courtesy of the researchers

Toward all-solid lithium batteries

Researchers investigate mechanics of lithium sulfides, which show promise as solid electrolytes.

David L. Chandler | MIT News Office
February 2, 2017

Most batteries are composed of two solid, electrochemically active layers called electrodes, separated by a polymer membrane infused with a liquid or gel electrolyte. But recent research has explored the possibility of all-solid-state batteries, in which the liquid (and potentially flammable) electrolyte would be replaced by a solid electrolyte, which could enhance the batteries' energy density and safety.

Now, for the first time, a team at MIT has probed the mechanical properties of a sulfide-based solid electrolyte material, to determine its mechanical performance when incorporated into batteries.

The new findings were published this week in the journal *Advanced Energy Materials*, in a paper by Frank McGrogan and Tushar Swamy, both MIT graduate students; Krystyn Van Vleet, the Michael (1949) and Sonja Koerner Professor of Materials Science and Engineering; Yet-Ming Chiang, the Kyocera Professor of Materials Science and Engineering; and four others including an undergraduate participant in the National Science Foundation Research Experience for Undergraduate (REU) program administered by MIT's Center for Materials Science and Engineering and its Materials Processing Center.

Lithium-ion batteries have provided a lightweight energy-storage solution that has enabled many of today's high-tech devices, from smartphones to electric cars. But substituting the

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conventional liquid electrolyte with a solid electrolyte in such batteries could have significant advantages. Such all-solid-state lithium-ion batteries could provide even greater energy storage ability, pound for pound, at the battery pack level. They may also virtually eliminate the risk of tiny, fingerlike metallic projections called dendrites that can grow through the electrolyte layer and lead to short-circuits.



Faculty highlight:
Krystyn Van Vliet

"Batteries with components that are all solid are attractive options for performance and safety, but several challenges remain," Van Vliet says. In the lithium-ion batteries that dominate the market today, lithium ions pass through a liquid electrolyte to get from one electrode to the other while the battery is being charged, and then flow through in the opposite direction as it is being used. These batteries are very efficient, but "the liquid electrolytes tend to be chemically unstable, and can even be flammable," she says. "So if the electrolyte was solid, it could be safer, as well as smaller and lighter."



Finding a needle in a
haystack

But the big question regarding the use of such all-solid batteries is what kinds of mechanical stresses might occur within the electrolyte material as the electrodes charge and discharge repeatedly. This cycling causes the electrodes to swell and contract as the lithium ions pass in and out of their crystal structure. In a stiff electrolyte, those dimensional changes can lead to high stresses. If the electrolyte is also brittle, that constant changing of dimensions can lead to cracks that rapidly degrade battery performance, and could even provide channels for damaging dendrites to form, as they do in liquid-electrolyte batteries. But if the material is resistant to fracture, those stresses could be accommodated without rapid cracking.



Exploring the inner
workings of materials

Until now, though, the sulfide's extreme sensitivity to normal lab air has posed a challenge to measuring mechanical properties including its fracture toughness. To circumvent this problem, members of the research team conducted the mechanical testing in a bath of mineral oil, protecting the sample from any chemical interactions with air or moisture. Using that technique, they were able to obtain detailed measurements of the mechanical properties of the lithium-conducting sulfide, which is considered a promising candidate for electrolytes in all-solid-state batteries.

"There are a lot of different candidates for solid electrolytes out there," McGrogan says. Other groups have studied the mechanical properties of lithium-ion conducting oxides, but there had been little work so far on sulfides, even though those are especially promising because of their ability to conduct lithium ions easily and quickly.

Previous researchers used acoustic measurement techniques, passing sound waves through the material to probe its mechanical behavior, but that method does not quantify the resistance to fracture. But the new study, which used a fine-tipped probe to poke into the material and monitor its responses, gives a more complete picture of the important properties, including hardness, fracture toughness, and Young's modulus (a measure of a material's capacity to stretch reversibly under an applied stress).

"Research groups have measured the elastic properties of the sulfide-based solid electrolytes, but not fracture properties," Van Vliet says. The latter are crucial for predicting whether the material might crack or shatter when used in a battery application.

The researchers found that the material has a combination of properties somewhat similar to silly putty or salt water taffy: When subjected to stress, it can deform easily, but at sufficiently high stress it can crack like a brittle piece of glass.

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By knowing those properties in detail, "you can calculate how much stress the material can tolerate before it fractures," and design battery systems with that information in mind, Van Vliet says.

The material turns out to be more brittle than would be ideal for battery use, but as long as its properties are known and systems designed accordingly, it could still have potential for such uses, McGrogan says. "You have to design around that knowledge."

"The cycle life of state-of-the-art Li-ion batteries is primarily limited by the chemical/electrochemical stability of the liquid electrolyte and how it interacts with the electrodes," says Jeff Sakamoto, a professor of mechanical engineering at the University of Michigan, who was not involved in this work. "However, in solid-state batteries, mechanical degradation will likely govern stability or durability. Thus, understanding the mechanical properties of solid-state electrolytes is very important," he says.

Sakamoto adds that "Lithium metal anodes exhibit a significant increase in capacity compared to state-of-the-art graphite anodes. This could translate into about a 100 percent increase in energy density compared to [conventional] Li-ion technology."

The research team also included MIT researchers Sean Bishop, Erica Eggleton, Lukas Porz, and Xinwei Chen. The work was supported by the U.S. Department of Energy's Office of Basic Energy Science for Chemomechanics of Far-From-Equilibrium Interfaces.

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Hardrock Mining on Federal Lands

Thousands of mining operators have extracted billions of dollars worth of hardrock mineral from land now managed by the Department of the Interior's Bureau of Land Management (BLM) without being required to pay a federal royalty. In addition, some operators have abandoned hardrock mining sites and did not reclaim BLM land disturbed by their exploration, mining, and mineral processing operations.

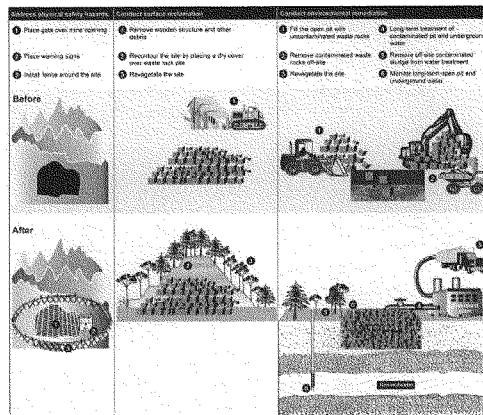
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The General Mining Act of 1872 helped open the West by allowing individuals to obtain exclusive rights to mine billions of dollars worth of hardrock minerals, including gold, silver, copper, uranium, and other valuable mineral deposits on land belonging to the United States without having to pay a federal royalty. Additional revenues could be generated by amending the General Mining Act of 1872 so that the federal government could collect federal royalties on minerals extracted from federal lands.

Regarding mine reclamation, BLM issued regulations effective in 1981 requiring all operators of hardrock mines to reclaim the land disturbed by mining when operations cease. BLM amended the regulations in 2001 to require all mining operations to provide bonds or other financial assurances before beginning exploration or mining operations on BLM land. Prior to these regulatory changes, some operators left BLM with many thousands of acres of unreclaimed land, some of which posed environmental and health and safety risks. Having adequate financial assurances to pay reclamation costs for BLM land disturbed by hardrock operations is critical to ensuring that the land is reclaimed if the mining operators fail to do so.

Figure 1: Examples of Cleanup Activities That Could Take Place at Abandoned Uranium Mine Sites



Note: This figure is illustrative and does not include all possible activities that may take place based on site-specific conditions.

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Mining and Environmental Health Disparities in Native American Communities

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Abstract

Purpose of Review

More than a century of hard rock mining has left a legacy of >160,000 abandoned mines in the Western USA that are home to the majority of Native American lands. This article describes how abrogation of treaty rights, ineffective policies, lack of infrastructure, and a lack of research in Native communities converge to create chronic exposure, ill-defined risks, and tribal health concerns.

Recent Findings

Recent results show that Native Americans living near abandoned uranium mines have an increased likelihood for kidney disease and hypertension, and an increased likelihood of developing multiple chronic diseases linked to their proximity to the mine waste and activities bringing them in contact with the waste. Biomonitoring confirms higher than expected exposure to uranium and associated metals in the waste in adults, neonates, and children in these communities.

Summary

These sites will not be cleaned up for many generations making it critical to understand and prioritize exposure-toxicity relationships in Native populations to appropriately allocate limited resources to protect health. Recent initiatives, in partnership with Native communities, recognize these needs and support development of tribal research capacity to ensure that research respectful of tribal culture and policies can address concerns in the future. In addition, recognition of the risks posed by these abandoned sites should inform policy change to protect community health in the future.

Keywords: Abandoned mines, Native Americans, Environmental health, Environmental justice, Heavy metals, Environmental policy

Introduction

Contamination of soil and water by waste from more than 160,000 abandoned hard rock mines throughout the Western USA (operationally defined to include Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, South Dakota, Utah, Washington, and Wyoming) has created a legacy of chronic exposures to metal mixtures in Native American communities. Biomonitoring in the Strong Heart Study cohort which included Native Americans from these Western states supports increased metal exposures by identifying unique patterns of elevated metal mixtures relative to several other races in urban, suburban, and rural settings [1]. The political and social context in which these exposures developed highlights a history of environmental injustices based in clashes of cultural values, and political and ethical failures to support negotiated treaty rights. Understanding the health impacts of these exposures is complicated by a lack of understanding of the toxicity of metals in complex mixtures in any population, exacerbated by a general lack of environmental health studies in Native populations in particular. In addition, many of the Native communities in proximity to these waste sites have numerous risk factors associated with disparities in health outcomes such as poverty, educational status, infrastructure, and frequently, compromised underlying health status. Further complications to predicting toxicological responses arise from the traditional and subsistence lifestyles of many Native communities that create distinct exposure patterns not captured in the assumptions of standard suburban, recreational, or occupational exposure scenarios used for risk assessments [2]. Traditional lifestyles, such as eating or harvesting local plants for sustenance, ceremonial or medicinal purposes, or drinking from historically used water sources may result in greater than predicted exposures of Native Americans to mine wastes now contaminating these sources.

The impacts of the waste on tribal nations are not likely to resolve for generations to come. In addition to the number of sites and estimated clean-up costs that exceed any available resources, the sheer volume of wastes at these sites is a barrier. Laguna Pueblo's Jackpile Mine Superfund site alone is greater than 34 km² including disturbance of more than 12 km² [3]. Geochemical and physical factors complicate understanding mobility and challenge technological remediation strategies as the complexities in mixture composition and geochemistry produce varying results across sites. Removal of waste is complicated by the hazards inherent in transport of such large volumes of hazardous materials through communities, and in the case of uranium, by the fact that the mixture of toxic and radioactive metals creates a mixed waste with limited disposal options. This paper will highlight the framework in which these health, political, social, and environmental factors converge to create ongoing uncertainty about tribal health and to discuss new initiatives to reduce these uncertainties for generations likely to face these risks well into the future.

Treaty Rights vs. Mining Interests on Tribal Lands

Through various treaties developed between Native American tribes and the US Government, the tribes ceded vast amounts of their traditional land base in exchange for recognition of their sovereign status to self-government and commitments to ensure protection of their health and culture. Through these treaties, certain regions of the country were set aside as Tribal "Reservations"—lands over which a tribe had sovereignty. As mineral resources were identified on those lands, ethical and legal responsibilities set in the treaties were abrogated by the US government to provide access for mining by successively shrinking the area of lands designated to each tribe; by legislating in the 66th Congress the leasing of tribal lands in the Western USA by individuals and corporations for purposes of mineral extraction for 20 years, renewable in successive 10 year periods; and by prohibiting in a 1919 law the creation of any future Reservations on Public Lands through executive orders of the President [4]. In *If You Poison Us*, Peter Eichstaedt's comprehensive review of congressional debates and policies leading up to this legislation describes discussions indicating that the creation of Reservations by Executive Order on lands holding such vast reserves of minerals would never have been allowed had Congress

been aware of those reserves [5•]. In 1902, Indian Affairs Commissioner William Jones argued that land should not be set aside exclusively for Native American use and the more than 200,000 km² currently in Reservations should be “thrown open as rapidly as possible”, acknowledging that the treaties made it necessary for Congress to “treat with them” before opening their lands to settlement, and therefore Congress should use some arbitrary means to open the land [6•].

The 1919 legislation provided for 5% of the net value of the extracted resources paid to the USA “for benefit of the Indians” to be deposited in the Treasury to the credit of those Indians having tribal rights to lease land, but at all times subject to “appropriation by Congress for their benefit”. However, documented shadow accounting by mining companies reduced that net value and therefore the amount paid into those accounts [5•]. The continued disregard for the ethical and legal guarantees of the treaties resulted in long-term mismanagement of Native American Tribal Trust funds by the US government and further limited tribal benefits. Nearly a century later, between 2009 and 2016, the US Attorney General and Secretary of the Interior reached settlements with more than 100 tribes totaling \$3.3 billion USD for mismanagement of monetary and natural resource assets held in trust by the USA for the benefit of the tribes [7]. These settlements, however, do not come close to addressing the mining legacy. A recent \$1 billion USD settlement from Tronox awarded to the Navajo Nation has been estimated sufficient to address remedial action of only ~10% of the 3.6 billion kg of uranium mine waste on Navajo Nation alone [8]. The 520 abandoned uranium mines on Navajo represent less than 12% of the more than 4000 abandoned uranium mines in the Western USA, and an even smaller fraction of the more than 161,000 abandoned hard rock mines in the Western USA. These numbers provide a perspective on the scope of the problem being faced by tribal communities.

Scope of the Problem and Ongoing Threats

As a result of the disregard of treaty rights, lands on and proximal to Native lands in the Western states (Fig. 1) were extensively mined for metals such as gold, silver, lead, copper, molybdenum, and vanadium since the mid-1800s and uranium since the 1940s. As deposits played out and demand for specific metals declined, the mines were abandoned—resulting in more than 160,000 abandoned hard rock mines (not including coal) in the Western states [9], more than 4000 of which are abandoned uranium mines (AUMs) [10]. Today, more than 4.1 million Native Americans live in the Western USA, 478,000 on Reservation lands [11]. Combining US Census information [11] and a gridded population dataset [12], we estimated that more than 600,000 Native Americans live within 10 km of an abandoned mine (Table 1). Potential associated contaminants of concern for Native Americans within 10 km based on the primary metal mined are listed in Table 1. In addition, depending on the process, chemicals such as cyanide, sulfate, nitrate, and others used in ore extraction could remain in the waste or water sources. Population estimates based on census data assume inclusion of tribal members in the Census pool. While estimates of accuracy of count for the most recent census are not yet available, previous estimates have indicated an undercount of Native Americans ranging from 5% [13] to nearly 20% [14].

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Mining and Environmental Health Disparities in Native American Communities

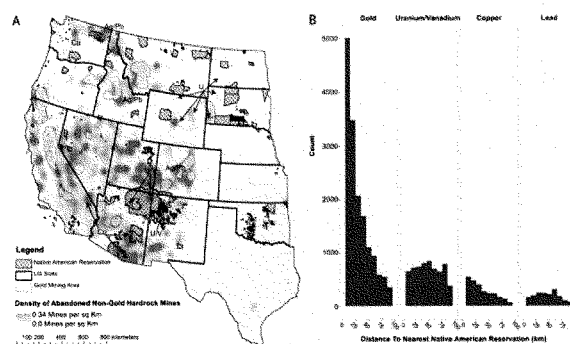


Fig. 1

a Density of hard rock metallic mines in the Western USA. Native American Reservation land is indicated by *hatched polygon areas*, and mine densities are associated with intensity of *red hues*. The predominate commodity type is also indicated on the map by its *chemical symbol* (*Au* [Gold]; *Pb* [Lead]; *U* [Uranium]; *V* [Vanadium]; *Cu* [Copper]). b Histogram of distance between hard rock mines (by primary commodity type) and the nearest Native American Reservation

Table 1

Summary of common metals and metalloids associated with waste from mines and an estimate of the number of Native Americans living within 10 km of each mine type

Hard rock metal mine type	Common metal contaminants of concern	Estimated count of Native Americans living <10 km from mine type
Gold	Arsenic, cadmium, cobalt, copper, mercury, nickel, lead, zinc [15, 16]	417,846 people
Uranium/vanadium	Arsenic, copper, molybdenum, nickel, selenium, uranium, vanadium [17, 18]	286,346 people
Copper	Arsenic, cadmium, copper, iron, nickel [19–21]	243,722 people
Lead	Arsenic, cadmium, chromium, manganese, lead, zinc [22–25]	116,925 people

Additional associated exposure sources include ore transfer stations, waste piles, mill tailings piles, and areas affected by spills, resulting in more than 500,000 discrete contamination sources [2]. Sites are most often unmarked, unfenced, and located only through historical memory or mining records. Using available geospatial information on mineral extraction from the US Mineral Resources Data System [26], Fig. 1 visually highlights the proximity of reservation land to these mining regions.

Although tribal control of mineral resource leasing and extraction has strengthened during the twentieth century due to laws such as the Indian Mineral Development Act of 1982 and the 2001 Bureau of Land Management Rule 3809 [27], the General Mining Law of 1872 remains in effect as the overarching regulation. The location of abandoned mines within tribal watersheds and the lack of environmental protections in the 1872 Mining Law has left a legacy for exposure not only through direct contamination of tribal lands, but through continuing drainage of contaminated mine water. Impoundments of untreated mine waste and water are designated as waste treatment systems, which exempts many bodies of water from Clean Water Act regulations [28]. This designation supported by the 1872 Mining Law allows discharge of untreated mine waste into surface water and has resulted in contamination of an estimated 40% of the headwaters of Western US watersheds [29], water sources still relied on by virtually all Native American tribes for survival and cultural preservation [28].

The Gold King Mine Spill in 2015 was but an example of the implications this legacy poses throughout watersheds in the West. In that spill, 11,300 m³ of contaminated mine water breached containment from the abandoned Gold King Mine in Southern Colorado, carrying lead, arsenic, and other metals (see Table 1) through Ute and Navajo tribal lands as well as non-tribal lands along the San Juan River [16], leading Navajo Nation to file a lawsuit against USEPA [30]. Releases from abandoned gold mines have also contaminated waters and lands of tribes including, among others, Fort Belknap in north-central Montana and numerous tribal lands in California, Colorado, Nevada [31–33] and South Dakota (see “Case Study 1” below).

The threats to tribal lands, however, are not only from legacy mines. New mines continue to be fought by tribal communities as illustrated by legal actions taken by the Western Shoshone Tribe in Nevada [31], the Menominee Tribe along the Michigan-Wisconsin border [34] and Navajo communities [35]. Pressure to open new uranium mines led Navajo Nation to pass the Natural Resources Protection Act of 2005 banning uranium mining and processing within Navajo Indian Country as the Fundamental Laws of the Diné indicate substances in the Earth harmful to the people should not be disturbed [36].

Sociodemographic and Infrastructure Risk Factors in Native Communities

Without proper understanding of toxicity and factors controlling it in Native American populations, the risks represented by these wastes remain ill-defined. Native Americans have lower life expectancy and more health challenges than other populations in the USA. Data compiled by Indian Health Services (2007–2009) and other entities illustrate the significant health disparities observed within these communities (Table 2). These disparities are frequently attributed to genetic susceptibility, and while some studies show mutations in individuals with a specific disease, the lack of population genetic data defining prevalence questions this assumption [37•]. The persistence of disparities in virtually all prevailing diseases across multiple language groups suggests other contributors to these outcomes, such as social determinants, underexplored disparities in environmental exposures and response to toxic insults, or gene-environment interactions [38].

Table 2

Summary of key health disparity measures for the Native American population in the USA

Health measure	Native American disparity
Suicide	Rate is 2.5 times higher for Native youth [39].
Infectious disease mortality	40–60% higher than all races in the USA [40]
Diabetes and liver disease mortality	2.8–4.7 times higher than all races in the USA [41]
Infant mortality	28% higher than non-Hispanic whites [42]
Overall mortality (0–44 years old)	2.23–2.69 times greater than non-Hispanic whites [43]
Birth defects	50% higher prevalence in Native Americans [40]
Life expectancy	4.4 years lower for Native Americans [39, 40]

Experimental and epidemiologic data support the association between exposure to toxic metals and increased risk for a variety of negative health outcomes including kidney and cardiovascular disease, neurocognitive disorders, and various cancers in both Native and non-Native populations [44–56]. Cancer mortality rates for the Native American population increased over a 20-year period (1990–2009), while decreasing for Whites during the same time [43]. Two prospective studies have specifically linked exposure to the metals cadmium and arsenic to cancer mortality in Native populations [53, 56]. Preliminary epidemiologic data document nearly 4 out of every 10 residents of the Wind River Reservation of Eastern Shoshone and Northern Arapaho have a blood relative who has died of cancer [57]. Wind River was the site of a former uranium mill and the remediated waste pile remains in the community. The preliminary report falls short of making a direct association but reinforces their concern that the waste is adversely affecting health [57, 58]. In 1988, US DOE found soil, surface water, and shallow groundwater on Wind River Reservation were contaminated with uranium, radium, and thorium and chose to use natural attenuation to reduce the contamination over time. However, following floods in 2010, monitoring wells showed uranium spikes as high as 100 times the USEPA Maximum Contaminant Level (MCL) for drinking water (0.03 mg/L) [58]. Despite this and other reports of contamination linked to increased cancer incidence and other negative health outcomes, there remains a paucity of population studies in these Native communities. Moreover, our understanding of exposure-toxicity relationships in Native communities continues to be limited by our general lack of understanding of the toxicity of any complex mixtures. Even determination of dose in Native communities can be grossly underestimated by neglecting traditional cultural practices resulting in frequent and direct contact with contaminated lands and waters, and a greater, sometimes 100%, reliance on traditional and locally grown foods [2].

Disparities in tribal infrastructure further exacerbate risk. Nearly 14% of Native households lack access to a public water system compared to 0.6% of the USA as a whole; with some tribes lacking access for more than 30% of their populations [59], creating a greater reliance on unregulated sources. Uranium MCLs are exceeded in more than 13% of unregulated wells on Navajo Nation, with arsenic exceeding the MCL in 15% and co-occurrence in 7% of wells [60]. Concentrations are strongly associated with distance from abandoned mines. Moreover, when regulated public water is available, drinking water systems in Indian country experience “significant violations” or health-based violations of Safe Drinking Water Act regulations twice as frequently as other systems [61], exceeding MCLs for various

metals, polycyclic aromatic hydrocarbons, trihalomethanes, pesticides, and nitrates. Two months prior to detection of lead in the Flint, MI, water supply, a *regulated* community drinking water supply serving the Navajo community of Sanders was found to have exceeded uranium MCLs for more than a decade as a result of migration of contaminants from a 1979 uranium mill tailings spill [62]. Although state officials were aware of the problem, in contrast to Flint, no notification to the community occurred, and no federal outcry or resources resulted. These challenges and others demonstrate the need for infrastructure [63] and that the gap in fundamental infrastructure sets a background exposure upon which other environmental exposures and health disparities are overlaid.

Case Study 1: Black Hills Gold and the Sioux Nation

For the nine tribes of the Great Sioux Nation, the Black Hills are sacred lands of their traditional homeland in the northern Great Plains. Following the Battle of Little Big Horn, the 1868 Fort Laramie Treaty between the US government and Sioux Nation guaranteed them “undisturbed use and occupation” of the Black Hills and stated that no treaty for the cession of any part of the reservation would be valid unless signed by three-fourths of the adult male Sioux population. However, when gold was discovered, those treaty rights were abandoned by US confiscation of the Black Hills in the 1877 Act, signed by fewer than 10% of the adult male Sioux population, to allow for mining. Over the next century, mining companies extracted billions of dollars in metals from these lands. Production from 1875 to 1971 reported more than 1.1 million kg of gold extracted, which even at \$1 USD per gram would exceed \$1 billion USD. The Sioux never accepted the legality of the Black Hills confiscation and sued the US government for return of the land. In 1980, the US Supreme Court upheld a decision to support the Sioux claim that US government’s decision to occupy the Black Hills constituted a “taking of tribal property” with an implied obligation for the government to make just compensation. Rather than returning the land, however, the US Supreme Court awarded the nine tribes of the Great Sioux Nation \$102 million USD as compensation for their loss. The Sioux have never collected this payment, which remains in trust and now exceeds \$1.3 billion USD [64].

Why would some of the poorest tribes in the country, with unemployment rates as high as 80%, turn down such a large sum of money? The award of financial compensation misses many key points central to the disputes between the tribes and the federal government. First, the suit was never about money but about the return of lands central to the spirit of the Sioux Nation. Second, the value is small relative to the profit made from both the land and resource extraction in the intervening years. Third, to take money for the land is acknowledging a real estate transaction, and in the words of former Oglala president Teresa Two Bulls “If we accept the money, then we have no more of the treaty obligations that the federal government has with us for taking our land, for taking our gold, all our resources out of the Black Hills ... we’re poor now, we’ll be poorer then when that happens,” [64]. While the Sioux and the federal government continue to seek a compromise, the legacy of the Black Hills mining continues to pose concerns for the health of the Sioux.

As illustrated in Fig. 1, more than 10,000 abandoned gold mines are on or near Native American Reservation lands throughout the Western USA. In the Black Hills, there are hundreds of gold mines but few as profitable as the Homestake Mine near Lead, which produced more than 964,000 kg of the 1.1 million kg reported for the Black Hills from 1875 to 1971 [65]. Homestake discharged high concentrations of arsenic from their mill directly into the Cheyenne River drainage for decades [66] contaminating 29 km of downstream creeks that received Superfund action for arsenic contaminated soil, sediments, and water. Although the site was removed from the National Priorities List in 1996, there remains a band of arsenic-containing sediment in the Cheyenne River banks and floodplains that form the southern boundary of the Cheyenne River Sioux Tribe Reservation (more than 250 km downstream) [67]. While the arsenic-contaminated sediment in the banks has been buried by years of deposition since the closure of the mine in 2002, intermittent floods during operational years deposited

contaminated sediment that remains in surface soils of lands used for agriculture, ranching, and ceremonial purposes as far as 1 km from the river (*personal communication*, Dec. 2016, C. Ducheneaux, Department of Environment and Natural Resources, Cheyenne River Sioux Tribe).

Within the Cheyenne River Sioux, antinuclear antibody (ANA) prevalence exceeds that found in the US population, with occurrence predicted by the proximity to the arsenic deposits [68]. While the presence of ANA does not alone indicate frank autoimmune disease, an associated elevated prevalence of several specific autoantibodies was also observed [68]. ANAs serve as early serologic markers in a variety of autoimmune diseases [69–71] and have also been linked to mercury exposure from Amazonian gold mines, to consumption of fish contaminated with methylmercury, and to drinking arsenic contaminated water [72–76].

The arsenic is located in the floodplains where gathering of fruit for sustenance and herbs for medicinal, traditional, and ceremonial practices has been documented as well as other traditional land use practices that create direct exposure pathways through ingestion, inhalation, and dermal contact. These uses raise ethical and policy issues around how exposure and health are evaluated. If standard exposure assessment assumptions interpreted through extant health research are applied to a Native community practicing a traditional lifestyle, such as the Cheyenne River Sioux, results may underestimate exposure [2]. Secondly, not only are data on response to toxicants limited for Native Americans, the definition of health itself may differ substantially between the cultures with regulatory agencies interpreting health from a Western disease model and the tribal population using a more holistic view based their belief of interconnection between people, their ecosystem, and their well-being [77•]. Our team is currently working with the CRST to understand the mobility of the Homestake arsenic; evaluate human exposure through ceremonial, traditional, ranching, and recreation activities; and assess the contribution of exposure to the high prevalence of autoimmune markers observed in those living in the floodplain [68].

Case Study 2: Uranium and the Navajo Nation

Uranium mines present a special subset of abandoned hard rock mines resulting from the Cold War and associated political stressors. Although reservations encompass only 5.6% of land area in the Western USA, approximately one in five uranium mines are located within 10 km of a Native American Reservation with more than 75% (more than 3200 of the 4600) within 80 km (Fig. 1). This does not include lands traditionally used by the tribes or lands feeding tribal water- and airsheds. Figure 1 highlights areas where uranium was the dominant ore extracted and illustrates that multiple tribes are affected by AUMs, including Navajo Nation in the Four Corners region, multiple Sioux tribes in the Black Hills region, Northern Arapahoe and Eastern Shoshone at Wind River in Wyoming, and several tribes including the Spokane in Washington State.

The development of the atomic bomb and the subsequent nuclear arsenal that fueled the Cold War led to prioritization of uranium mining above protection of human health, as well documented by Eichstaedt in *If You Poison Us* [5•]. Vanadium, which occurs in combination with uranium in carnotite, was mined on Navajo as early as 1902 to support steel hardening. The Manhattan Project's need for uranium made the repurposing of these mines expedient and led to government action to promote uranium exploration without regard for protection of human health. The hazards of radiation were recognized since the 1920s, and increased respiratory disease and lung cancer in European uranium miners was well known by the US Atomic Energy Commission (AEC) and others from the findings of lung cancer and respiratory disease in European miners. However, the AEC was reluctant to set standards within mines or take any other measures to protect miners' health, fearing that public awareness of the dangers in the mines would limit their ability to obtain uranium. Following the US Public Health Service's (PHS) requests to set safety standards, the AEC set standards of 10 pCi/L in all operations *except* uranium mines; after lengthy debate, a standard of 100 pCi/L in uranium mines was

set in 1967—23 years after the beginning of uranium mining on the Navajo Nation and 17 years after the first US Public Health Service uranium miners' health study identified respiratory risks. It would be another 33 years before these details were made public and the US Congress passed the Radiation Exposure Compensation Act (RECA) that would begin a process of compensating those affected. Compensation of Navajo miners was slowed significantly, however, as a result of barriers in the law requiring documentation of births, marriages, and death records not routinely kept within the tribe and the restriction of compensable health effects to lung cancer only. The law has been revised only once, in 2000, to incorporate additional compensable diseases and include uranium mill workers [78], while additional revisions to compensate miners who worked after the government turned over mine safety to the private sector in 1971 remain in limbo.

As late as 1991–2005, 25% of the deaths in the 4137 former uranium miners followed by US PHS were attributed to lung cancer, with Native miners at triple the expected rate [79]. Native miners bore a disproportionate burden of non-malignant respiratory disease as well. Their rate of pneumoconiosis was as much as fourfold higher than in non-Hispanic whites (NHW), and they also had an increased risk of restrictive lung disease and decreased FEV₁ [80]. For Navajo miners, underground uranium mining was the primary contributor to non-malignant disease including obstructive lung disease, while in non-Native populations, smoking was the major contributor. More than 70% of Navajo miners had never smoked (compared to 23% of NHW miners) [80]. However, compensation through the government's Radiation Exposure Compensation Act, discriminated against Native miners by requiring, in addition to radiographic evidence of lung damage, a second measure of spirometry less than 75% of a comparison value derived from a NHW population. Clinical researchers demonstrated that using that criterion to determine loss of function resulted in exclusion of 24% of Native miners who would qualify with a 75% reduction in lung function if Native American-based function formulas were used [80]. Other studies concluded that Colorado Plateau Native American uranium miners disproportionately suffer excess mortality risks from lung cancer [81, 82]. Native Americans were a substantial portion of the underground workforce, and it has been argued that the observed differences in effect related to a higher exposure. Disease rates reported above, however, were corrected for exposure, and Native miners were shown to have significantly *lower* average lifetime mining exposure than NHWs and Hispanics [80]. As many as 4000 Navajo men worked in the uranium mines and mills and hundreds of Navajo miners died and continue to die of lung cancer and other respiratory disease [83, 84], essentially wiping out a generation of Navajo men in some communities and leaving a legacy of psychological and environmental trauma [84]. The increased toxicity to Native miners underscores the potential for unique sensitivities to toxicants within the Native community as compared to all races results, questioning the derivation of standards on the basis of data collected from other populations.

While the fights over RECA proceeded, people living in Navajo communities continued to be chronically exposed to waste from the 520 abandoned uranium mines, 4 abandoned uranium mills, and more than 1100 waste sites [85] in and proximal to their communities. Uranium mine waste presents a unique hazard resulting from the associated radioactive decay chain introducing additional contaminants including radium, thorium, and radon to the already complex mixture of associated metals often including, for example, arsenic, cadmium, and lead [86]. The lack of regulation and security of waste associated with these facilities and abandoned sites, as well as lack of concern during the operational phase led to the use of contaminated material in the construction of homes [85], as well as contamination of water sources potentially used for drinking [59]. Looking at >1300 Navajo community members with and without exposure to uranium mine waste, we find a significant strong association between exposures occurring during the active mining era (1940s–1980s) and later development of kidney disease, exposure more than doubling the odds ratio. For those exposed to legacy waste, controlling for the mining era exposures, exposure is significantly associated with an increased likelihood of hypertension and of developing one or more chronic diseases including hypertension, diabetes, and kidney disease [87•]. Serum from a subset of >200 individuals from that

cohort, representing a full range of exposure, showed a significant inverse relationship between inflammatory potential in cellular bioassays and distance from legacy waste sites consistent with induction of pathways that contribute to atherosclerosis and cardiovascular disease [88]. While risk factors traditionally considered for these diseases clinically were also significant predictors, these results underscore the need for clinicians to probe for information about exposure as well in identifying those at risk.

Ongoing Concern for Future Generations

Among Native communities, there is concern about not only the health of people living in impacted communities today but also the health of generations yet to come. The Women of All Red Nations (WARN) worry that uranium mining may contribute to high rates of miscarriage and reproductive cancers observed among Lakota women [89]. While studies of direct impacts of mine waste exposures on tribal lands have been extremely limited, several recent initiatives are beginning to fill these gaps.

A 1981 study in Navajo babies showed that congenital anomalies, developmental disorders, and other adverse birth outcomes were associated with maternal proximity to uranium mining operations, tailings, or mine dumps [90]. Uncertainties in these results were not followed up until 2010 when the Navajo Birth Cohort Study (NBCS) [37, 91] was initiated as part of a Congressional Five-Year Plan to Address Uranium Contamination on Navajo [92]. The NBCS is a prospective assessment of the effect of exposure to uranium and co-occurring metals in mine waste on birth outcomes and neurodevelopment through 1 year of age conducted as a partnership with the University of New Mexico, Southwest Research Information Center, Navajo Nation Indian Health Service, Navajo Nation Department of Health, and funders CDC/ATSDR. This is the first prospective birth cohort addressing the impacts of environmental contamination on birth outcomes in a Native population. Preliminary data confirm exposures to uranium prenatally and over the first year of life. The recently funded NIH National Environmental Influences on Child Health Outcomes (ECHO) initiative will include both the NBCS and a Sioux cohort in this national synthetic cohort of more than 50,000 children, allowing assessment of the relationship of metal exposure, neurodevelopment, and other outcomes through at least age 5. ECHO will also allow determination of unique sensitivities within these tribal populations through comparisons of exposure-toxicity relationships across cultures, races, and lifestyles.

Two of five NIEHS/NIMHD/USEPA P50 Centers of Excellence in Environmental Health Disparities funded in 2015 focus on multiple Native American populations and metals exposures. These centers will also help to identify unique exposure pathways, understand the biogeochemical characteristics of metal mixtures, and document mechanisms of toxicity.

These multigenerational studies using common methods and involving Native American communities in data collection and interpretation at all stages begin to answer the longstanding questions on health, and, importantly, to build capacity for investigation of these questions by tribal researchers.

Ethical, Scientific, and Policy Challenges to Increasing Native American Research

To fully understand the impacts of abandoned mine waste and to inform policies that protect tribal populations from future adverse health impacts, the body of scientific studies will need to incorporate more tribal studies, incorporate cultural and traditional practices into assessments of toxicity, and better understand unique responses in these populations. This broader inclusion, however, comes with its own challenges.

The recognition of treaties granting sovereign status to tribal nations within the USA brings with it rights of tribes to control the research process through their own institutional review boards, to mandate that all data and specimens generated through research remain the property of the tribe, and to mandate conditions for data sharing and certain types of analyses, such as genetic analyses. Recent requirements

of the US National Institutes of Health (NIH), the major funders of health research in the USA, require sharing of all data collected with public funds, and often require investigators to obtain consent for genetic analyses, creating cultural conflicts between the tribes and research funders. Models are emerging, however, that show these issues are not insurmountable. Alaska Natives have developed a biospecimen and data repository that stores all samples and data collected on Alaska Natives and controls future use through a board on which Alaska Natives are in the majority [93]. NIH recognition of the importance of these concerns is supported by their creation of a Tribal Research Office within the office of the director, currently led by a Native molecular biologist [94].

Tribal demands previously seen as challenging, such as involvement of tribal communities in all phases and aspects of research; insistence on honest communication of research goals and progress throughout the study; and ensuring research has benefits for tribal communities by informing policy for improved health care and prevention of future health impacts are now consistent with best practices for environmental health studies as discussed in the Ethics Guidelines for Environmental Epidemiologists [95]. While recognition of the need to include tribal populations in research has grown in the federal agencies and research community, grant reviewers even recently have expressed ethical concerns over funding research in Native American populations because it will not be generalizable. Additional education and guidance to point out the ethical fallacy in the current practice of generalizing dominant culture results to policies affecting tribal populations may be necessary before equity is achieved.

Conclusions and Future Research Directions

The abandoned mines on and near Native lands in the Western USA are but one in an ongoing series of insults. The sheer number of mines and the volumes of waste guarantee that the legacy will persist for generations to come. In addition, the mines present only one chapter in the history of environmental injustices on Native lands. Similar articles could be written focusing on impacts to tribal lands from coal strip mining, from the legacy of military bases, and from oil and gas development. The support from thousands representing tribes across the country for the Standing Rock Sioux camp opposing the Dakota Access Pipeline in 2016 is indicative of the common theme felt by tribes not only in the Western USA but throughout the country and the world where treaty rights to protect health and culture have been continually challenged and eroded in favor of resource development.

In spite of the recognized threats to tribal health posed by these ongoing toxicant exposures, and the demonstrated risk factors that put tribal populations in a position of increased vulnerability, research to understand the health impacts has been hampered by the small sizes of the communities, reviewers concerns about generalizability of results, and in some cases by the distrust of research within tribal communities who have witnessed researchers build careers but leave nothing behind to improve the health of the population. In contrast to the identified risks, the strength and support derived from the maintenance of culture, ceremonies, and traditional lifestyles may also provide a resiliency to offset some of the adverse effects. Understanding how these factors interact is critical to designing effective interventions to protect health benefitting all populations.

The history of mining in the Western USA and the legacy that affects so many Native American communities highlight the need for not only better inclusion of tribal populations in toxicologic studies but also in using these data in the development of standards that ensure the cleanup of the sites is truly protective of the health of the tribes. Ongoing studies point increasingly to the fact that the mixed metal wastes from these mines continue to have multigenerational impacts to the health of Native tribes. Our work and others have shown that metals can inhibit DNA-repair processes [96, 97, 98, 99, 100] and induce immunotoxicity [101–104], providing important clues into the mechanisms by which these mixtures affect health. Through understanding the mechanisms by which these effects occur and

understanding the role of exposures in the health disparities seen in these communities, effective interventions can be designed to protect populations for the decades likely to remain before the mine waste is removed or remediated.

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Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent

All procedures performed in cited studies involving human participants conducted by the authors were in accordance with the ethical standards of the University of New Mexico Institutional Review Board, the Navajo Nation Human Research Review Board, and the Cheyenne River Sioux Tribal Council, and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Footnotes

This article is part of the Topical Collection on *Ethics and Policy*

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Mining and Environmental Health Disparities in Native American Communities

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Abstract

Purpose of Review More than a century of hard rock mining has left a legacy of >160,000 abandoned mines in the Western USA that are home to the majority of Native American lands. This article describes how abrogation of treaty rights, ineffective policies, lack of infrastructure, and a lack of research in Native communities converge to create chronic exposure, ill-defined risks, and tribal health concerns.

Recent Findings Recent results show that Native Americans living near abandoned uranium mines have an increased likelihood for kidney disease and hypertension, and an increased likelihood of developing multiple chronic diseases linked to their proximity to the mine waste and activities bringing them in contact with the waste. Biomonitoring confirms higher than expected exposure to uranium and associated metals in the waste in adults, neonates, and children in these communities.

Summary These sites will not be cleaned up for many generations making it critical to understand and prioritize exposure-toxicity relationships in Native populations to appropriately allocate limited resources to protect health. Recent initiatives, in partnership with Native communities, recognize these needs and support development of tribal research capacity to ensure that research respectful of tribal culture and policies can address concerns in the future. In addition, recognition of the risks posed by these abandoned sites should inform policy change to protect community health in the future.

Keywords Abandoned mines · Native Americans · Environmental health · Environmental justice · Heavy metals · Environmental policy

Introduction

Contamination of soil and water by waste from more than 160,000 abandoned hard rock mines throughout the Western USA (operationally defined to include Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, South Dakota, Utah, Washington, and Wyoming) has created a legacy of chronic exposures to metal mixtures in Native American communities. Biomonitoring in the Strong Heart Study cohort which included Native Americans from these Western states supports increased metal exposures by identifying unique patterns of elevated metal mixtures relative to several other races in urban, suburban, and rural settings [1]. The political and social context in which these exposures developed highlights a history of environmental injustices based in clashes of cultural values, and political and ethical failures to support negotiated treaty rights. Understanding the health impacts of these exposures is complicated by a lack of understanding of the toxicity of metals in complex mixtures in any population, exacerbated by a general lack of environmental health studies in Native populations in particular. In addition, many of the Native communities in proximity to these waste sites have numerous risk factors associated with disparities in health outcomes such as poverty, educational status, infrastructure, and frequently, compromised underlying health status. Further complications to predicting toxicological responses arise from the traditional and subsistence lifestyles of many Native communities that create distinct exposure patterns not captured in the assumptions of standard suburban, recreational, or occupational exposure scenarios used for risk

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assessments [2]. Traditional lifestyles, such as eating or harvesting local plants for sustenance, ceremonial or medicinal purposes, or drinking from historically used water sources may result in greater than predicted exposures of Native Americans to mine wastes now contaminating these sources.

The impacts of the waste on tribal nations are not likely to resolve for generations to come. In addition to the number of sites and estimated clean-up costs that exceed any available resources, the sheer volume of wastes at these sites is a barrier. Laguna Pueblo's Jackpile Mine Superfund site alone is greater than 34 km² including disturbance of more than 12 km² [3]. Geochemical and physical factors complicate understanding mobility and challenge technological remediation strategies as the complexities in mixture composition and geochemistry produce varying results across sites. Removal of waste is complicated by the hazards inherent in transport of such large volumes of hazardous materials through communities, and in the case of uranium, by the fact that the mixture of toxic and radioactive metals creates a mixed waste with limited disposal options. This paper will highlight the framework in which these health, political, social, and environmental factors converge to create ongoing uncertainty about tribal health and to discuss new initiatives to reduce these uncertainties for generations likely to face these risks well into the future.

Treaty Rights vs. Mining Interests on Tribal Lands

Through various treaties developed between Native American tribes and the US Government, the tribes ceded vast amounts of their traditional land base in exchange for recognition of their sovereign status to self-government and commitments to ensure protection of their health and culture. Through these treaties, certain regions of the country were set aside as Tribal "Reservations"—lands over which a tribe had sovereignty. As mineral resources were identified on those lands, ethical and legal responsibilities set in the treaties were abrogated by the US government to provide access for mining by successively shrinking the area of lands designated to each tribe; by legislating in the 66th Congress the leasing of tribal lands in the Western USA by individuals and corporations for purposes of mineral extraction for 20 years, renewable in successive 10 year periods; and by prohibiting in a 1919 law the creation of any future Reservations on Public Lands through executive orders of the President [4]. In *If You Poison Us*, Peter Eichstaedt's comprehensive review of congressional debates and policies leading up to this legislation describes discussions indicating that the creation of Reservations by Executive Order on lands holding such vast reserves of minerals would never have been allowed had Congress been aware of those reserves [5••]. In 1902, Indian Affairs Commissioner William Jones argued that land should not be set aside exclusively for Native American use and the more

than 200,000 km² currently in Reservations should be "thrown open as rapidly as possible", acknowledging that the treaties made it necessary for Congress to "treat with them" before opening their lands to settlement, and therefore Congress should use some arbitrary means to open the land [6•].

The 1919 legislation provided for 5% of the net value of the extracted resources paid to the USA "for benefit of the Indians" to be deposited in the Treasury to the credit of those Indians having tribal rights to lease land, but at all times subject to "appropriation by Congress for their benefit". However, documented shadow accounting by mining companies reduced that net value and therefore the amount paid into those accounts [5••]. The continued disregard for the ethical and legal guarantees of the treaties resulted in long-term mismanagement of Native American Tribal Trust funds by the US government and further limited tribal benefits. Nearly a century later, between 2009 and 2016, the US Attorney General and Secretary of the Interior reached settlements with more than 100 tribes totaling \$3.3 billion USD for mismanagement of monetary and natural resource assets held in trust by the USA for the benefit of the tribes [7]. These settlements, however, do not come close to addressing the mining legacy. A recent \$1 billion USD settlement from Tronox awarded to the Navajo Nation has been estimated sufficient to address remedial action of only ~10% of the 3.6 billion kg of uranium mine waste on Navajo Nation alone [8]. The 520 abandoned uranium mines on Navajo represent less than 12% of the more than 4000 abandoned uranium mines in the Western USA, and an even smaller fraction of the more than 161,000 abandoned hard rock mines in the Western USA. These numbers provide a perspective on the scope of the problem being faced by tribal communities.

Scope of the Problem and Ongoing Threats

As a result of the disregard of treaty rights, lands on and proximal to Native lands in the Western states (Fig. 1) were extensively mined for metals such as gold, silver, lead, copper, molybdenum, and vanadium since the mid-1800s and uranium since the 1940s. As deposits played out and demand for specific metals declined, the mines were abandoned—resulting in more than 160,000 abandoned hard rock mines (not including coal) in the Western states [9], more than 4000 of which are abandoned uranium mines (AUMs) [10]. Today, more than 4.1 million Native Americans live in the Western USA, 478,000 on Reservation lands [11]. Combining US Census information [11] and a gridded population dataset [12], we estimated that more than 600,000 Native Americans live within 10 km of an abandoned mine (Table 1). Potential associated contaminants of concern for Native Americans within 10 km based on the primary metal

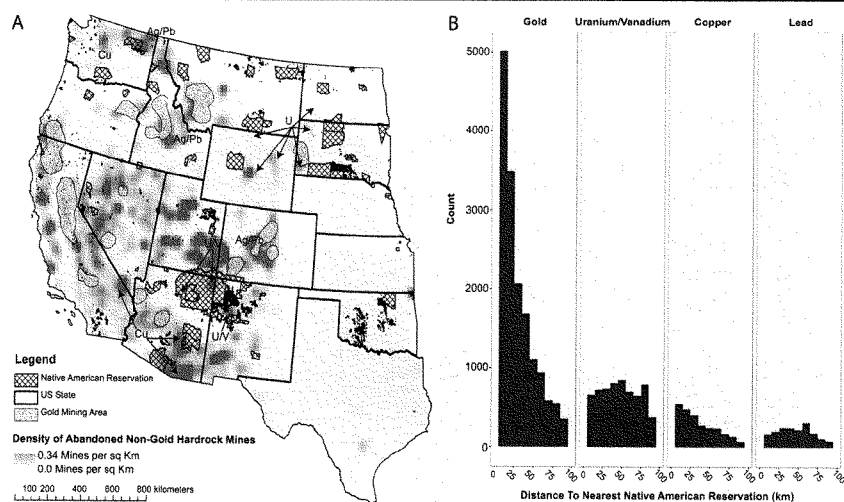


Fig. 1 a Density of hard rock metallic mines in the Western USA. Native American Reservation land is indicated by hatched polygon areas, and mine densities are associated with intensity of red hues. The predominate commodity type is also indicated on the map by its chemical symbol (Au

[Gold]; Pb [Lead]; U [Uranium]; V [Vanadium]; Cu [Copper]). b Histogram of distance between hard rock mines (by primary commodity type) and the nearest Native American Reservation

mined are listed in Table 1. In addition, depending on the process, chemicals such as cyanide, sulfate, nitrate, and others used in ore extraction could remain in the waste or water sources. Population estimates based on census data assume

inclusion of tribal members in the Census pool. While estimates of accuracy of count for the most recent census are not yet available, previous estimates have indicated an undercount of Native Americans ranging from 5% [13] to nearly 20% [14].

Additional associated exposure sources include ore transfer stations, waste piles, mill tailings piles, and areas affected by spills, resulting in more than 500,000 discrete contamination sources [9]. Sites are most often unmarked, unfenced, and located only through historical memory or mining records. Using available geospatial information on mineral extraction from the US Mineral Resources Data System [26], Fig. 1 visually highlights the proximity of reservation land to these mining regions.

Although tribal control of mineral resource leasing and extraction has strengthened during the twentieth century due to laws such as the Indian Mineral Development Act of 1982 and the 2001 Bureau of Land Management Rule 3809 [27], the General Mining Law of 1872 remains in effect as the overarching regulation. The location of abandoned mines within tribal watersheds and the lack of environmental protections in the 1872 Mining Law has left a legacy for exposure not only through direct contamination of tribal lands, but through continuing drainage of contaminated mine water. Impoundments of untreated mine waste and water are

Table 1 Summary of common metals and metalloids associated with waste from mines and an estimate of the number of Native Americans living within 10 km of each mine type

Hard rock metal mine type	Common metal contaminants of concern	Estimated count of Native Americans living <10 km from mine type
Gold	Arsenic, cadmium, cobalt, copper, mercury, nickel, lead, zinc [15, 16]	417,846 people
Uranium/vanadium	Arsenic, copper, molybdenum, nickel, selenium, uranium, vanadium [17, 18]	286,346 people
Copper	Arsenic, cadmium, copper, iron, nickel [19–21]	243,722 people
Lead	Arsenic, cadmium, chromium, manganese, lead, zinc [22–25]	116,925 people

designated as waste treatment systems, which exempts many bodies of water from Clean Water Act regulations [28]. This designation supported by the 1872 Mining Law allows discharge of untreated mine waste into surface water and has resulted in contamination of an estimated 40% of the headwaters of Western US watersheds [29], water sources still relied on by virtually all Native American tribes for survival and cultural preservation [28].

The Gold King Mine Spill in 2015 was but an example of the implications this legacy poses throughout watersheds in the West. In that spill, 11,300 m³ of contaminated mine water breached containment from the abandoned Gold King Mine in Southern Colorado, carrying lead, arsenic, and other metals (see Table 1) through Ute and Navajo tribal lands as well as non-tribal lands along the San Juan River [16], leading Navajo Nation to file a lawsuit against USEPA [30]. Releases from abandoned gold mines have also contaminated waters and lands of tribes including, among others, Fort Belknap in north-central Montana and numerous tribal lands in California, Colorado, Nevada [31–33] and South Dakota (see “Case Study 1” below).

The threats to tribal lands, however, are not only from legacy mines. New mines continue to be fought by tribal communities as illustrated by legal actions taken by the Western Shoshone Tribe in Nevada [31], the Menominee Tribe along the Michigan-Wisconsin border [34] and Navajo communities [35]. Pressure to open new uranium mines led Navajo Nation to pass the Natural Resources Protection Act of 2005 banning uranium mining and processing within Navajo Indian Country as the Fundamental Laws of the Diné indicate substances in the Earth harmful to the people should not be disturbed [36].

Sociodemographic and Infrastructure Risk Factors in Native Communities

Without proper understanding of toxicity and factors controlling it in Native American populations, the risks represented by these wastes remain ill-defined. Native Americans have lower life expectancy and more health challenges than other populations in the USA. Data compiled by Indian Health Services (2007–2009) and other entities illustrate the significant health disparities observed within these communities (Table 2). These disparities are frequently attributed to genetic susceptibility, and while some studies show mutations in individuals with a specific disease, the lack of population genetic data defining prevalence questions this assumption [37•]. The persistence of disparities in virtually all prevailing diseases across multiple language groups suggests other contributors to these outcomes, such as social determinants, underexplored disparities in environmental exposures and response to toxic insults, or gene-environment interactions [38].

Experimental and epidemiologic data support the association between exposure to toxic metals and increased risk for a variety of negative health outcomes including kidney and cardiovascular disease, neurocognitive disorders, and various cancers in both Native and non-Native populations [44–56]. Cancer mortality rates for the Native American population increased over a 20-year period (1990–2009), while decreasing for Whites during the same time [43]. Two prospective studies have specifically linked exposure to the metals cadmium and arsenic to cancer mortality in Native populations [53, 56]. Preliminary epidemiologic data document nearly 4 out of every 10 residents of the Wind River Reservation of Eastern Shoshone and Northern Arapaho have a blood relative who has died of cancer [57]. Wind River was the site of a former uranium mill and the remediated waste pile remains in the community. The preliminary report falls short of making a direct association but reinforces their concern that the waste is adversely affecting health [57, 58]. In 1988, US DOE found soil, surface water, and shallow groundwater on Wind River Reservation were contaminated with uranium, radium, and thorium and chose to use natural attenuation to reduce the contamination over time. However, following floods in 2010, monitoring wells showed uranium spikes as high as 100 times the USEPA Maximum Contaminant Level (MCL) for drinking water (0.03 mg/L) [58]. Despite this and other reports of contamination linked to increased cancer incidence and other negative health outcomes, there remains a paucity of population studies in these Native communities. Moreover, our understanding of exposure-toxicity relationships in Native communities continues to be limited by our general lack of understanding of the toxicity of any complex mixtures. Even determination of dose in Native communities can be grossly underestimated by neglecting traditional cultural practices resulting in frequent and direct contact with contaminated lands and waters, and a greater, sometimes 100%, reliance on traditional and locally grown foods [2].

Disparities in tribal infrastructure further exacerbate risk. Nearly 14% of Native households lack access to a public water system compared to 0.6% of the USA as a whole; with some tribes lacking access for more than 30% of their populations [59], creating a greater reliance on unregulated sources. Uranium MCLs are exceeded in more than 13% of unregulated wells on Navajo Nation, with arsenic exceeding the MCL in 15% and co-occurrence in 7% of wells [60]. Concentrations are strongly associated with distance from abandoned mines. Moreover, when regulated public water is available, drinking water systems in Indian country experience “significant violations” or health-based violations of Safe Drinking Water Act regulations twice as frequently as other systems [61], exceeding MCLs for various metals, polycyclic aromatic hydrocarbons, trihalomethanes, pesticides, and nitrates. Two months prior to detection of lead in the Flint, MI, water supply, a *regulated* community drinking water supply serving the

Table 2 Summary of key health disparity measures for the Native American population in the USA

Health measure	Native American disparity
Suicide	Rate is 2.5 times higher for Native youth [39].
Infectious disease mortality	40–60% higher than all races in the USA [40]
Diabetes and liver disease mortality	2.8–4.7 times higher than all races in the USA [41]
Infant mortality	28% higher than non-Hispanic whites [42]
Overall mortality (0–44 years old)	2.23–2.69 times greater than non-Hispanic whites [43]
Birth defects	50% higher prevalence in Native Americans [40]
Life expectancy	4.4 years lower for Native Americans [39, 40]

Navajo community of Sanders was found to have exceeded uranium MCLs for more than a decade as a result of migration of contaminants from a 1979 uranium mill tailings spill [62]. Although state officials were aware of the problem, in contrast to Flint, no notification to the community occurred, and no federal outcry or resources resulted. These challenges and others demonstrate the need for infrastructure [63] and that the gap in fundamental infrastructure sets a background exposure upon which other environmental exposures and health disparities are overlaid.

Case Study 1: Black Hills Gold and the Sioux Nation

For the nine tribes of the Great Sioux Nation, the Black Hills are sacred lands of their traditional homeland in the northern Great Plains. Following the Battle of Little Big Horn, the 1868 Fort Laramie Treaty between the US government and Sioux Nation guaranteed them “undisturbed use and occupation” of the Black Hills and stated that no treaty for the cession of any part of the reservation would be valid unless signed by three-fourths of the adult male Sioux population. However, when gold was discovered, those treaty rights were abandoned by US confiscation of the Black Hills in the 1877 Act, signed by fewer than 10% of the adult male Sioux population, to allow for mining. Over the next century, mining companies extracted billions of dollars in metals from these lands. Production from 1875 to 1971 reported more than 1.1 million kg of gold extracted, which even at \$1 USD per gram would exceed \$1 billion USD. The Sioux never accepted the legality of the Black Hills confiscation and sued the US government for return of the land. In 1980, the US Supreme Court upheld a decision to support the Sioux claim that US government’s decision to occupy the Black Hills constituted a “taking of tribal property” with an implied obligation for the government to make just compensation. Rather than returning the land, however, the US Supreme Court awarded the nine tribes of the Great Sioux Nation \$102 million USD as compensation for their loss. The Sioux have never collected this payment, which remains in trust and now exceeds \$1.3 billion USD [64].

Why would some of the poorest tribes in the country, with unemployment rates as high as 80%, turn down such a large sum of money? The award of financial compensation misses many key points central to the disputes between the tribes and the federal government. First, the suit was never about money but about the return of lands central to the spirit of the Sioux Nation. Second, the value is small relative to the profit made from both the land and resource extraction in the intervening years. Third, to take money for the land is acknowledging a real estate transaction, and in the words of former Oglala president Teresa Two Bulls “If we accept the money, then we have no more of the treaty obligations that the federal government has with us for taking our land, for taking our gold, all our resources out of the Black Hills ... we’re poor now, we’ll be poorer then when that happens.” [64]. While the Sioux and the federal government continue to seek a compromise, the legacy of the Black Hills mining continues to pose concerns for the health of the Sioux.

As illustrated in Fig. 1, more than 10,000 abandoned gold mines are on or near Native American Reservation lands throughout the Western USA. In the Black Hills, there are hundreds of gold mines but few as profitable as the Homestake Mine near Lead, which produced more than 964,000 kg of the 1.1 million kg reported for the Black Hills from 1875 to 1971 [65]. Homestake discharged high concentrations of arsenic from their mill directly into the Cheyenne River drainage for decades [66] contaminating 29 km of downstream creeks that received Superfund action for arsenic contaminated soil, sediments, and water. Although the site was removed from the National Priorities List in 1996, there remains a band of arsenic-containing sediment in the Cheyenne River banks and floodplains that form the southern boundary of the Cheyenne River Sioux Tribe Reservation (more than 250 km downstream) [67]. While the arsenic-contaminated sediment in the banks has been buried by years of deposition since the closure of the mine in 2002, intermittent floods during operational years deposited contaminated sediment that remains in surface soils of lands used for agriculture, ranching, and ceremonial purposes as far as 1 km from the river (*personal communication*, Dec. 2016, C. Ducheneaux, Department of Environment and Natural Resources, Cheyenne River Sioux Tribe).

Within the Cheyenne River Sioux, antinuclear antibody (ANA) prevalence exceeds that found in the US population, with occurrence predicted by the proximity to the arsenic deposits [68]. While the presence of ANA does not alone indicate frank autoimmune disease, an associated elevated prevalence of several specific autoantibodies was also observed [68]. ANAs serve as early serologic markers in a variety of autoimmune diseases [69–71] and have also been linked to mercury exposure from Amazonian gold mines, to consumption of fish contaminated with methylmercury, and to drinking arsenic contaminated water [72–76].

The arsenic is located in the floodplains where gathering of fruit for sustenance and herbs for medicinal, traditional, and ceremonial practices has been documented as well as other traditional land use practices that create direct exposure pathways through ingestion, inhalation, and dermal contact. These uses raise ethical and policy issues around how exposure and health are evaluated. If standard exposure assessment assumptions interpreted through extant health research are applied to a Native community practicing a traditional lifestyle, such as the Cheyenne River Sioux, results may underestimate exposure [2]. Secondly, not only are data on response to toxicants limited for Native Americans, the definition of health itself may differ substantially between the cultures with regulatory agencies interpreting health from a Western disease model and the tribal population using a more holistic view based their belief of interconnection between people, their ecosystem, and their well-being [77•]. Our team is currently working with the CRST to understand the mobility of the Homestake arsenic; evaluate human exposure through ceremonial, traditional, ranching, and recreation activities; and assess the contribution of exposure to the high prevalence of autoimmune markers observed in those living in the floodplain [68].

Case Study 2: Uranium and the Navajo Nation

Uranium mines present a special subset of abandoned hard rock mines resulting from the Cold War and associated political stressors. Although reservations encompass only 5.6% of land area in the Western USA, approximately one in five uranium mines are located within 10 km of an Native American Reservation with more than 75% (more than 3200 of the 4600) within 80 km (Fig. 1). This does not include lands traditionally used by the tribes or lands feeding tribal water- and airsheds. Figure 1 highlights areas where uranium was the dominant ore extracted and illustrates that multiple tribes are affected by AUMs, including Navajo Nation in the Four Corners region, multiple Sioux tribes in the Black Hills region, Northern Arapahoe and Eastern Shoshone at Wind River in Wyoming, and several tribes including the Spokane in Washington State.

The development of the atomic bomb and the subsequent nuclear arsenal that fueled the Cold War led to prioritization of uranium mining above protection of human health, as well documented by Eichstaedt in *If You Poison Us* [5•]. Vanadium, which occurs in combination with uranium in carnotite, was mined on Navajo as early as 1902 to support steel hardening. The Manhattan Project's need for uranium made the repurposing of these mines expedient and led to government action to promote uranium exploration without regard for protection of human health. The hazards of radiation were recognized since the 1920s, and increased respiratory disease and lung cancer in European uranium miners was well known by the US Atomic Energy Commission (AEC) and others from the findings of lung cancer and respiratory disease in European miners. However, the AEC was reluctant to set standards within mines or take any other measures to protect miners' health, fearing that public awareness of the dangers in the mines would limit their ability to obtain uranium. Following the US Public Health Service's (PHS) requests to set safety standards, the AEC set standards of 10 pCi/L in all operations *except* uranium mines; after lengthy debate, a standard of 100 pCi/L in uranium mines was set in 1967—23 years after the beginning of uranium mining on the Navajo Nation and 17 years after the first US Public Health Service uranium miners' health study identified respiratory risks. It would be another 33 years before these details were made public and the US Congress passed the Radiation Exposure Compensation Act (RECA) that would begin a process of compensating those affected. Compensation of Navajo miners was slowed significantly, however, as a result of barriers in the law requiring documentation of births, marriages, and death records not routinely kept within the tribe and the restriction of compensable health effects to lung cancer only. The law has been revised only once, in 2000, to incorporate additional compensable diseases and include uranium mill workers [78], while additional revisions to compensate miners who worked after the government turned over mine safety to the private sector in 1971 remain in limbo.

As late as 1991–2005, 25% of the deaths in the 4137 former uranium miners followed by US PHS were attributed to lung cancer, with Native miners at triple the expected rate [79]. Native miners bore a disproportionate burden of non-malignant respiratory disease as well. Their rate of pneumoconiosis was as much as fourfold higher than in non-Hispanic whites (NHW), and they also had an increased risk of restrictive lung disease and decreased FEV₁ [80]. For Navajo miners, underground uranium mining was the primary contributor to non-malignant disease including obstructive lung disease, while in non-Native populations, smoking was the major contributor. More than 70% of Navajo miners had never smoked (compared to 23% of NHW miners) [80]. However, compensation through the government's Radiation Exposure Compensation Act, discriminated against Native miners by

requiring, in addition to radiographic evidence of lung damage, a second measure of spirometry less than 75% of a comparison value derived from a NHW population. Clinical researchers demonstrated that using that criterion to determine loss of function resulted in exclusion of 24% of Native miners who would qualify with a 75% reduction in lung function if Native American-based function formulas were used [80]. Other studies concluded that Colorado Plateau Native American uranium miners disproportionately suffer excess mortality risks from lung cancer [81, 82]. Native Americans were a substantial portion of the underground workforce, and it has been argued that the observed differences in effect related to a higher exposure. Disease rates reported above, however, were corrected for exposure, and Native miners were shown to have significantly *lower* average lifetime mining exposure than NHWs and Hispanics [80]. As many as 4000 Navajo men worked in the uranium mines and mills and hundreds of Navajo miners died and continue to die of lung cancer and other respiratory disease [83, 84], essentially wiping out a generation of Navajo men in some communities and leaving a legacy of psychological and environmental trauma [84]. The increased toxicity to Native miners underscores the potential for unique sensitivities to toxicants within the Native community as compared to all races results, questioning the derivation of standards on the basis of data collected from other populations.

While the fights over RECA proceeded, people living in Navajo communities continued to be chronically exposed to waste from the 520 abandoned uranium mines, 4 abandoned uranium mills, and more than 1100 waste sites [85] in and proximal to their communities. Uranium mine waste presents a unique hazard resulting from the associated radioactive decay chain introducing additional contaminants including radium, thorium, and radon to the already complex mixture of associated metals often including, for example, arsenic, cadmium, and lead [86]. The lack of regulation and security of waste associated with these facilities and abandoned sites, as well as lack of concern during the operational phase led to the use of contaminated material in the construction of homes [85], as well as contamination of water sources potentially used for drinking [59]. Looking at >1300 Navajo community members with and without exposure to uranium mine waste, we find a significant strong association between exposures occurring during the active mining era (1940s–1980s) and later development of kidney disease, exposure more than doubling the odds ratio. For those exposed to legacy waste, controlling for the mining era exposures, exposure is significantly associated with an increased likelihood of hypertension and of developing one or more chronic diseases including hypertension, diabetes, and kidney disease [87•]. Serum from a subset of >200 individuals from that cohort, representing a full range of exposure, showed a significant inverse relationship between inflammatory potential in cellular bioassays and

distance from legacy waste sites consistent with induction of pathways that contribute to atherosclerosis and cardiovascular disease [88]. While risk factors traditionally considered for these diseases clinically were also significant predictors, these results underscore the need for clinicians to probe for information about exposure as well in identifying those at risk.

Ongoing Concern for Future Generations

Among Native communities, there is concern about not only the health of people living in impacted communities today but also the health of generations yet to come. The Women of All Red Nations (WARN) worry that uranium mining may contribute to high rates of miscarriage and reproductive cancers observed among Lakota women [89]. While studies of direct impacts of mine waste exposures on tribal lands have been extremely limited, several recent initiatives are beginning to fill these gaps.

A 1981 study in Navajo babies showed that congenital anomalies, developmental disorders, and other adverse birth outcomes were associated with maternal proximity to uranium mining operations, tailings, or mine dumps [90]. Uncertainties in these results were not followed up until 2010 when the Navajo Birth Cohort Study (NBCS) [37•, 91] was initiated as part of a Congressional Five-Year Plan to Address Uranium Contamination on Navajo [92]. The NBCS is a prospective assessment of the effect of exposure to uranium and co-occurring metals in mine waste on birth outcomes and neurodevelopment through 1 year of age conducted as a partnership with the University of New Mexico, Southwest Research Information Center, Navajo Nation Indian Health Service, Navajo Nation Department of Health, and funders CDC/ATSDR. This is the first prospective birth cohort addressing the impacts of environmental contamination on birth outcomes in a Native population. Preliminary data confirm exposures to uranium prenatally and over the first year of life. The recently funded NIH National Environmental Influences on Child Health Outcomes (ECHO) initiative will include both the NBCS and a Sioux cohort in this national synthetic cohort of more than 50,000 children, allowing assessment of the relationship of metal exposure, neurodevelopment, and other outcomes through at least age 5. ECHO will also allow determination of unique sensitivities within these tribal populations through comparisons of exposure-toxicity relationships across cultures, races, and lifestyles.

Two of five NIEHS/NIMHD/USEPA P50 Centers of Excellence in Environmental Health Disparities funded in 2015 focus on multiple Native American populations and metals exposures. These centers will also help to identify unique exposure pathways, understand the biogeochemical characteristics of metal mixtures, and document mechanisms of toxicity.

These multigenerational studies using common methods and involving Native American communities in data collection and interpretation at all stages begin to answer the longstanding questions on health, and, importantly, to build capacity for investigation of these questions by tribal researchers.

Ethical, Scientific, and Policy Challenges to Increasing Native American Research

To fully understand the impacts of abandoned mine waste and to inform policies that protect tribal populations from future adverse health impacts, the body of scientific studies will need to incorporate more tribal studies, incorporate cultural and traditional practices into assessments of toxicity, and better understand unique responses in these populations. This broader inclusion, however, comes with its own challenges.

The recognition of treaties granting sovereign status to tribal nations within the USA brings with it rights of tribes to control the research process through their own institutional review boards, to mandate that all data and specimens generated through research remain the property of the tribe, and to mandate conditions for data sharing and certain types of analyses, such as genetic analyses. Recent requirements of the US National Institutes of Health (NIH), the major funders of health research in the USA, require sharing of all data collected with public funds, and often require investigators to obtain consent for genetic analyses, creating cultural conflicts between the tribes and research funders. Models are emerging, however, that show these issues are not insurmountable. Alaska Natives have developed a biospecimen and data repository that stores all samples and data collected on Alaska Natives and controls future use through a board on which Alaska Natives are in the majority [93]. NIH recognition of the importance of these concerns is supported by their creation of a Tribal Research Office within the office of the director, currently led by a Native molecular biologist [94].

Tribal demands previously seen as challenging, such as involvement of tribal communities in all phases and aspects of research; insistence on honest communication of research goals and progress throughout the study; and ensuring research has benefits for tribal communities by informing policy for improved health care and prevention of future health impacts are now consistent with best practices for environmental health studies as discussed in the Ethics Guidelines for Environmental Epidemiologists [95]. While recognition of the need to include tribal populations in research has grown in the federal agencies and research community, grant reviewers even recently have expressed ethical concerns over funding research in Native American populations because it will not be generalizable. Additional education and guidance to point out the ethical fallacy in the current practice of

generalizing dominant culture results to policies affecting tribal populations may be necessary before equity is achieved.

Conclusions and Future Research Directions

The abandoned mines on and near Native lands in the Western USA are but one in an ongoing series of insults. The sheer number of mines and the volumes of waste guarantee that the legacy will persist for generations to come. In addition, the mines present only one chapter in the history of environmental injustices on Native lands. Similar articles could be written focusing on impacts to tribal lands from coal strip mining, from the legacy of military bases, and from oil and gas development. The support from thousands representing tribes across the country for the Standing Rock Sioux camp opposing the Dakota Access Pipeline in 2016 is indicative of the common theme felt by tribes not only in the Western USA but throughout the country and the world where treaty rights to protect health and culture have been continually challenged and eroded in favor of resource development.

In spite of the recognized threats to tribal health posed by these ongoing toxicant exposures, and the demonstrated risk factors that put tribal populations in a position of increased vulnerability, research to understand the health impacts has been hampered by the small sizes of the communities, reviewers concerns about generalizability of results, and in some cases by the distrust of research within tribal communities who have witnessed researchers build careers but leave nothing behind to improve the health of the population. In contrast to the identified risks, the strength and support derived from the maintenance of culture, ceremonies, and traditional lifestyles may also provide a resiliency to offset some of the adverse effects. Understanding how these factors interact is critical to designing effective interventions to protect health benefitting all populations.

The history of mining in the Western USA and the legacy that affects so many Native American communities highlight the need for not only better inclusion of tribal populations in toxicologic studies but also in using these data in the development of standards that ensure the cleanup of the sites is truly protective of the health of the tribes. Ongoing studies point increasingly to the fact that the mixed metal wastes from these mines continue to have multigenerational impacts to the health of Native tribes. Our work and others have shown that metals can inhibit DNA-repair processes [96, 97, 98, 99, 100] and induce immunotoxicity [101–104], providing important clues into the mechanisms by which these mixtures affect health. Through understanding the mechanisms by which these effects occur and understanding the role of exposures in the health disparities seen in these communities, effective interventions can be designed to protect populations for the decades likely to remain before the mine waste is removed or remediated.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent All procedures performed in cited studies involving human participants conducted by the authors were in accordance with the ethical standards of the University of New Mexico Institutional Review Board, the Navajo Nation Human Research Review Board, and the Cheyenne River Sioux Tribal Council, and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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NEWS

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Lithium production from geothermal plant at the Salton Sea – soon to be reality

A project to derive lithium from a planned geothermal plant at the Salton Sea in California will receive \$2.5 million from a Federal Trust Fund under a Bill that was set up to utilise revenues from geothermal plants on federal land to projects utilising highly mineralized geothermal brines at existing geothermal facilities.

Over the years, the potential and opportunity represented by Lithium production at the Salton Sea has been topic of numerous studies and reports, but now seems to become a reality. With new plans, Imperial County could actually become the lithium capital of the United States.

In news this week, it has been reported that \$2.5 million will be invested in lithium production from a planned 50 MW geothermal plant. This was reported by Senator Ben Hueso at a recent event at the El Centro Chamber of Commerce. The funds will come Bill SB-1074 which Senator Hueso created two years ago.

Entered into force in September 2016, the Bill SB-1074 (https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1074), opens the opportunities to use funds under the Federal Trust Fund for geothermal projects.

"Existing law requires that all revenues received by the state pursuant to specified federal laws be deposited in the Geothermal Resources Development Account and continuously appropriated as specified. Existing law requires some of those revenues to be disbursed to counties in which the federal government has leased land for geothermal development and another portion of those revenues to be available for distribution by the State Energy Resources Conservation and Development Commission (Energy Commission) as grants or loans made to local jurisdictions or private entities. Existing law specifies purposes primarily relating to geothermal energy development and mitigation for which recipients may expend these moneys.

This bill would additionally authorize those recipients to expend those revenues to undertake projects to recover lithium, metals, agricultural products, and other beneficial minerals from highly mineralized geothermal brines at existing geothermal facilities that are in disadvantaged communities and provide local employment opportunities."

With that bill and the funding now provided it will "... put Imperial County on the map as an energy producer and also as a county that will, in addition to important agricultural products, be producing important elements such as Lithium," Hueso said.

It is planned that the project will start design work this month and is expected to get off the ground in about one year with hopes to create hundreds of jobs. The grant was awarded to EnergySource LLC.

Source: KYMA (<http://www.kyma.com/news/lithium-soon-to-be-mined-at-salton-sea/738369720>)

Note: This article saw a correction as we wrongly referred to "Controlled Thermal Resources" as the recipient of the grant, but this was incorrect.

7/18/2019

Life Cycle Electric Vehicle Emissions (2015) | Union of Concerned Scientists

Union of Concerned Scientists

Science for a Healthy Planet and Safer World

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Life Cycle Electric Vehicle Emissions (2015) | Union of Concerned Scientists

Cleaner Cars from Cradle to Grave (2015)**Cleaner Cars from
Cradle to Grave**How Electric Cars Beat Gasoline Cars on Lifetime
Global Warming Emissions

Over their lifetime, battery electric vehicles produce far less global warming pollution than their gasoline counterparts—and they're getting cleaner.

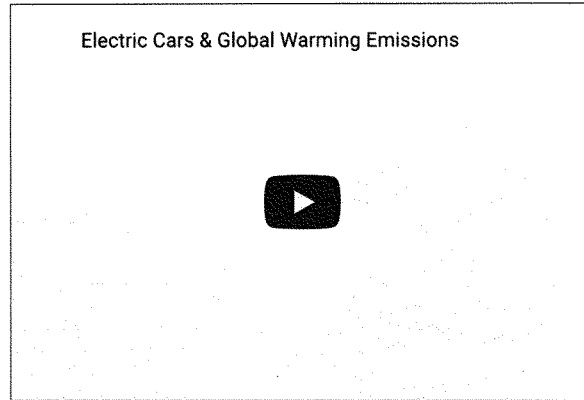
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Since we first published our State of Charge report in 2012, the environmental benefits of electric vehicles (EVs) have continued to grow. Two-thirds of all Americans now live in areas where driving an EV produces fewer climate emissions than almost all comparable gasoline and gasoline hybrid cars—a fact attributable to more efficient EVs and an increasingly clean electricity grid.

But what are the global warming emissions of electric cars on a *life cycle* basis—from the manufacturing of the vehicle's body and battery to its ultimate disposal and reuse? To answer this, the Union of Concerned Scientists undertook a comprehensive, two-year review of the climate emissions from vehicle production, operation, and disposal. We found that battery electric cars generate *half* the emissions of the average comparable gasoline car, even when pollution from battery manufacturing is accounted for.

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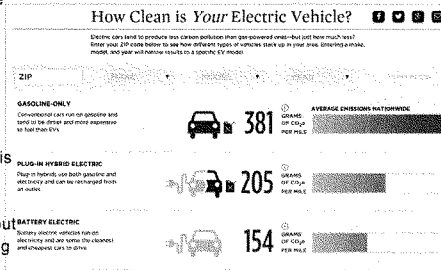


A life cycle analysis of EVs

All vehicles experience three distinct life stages: manufacturing, operation, and end-of-life. Each stage is linked with carbon dioxide and other greenhouse gas emissions—but those emissions differ between gas-powered cars and electric cars.

Both types of vehicle begin in much the same way. Raw materials are extracted, refined, transported, and manufactured into various components that are assembled into the car itself. Because electric cars store power in large lithium-ion batteries, which are particularly material- and energy-intensive to produce, their global warming emissions at this early stage usually exceed those of conventional vehicles. Manufacturing a mid-sized EV with an 84-mile range results in about 15 percent more emissions than manufacturing an equivalent gasoline vehicle. For larger, longer-range EVs that travel more than 250 miles per charge, the manufacturing emissions can be as much as 68 percent higher.

These differences change as soon as the cars are driven. EVs are powered by electricity

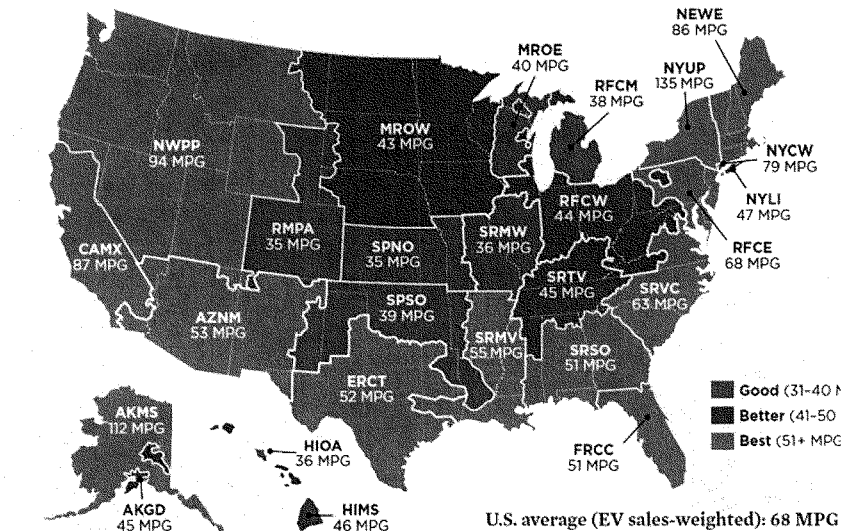


Use our EV emissions tool to see emissions in *your* area—or explore specific EV models.

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Electric Vehicle Global Warming Pollution Ratings and Gasoline Vehicle Emissions Equivalents by Region



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EV? The answer depends on where you live. Numbers based on the EPA's eGRID 2015 database. Click to enlarge.

How many miles per gallon would a gas car have to achieve to produce global warming emissions equivalent EV? The answer depends on where you live. Numbers based on the EPA's eGRID 2015 database. Click to enlarge.

The specific emissions of any given EV model will depend on the vehicle's efficiency and the electricity that powers it (check out our interactive tool to explore EV emissions in *your* area). For **all** Americans, charging the average new EV produces far fewer global warming pollutants than driving the average new gasoline car. In some of the country's cleanest regions (including parts of California, New York, and the Pacific Northwest), driving an electric car is equivalent to getting 85 miles per gallon.

By the end of their lives, gas-powered cars spew out almost twice as much global warming pollution than the equivalent electric car. Disposing of both types of vehicles (excluding reusing or recycling their batteries) produces less than a ton each.

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7/18/2019

Life Cycle Electric Vehicle Emissions (2015) | Union of Concerned Scientists

Electric vehicles already result in far less climate pollution than their gas-powered counterparts, and they're getting cleaner. Optimizing EV production and the disposal or reuse of batteries could further increase their environmental benefits. And as electricity becomes cleaner (which it is), the difference between electric cars and gasoline cars will only grow—cementing the role of electric vehicles in halving U.S. oil use and cutting global warming emissions.

Read more by downloading the full report, use our interactive tool to explore EV emissions in *your* area, or read most recent updates in our blog.

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Electric Vehicles, Batteries, Cobalt, and Rare Earth Metals

JOSH GOLDMAN, SENIOR POLICY AND LEGAL ANALYST | OCTOBER 25, 2017, 11:59 AM EDT

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The case for switching to electric vehicles (EVs) is nearly settled. They are cheaper to use, cut emissions, and offer a whisper quiet ride. One of the last arguments available to the EV-hater club, which is largely comprised of thinly veiled oil-industry front groups funded by the Koch brothers, focuses on the impacts from the materials used to make an EV's battery pack.

Specifically, the use of lithium, cobalt, nickel, and other metals that are part of an EV lithium-ion battery pack has raised red flags about the poor human rights and worker protection records in the countries where these materials are mined.

A lot of these warnings have been incorrectly categorized under "EVs and rare earth metals." Though neither lithium nor cobalt are rare earth

metals, and rare earth metals aren't nearly as rare as precious metals like gold, platinum, and palladium, there are important issues surrounding the production of lithium-ion batteries that must be acknowledged and addressed.

It is also important to note that these impacts are not happening just because of EVs. They are also being driven by the global demand for cell phones, laptop computers, and the multitude of other electronic devices that use lithium-ion batteries.

As EVs gain market share, they will be more responsible for the impacts from battery production. But today, EVs comprise a small fraction of global vehicle sales. So, concerns about lithium-ion batteries should be directed not just to the suppliers of EV battery packs, but also toward Apple, Samsung, and the other companies that source lithium-ion batteries for their electronic goods.

Let's also not forget that the supply chain for gasoline-powered vehicles has its fair share of issues, ranging from human rights violations like the use of child labor, to disastrous oil spills like Deepwater Horizon. But unlike gasoline-powered vehicles, EVs will be able to take advantage of emerging battery chemistries that don't rely on cobalt or other materials that are linked to exploitative practices.

Cobalt and electric vehicle batteries

Cobalt, a bluish-gray metal found in the Earth's crust, is one of today's preferred components used to make the lithium-ion batteries that power laptops, cell phones, and EVs. Cobalt is mined all over the world, but 50 to 60 percent of the global supply comes from the Democratic Republic of Congo (DRC), which has a poor human rights track record. According to UNICEF and Amnesty International, around 40,000

children are involved in cobalt mining in DRC where they make only \$1 – \$2 USD per day. DRC’s cobalt trade has been the target of criticism for nearly a decade, and the U.S. Labor Department lists Congolese cobalt as a product it has reason to think is produced by child labor. More troubling, cobalt demand has tripled in the past five years and is projected to at least double again by 2020.

What can be done about EV batteries sourcing issues

First, companies should be held accountable for enacting and enforcing policies to only use ethically-sourced materials. Some companies are off to a good start. Apple has pledged to end its reliance on mining altogether, and one day make its products from only renewable resources or recycled materials. Other tech giants like HP, Samsung, and Sony joined an effort called the “Responsible Cobalt Initiative.” Members of the initiative pledged to follow global guidelines for mining supply chains, which call for companies to trace how cobalt is being extracted, transported, manufactured and sold.

On the EV side of things, Tesla has committed to sourcing materials only from North America for its new battery production facility, the Gigafactory. In 2015, Tesla secured two contracts with mining companies to explore lithium deposits in northern Nevada and Mexico, though Tesla still relies on cobalt that may have been sourced from the DRC.

Both Ford and GM get their EV batteries from LG Chem, who has said they have stopped using DRC-sourced cobalt and stated that neither Ford nor GM batteries rely on DRC-sourced cobalt, but some of the LG practices and statements have been called into question by the WaPo.

Second, recycling can help reduce the need to search for new source of battery materials, or rely on sourcing materials from countries with poor worker protections. Cobalt, for example, (as opposed to gasoline) is fully recyclable and roughly 15 percent of U.S. cobalt consumption is from recycled scrap today.

Companies like Umicore are in the cobalt recycling business and have demonstrated that there is a business model for recycling cobalt that can help reduce demand for DRC-mined cobalt.

Third, battery technology is continuing to improve. The multitude of battery applications has generated a strong financial incentive for researchers to find the next greatest battery chemistry, and some of the most promising next-gen battery types don't rely on cobalt at all.

Lithium-titanate and lithium-iron-phosphate, for example, are gaining importance in EV powertrain applications and don't need cobalt. Other battery chemistries that rely on magnesium, sodium, or lithium-sulfur are also gaining traction as they have the potential to beat lithium-ion batteries on energy density and cost. Battery research has seen a big shift in recent years. Nearly half of the presentations at the Battery Symposium in Japan were once about fuel cells and lithium-ion battery materials. But since 2012, these topics have been supplanted by presentations about solid-state, lithium-air and non-lithium batteries.

Overall, the human rights issues related to the lithium-ion battery supply chain cannot be ignored. At the same time, they shouldn't be used by the oil industry and their allies as a rallying cry to dismantle EV policy support, or as reason to stop the growth of the EV industry. Again, it's not just EVs that are at issue here. All manufacturers of electronic devices need to find better sources for their batteries and it is their responsibility to source materials from places that have worker protections. It's also the

responsibility of our government to ensure that Americans can buy products that are ethically and sustainably sourced.

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Posted in: Vehicles Tags: cobalt, congo, drc, electric vehicles, mining practices, rare earth metals

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Senator BARRASSO. We are sorry to run off. We are in the final seconds of a vote.

Fifteen Senators attended today, which shows how much interest there is in what you had to say and the questions, in asking those.

Others may submit questions for the record. We would ask for your written answers to those. The hearing is going to remain open for 2 weeks.

I want to thank all of you for being here. Thank you for bringing your son, and thanks for discussing such an important issue.

The hearing is adjourned.

[Whereupon, at 11:29 a.m., the Committee was adjourned.]

[Additional material submitted for the record follows:]

The Washington Post

THE COBALT PIPELINE

Tracing the path from deadly hand-dug mines in Congo to consumers' phones and laptops

Story by Todd C. Frankel
Photos by Michael Robinson Chavez
Video editing by Jorge Ribas

September 30, 2016

The sun was rising over one of the richest mineral deposits on Earth, in one of the poorest countries, as Sidiki Mayamba got ready for work.

Mayamba is a cobalt miner. And the red-dirt savanna stretching outside his door contains such an astonishing wealth of cobalt and other minerals that a geologist once described it as a “scandale geologique.”

This remote landscape in southern Africa lies at the heart of the world's mad scramble for cheap cobalt, a mineral essential to the rechargeable lithium-ion batteries that power smartphones, laptops and electric vehicles made by companies such as Apple, Samsung and major automakers.

But Mayamba, 35, knew nothing about his role in this sprawling global supply chain. He grabbed his metal shovel and broken-headed hammer from a corner of the room he shares with his wife and child. He pulled on a dust-stained jacket. A proud man, he likes to wear a button-down shirt even to mine. And he planned to mine by hand all day and through the night. He would nap in the underground tunnels.

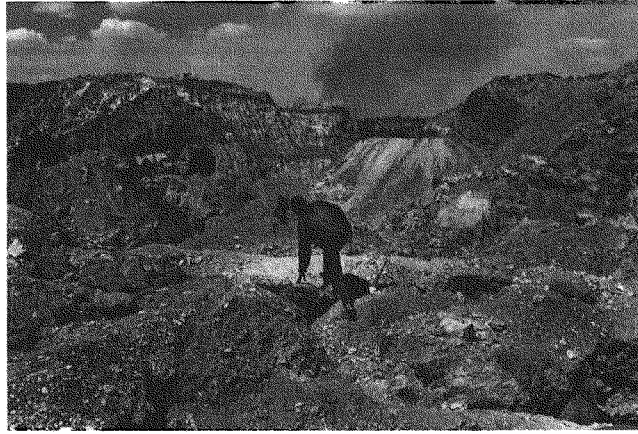
No industrial tools. Not even a hard hat. The risk of a cave-in is constant.

“Do you have enough money to buy flour today?” he asked his wife.

She did. But now a debt collector stood at the door. The family owed money for salt. Flour would have to wait.

Mayamba tried to reassure his wife. He said goodbye to his son. Then he slung his shovel over his shoulder. It was time.

The world’s soaring demand for cobalt is at times met by workers, including children, who labor in harsh and dangerous conditions. An estimated 100,000 cobalt miners in Congo use hand tools to dig hundreds of feet underground with little oversight and few safety measures, according to workers, government officials and evidence found by The Washington Post during visits to remote mines. Deaths and injuries are common. And the mining activity exposes local communities to levels of toxic metals that appear to be linked to ailments that include breathing problems and birth defects, health officials say.



A “creuseur,” or digger, climbs through a cobalt and copper mine in Kawama, Congo, in June.

The Post traced this cobalt pipeline and, for the first time, showed how cobalt mined in these harsh conditions ends up in popular consumer products. It moves from small-scale Congolese mines to a single Chinese company — Congo DongFang International Mining, part of one of the world’s biggest cobalt producers, Zhejiang Huayou Cobalt — that for years has supplied some of the world’s largest battery makers. They, in turn, have produced the batteries found inside products such as Apple’s iPhones — a finding that calls into question corporate assertions that they are capable of monitoring their supply chains for human rights abuses or child labor.

Mobile power, human toll



The world has grown reliant on lithium-ion batteries that power smartphones, laptops and electric cars. But the desperate search for the ingredients carries a steep cost.

More in this series: [Graphite in China](#) and [Lithium in Argentina](#)

Apple, in response to questions from The Post, acknowledged that this cobalt has made its way into its batteries. The Cupertino, Calif.-based tech giant said that an estimated 20 percent of the cobalt it uses comes from Huayou Cobalt. Paula Pyers, a senior director at Apple in charge of supply-chain social responsibility, said the company plans to increase scrutiny of how all its cobalt is obtained. Pyers also said Apple is committed to working with Huayou Cobalt to clean up the supply chain and to addressing the underlying issues, such as extreme poverty, that result in harsh work conditions and child labor.

Another Huayou customer, LG Chem, one of the world's leading battery makers, told The Post it stopped buying Congo-sourced minerals late last year. Samsung SDI, another large battery maker, said that it is conducting an internal investigation but that "to the best of our knowledge," while the company does use cobalt mined in Congo, it does not come from Huayou.

Few companies regularly track where their cobalt comes from. Following the path from mine to finished product is difficult but possible, The Post discovered. Armed guards block access to many of

Congo's mines. The cobalt then passes through several companies and travels thousands of miles.

Yet 60 percent of the world's cobalt originates in Congo — a chaotic country rife with corruption and a long history of foreign exploitation of its natural resources. A century ago, companies plundered Congo's rubber sap and elephant tusks while the country was a Belgian colony. Today, more than five decades after Congo gained its independence, it is minerals that attract foreign companies.

Scrutiny is heightened for a few of these minerals. A 2010 U.S. law requires American companies to attempt to verify that any tin, tungsten, tantalum and gold they use is obtained from mines free of militia control in the Congo region. The result is a system widely seen as preventing human rights abuses. Some say cobalt should be added to the conflict-minerals list, even if cobalt mines are not thought to be funding war. Apple told The Post that it now supports including cobalt in the law.

Congo's cobalt trade has been the target of criticism for nearly a decade, mostly from advocacy groups. Even U.S. trade groups have acknowledged the problem. The Electronic Industry Citizenship Coalition — whose members include companies such as Apple — raised concerns in 2010 about the potential for human rights abuses in the mining of minerals, including cobalt, and the difficulty in tracking supply chains. The U.S. Labor Department lists Congolese cobalt as a product it has reason to think is produced by child labor.

Concern about how cobalt is mined “comes to the fore every now and again,” said Guy Darby, a veteran cobalt analyst with Darton

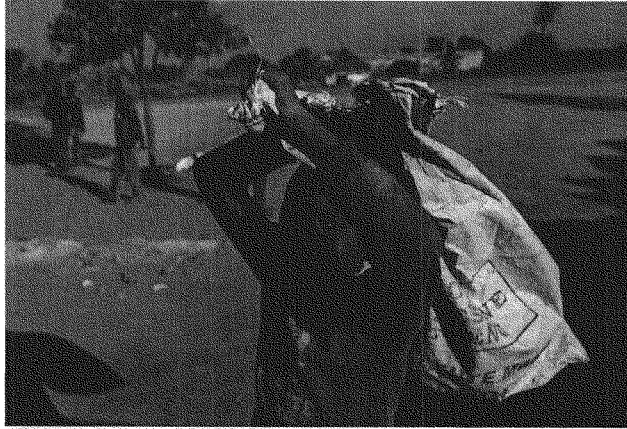
Commodities in London. “And it’s met with much muttering and shaking of the head and tuttering — and goes away again.”

In the past year, a Dutch advocacy group called the Center for Research on Multinational Corporations, known as SOMO, and Amnesty International have put out reports alleging improprieties including forced relocations of villages and water pollution. Amnesty’s report, which accused Congo DongFang of buying materials mined by children, prompted a fresh wave of companies to promise that their cobalt connections were being vetted.

But the problems remained starkly evident when Post journalists visited mining operations in Congo this summer.







Digger Sidiki Mayamba, left, puts on his shoes in the room he shares with wife Ivette Mujombo Tshatela and their 2-year-old son, Harold Muhiya Mwehu, in Kolwezi, Congo, in June. “Creuseurs,” or diggers, work in the mine at Kawama. The cobalt that is extracted is sold to a Chinese company, Congo DongFang Mining. A man pushes a bicycle laden with charcoal, which is used for cooking and heating, past Musompo, a mineral market outside Kolwezi. A boy carries a bag used to transport cobalt-laden dirt and rock at the Musompo market.

In September, Chen Hongliang, the president of Congo DongFang parent Huayou Cobalt, told The Post that his company had never questioned how its minerals were obtained, despite operating in Congo and cities such as Kolwezi for a decade.

“That is our shortcoming,” Chen said in an interview in Seattle, in his first public comments on the topic. “We didn’t realize.”

Chen said Huayou planned to change how it buys cobalt, had hired an outside company to oversee the process and was working with customers such as Apple to create a system for preventing abuse.

But how such serious problems could persist for so long — despite frequent warning signs — illustrates what can happen in hard-to-

decipher supply chains when they are mostly unregulated, low price is paramount and the trouble occurs in a distant, tumultuous part of the world.

Amount of cobalt in different devices



SMARTPHONE

5 to 10 grams

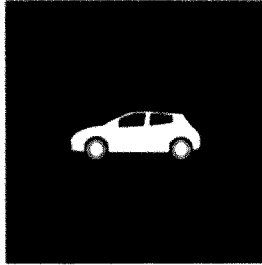
(as heavy as 2 to 4 pennies)



LAPTOP

1 ounce

(a slice of bread)



TYPICAL ELECTRIC CAR

10 to 20 pounds

(2 to 3 gallons of milk)

Lithium-ion batteries were supposed to be different from the dirty, toxic technologies of the past. Lighter and packing more energy than conventional lead-acid batteries, these cobalt-rich batteries are seen as “green.” They are essential to plans for one day moving beyond smog-belching gasoline engines. Already these batteries have defined the world’s tech devices.

Smartphones would not fit in pockets without them. Laptops would not fit on laps. Electric vehicles would be impractical. In many ways, the current Silicon Valley gold rush — from mobile devices to driverless cars — is built on the power of lithium-ion batteries.

But this comes at an exceptional cost.

“It is true, there are children in these mines,” provincial governor Richard Muyeji, the highest-ranking government official in Kolwezi, said in an interview. He also acknowledged problems with mining-related deaths and pollution.

But, he said, his government is too poor to tackle these issues alone.

“The government is not a beggar,” Muyej said. “These companies have an obligation to create wealth in the area where they operate.”

Companies are unlikely to abandon Congo, for a simple reason: The world needs what Congo has.

Chen said he expected controversy surrounding how cobalt is mined in Congo to ripple far beyond Huayou Cobalt.

“This issue, I believe, we are not the only ones,” he said. “We believe there are many companies in similar situations as us.”

‘LUNGS OF THE CONGO’

The worst conditions affect Congo’s “artisanal” miners — a too-quiet name for the impoverished workers who mine without pneumatic drills or diesel draglines.

This informal army is big business, responsible for an estimated 10 to 25 percent of the world’s cobalt production and about 17 to 40 percent of production in Congo. Artisanal miners alone are responsible for more cobalt than any nation other than Congo, ranking behind only Congo’s industrial mines.

The industry should be a boon for a country that the United Nations ranks among the least developed. But it hasn’t worked out that way.

“We are challenged by the paradox of having so many resource riches, but the population is very poor,” Muyej said.

Kolwezi is a remote city steeped in cobalt and copper, which are often found together. It is sometimes called the “Lungs of the Congo” because of its economic importance. The city sits along a two-lane highway best known for carrying tractor-trailers laden with minerals as they hurtle for the border with Zambia 250 miles away.

Then it’s on to seaports in Tanzania or South Africa.

From there, most of the cobalt floats by ship to Asia, home to the vast majority of the world’s lithium-ion battery manufacturing.

About 90 percent of China’s cobalt originates in Congo, where Chinese firms dominate the mining industry.

The cobalt begins its journey at a mine such as Tilwezembe, a former industrial site turned artisanal operation on the outskirts of Kolwezi where hundreds of men scour the earth with hand tools.

These men call themselves “creuseurs,” French for “diggers.” They toil inside dozens of holes pockmarking the mine’s moonscape-like bottom. The tunnels are dug by hand and burrow deep underground, illuminated only by the toylike plastic lamps strapped to the miners’ heads.

During a visit in June, the scene looked preindustrial. Dozens of diggers were at work, but the only sound was the occasional muffled clink of metal on stone.

“We are suffering,” said one digger, Nathan Muyamba, 29. “And our suffering is for what?”

'LA FLEUR DU COBALT'



Diggers don't have mining maps or exploratory drills.

Instead, they rely on intuition.

"You travel with the faith believing that one day you can find good production," said digger Andre Kabwita, 49.

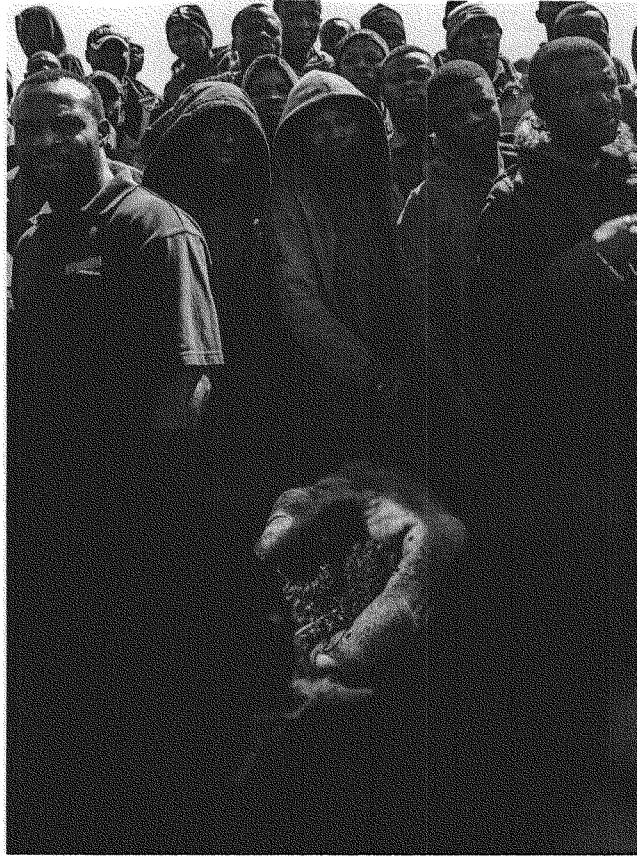
Nature is said to be one guide. Yellow wildflowers are considered a sign of copper. A plant with tiny green flowers carries the telling name "la fleur du cobalt."

With few formal sites to claim for themselves, artisanal miners dig anywhere they can. Along roads. Under railroad tracks. In back yards. When a major cobalt deposit was discovered a few years ago in the dense neighborhood of Kasulo, diggers tunneled right through their homes' dirt floors, creating a labyrinth of underground caves.

Other diggers wait until dark to invade land owned by private mining companies, leading to deadly clashes with security guards and police.

The diggers are desperate, said Papy Nsenga, a digger and president of a fledgling diggers union.

Pay is based on what they find. No minerals, no money. And the money is meager — the equivalent of \$2 to \$3 on a good day, Nsenga said.



Diggers gather at the Tilwezembe cobalt mine outside Kolwezi. Miners make an average of \$2 or \$3 a day. A fistful of cobalt-laden dirt is held up at the Musompo mineral market, where diggers sell their cobalt at small shops known as "comptoirs."

"We shouldn't have to live like this," he said.

And when accidents occur, diggers are on their own.

Last year, after one digger's leg was crushed and another suffered a head wound in a mine collapse, Nsenga was left to raise the hundreds

of dollars for treatment from other diggers. The companies that buy the minerals rarely help, Nsenga and other diggers said.

Deaths happen with regularity, too, diggers said. But only mass casualties seem to filter out to the scant local media, such as the U.N.-funded Radio Okapi. Thirteen cobalt miners were killed in September 2015 when a dirt tunnel collapsed in Mabaya, near the Zambia border. Two years ago, 16 diggers were killed by landslides in Kawama, followed months later by the deaths of 15 diggers in an underground fire in Kolwezi.

In Kolwezi, a provincial mine inspector frustrated by a recent run of accidents agreed to talk to The Post on the condition that he not be identified, because he was not permitted to talk to the media.

He met the journalists in a minibus — jumping in, closing the door and taking a seat in the middle, far from the tinted windows so no one on the street could see him.

That morning, he said, he had helped rescue four artisanal miners nearly overcome by fumes from an underground fire in Kolwezi. The day before, two men had died in a mining tunnel collapse, he said.

He said he had personally pulled 36 bodies from local artisanal mines in the past several years. The Post was not able to independently verify his claims, but they echoed stories from diggers about the frequency of mining accidents.

The inspector blamed companies such as Congo DongFang that buy the artisanal cobalt and ship it overseas.

“They don’t care,” he said. “To them, if you bring them minerals and you’re sick or hurt, they don’t care.”

Congo DongFang responded that it had incorrectly assumed that these issues were the concern of its trading partners, who buy the cobalt from the miners and pass it on to the mining company.

CHILD LABOR

No one knows exactly how many children work in Congo’s mining industry. UNICEF in 2012 estimated that 40,000 boys and girls do so in the country’s south. A 2007 study funded by the U.S. Agency for International Development found 4,000 children worked at mining sites in Kolwezi alone.

Local government officials say they lack the resources to address the problem.

“We have a big challenge with the children, because it is difficult to take them out of the mines when there are no schools for these children to go to,” said Muyej, the provincial governor. “We have to find a solution for this.”



While officials and diggers acknowledge the problem of child labor, it remains a sensitive topic. Children work not just in underground mines, in violation of Congo’s mining code, but also on the fringes of the cobalt trade.

Guards prevented Post journalists from visiting areas where, according to local diggers, children often can be found working. At one point, The Post saw a boy in a red sweatshirt struggling to carry a half-full sack of mineral rocks. Another boy in a black soccer jersey ran up to help. Kabwita, the digger, watched them.

“They are just 10 or 12,” he said.

The Post also gave an iPhone to a digger to capture video of how women and children wash cobalt ores together.

One of these children is Delphin Mutela, a quiet boy who looks younger than his 13 years.

When he was about 8, his mother began taking Delphin with her on her trips to the river to clean cobalt ores. Washing minerals is a popular job for women here. At first, Delphin was tasked with keeping an eye on his siblings.

But he learned to distinguish the loose mineral pieces that fell into the water during washing.

Copper carried a hint of green.

Cobalt looked like dark chocolate.

If he could collect enough bits, he could get paid, maybe \$1.

“The money I get I use to buy notebooks and so I can pay school fees,” Delphin said.

His mother, Omba Kabwiza, said this is normal.

“There are many children there,” she said. “That’s how we live.”

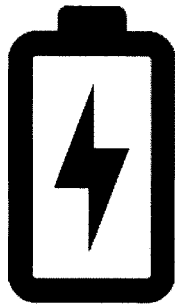
SKYROCKETING DEMAND

Cobalt is the most expensive raw material inside a lithium-ion battery.

That has long presented a challenge for the big battery suppliers — and their customers, the computer and carmakers. Engineers have tried for years to craft cobalt-free batteries. But the mineral best known as a blue pigment has a unique ability to boost battery performance.

The price of refined cobalt has fluctuated in the past year from \$20,000 to \$26,000 a ton.

Video: How lithium-ion batteries work



Lithium-ion batteries work much like other batteries — there's a positive electrode and a negative electrode, and the electrons move from one end to another, creating a charge. The difference is the materials inside, which make them lighter, longer-lasting and rechargeable.

[Watch the video](#)

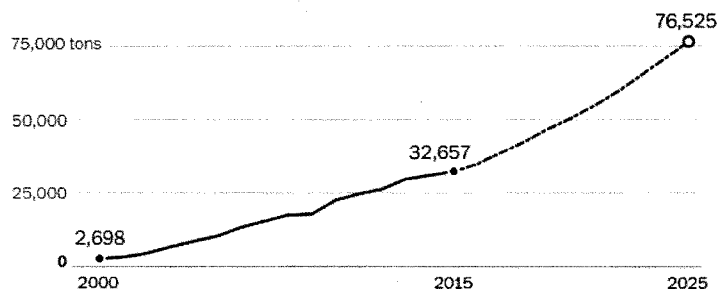
Worldwide, cobalt demand from the battery sector has tripled in the past five years and is projected to at least double again by 2020, according to Benchmark Mineral Intelligence.

This increase has mostly been driven by electric vehicles. Every major automaker is rushing to get its battery-powered car to market. Tesla's \$5 billion battery factory in Nevada, known as the Gigafactory, is ramping up production. Daimler aims to open a second battery plant in Germany soon. LG Chem makes batteries for General Motors at a plant in Holland, Mich. Chinese company BYD is working on huge new battery plants in China and Brazil.

While a smartphone battery might contain five to 10 grams of refined cobalt, a single electric-car battery can contain up to 15,000 grams.

As demand has grown, so has artisanal cobalt's importance in global markets. That became clear to everyone in the battery world two years ago, said Kurt Vandeputte, vice president of the rechargeable-battery materials unit at Belgium-based Umicore, one of the world's largest cobalt refiners.

Cobalt demand for lithium-ion batteries is expected to double by 2025



Source: Christophe Pillot, Avicenne Energy

The cobalt price was falling, even as battery demand shot up. The price of lithium, another key battery material, was skyrocketing.

“It got so clear that artisanal mining was taking a big place in the supply chain,” Vandeputte said, adding that Umicore buys only from industrial mines, including mines in Congo.

Artisanal cobalt is usually cheaper than product from industrial mines. Companies do not have to pay miners’ salaries or fund the operations of a large-scale mine.

With cheap cobalt flooding the market, some international traders canceled contracts for industrial ores, opting to scoop up artisanal ones.

“Everyone knew something was going on,” said Christophe Pillot, a battery consultant at Avicenne Energy in France.

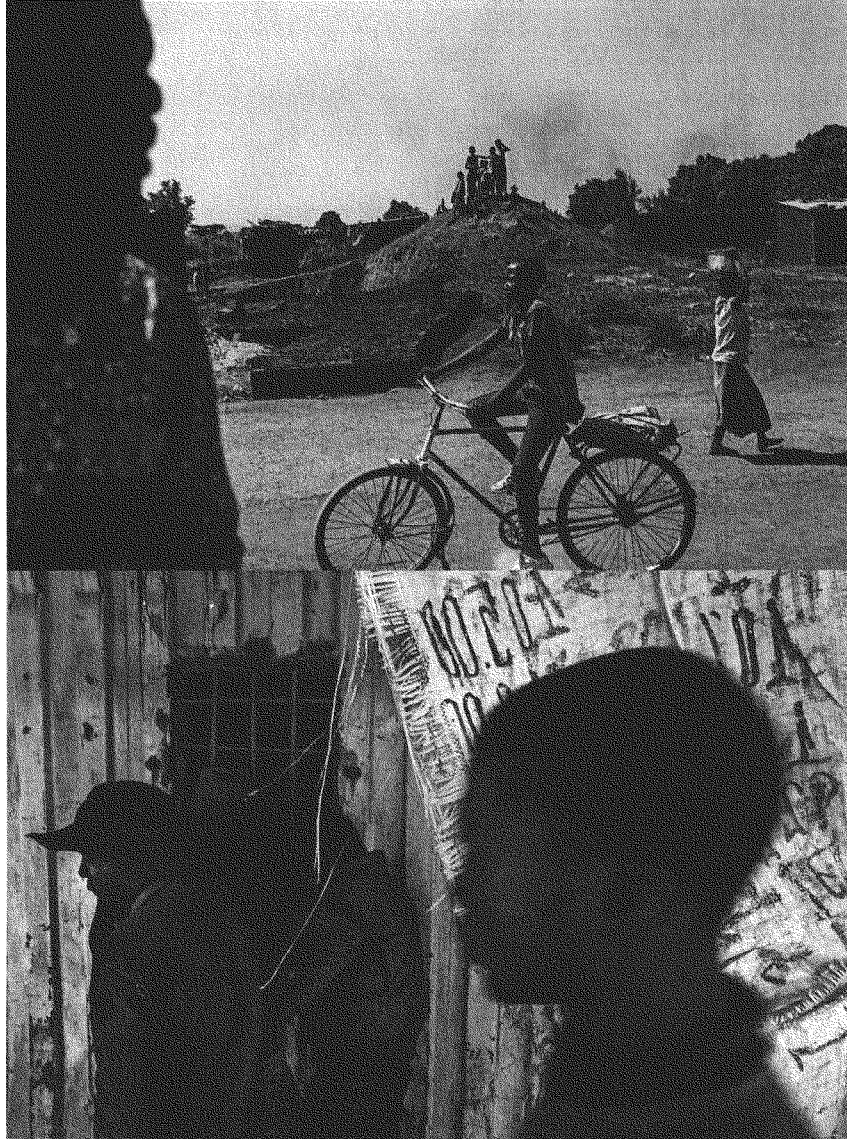
At the same time, companies face growing scrutiny of their supply chains.

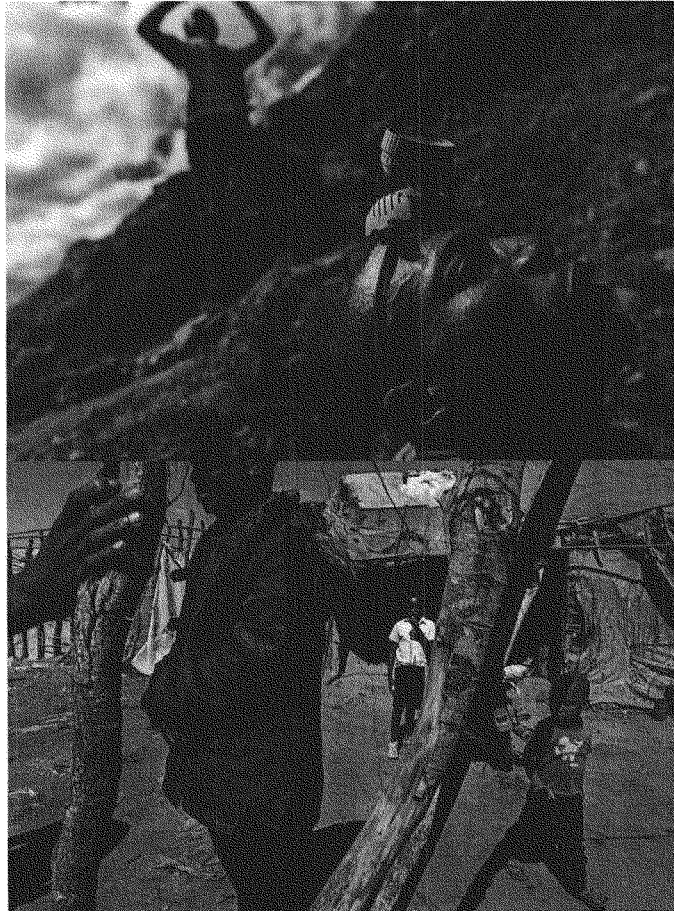
Consumers demand accountability; companies respond with promises of “ethical sourcing” and “supply chain due diligence.”

One result of this increased scrutiny can be found in Congo.

In 2010, the United States passed a conflict-minerals law to stem the flow of money to Congo’s murderous militias, focusing on the artisanal mining of four minerals.

But this same diligence is not required when it comes to cobalt.





Children gather along the principal highway linking Kolwezi and Lubumbashi. Diggers wait to be paid at the Tilwezembe cobalt mine. The prices, based on weight and content, are written on a burlap sign. A digger gets ready to go into a mine shaft in Kawama. Residents stand outside of their homes in impoverished Kawama. Living conditions for miners and their families are harsh, with no electricity or running water.

While cobalt mining is not thought to be funding wars, many activists and some industry analysts say cobalt miners could benefit from the

law's protection from exploitation and human rights abuses. The law forces companies to attempt to trace their supply chains and opens up the entire route to inspection by independent auditors.

But while Congo is a minor supplier of the four designated conflict minerals, the world depends on Congo for cobalt.

Analyst Simon Moores at Benchmark said he thinks this is one reason that cobalt has so far been excluded.

Any crimp in the cobalt supply chain would devastate companies.

'WE SELL THIS TO THE CHINESE'

For most artisanal miners in Kolwezi, the global supply chain begins in a marketplace called Musompo.

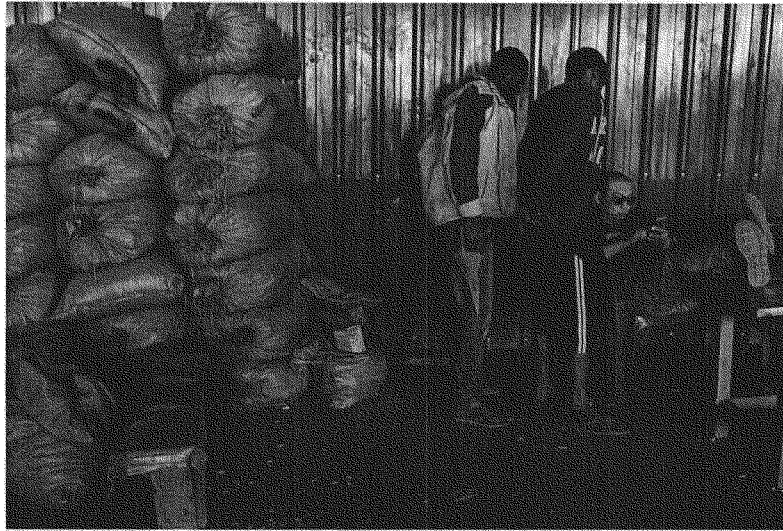
The 70 or so small shops, known as "comptoirs," are stacked cheek by jowl along the highway that leads to the border. Shop names are painted on cement walls: Maison Saha, Depot Grand Tony, Depot Sarah. Each shop has a handwritten board listing the going rate for cobalt and copper.

At a shop named Louis 14, the price list offered the equivalent of \$881 for a ton of 16 percent cobalt rock. Rock with 3 percent cobalt was worth \$55.

Nearby, minibuses pulled up with white sacks of freshly mined cobalt to sell. More sacks arrived on bicycles loaded down like pack animals.

Each load was tested by a radar-gun-like device called a Metorex, which detects mineral content. Some of the miners said they do not trust the machines, believing them to be rigged, but they have no alternative. Muyej, the governor, said he was looking for funds to buy a Metorex machine so diggers could independently test their minerals. There are many shops in Musompo, but diggers said the shops sold to the same company: Congo DongFang Mining.

“We sell this to the Chinese, and then the Chinese take it to CDM,” said Hubert Mukekwa, a shop worker shoveling cobalt.



An Asian man working at a “comptoir,” or counter, shop calculates a payment as “creuseurs,” or diggers, eagerly look on at the Musompo market.

In Congo, it is illegal for foreigners to own a comptoir. But not a single shop visited by Post journalists appeared to be run by Congolese. Asian men operated the Metorex machines. They punched up the tallies on oversize calculators. They handled the cash — thick wads of

Congolese francs. And they often could be seen sitting in the back while Congolese men carried the 120-pound sacks. None of the comptoir bosses would talk to The Post.

Mukekwa finished filling up one sack.

“Once we have enough stock to take it to CDM,” he said, “we take it there.”

He pointed at a large blue-walled compound in the distance.

At a comptoir named Boss Wu, two Congolese workers, in jumpsuits with CDM printed in block letters on the back, stood watching other men loading cobalt sacks onto a truck.

Later, The Post witnessed an orange truck loaded with cobalt sacks pulling away from Musompo and onto the main highway.

“C24” was painted in blue on the truck’s cab. The Post followed C24 two miles up the highway, where it turned onto a dirt road running next to a tall brick wall. The truck continued on the road until it reached an entrance with armed guards and turned inside.

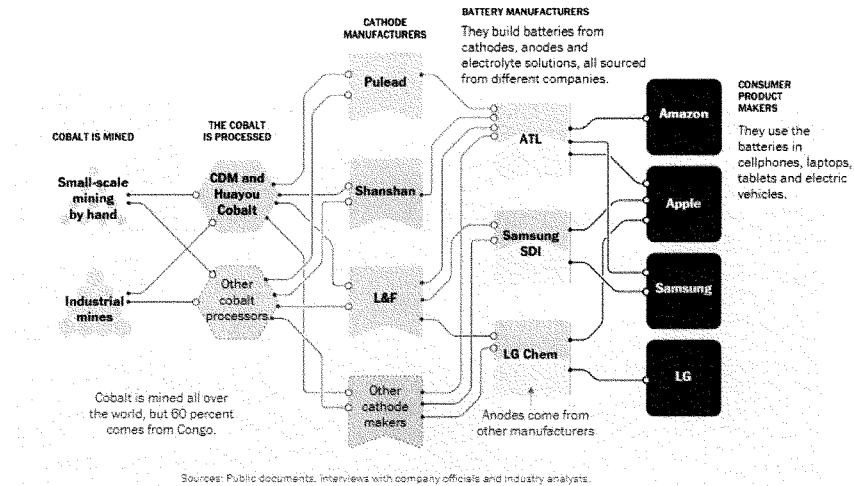
The facility with big blue walls was clearly marked CDM.

It was at these same gates that CDM says its inspection of its supply chain had stopped, never extending to the mines or marketplace, said Chen, the president of Huayou Cobalt, the parent company of CDM.

“We, in fact, didn’t know that much” about who they bought cobalt from, Chen said. “Now, we do due diligence.”

Tracing your battery’s cobalt

The lithium-ion battery industry has a massively complicated supply chain. Each consumer company has dealt with multiple suppliers — and their suppliers have dealt with multiple suppliers. This shows some of the connections within the industry. See companies' responses to Washington Post's investigation.



WHAT THE COMPANIES SAY

Companies, in response to The Post's questions, sounded equally uncertain about their cobalt supply chain, illustrating how little is known about the sources of raw materials.

But expectations are different today, said Lara Smith of Johannesburg-based Core Consultants, a firm that helps mining companies with this problem.

"Companies can't claim ignorance," Smith said. "Because if they wanted to understand, they could understand. They don't."

Last year, CDM reported exporting 72,000 tons of industrial and artisanal cobalt from Congo, making it No. 3 on the list of the

country's largest mining companies, according to Congolese mining statistics.

And CDM is by far Congo's top exporter of artisanal cobalt, according to analysts and the company.

CDM ships its cobalt to its parent company, Huayou, in China, where the ore is refined. Among Huayou's largest customers are battery cathode makers Hunan Shanshan, Pulead Technology Industry and L&F Material, according to financial documents and interviews.

Company responses



The Washington Post asked consumer-product companies and battery makers about their cobalt supply chains. Here is what they said:

Congo DongFang Mining/Huayou Cobalt, Apple, LG Chem, LG, Ford, General Motors, Samsung SDI, Samsung, BMW, Amazon.com, Pulead L&F Material, Hunan Shanshan, Amperex Technology Limited (ATL)

These companies — which also buy refined minerals from other companies — make the cobalt-rich battery cathodes that play a critical role in lithium-ion batteries. These cathodes are sold to battery makers, including companies such as Amperex Technology Ltd. (ATL), Samsung SDI and LG Chem.

All of these battery makers supply Apple, providing power for iPhones, iPads and Macs.

Apple said its investigation revealed that its batteries from LG Chem and Samsung SDI contain cathodes from Umicore, which may contain cobalt from Congo but not from CDM. Apple said it thought its suspect cobalt was contained in ATL batteries with Pulead cathodes.

“I think the risks can be managed,” Pulead chief executive Yuan Gao told The Post, adding that he believes “the increased awareness is actually working, as everyone is monitoring everyone else along the supply chain.”

ATL also has supplied battery cells found in some Amazon Kindles, according to analysis by IHS, the global information company. ATL declined to comment.

Amazon.com, the company founded by Post owner Jeffrey P. Bezos, did not directly answer The Post’s questions about potential connections to suspect cobalt. The company issued a statement, reading in part: “We work closely with our suppliers to ensure they meet our standards, and conduct a number of audits every year to ensure our manufacturing partners are in compliance with our policies.”

More from this series

Graphite in China There’s a trace of graphite in many of today’s consumer devices. In these Chinese villages, it’s in their water, inside their homes and on their food.
Lithium in Argentina Indigenous people are left poor as tech world takes lithium from under their feet.

Samsung SDI, which supplies batteries for Samsung, Apple and automakers such as BMW, said that its own ongoing investigation “has

not shown any presence” of suspect cobalt, although it does use cobalt from Congo.

Samsung, the phonemaker, provided The Post with a statement saying that it takes supply-chain issues seriously but not addressing a potential connection to CDM. Samsung buys batteries for its phones from Samsung SDI and ATL, among others, according to industry data.

BMW acknowledged that some of the cobalt in its Samsung SDI batteries comes from Congo but said The Post should ask Samsung SDI for more details.

LG Chem, the world’s largest supplier of electric-car batteries, said the company it buys cathodes from, L&F Material, stopped using Congo-sourced cobalt from Huayou last year. Instead, it said, Huayou now supplies L&F Material with cobalt mined from the South Pacific island of New Caledonia. As proof, LG Chem provided a “certificate of origin” for a cobalt shipment in December 2015 for 212 tons.

But two minerals analysts were skeptical that LG Chem’s cathode supplier could switch from Congo cobalt to minerals from New Caledonia — or, at least, do so for long. LG Chem consumes more cobalt than the entire nation of New Caledonia produces, according to analysts and publicly available data. L&F Material did not respond to repeated requests for comment. When The Post asked LG Chem to “respond to claims that the numbers don’t add up,” LG Chem did not answer the question directly, responding that it checks certificates of origin on a routine basis.

LG Chem also runs a Michigan battery plant for one of its biggest customers, GM, which plans to start selling its electric Chevrolet Bolt later this year. LG Chem said the Michigan plant has never received Congolese cobalt.

Another LG Chem customer, Ford Motor, said it has been told by LG Chem that Ford batteries have no history of CDM cobalt.

Most Tesla models use batteries from Panasonic, which buys cobalt from Southeast Asia and Congo. Replacement batteries for Tesla are manufactured by LG Chem. Tesla told The Post it knows LG Chem's Tesla batteries do not contain Congolese cobalt, but it did not say how it knows this.

Tesla, more than any other automaker, has staked its reputation on "ethically sourcing" every piece of its celebrated vehicles.

"It is something we do take very seriously," Kurt Kelty, Tesla's director of battery technology, said in March at a battery conference in Fort Lauderdale, Fla. "And we need to take it even more seriously. So we are going to send one of our guys there."

Six months later, Tesla told The Post it is still working on sending someone to Congo.

BIRTH DEFECTS, ILLNESS

In Lubumbashi, another center of Congo's mining industry, 180 miles from Kolwezi, doctors have begun to unravel what has long been a mystery behind a range of health problems for local residents.

Their findings point to the mining industry as the problem.

These doctors at the University of Lubumbashi already know miners and residents are exposed to metals at levels many times higher than what is considered safe.

One of their studies found residents who live near mines or smelters in southern Congo had urinary concentrations of cobalt that were 43 times as high as that of a control group, lead levels five times as high, and cadmium and uranium levels four times as high. The levels were even higher in children.

Another study, published earlier this year, found elevated levels of metals in the mining region's fish. A study of soil samples around mine-heavy Lubumbashi concluded the area was "among the ten most polluted areas in the world."

Now the doctors are working to connect the dots.

"We are trying to draw a line between disease and metals," said Eddy Mbuyu, a university chemist.

But they are cautious about their task.

"The mining business has the money, and that money means power," said Tony Kayembe, an epidemiologist at the university's hospital.

Current studies are looking at thyroid conditions and breathing problems. But doctors are most concerned by possible connections to birth defects. One study the university doctors published in 2012 found preliminary evidence of an increased risk of a baby being born

with a visible birth defect if the father worked in Congo's mining industry.

The Lubumbashi doctors also have issued reports on birth defects so rare — one is called Mermaid syndrome — that they are the only cases ever known in Congo. All occurred in children born in heavy mining regions.

For Kayembe, the study that stood out most looked at babies born with holoprosencephaly, a usually fatal condition that causes severe, distinctive facial deformities. It is almost unheard of. Entire medical careers pass without seeing one. But last year, doctors in Lubumbashi recorded three cases in three months.

"This is not normal," Kayembe said.

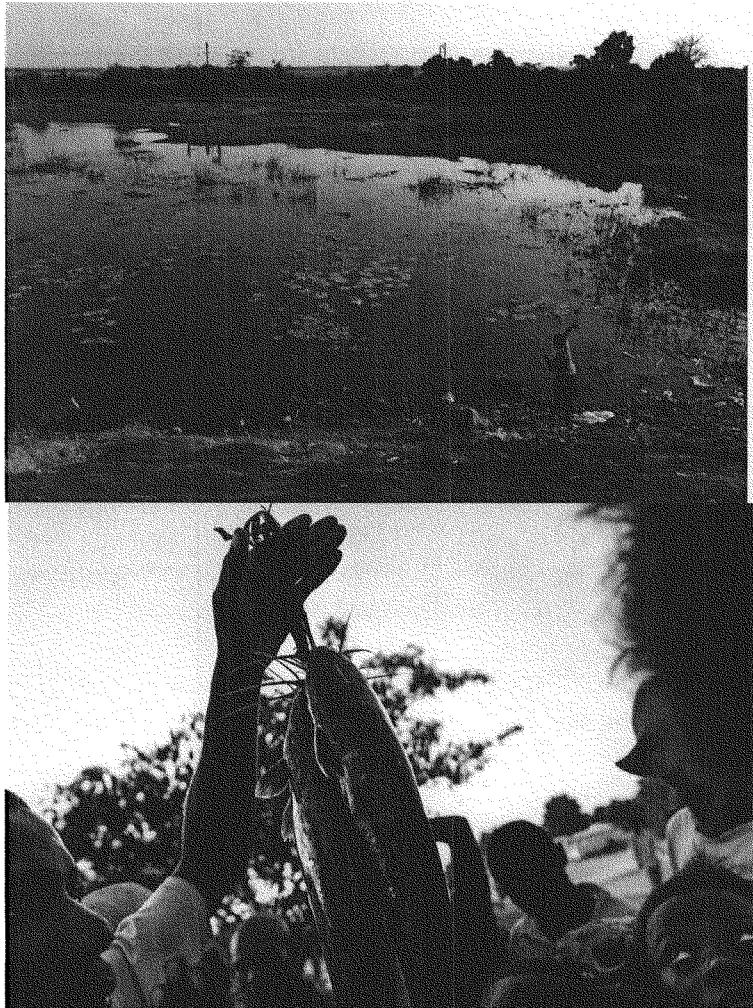
These medical inquiries could bring some relief to residents such as Aimerance Masengo, 15, who has been blaming herself since giving birth last year to a baby boy with severe, fatal birth defects.

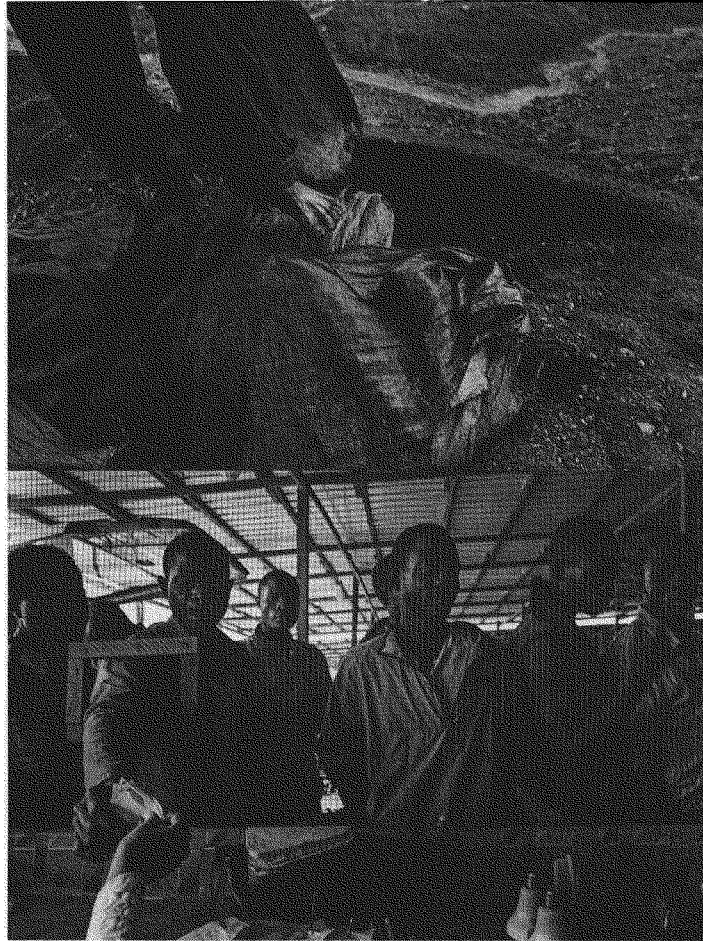
In a voice barely above a whisper, Aimerance recalled how she had been so scared when she saw her newborn. The doctor was scared, too, she said.

The doctor told Aimerance it was impossible to know for certain what went wrong. But, he noted, the baby's father worked as a cobalt digger. He told Aimerance he had seen many problems in the children born to diggers.

Aimerance and the baby's father lived in the nearby village of Luiswishi, home to 8,000 people. Everyone there seemed to be connected to artisanal mining. And in the past three years, according

to local activists, four newborns from this tiny village have died of severe birth defects.





A child throws a stone into the Kapolowe River outside Lubumbashi. Environmentalists, doctors and activists say that the region's rivers suffer from severe pollution that they think is from the copper and cobalt mining throughout the area. Catfish caught in the Kapolowe River is offered to prospective customers near the river's banks. A study published this year showed elevated levels of metals in the mining region's fish. A digger works at the mine in Kawama. Most of the work is done with manual tools and with virtually no environmental or safety precautions. Diggers wait for their pay at the Musompo market.

THE 'CREUSEURS' WAIT

For diggers such as Sidiki Mayamba, worried about affording flour for his family, the greatest concern is not safety or potential health problems. It is money. He needs the work. But he doesn't want his 2-year-old son, Harold, to follow him into the mines.

"A digger is a hard job with many risks," Mayamba said. "I cannot wish for my child to have this kind of job."

Cleaning up the cobalt supply chain will not be easy for Huayou Cobalt, even with the support of a powerful company such as Apple.

But Chen, Huayou's president, said it is the proper action, not only for the company but also for the Congolese miners.

"Some companies just want to get away from the problem," Chen said. "But Congo's problem is still there. The poverty is still there."

The question is whether Huayou's other customers, after years of buying cheap cobalt with no questions, will be supportive.

Pyers, the Apple senior director, said the company does not want to take steps aimed at just "making the supply chain look pretty."

"If we all cut and run from the Democratic Republic of Congo, it would leave the Congolese people in a devastating position," Pyers said. "And we will not be a party to that here."

Starting next year, Apple will internally treat cobalt like a conflict mineral, requiring all cobalt refiners to agree to outside supply-chain audits and conduct risk assessments.

Apple's action could have major repercussions throughout the battery world. But change will be slow. Apple spent five years working to certify that its supply chain was free of conflict minerals — and that action was enforced by law.

None of these efforts change the fate of diggers such as Kandolo Mboma.

At the Tilwezembe mine this summer, Mboma sat on a boulder, seemingly catatonic, his blue jeans stained black, his bare feet dangling just above the red dirt. His eyes failed to register the other diggers filing past.

"He was working all night, and he has not eaten," a fellow digger said.

Mboma, 35 and a father of three, was waiting for his cobalt to be weighed. Then, he hoped, he would get paid.

He sat next to a series of small food stalls, stout squares of discarded mining sacks stretched over sticks, where a digger could buy a bread roll for 100 Congolese francs, equal to about 10 cents. The bread came with a free cup of water.

"You eat what you make," Mboma said finally.

And eating would have to wait.



A "creuseur" descends into a tunnel at the mine in Kawama. The tunnels are dug with hand tools and burrow deep underground.

Peter Whoriskey in Washington contributed to this report.

The Guardian



The rise of electric cars could leave us with a big battery waste problem

Carmakers, recyclers and tech startups are working to solve the question of how to deal with lithium-ion batteries when they wear out

Joey Gardiner

Thu 10 Aug 2017 04:15 EDT

The drive to replace polluting petrol and diesel cars with a new breed of electric vehicles has gathered momentum in recent weeks. But there is an unanswered environmental question at the heart of the electric car movement: what on earth to do with their half-tonne lithium-ion batteries when they wear out?

British and French governments last month committed to outlaw the sale of petrol- and diesel-powered cars by 2040, and carmaker Volvo pledged to only sell electric or hybrid vehicles from 2019.

The number of electric cars in the world passed the 2m mark last year and the International Energy Agency estimates there will be 140m electric cars globally by 2030 if countries meet Paris climate agreement targets. This electric vehicle boom could leave 11m tonnes of spent lithium-ion batteries in need of recycling between now and 2030, according to Ajay Kochhar, CEO of Canadian battery recycling startup Li-Cycle.

Recycling gap

However, in the EU as few as 5% (pdf) of lithium-ion batteries are recycled. This has an environmental cost. Not only do the batteries carry a risk of giving off toxic gases if damaged, but core ingredients such as lithium and cobalt are finite and extraction can lead to water pollution and depletion among other environmental consequences.

There are, however, grounds for optimism. Thus far, the poor rates of lithium-ion battery recycling can be explained by the fact that most are contained within consumer electronics, which commonly end up neglected in a drawer or chucked into landfill.

This won't happen with electric vehicles, predicts Marc Grynberg, chief executive of Belgian battery and recycling giant Umicore. "Car producers will be accountable for the collection and recycling of spent lithium-ion batteries," he says. "Given their sheer size, batteries cannot be stored at home and landfilling is not an option."

EU Regulations, which require the makers of batteries to finance the costs of collecting, treating and recycling all collected batteries, are already encouraging tie-ups between carmakers and recyclers.

Umicore, which has invested €25m (£22.6m) into an industrial pilot plant in Antwerp to recycle lithium-ion batteries, has deals in Europe with both Tesla and Toyota to use smelting to recover precious metals such as cobalt and nickel. Grynberg says: "We have proven capabilities to recycle spent batteries from electric vehicles and are prepared to scale them up when needed."

Problem solved? Not exactly. While commercial smelting processes such as Umicore's can easily recover many metals, they can't directly recover the vital lithium, which ends up in a mixed byproduct. Umicore says it can reclaim lithium from the byproduct, but each extra process adds cost.

This means that while electric vehicle batteries might be taken to recycling facilities, there's no guarantee the lithium itself will be recovered if it doesn't pay to do so.

Investment bank Morgan Stanley in June said it forecast no recycling of lithium at all over the decade ahead, and that there risked being insufficient recycling infrastructure in place when the current wave of batteries die. "There still needs to be more development to get to closed loop recycling where all materials are reclaimed," says Jessica Alsford, head of the bank's global sustainable research team. "There's a difference between being able to do something and it making economic sense."

Second life for batteries

Francisco Carranza, energy services MD at Nissan, says the fundamental problem is that while the cost of fully recycling a battery is falling toward €1 per kilo, the value of the raw materials that can be reclaimed is only a third of that.

Nissan has partnered with power management firm Eaton for its car batteries to be re-used for home energy storage, rather than be recycled, and this economic problem is a big reason why. "Cost of recycling is the barrier," says Carranza. "It has to be lower than the value of the recovered materials for this to work."

The lack of recycling capacity is "a tragedy", says Amrit Chandan, a chemical engineer leading business development at Aceleron, a hi-tech British startup looking to transform end of life batteries. "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," he says.

Aceleron, like Nissan, thinks the answer lies in re-using rather than recycling car batteries - for which the company has patented a process. Chandan says car batteries can still have up to 70% of their capacity when they stop being good enough to power electric vehicles, making them perfect - when broken down, tested and re-packaged - for functions such as home energy storage.

Fresh from recognition by Forbes as one of the 30 most exciting hi-tech startups in Europe, Aceleron is looking for investors to help it roll out pilot projects. "There's going to be a storm of electric vehicle batteries that will reach the end of their life in a few years, and we're positioning ourselves to be ready for it," says Chandan.

This is not the only alternative. Li-Cycle is pioneering a new recycling technology using a chemical process to retrieve all of the important metals from batteries. Kochhar says he is looking to build a first commercial plant to put 5,000 tonnes of batteries a year through this "wet chemistry" process. However, it is early days for the commercial exploitation of this technology.

Linda Gaines, transportation system analyst and electric vehicle battery expert at the Argonne National Laboratory in the US says: "The bottom line is there's time to build plants". "But", she adds, "we don't know what kinds of batteries they'll

be yet. It would help if the batteries were standardised and designed for recycling, but they're not."

As the crisis escalates...

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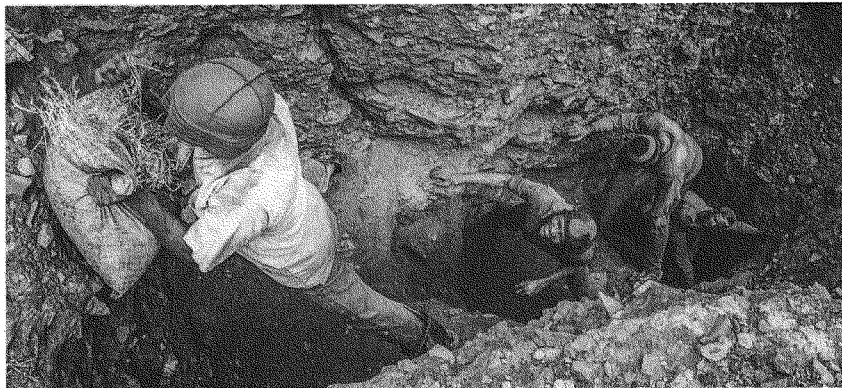


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Backbreaking work: Miners in the Democratic Republic of Congo pass up sacks filled with ore.

Meinrad Schade/laif/Redux

The Real Cost of Your Phone

In the heart of Africa, miners as young as seven risk their lives searching for cobalt, a key element in smartphones and other electronics we use every day

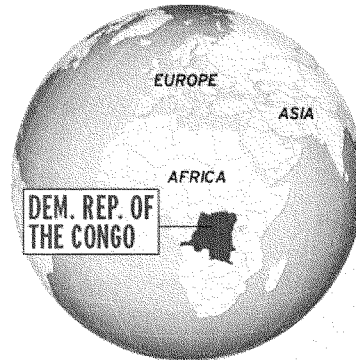
October 30, 2017

By Rebecca Zissou

Jim McMahon

Paul* was just 12 years old when he was forced to start working in mines in the Democratic Republic of the Congo (DRC), a country in Central Africa.

Day after day, he'd descend hundreds of feet underground without any protective gear. Using a small chisel, he'd spend up to 24 hours at a time searching for cobalt, an essential component of the rechargeable batteries that power our smartphones, laptops, and other electronic devices.



Collecting cobalt is backbreaking—and life-threatening—work. At any moment, the mine's tunnels could have caved in, leaving Paul buried in an avalanche of rocks and dirt. Cobalt miners are also exposed to toxic materials that can cause cancer, lung disease, and other serious health problems.

Last fall, an investigation by American journalists highlighted the hazardous conditions of the cobalt industry in the DRC, where 60 percent of the world's cobalt is mined. The report detailed a number of human rights abuses, including a lack of worker protections and the use of child laborers like Paul.

In response, Apple and other tech companies vowed to clean up their supply chains and pay more attention to how the materials in their products are obtained.

But experts say the problems surrounding cobalt mining won't be easy to fix. That's partly because demand for electronics—and the cobalt that helps power them—is on the rise. The amount of cobalt needed for battery manufacturing is expected to double by 2025. (Cobalt is also used in paint, jet engines, and other products.)

Mark Dummett of Amnesty International, an aid organization, says the DRC must do a better job protecting cobalt miners' safety and making sure that kids aren't working in the industry. Consumers need to get involved too, he adds, by holding companies accountable.

"Millions of people enjoy the benefits of new technologies but rarely ask how they are made," Dummett says. "It is high time the big brands took some responsibility for the mining of the raw materials that make their lucrative products."

Cobalt Mining in the DRC

Adults and children in the Democratic Republic of the Congo extract cobalt from hand-dug tunnels.

A Vital Source of Income

The DRC is one of the world's poorest countries. According to the World Bank, 77 percent of the nation's population lives in extreme poverty—often defined as living on less than \$1.90 a day. Many people there lack running water, access to electricity, and economic opportunities.

But the country is also rich in natural resources. In addition to cobalt, the DRC has huge deposits of gold, diamonds, and copper. Mining these and other materials can be a vital source of income for hundreds of thousands of people. On a good day, for example, cobalt miners can earn \$2 to \$3 for their haul. That can be enough for workers to feed their families.

Still, the risks associated with cobalt mining are huge. Many workers lack safety equipment, such as helmets, gloves, and face masks.

"The work is very dangerous," says Benoit Nemery, a public health researcher in Belgium who has studied the DRC's mining industry. "Accidents are common."

Indeed, in 2014, 16 cobalt miners were killed in a landslide, and another 15 died in an underground fire. The following year, 13 people were killed when a mine collapsed.

Child labor is also common in the DRC. In 2012, the United Nations Children's Fund estimated that 40,000 kids work in the mining industry in the southern part of the country, mainly in cobalt and copper mines.

Many of them are forced to work to help support their families. One girl said she started mining at the age of 9, after her father lost his job and couldn't afford to feed their family. "I could only eat when I had enough money," she said.

Communities at Risk

Even children who don't work in the mines are still exposed to toxic chemicals. Many kids sort through and wash the pieces of cobalt brought up by the miners.

Delphin Mutela, now 13, began helping his mother clean cobalt in a river when he was just 8 years old. He told reporters that he needed the money to help fund his education: "The money I get I use to buy notebooks and so I can pay school fees."

People who work in the cobalt industry aren't the only ones in danger. Families that live near mines or cobalt--processing areas are also exposed to hazardous elements through the foods they eat, including fruits and vegetables. Crops can become contaminated when dust

from the mines or from trucks transporting cobalt settles on the ground. Dangerous materials also make their way into yards and rivers, posing additional risks for people.

To make matters worse, says Nemery, miners often find cobalt alongside uranium and arsenic. Uranium can damage the kidneys, and arsenic can cause cancer.

"These communities are being exposed to a whole -cocktail of toxic metals," he says.

To help end the many abuses of the DRC's mining industry, experts say, the nation's government needs to better ensure workers' safety. The country already has some laws protecting children, but they're rarely enforced.

No Easy Fix

Following a 2016 story in *The Washington Post* about cobalt mining practices, some tech companies promised to reexamine their cobalt suppliers. Earlier this year, Apple announced that it had stopped buying cobalt mined by hand in the DRC until it could verify that the element was being collected safely. But many other tech companies have so far refused to acknowledge their part in the problem.

Advocacy groups in the United States are pushing for tougher laws here at home. Many activists say American companies should be required to prove that the cobalt in their products is mined ethically and without the use of child labor.

In the meantime, Nemery says, it's important for consumers to educate themselves about how their favorite electronics are made.

"Our smartphones and computers—and many other products we use every day," he says, "come at a very high human cost."

**Name has been changed to protect his privacy*

Reporting by Jennifer Barone and Amnesty International

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Comparative Study on Life Cycle CO₂ Emissions from the Production of Electric and Conventional Vehicles in China

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Abstract

Electric Vehicles (EVs), as expected to help save energy and reduce CO₂ emissions, are facing a rapid growth in China, the country with approximately one quarter of global vehicle production. However, the ability of EVs is estimated mainly on the basis of use phase, which is not complete enough. Aiming to identify the real ability of EVs in China, this study estimates the CO₂ emissions from production phase and compares the results with the level of Internal Combustion Engine Vehicles (ICEVs), the current dominating vehicles in China. The results reveal that the CO₂ emissions from the production of an EV range from 14.6 to 14.7 t, 59% to 60% higher than the level of an ICEV, 9.2 t. The Li-ion batteries and additional components such as the traction motor and electronic controller in an EV are the major reasons, while different curb weights and different composition between these two vehicles contribute as well. As the manufacture techniques of Li-ion batteries are growing and the material recycle industry is developing, huge reduction potential of CO₂ emissions from EVs exists in China.

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Keywords: vehicle production; Li-ion battery; life cycle assessment; comparative study

1. Introduction

As expected to save energy and slow down the climate change all over the world, Electric Vehicles (EVs) are growing rapidly now and in the future, especially in China. According to Chinese government, the cumulative output of EVs will reach 5 million in 2020, which is over 10 times larger than the number in 2015[1]. This pattern forecasts a significant change of life cycle CO₂ emissions related to vehicles[2], including material production, components manufacturing, assembly, using, disposal, recycling, etc.

Many scholars have carried out researches focusing on the life cycle emissions from different vehicles. Samaras provided a full Life Cycle Inventory (LCI) of EV production based primarily on energy

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consumption[3]. Lewis assessed the reduction potential of life cycle emissions through vehicle electrification mainly based on the use phase[4]. Oris compared the emissions related to well-to-wheels energy consumption of different vehicles in different regions, including China[5]. And Daimler AG carried out a Life Cycle Assessment (LCA) of its S400 car, providing a comparative result of two different versions (hybrid and conventional)[6].

Many studies pointed out that the emissions from the use phase accounted for the majority. However, as CO₂ emissions from the production of an Internal Combustion Engine Vehicle (ICEV) contributed about 10% to the full life cycle CO₂ emissions, the vehicle production phase is not insignificant[7]. Actually, with the growth of EVs, CO₂ emissions from vehicle production account for a growing proportion, which has seized much attention all over the world in recent years. This subject is an essential complement to the studies focusing on the use phase and is sure to play a more important role in the future.

On the other hand, CO₂ emissions from vehicle production vary among different regions owing to the discrepancies in manufacture techniques. Although existing studies have provided several referential results, it is far from completed due to the rapid growing techniques. In order to delve into this subject, this study focuses on the CO₂ emissions from vehicle production in China, the country with approximately one quarter of global vehicle production[8]. For this purpose, this study employs a life cycle framework of vehicle production, in which the energy consumption of all the processes is taken into consideration.

Nomenclature

E	CO ₂ emissions, kg
EF	emission factor, kg-CO ₂ /MJ
MM	mass of materials, kg
MPF	mass of process fuel, MJ
RP	replacements during life time

Subscripts

A	assembly
B	batteries
BA	batteries and attachments
BC	basic components
F	fluids
SC	special components
T	total
Ti	tires

2. Method and System

2.1. Assumption and system boundary

objects. When it comes to tires, the standard radial tires for mid-size passenger cars are considered both for ICEVs and EVs. Finally, all kinds of fluids used in vehicles are considered, including engine oil, brake fluid transmission fluid, powertrain coolant, windshield fluid and adhesives.

2.3. Methods and data

Equation (1) to (4) describe the life cycle CO₂ emissions from the production phase.

$$E_{BC/SC/B/Ti/F} = RP \cdot \sum MM \cdot \sum MPF \cdot EF \quad (1)$$

$$E_{BA} = E_B + E_{Ti} + E_F \quad (2)$$

$$E_A = \sum MPF \cdot EF \quad (3)$$

$$E_T = E_{BA} + E_A + \sum E_{BC} + \sum E_{SC} \quad (4)$$

Where,

$E_{BC/SC/B/Ti/F}$ is the CO₂ emissions from the production of basic components/special components/batteries/tires/fluids (kg-CO₂ per vehicle);

E_{BA} is the CO₂ emissions from batteries and attachments (kg-CO₂ per vehicle);

E_A is the CO₂ emissions from assembly, for both batteries and vehicle (kg-CO₂ per vehicle);

E_T is the total CO₂ emissions from vehicle production (kg-CO₂ per vehicle).

The emission factors of process fuels and energy consumption of materials and other parts are calculated on the basis of a wide range of sources as presented in Table 1 and Table 2.

Table 1. Life cycle CO₂ emission factors of process fuels

Process fuel	CO ₂ emissions factor (kg-CO ₂ /MJ, kg-CO ₂ /kWh)	Data source
Coal	94.8	[13]
Electricity	834.5	[14], [15]
Natural gas	63.5	[13]
Coke	105.9	[16], [17]
Residual oil	89.3	[13]
Gasoline	82.0	[13]
Diesel	79.9	[13]
Blast furnace gas	260.0	[16]
Coke oven gas	44.4	[16]

Note: Coke, blast furnace gas and coke oven gas are produced during the coke production process included in the steel production.

Table 2. Energy consumption of different materials, batteries, tires and fluids

Material	Data source	Batteries, tires and fluids	Data source
Steel	[18], [19], [20]	LFP battery: active material	[27]
Iron	[18]	LFP battery: other materials	[28]

Cast aluminum	[18], [21]	NCM battery: active material	[27]
Wrought aluminum	[18], [21]	NCM battery: other materials	[28]
Copper/brass	[22], [23]	Tires	[18], [29]
Glass	[24]	Fluids	[11], [23], [25]
Rubber	[25], [26]		
Average plastic	[18], [23], [24]		
Magnesium	[25]		

Note: Most of the energy consumption of the materials and other parts listed above are calculated under the circumstance of China. For instance, as the recycled steel used for steel production only accounts for 11% in China[30], this study mainly considers the virgin steel production in China.

Furthermore, due to the lack of related studies in China, the energy consumption of assembly (including battery and vehicle assembly) is provided by Lu[31], Papasavva[32]–[33] and Sullivan[23].

3. Results

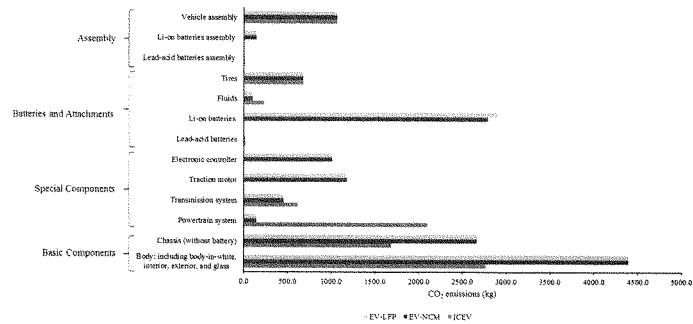
3.1. Overview

Table 3 presents the CO₂ emissions from vehicle production. It is clear that the CO₂ emissions are about 14.6 t per EV with NCM battery, 59% higher than the level of an ICEV, about 9.2 t. And the number is larger for an EV with LFP battery, about 14.7 t, 60% higher than the level of an ICEV.

Table 3. CO₂ emissions from vehicle production

Component		CO ₂ emissions per vehicle (kg)		
		ICEV	EV-NCM	EV-LFP
Basic	Body: including body-in-white, interior, exterior, and glass	2767.9	4393.5	4393.5
Components	Chassis (without battery)	1684.7	2665.5	2665.5
	Powertrain system	2092.5	145.6	145.6
	Transmission system	617.4	455.2	455.2
Special Components	Traction motor	/	1179.1	1179.1
	Electronic controller	/	1010.2	1010.2
	Lead-acid batteries	24.5	15.1	15.1
Batteries and attachments	Li-ion batteries	/	2788.8	2892.4
	Fluids	230.2	98.3	98.3
	Tires	677.1	677.1	677.1
Assembly	Lead-acid batteries assembly	14.1	8.7	8.7
	Li-ion Batteries assembly	/	141.5	141.5
	Vehicle assembly	1064.1	1064.1	1064.1
Total		9172.5	14642.5	14746.1

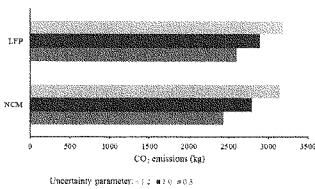
The decomposition of CO₂ emissions from each part is revealed in Fig. 2. It can be found that the CO₂ emissions from Li-ion battery production account for a large proportion in both kinds of EVs, about 19%/20% for an EV with NCM/LFP battery. Meanwhile, more CO₂ emissions are produced from other parts of an EV than the level of an ICEV.

Fig. 2. Decomposition of CO₂ emissions by different parts

3.2. Uncertainty analysis

Li-ion batteries have just been massively applied to EVs in recent years. Therefore few studies focusing on CO₂ emissions from battery production exist and few production standards have been established for battery manufacture in China, which creates uncertainty in this study.

Among the inventory, CO₂ emissions from active material production are the most influential variable for both LFP and NCM batteries. Fig. 3 presents the CO₂ emissions from the production of these two batteries when the variable is multiplied by the uncertainty parameters 0.8, 1.0 and 1.2. The result ranges from 2435.2 to 3142.4 kg-CO₂ per NCM battery and 2596.3 to 3188.5 kg-CO₂ per LFP battery, which is quite wide. Therefore care must be taken when drawing conclusions on the basis of the results.

Fig. 3. Uncertainty of CO₂ emissions from battery production

4. Discussions

4.1. Comparative simulation results

Several literature results provided benchmarks of CO₂ emissions from the production of an ICEV and an EV. GREET-2015 used the same vehicle specification as this study, however, it revealed that in the U.S., CO₂ emissions from the production of an ICEV was about 6.4 t and the level of an EV with NCM/LFP battery was about 8.6/8.4 t[11], which is much lower than the level in China. The advanced Li-ion battery production techniques and developed materials recycle industries are the dominated reasons. From another point of view, Hawkins estimated the CO₂ emissions from the production of the Mercedes A-Class ICEV and EV with NCM/LFP battery in Europe based on Ecoinvent v2.2. The results showed that the global warming potential from an EV with NCM/LFP production is about 13/14 t CO₂-eq, which is roughly twice the level of ICEV production, 6.5 t CO₂-eq[7].

In short, results based on different situations vary in a wide range due to the different manufacture techniques, however, they all revealed that EV production caused much more CO₂ emissions.

4.2. Difference analysis

Much more CO₂ emissions are produced from vehicle production for an EV than an ICEV for a series of reasons. Considering the basic components contained in both kinds of vehicles including body and chassis (without battery), CO₂ emissions from the production of them in an EV are 59% more than the level of an ICEV, which is mainly caused by the larger weight. When it comes to the special components, production of the powertrain system and transmission system in an ICEV produces more CO₂ emissions due to the larger weight and different compositions. However, the traction motor and electronic controller only exist in an EV and makes the whole CO₂ emissions from the production of special components in an EV 3% more than the level of an ICEV. Furthermore, it can be found that the production of batteries and attachments, including tires and fluids, produces 3.8/4.0 times CO₂ emissions in an EV with NCM/LFP battery as many as the level of an ICEV due to the mass CO₂ emissions from Li-ion battery production. Finally, more CO₂ emissions are produced from EV assembly due to the Li-ion battery assembly.

4.3. CO₂ emissions reduction potentials

As designed to help save energy and reduce emissions, EVs are not performing well in the production phase currently in China. However, there are reduction potentials to be expected:

- The manufacture techniques of Li-ion batteries in China are still in the primary stage. As a comparison, due to the cleaner production of active materials, one Li-ion battery, such as NCM or LFP battery, produced in the U.S. only leads to around 1.1 t CO₂ emissions[18], one third of the level in China. Therefore the situation is sure to improve with technique growth in China.
- Compared with an ICEV, more steel and aluminum are used in an EV, leading to significant CO₂ emissions. However, the situation can be effectively improved by using recycled materials instead of virgin materials. For instance, as mentioned above, the share of recycled steel used in China is only 11%, compared to 70% in the U.S. and 56% in the EU[30], which implies a huge reduction potential.

5. Conclusions

In this study, life cycle CO₂ emissions from the production of an standard mid-size passenger EV and ICEV with conventional materials in China are estimated from the component point of view, where all the stages and materials are considered in details. The results reveal that the CO₂ emissions from the production of an EV with NCM/LFP battery are about 14.6/14.7 t, 59%/60% higher than the level of an

ICEV, 9.2 t. The Li-ion battery and additional components such as the traction motor and electronic controller in an EV are the major reasons, and different curb weights with different composition between these two vehicles contribute to the difference as well.

Meanwhile, reduction potentials of CO₂ emissions from EV production are analyzed in this study. With the development of battery manufacture techniques, especially active materials, the CO₂ emissions from Li-ion battery production can be reduced to approach the level in the U.S., about one third of it in China. At the same time, as more steel and aluminum are used in an EV than ICEV, huge reduction can be performed with the growth of steel and aluminum recycle industry.

Despite the important results obtained in this study, further steps are needed to carry out more precise estimations. As mentioned in this study, the vehicle specification of standard vehicle is unclear in China, which is sure to lead deviation. And the manufacture standards of batteries have not been established in China, leading to the data's variation in a wide range.

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Biography

Dr. Han Hao is a research assistant at the Department of Automotive Engineering, Tsinghua University. His research interests include transport energy system modeling, technology assessment, and transport policy in the context of climate change.

Appendix A. Vehicle specification

Table 1. Weight composition by components (excluding batteries, fluids and tires)

Component	ICEV: Conventional Material (kg)	EV: Conventional Material (kg)
	332.2	28.8
Powertrain system	39.5% steel, 28.6% cast iron, 17.1% cast aluminum, 2.9% copper/brass, 9.3% average plastic, 2.6% rubber	50.0% steel, 20.5% copper/brass, 29.5% average plastic
	81.4	55.8
Transmission system	30.0% steel, 30.0% cast iron, 30.0% wrought aluminum, 5.0% average plastic, 5.0% rubber	60.5% steel, 18.9% copper/brass, 20.0% wrought aluminum, 0.2% average plastic, 0.4% others

		113.3	
Traction motor	/	36.1% steel, 36.1% cast aluminum, 27.8% copper/brass	
		99.8	
Electronic controller	/	5.0% steel, 46.9% cast aluminum, 8.2% copper/brass, 3.7% rubber, 23.8% average plastic, 12.4% others	
	309.0	488.8	
Chassis (without battery)		84.1% steel, 6.9% cast iron, 1.0% cast aluminum, 1.2% copper/brass, 1.8% average plastic, 4.4% rubber, 0.6% others	
	570.1	904.9	
Body: including body-in-white, interior, exterior and glass		68.3% steel, 0.7% wrought aluminum, 1.9% copper/brass, 6.5% glass, 18.1% average plastic, 0.5% rubber, 4.0% others	

Table 2. Weight composition and replacements during life time of batteries, tires and fluids

Batteries, tires and fluids	ICEV: Conventional Material (kg)	EV: Conventional Material (kg)	Replacement
	16.3	10.0	
Lead-acid battery	6.1% polypropylene, 69.0% lead, 7.9% sulfuric acid, 2.1% fiber glass, 14.1% water, 0.8% others	230.0	2
		24.4% active material, 15.2% graphite/carbon, 2.1% binder, 12.4% copper, 20.3% wrought aluminum, 18.2% LiPF ₆ , 7.8% ethylene carbonate, 7.8% dimethyl carbonate, 1.9% polypropylene, 0.3% polyethylene, 1.3% polyethylene terephthalate, 1.5% steel, 0.3% thermal insulation, 1.0% glycol, 1.0% electronic parts	0
LFP battery	/	170.0	
		28.2% active material, 18.3% graphite/carbon, 2.4% binder, 11.4% copper, 19.7% wrought aluminum, 1.9% LiPF ₆ , 5.4% ethylene carbonate, 5.4% dimethyl carbonate, 1.7% polypropylene, 0.3% polyethylene, 1.2% polyethylene terephthalate, 1.4% steel, 0.4% thermal insulation, 1.0% glycol, 1.3% electronic parts	0
NCM battery	/		
	9.1 (one tire)	9.1 (one tire)	
Tires	66.7% rubber, 33.3% steel	66.7% rubber, 33.3% steel	3
Fluids			
engine oil	3.9	0.0	39
brake oil	0.9	0.9	3
transmission fluid	10.9	0.8	1
powertrain coolant	10.4	7.2	3
windshield fluid	2.7	2.7	19

adhesives	13.6	13.6	0
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Amnesty challenges industry leaders to clean up their batteries

[amnesty.org/en/latest/news/2019/03/amnesty-challenges-industry-leaders-to-clean-up-their-batteries](https://www.amnesty.org/en/latest/news/2019/03/amnesty-challenges-industry-leaders-to-clean-up-their-batteries)

21 March 2019, 00:01 UTC

Amnesty International is today publicly challenging leaders within the electric vehicle industry to make the world's first completely ethical battery within five years. At the [Nordic Electric Vehicle \(EV\) Summit in Oslo](#), the organization is highlighting how lithium-ion batteries, which power electric cars and electronics, are linked to human rights abuses including child labour in the Democratic Republic of Congo (DRC), and environmental risks which could undermine their green potential.

Without radical changes, the batteries which power green vehicles will continue to be tainted by human rights abuses

"Finding effective solutions to the climate crisis is an absolute imperative, and electric cars have an important role to play in this. But without radical changes, the batteries which power green vehicles will continue to be tainted by human rights abuses," said Kumi Naidoo, Amnesty International's Secretary General.

"The massive global corporations that dominate the electric vehicle industry have the resources and expertise to create energy solutions that are truly clean and fair, and we are challenging them to come back to Oslo next year with proof of real progress. With demand for batteries soaring, now is the time for a drastic overhaul of our energy sources that prioritizes protection of human rights and the environment."

Human rights violations linked to mineral extraction

Electric vehicles are key to shifting the motor industry away from fossil fuels, but they are currently not as ethical as some retailers would like us to believe. Years of unregulated industry practices have led to detrimental human rights and environmental impacts, which governments and industry are not doing enough to tackle.

Amnesty International has documented serious human rights violations linked to the extraction of the minerals used in lithium-ion batteries, particularly in the DRC. [A 2016 investigation](#) found children and adults in southern DRC working in hand-dug cobalt mines facing serious health risks, neither protected by the government nor respected by companies that profit from their labour. Amnesty's [research has linked](#) these mines to the supply chains of many of the world's leading electronics brands and electric vehicle companies.

Despite projections that the demand for cobalt will reach 200,000 tons per year by 2020, no country legally requires companies to publicly report on their cobalt supply chains. With more than half of the world's cobalt originating in southern DRC, the chance that the batteries powering electric vehicles are tainted with child labour and other abuses is unacceptably high.

We need to change course now, or those least responsible for climate change – indigenous communities and children – will pay the price for the shift away from fossil fuels. The energy solutions of the future must not be based on the injustices of the past.

There has been some progress since 2016. In response to Amnesty's research several leading companies, including Apple, BMW, Daimler, Renault, and the battery manufacturer Samsung SDI, have published data about their supply chains, and the organization is today calling on others to do the same.

Amnesty International has also begun documenting violations of the human rights of Indigenous peoples living near lithium mines in Argentina. Indigenous communities are not being properly consulted about mining projects on their lands and are given insufficient information about the potential impacts of mining on their water sources. Without human rights protections, the harm to Indigenous communities could increase as lithium demand soars.

Other emerging threats

The environmental impact of producing batteries is also a concern. Most of the current manufacturing of lithium-ion batteries is concentrated in China, South Korea and Japan, where electricity generation remains dependent on coal and other polluting sources of power.

This means that, while electric vehicles are essential for shifting away from fossil fuels and reducing greenhouse gas emissions, more needs to be done to reduce the carbon footprint within the manufacturing phase. Meanwhile, rising demand for minerals like cobalt, manganese and lithium has led to a surge in interest in deep-sea mining, which studies predict will have serious and irreversible impacts on biodiversity.

Amnesty International is also calling on companies to ensure that batteries are disposed of responsibly. There is already significant evidence showing that battery waste from electronics, which contains various hazardous materials, has been irresponsibly disposed of, contaminating soil, water and air.

"Every stage of the battery lifecycle, from mineral extraction to disposal, carries human rights and environmental risks," said Kumi Naidoo.

"We need to change course now, or those least responsible for climate change – indigenous communities and children – will pay the price for the shift away from fossil fuels. The energy solutions of the future must not be based on the injustices of the past."

An alternative vision

Using the Nordic EV Summit as a platform, Amnesty International today outlined its vision for an ethical battery which does not harm human rights or the environment at any stage of its lifecycle. The organization is calling for action by government, industry, innovators, investors and consumers to create an ethical and sustainable battery, which can be used for electric vehicles and in the electronic industry, within five years.

With a climate crisis looming, consumers have the right to demand that products marketed as the ethical choice really stand up to scrutiny

Amnesty International's work will focus on all three phases of the battery lifecycle:

Extraction: Mapping supply chains of key minerals, calling for human rights impacts to be identified, prevented and addressed, and calling for a prohibition on commercial deep-sea mining;

Manufacturing: Calling for carbon footprints to be properly disclosed, minimised, and offset; and for rights to and at work, including health, equality and non-discrimination, to be legally protected and enforced;

Re-use and recovery: Calling for products to be designed and regulated so that their potential for re-use is optimised and waste is penalized; and illegal or dangerous exportation and dumping of batteries is prevented.

The challenge to companies

Amnesty International today emphasized that electric vehicle and electronics companies have a responsibility to ensure their products do not contribute to or perpetuate human rights abuses. The organization is calling on industry leaders to commit to a radical overhaul of their approach to energy solutions.

Companies who overlook human rights concerns as they clean up their energy sources are presenting their customers with a false choice; people or planet. This approach is gravely flawed

As a first step, companies should publicly disclose information about how human rights abuses and environmental risks are being prevented, identified and addressed throughout the lithium-ion battery's lifecycle.

“With a climate crisis looming, consumers have the right to demand that products marketed as the ethical choice really stand up to scrutiny,” said Kumi Naidoo.

“Companies who overlook human rights concerns as they clean up their energy sources are presenting their customers with a false choice; people or planet. This approach is gravely flawed and will not deliver the sustainable changes we need to save humanity from climate devastation. We are asking industry leaders to think hard about what kind of future they want to build.”

Background

Amnesty is collaborating with Greenpeace USA to identify and map human rights and environmental impacts throughout the battery lifecycle, including critical points of intervention need to produce an ethical battery.

Efforts are underway in Norway to create on corporate actors to conduct human rights due diligence.

Bloomberg



Dry and cracked ground marks an area where water is being pumped by mining companies in the southern tip of the Atacama salt flat.

Photographer: Cristobal Olivares/Bloomberg

Saving the Planet With Electric Cars Means Strangling This Desert

Mining lithium and copper to supply the battery boom and fight climate change is wrecking a fragile ecosystem in Chile.

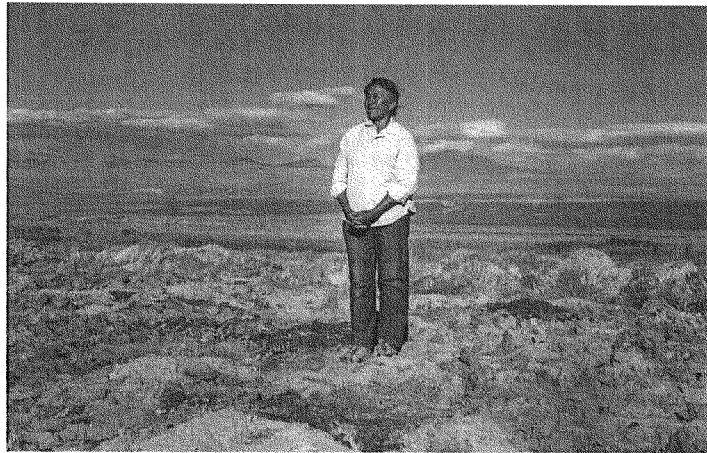
By

Laura Millan Lombrana

June 11, 2019, 6:00 AM EDT

The oases that once interrupted the dusty slopes of the Atacama desert in northern Chile allowed humans and animals to survive for thousands of years in the world's driest climate. That was before the mining started.

Sara Plaza, 67 years old, can still remember guiding her family's sheep along an ancient Inca trail running between wells and pastures. Today she is watching an engine pump fresh water from beneath the mostly dry Tilopozo meadow. "Now mining companies are taking the water," she says, pointing to dead grass around stone ruins that once provided a nighttime refuge for shepherds.



Sara Plaza stands on the dry meadow where her family's flock of sheep used to feed during winter months.

Photographer: Cristobal Olivares/Bloomberg

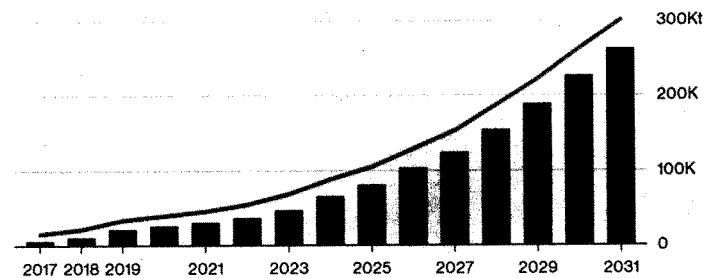
"No one comes here anymore, because there's not enough grass for the animals," Plaza says. "But when I was a kid, there was so much water you could mistake this whole area for the sea."

Atacama has become one of the busiest mining districts on the planet in the intervening decades, following discoveries of massive deposits of copper and lithium. In recent years that mining has intensified, thanks to booming demand for lithium, which is indispensable in the production of rechargeable batteries for electric vehicles. Chile exported nearly \$1 billion of lithium last year, almost quadruple the export value from four years ago.

EV-Driven Demand

Electric cars will make up for most of future lithium demand

■ Lithium demand for transport / Total lithium demand



Source: BloombergNEF

Note: Transport includes passenger EVs, E-buses and commercial vehicles

Bloomberg

Pursuit of the soft mineral is often seen as something that's good for the environment. Electric automakers such as [Tesla Inc.](#) want to make it easier and cheaper for drivers to adopt clean, battery-powered replacements for dirty combustion engines. Batteries are by far the most expensive part of an electric vehicle, so mining more lithium to meet rising demand helps lower prices. Putting more electric cars on the road is one of the most powerful ways to mitigate the effects of climate change, reducing the 15.6% of global carbon emissions that come from transportation.

But extracting Atacama's lithium means pumping large amounts of water and churning up salty mud known as brine—and that's having an irreversible impact on the local environment. Here, in this remote part of the Andes, the hopeful mission of saving the planet through electric cars is destroying a fragile ecosystem and depleting stores of drinking water.

"We're fooling ourselves if we call this sustainable and green mining," says Cristina Dorador, a Chilean biologist who studies microbial life in the Atacama desert. "The lithium fever should slow down because it's directly damaging salt flats, the ecosystem and local communities."

Lithium mining's crown jewel is a vast salt flat 10 times as big as New York's Central Park. To get the minerals out requires working at an elevation about 6,500 feet above sea level. The otherworldly desert landscape is dotted with shallow lagoons in which [flamingos nest](#) amid an enclosure of volcanoes and mountains. The stunning geography is akin to a gigantic bowl.



A flamingo feeds at the Chaxa lagoon in Atacama.

Photographer: Laura Millan Lombana

Dorador studies the microscopic life found in the lagoons, which are fed by underground reservoirs and thin streams coming down the mountains. Over millennia, that water has deposited the coveted minerals at the heart of the salt flat. It has also been the key to sustaining life in a place so hostile that scientists use it to simulate conditions on Mars.

Mining companies have made a study of the water, too. The world's largest copper mine, BHP Group Ltd.'s Escondida, pumps water from wells on the southern part of the salt flat; so, too, does Antofagasta Plc.'s Zaldivar copper operation. Copper miners use water at every step of the process to turn rocks into a 99.9% pure slab of mineral. Copper-rich rocks are crushed into a dust that's mixed with water to flow through giant pipes, and then water mixed with chemicals is used to separate the copper from the slurry.



A brine pool at a lithium mine in the Atacama salt flat.

Photographer: Cristobal Olivares/Bloomberg

Lithium mining needs less fresh water but requires pumping large amounts of brine, the salty mud sitting below the crust of the salt flats. The mineral-rich brine is left in large pools to evaporate before processing. The world's two largest lithium miners, Albemarle Corp. and Soc. Quimica & Minera de Chile SA, are currently extracting brine from the salt flat at unprecedented rates. Albemarle's process is "absolutely clean," a company official said in an email, and the company is developing technology to produce more lithium without pumping more brine than authorized. (SQM didn't immediately respond to a request for comment.)

Environmental impact studies conducted by the mining companies as part of the process to obtain government licenses consistently show no significant impact on water levels or wildlife. The government water authority, Dirección General de Aguas, which has no data of its own and monitors the salt flat through company reports, sees no risk of irreversible damage as long as legal requirements are fulfilled, said director Oscar Cristi.

The lack of government data or comprehensive independent research has made it hard to dispute statements from miners in the past. But recent studies and the testimony of local residents point to rapid deterioration.



A fuel engine pumps water from the Tilopozo well in the southern tip of the Atacama salt flat.

Photographer: Cristobal Olivares/Bloomberg

From 2000 to 2015, the amount of water pumped out of the salt flat was 21% higher than the amount that filtered in, according to several reports by the Chilean government's Committee of Non-Metallic Mining that analyzed data provided by mining companies. Water levels in some wells on the southern part of the salt flat declined by about one meter over the last decade in total. In the central part of the salt flat, levels dropped between 20 centimeters and 1 meter per year, on average, over the 15-year period covered by the data.

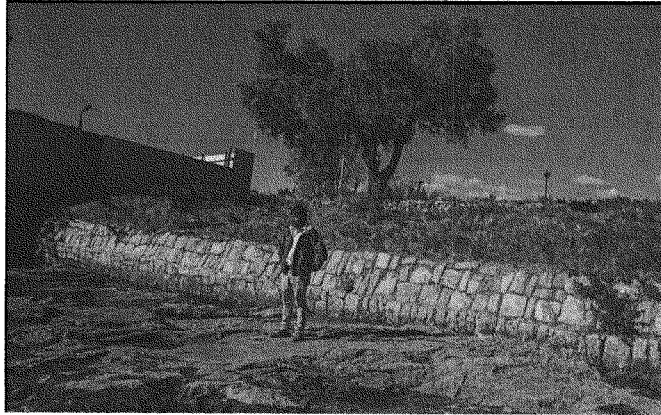
The falling water levels are felt by local people. Peine, the village closest to the mining, has license to pump 1.5 liters of water per second to supply 400 residents and a transient population of mine workers that can rise as high as 600. BHP's Escondida

copper mine has a license to pump 1,400 liters per second. Albemarle and SQM, the big lithium miners, have licenses to pump around 2,000 liters per second of brine.

The water allocated to homes in Peine often isn't enough, forcing the local government to shut off running water at night so tanks can refill. During the height of summer, water cuts can last up to four days.

The Committee of Non-Metallic Mining reports tied decreases in water levels to the increase in brine pumping by the lithium miners. It also started to work on a model that would allow the government to independently monitor environmental changes. But when Chilean President Sebastian Pinera took office in March, his administration dissolved the committee.

Atacama's infrequent rains and the highest solar radiation in the world—30% higher on average than in the Mojave desert—result in fast evaporation and allow miners to produce high-quality lithium at a low cost. But that method of mining, dating from the 1950s, results in the loss of large amounts of water. Companies and scientists are investigating ways to eliminate evaporation pools by capturing the lithium via chemical processes and then re-injecting water back into the salt flat, but these technologies haven't reached commercial implementation.



Sergio Cubillos, president of Atacama People's Council, stands on an empty water tank at the village of Peine.

Photographer: Cristobal Olivares/Bloomberg

Meadows and lagoons in the southern part of the salt flat have shrunk over the last few years, and the flamingo population has declined, according to the Atacama People's Council, the umbrella group representing the 18 indigenous communities living around the salt flat. "Every company has their own studies, which are fully compliant with the rules," says Francisco Mondaca, the council's coordinator for environmental issues. "The problem is that the rules are weak. Water, flora and fauna are measured separately, so we don't know how a change in one impacts the other."

Local communities want to change that, and last month the council set up its first monitoring station in a lagoon on the salt flat. The installation will continuously monitor water levels, as opposed to the once-a-month measurements that mining companies do. There are plans to build 14 additional stations over the next year.

Metal-Intensive

Electric cars use more mineral than combustion vehicles

Source: BloombergNEF

Note: Metals and materials demand from passenger EVs

"The Chilean government is encouraging more and more companies to come here to explore and mine lithium, but they don't have the capacity to oversee all of that," says Sergio Cubillos, president of the indigenous council. "People need to realize that there's an environmental cost associated to lithium, and that cost is being felt here."

BHP has vowed to completely stop using fresh water in Chile by 2030 and has so far invested \$4 billion in desalination plants. But the company is now requesting an extension of its water rights from 2020 to 2030, promising to cut the pumping rate to 640 liters per second. Monitoring hasn't shown environmental changes different than those anticipated under existing permits, a company official said in an email. Antofagasta's Zaldivar copper mine is also seeking a new license to pump 213 liters per second through 2029; the company wasn't immediately available for comment.

The huge increase in lithium demand is drawing additional mining companies into the Atacama and other salt flats in the Andes. About 40% of Chile's salt flats are now being explored for lithium, according to Dorador, the scientist. If the current way of mining continues, she warns, there's a risk that the salt flats will run out of water.



Lengths of pumping pipe lie on the ground at a lithium mine.

Photographer: Cristobal Olivares/Bloomberg

This has happened before: Dorador points to the Lagunillas salt flat, significantly impacted after more than a decade of pumping by BHP's Cerro Colorado mine. Also drier because of mining activity are the Punta Negra salt flat near BHP's Escondida and the Michincha salt flat near the Collahuasi copper mine, which is owned by Anglo American and Glencore.

The Atacama salt flat is the largest in Chile, meaning any changes there will happen slower, but it could share the fate of other salt flats, says Mondaca of the indigenous council. He cautions that mining companies' assessments of the environmental impacts don't account for warming temperatures, which could accelerate the drying process.

"Climate change is just making this problem bigger," Mondaca says. "Mining companies say the impact of what they're doing now will not be felt for another 20 years, but with climate change that could be 10 years, or it could be five. No one knows."

This could be the ultimate irony of the green revolution spurring demand for electric vehicles and batteries made from lithium. Scientists have come to view the fragile environment of Atacama as key to understanding the origins of life and the effects of climate change. Millions of years ago, the salt flat was a lake that has been slowly

drying up, a process similar to what could happen elsewhere around the planet as temperatures rise.

“It is a picture of how our lakes will look like in the future,” Dorador says. To her, pumping water out of this dying ecosystem means taking away its last breath before scientists have had the chance to fully understand it.



#recyclingworks

ISRI is the voice of the recycling industry, promoting safe, economically sustainable and environmentally responsible recycling through networking, advocacy, and education.

August 2, 2019

Senator John Barrasso
Chairman, Senate Environment & Public Works Committee
410 Dirksen Senate Office Building
Washington, D.C. 20510

Senator Tom Carper
Ranking Member, Senate Environment & Public Works Committee
410 Dirksen Senate Office Building
Washington, D.C. 20510

Dear Senators Barrasso and Carper:

The Institute of Scrap Recycling Industries, Inc. (ISRI) commends the Committee for addressing the opportunities and challenges regarding electric vehicles and welcomes this opportunity to submit our comments for the record on this important topic.

ISRI is a non-profit trade association representing approximately 1,300 companies operating in nearly 4,000 locations in the United States, and 41 countries worldwide that process, broker, and consume scrap commodities, including metals, paper, plastics, glass, rubber, electronics, and textiles. Currently, the U.S. scrap recycling industry is generating \$110 billion in domestic economic activity, while directly or indirectly supporting more than 530,000 well-paying jobs, and generating \$12.9 billion in federal, state and local tax revenue. The U.S. scrap recycling industry supplies the commodities that manufacturers use as raw material feedstock to make new products and serves as a substitute of mined raw materials in the amount of 138 million metric tons in 2018, with more than 70% being consumed in the United States. In addition to providing raw materials to domestic manufacturers, the U.S. scrap recycling industry exports approximately one-third of its commodities worth \$20 billion annually to more than 150 nations in 2018. Scrap vehicles comprise a large segment of those scrap commodities processed by the scrap recycling industry.

ISRI views the development of electric vehicles as presenting both challenges and opportunities for the recycling industry. Given the rapid rate of innovation in electric vehicles, the challenges and opportunities for recyclers are not precisely known. However, failure to meet these challenges and to seize the opportunities could result in the widespread production and use of electric vehicles that, at least from a resources/recycling perspective is unsustainable.

Innovation in electric vehicles involves the entire vehicle design and is not therefore limited to battery chemistry, design, system integration and material composition. Material composition is heavily influenced by battery system design in large measure to compensate for the relatively large weight of powertrain batteries. Nonetheless, we believe that mutually beneficial opportunities exist for all stakeholders to reduce the period of time of uncertainty and hasten the development of a sustainable recycling infrastructure for electric vehicles, their powertrain(s) and ancillary batteries. This infrastructure would also include opportunities for remanufacturing and reuse of batteries at their end of use or life.



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Proprietary Business Information

Automobile Recycling Operations

As a point of reference, the recycling infrastructure for vehicles is largely designed for “traditional” light-duty internal-combustion-engine vehicles, mainly passenger vehicles that use lead-acid batteries. Historically, such vehicles have consisted of 65% ferrous metal of several types (e.g., steel), 10% nonferrous metal (e.g., aluminum, copper, and lead), and non-metallic materials (e.g., plastics, rubber, glass, and fluids). At a vehicle’s end of life (EOL), often 10-15 years after manufacture, it is typically purchased by a vehicle dismantler.

Automobile Dismantling Operations

Over 14 million EOL vehicles are removed from the road each year. A sustainable vehicle recycling system is vital for managing those EOL vehicles and reintroducing parts back into use or their metal components back into the raw material stream. A vehicle dismantler values an EOL vehicle based on its potential for used parts for resale and also its scrap value. The value of a used part, whether for direct reuse or remanufacture, well exceeds its intrinsic scrap value. The vehicle dismantler removes the fluids and the lead-acid battery, known in the industry as a spent lead-acid battery or SLAB. After a certain period of time, or after all usable parts have been harvested, the vehicle dismantler sells the remainder of the EOL vehicle to a scrap metal recycler. The recycler on its own also may buy EOL vehicles directly from the public, auction house, etc., engaging in removal of the fluids and the SLAB prior to recycling.

Automobile Shredding Operations

The EOL vehicle is purchased by a recycler as feedstock material for a shredding operation based on market driven net scrap value of the contained metal commodities. Shredding operations typically consist of a large hammermill, with downstream separations technologies for ferrous and nonferrous metals. A recycler’s investment in such a facility may well exceed \$20 million. EOL vehicles, along with other metallic scrap, are fed into the shredder for rapid reduction into fist-sized pieces for subsequent separation. These separation systems process the shredded material separately extracting the ferrous metals and nonferrous metals. The remaining material, often referred to as auto shredder residue (ASR) may contain small percentages of nonferrous metallics and is often further processed involving sophisticated technology driven separation methods for as much of the remaining metallic recovery as possible. The residual material along with some recyclable plastics with challenging economics, is often called shredder residue. The streams of shredded ferrous metal and shredded nonferrous metal are valuable specification-grade commodities purchased by steel mills, foundries and secondary nonferrous facilities, respectively, for use as feedstock. The revenue from these metal product streams is reduced by the disposal cost of the nonmetallic shredder residue.

Even before any shredding may occur however the recyclable materials must undergo inbound source control procedures. It is at one or another point prior to shredding that batteries must be removed from the vehicle recycling stream. This is where the challenge of Li-Ion batteries resides for the industry.

Lead-Acid and Li-Ion Batteries

Removed from traditional vehicles, spent lead-acid batteries are one of the most highly recycled products, with a recent scrap value around \$700 per ton. According to the Department of Energy’s Lithium-Ion Battery Recycling Prize website, “a vast recycling supply chain collects, stores, transports, recycles, and re-introduces more than 99% of lead back into the lead-acid battery supply chain”. This recycling success reflects the standardization of lead-acid batteries in terms of their chemistry, design, and small size, and has been aided by U.S. EPA’s decision back in 1985 to allow well-handled, well-staged whole spent lead-acid batteries to move freely, as a commodity,

from point of removal from an EOL vehicle to a battery-breaking or lead-smelting facility, where these batteries are fully regulated. Additionally, it should be noted that the level of success for lead-acid battery recycling is significantly the result of the intrinsic value of the contained commodities (essentially the lead) exceeding all of the costs associated with the recycling of those batteries.

Achieving such recycling success for electric vehicle batteries is a worthy goal and would be ideal, but present conditions do not yet support such successes. This comes as no surprise with the rapid innovation taking place in electric vehicle batteries and electric vehicles themselves. Battery chemistries, design, and system integration are varied and still-evolving, and the same is true with the rest of the electric vehicle, including their materials of construction. Choices in EV deployment will almost certainly affect both of these. For instance, EVs intended for sale to consumers likely have more-limited design choices, due to affordability, than EVs intended for fleets to provide ride services to consumers. All of this is in great flux, with no obvious technology convergence or standards in sight; unlike lead-acid batteries, currently the costs related to the recycling of the EV batteries far exceed the commodity values of these battery components.

End-of Life Electric Vehicles

Nevertheless, ISRI members are already seeing EVs in the recycling stream and are currently seeing increasingly large numbers reaching end of life. The vehicle recycling industry handles millions of traditional internal combustion-engine vehicles every year, but as the percentage of EVs grows, so will the challenges associated with recycling them. Electric vehicle batteries are much larger and store much more energy than lead-acid batteries, mainly because electric vehicle batteries power vehicle propulsion and need to provide a certain range for distance driving. For instance, a Chevy Bolt battery pack weighs 960 pounds and stores up to 60 kWh of electrical energy, while a DieHard Gold battery weighs 42 pounds and contains ~1 kWh. In contrast to spent lead-acid batteries, electric vehicle batteries are not easy to remove from vehicles and do not have a vast recycling infrastructure.

Currently, electric vehicle batteries mostly appear to represent a significant cost to recyclers, especially when compared with the commodity value of the metal in those vehicles. This simply is not sustainable in the potentially large quantities anticipated for the near future. Likewise, to the extent that EVs, targeted for sale to the general consumer, are relatively new or do not have interchangeable parts across models and brands, their market potential as source of used parts is likely limited, reducing the value of EOL electric vehicles. To the extent that the remainder of electric vehicles have a different and less-recyclable composition than 65% ferrous and 10% nonferrous metals, their scrap value might be lower, even possibly less than the cost associated with the recycling process, particularly including the current negative value of the li-ion battery.

Utilizing the knowledge and experience of the existing, private, for profit auto dismantler and recycling industries is essential for ensuring the feasibility and economic success of EV recycling.

If the economics of recycling electric vehicles is perceived as having low or negative values, recyclers may offer less to buy them for recycling or not buy them at all. Nobody wants this to happen, but it likely will if this potential problem is not properly and urgently addressed. Therefore, it is crucial that the experts in the vehicle recycling industry be involved in policy discussions regarding end-of-life electric vehicles.

Department of Energy Programs

Fortunately, there have recently been encouraging steps. For example, the Department of Energy has created two complementary programs for electric vehicle batteries: The ReCell Center and the Lithium-Ion Battery Recycling Prize. The ReCell Center aims, among other things, to accelerate battery recycling research to reduce recycling costs and to promote new battery designs via Design for Recycling®, a concept that ISRI developed in the mid-1980s to address recycling impediments arising from the design of consumer durables. The Battery Recycling Prize aims to incentivize innovative solutions for efficiently moving lithium-ion batteries, including electric vehicle batteries, from point of removal at end of use or life to eventual reuse or recycling, regardless of chemistry or other attributes. These research activities are an excellent start to getting in place a sustainable recycling infrastructure in an expedited timeframe.

ISRI supports these Department of Energy activities and considers it even more necessary, as we are seeing electronic vehicles in our source stream already and encourages Congress to continue supporting such government-funded recycling research. Given the potential size of the electric vehicle sector, the potential economic and environmental benefits, leveraged by a relatively small amount of federal government funding, are extremely large and worthy of Congressional support.

Conclusion

As the voice of the recycling industry, ISRI commends the Committee for examining the various sustainability and safety challenges of electric vehicles, lithium ion batteries and other issues related to the recyclability of these vehicles. Electric vehicles are presenting new and difficult challenges for the scrap recycling industry and we look forward to working with the Committee to further explore and solve the myriad of issues that will result from these exciting technologies. We urge the committee to convene an opportunity for all stakeholders, including the vehicle dismantler and recycling industries, to meet and work cooperatively to find sustainable solutions to the challenges that have been, and will be identified, related to EV battery reuse, remanufacture, and recycling.