Summer 2024

CRITICAL MATERIALS

The BRIDGE

LINKING ENGINEERING AND SOCIETY

Key Issues, Approaches, and Strategies to Ensure Reliable Critical Materials
Jennie S. Hwang

Technology and Innovation Enablers for Critical Mineral Production
Mark E. Russell, Lindley Specht, Steve Klepper, and Alfred Pandiscio

Critical Materials Risks to Electronics Manufacturing: Global Impacts and Actions Needed
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Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

A complete copy of *The Bridge* is available in PDF format at *www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The
BRIDGE
LINKING ENGINEERING AND SOCIETY

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NATIONAL ACADEMIES *Sciences Engineering Medicine*

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

President’s Perspective

The Power of Member Engagement

John L. Anderson

Alton D. Romig Jr.

John L. Anderson (NAE) is president of the National Academy of Engineering and Alton D. Romig Jr. (NAE) is executive officer of the National Academy of Engineering.

The raison d’être for the National Academy of Engineering (NAE) is to provide technical advice to the government and public and to promote the profession of engineering. The members[1] of the NAE, elected by their peers, are expected to be role models for engineering and sources of expertise for the public. As officers of the NAE, we are tasked with promoting engagement of our members in activities related to our mission—from service on consensus studies by the National Research Council to the election of new NAE members. Participation by our members in such activities is a strong measure of the health of the NAE.

We define participation as the percentage of NAE members who engage in at least one activity sponsored by the NAE or the National Academies generally. Figure 1 shows participation by calendar year. NAE participation includes serving on recurring committees such as those related to membership and awards, as well as newer activities such as planning the annual meetings, presidential initiative committees, or writing/referencing new member nominations. The drop in participation rate between 2018 and 2021 could be the result of Covid-19. The upturn in participation through 2023 is promising, especially considering that a net increase of about 70 members occurred during this time.

Figure 2 shows the percentage of members who participated in various NAE and National Academies activities during 2023. These data show that our members are broadly engaged; however, we would like to have even more members, especially international members, involved. The participation rates by section in 2023 are shown in figure 3. An interesting observation is that some sections with a relatively low US member participation rate had a high international member participation rate.

In an effort to engage more of our members, we established “member-led events” (MLEs) in 2020. These events

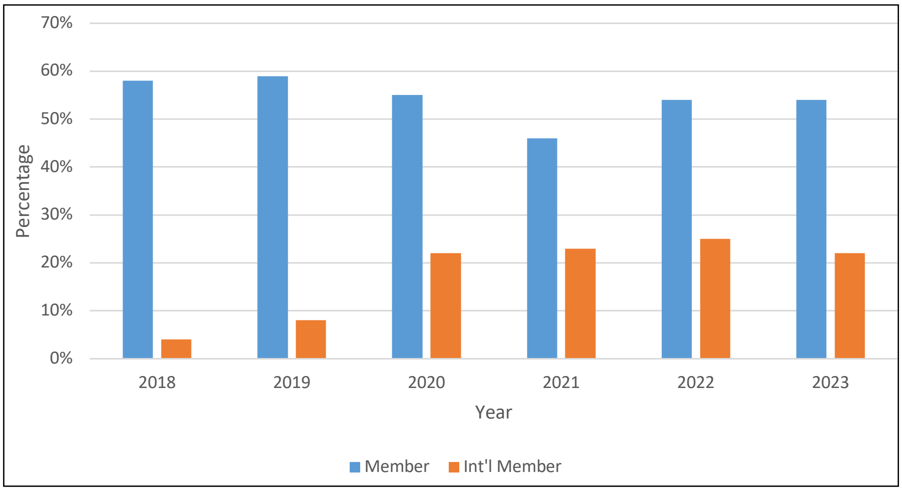

FIGURE 1 Member participation by year.

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[1] By “members” we mean US members and international members.

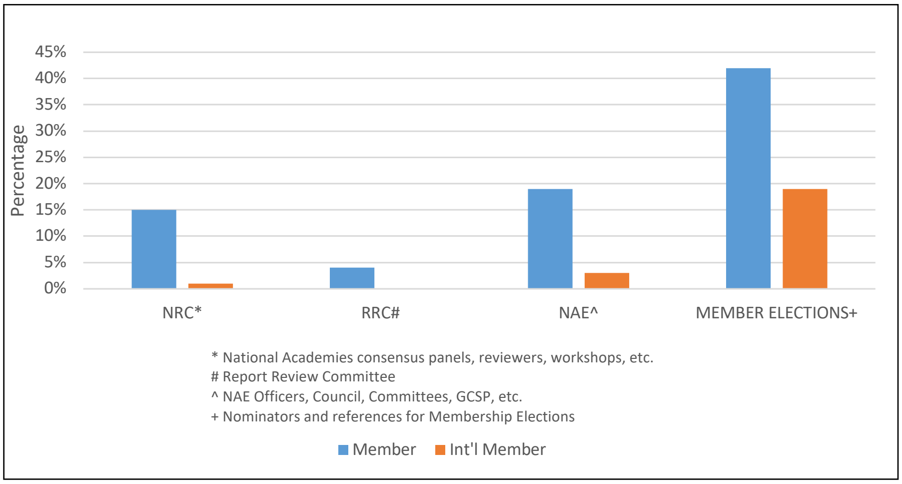

FIGURE 2 Percentage of members who participated in various activities.

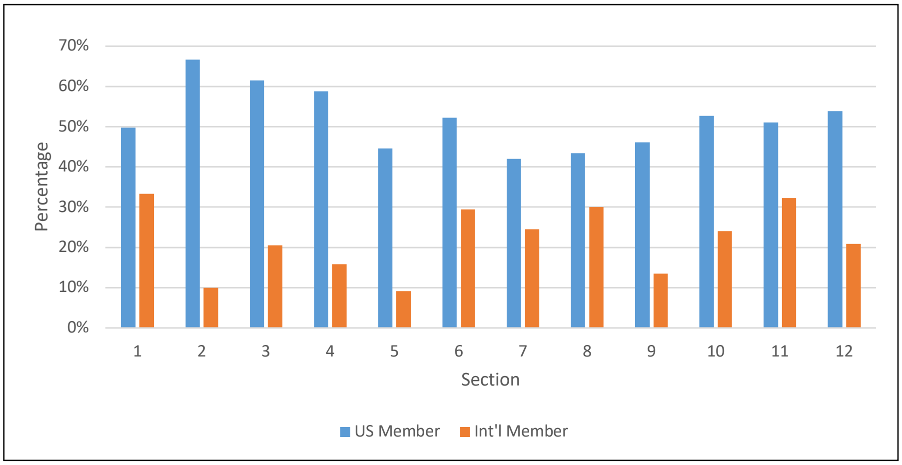

FIGURE 3 Participation by US and international members.

are led by members rather than the NAE office, but they are sponsored by the NAE with modest financial support. The first official MLE was the Technology for a Quieter America symposium. An MLE can be initiated either by a section of the NAE or by a "community," which could be a university, a geographic region (e.g., Southern California), or a group of members from different sections with related interests. The MLEs may be online or held in person, often at one of the Academy sites in Washington, DC, or the Beckman Center in Irvine, California. We are examining some options to increase the number of MLEs. Virtual events have had, on occasion, several hundred participants (measured by IP addresses). In-person MLEs have had as many as 100 participants.

In the past it has been difficult to engage international members because most meetings and conferences were in-person events. However, the development of virtual platforms such as Zoom has made it possible to overcome geographical obstacles and involve participants on a global level. There are now several MLEs being planned with other international academies, which will include the participation of our international members who are also members of their home academy. The concept of diversity extends to nationality. The viewpoints of our international members provide important input in our studies and committee deliberations and thus strengthen our organization.

An engaged community of professionals is vitally important to the effectiveness and sustainability of the NAE. We thank our members for their volunteer work on behalf of the Academy, the nation, and global society. You maintain the excellence and purpose we strive for.

Editor in Chief's Note

Ronald M. Latanision (NAE) is a senior fellow at Exponent, the Neil Armstrong Distinguished Visiting Professor at Purdue University, and editor in chief of *The Bridge*.

During the 1984–85 academic year while I was a professor at MIT, I arranged a year-long sabbatical as an advisor to the US House of Representatives Committee on Science and Technology. The chair of the committee was Don Fuqua, and the committee included Al Gore, Dan Glickman, and Ron Paul, among other members. During that year we arranged a hearing chaired by Dan Glickman on the materials stockpile. Admiral Bobby Inman testified before the committee along with other witnesses. At the time, there was no internet, and the concern was supply interruptions of materials critical to our economy and national defense. The hearing focused then on many of the relics of wars of the past that linger in the ongoing wars in Ukraine and Gaza.

But we are on a different trajectory in today's world. Weapons of mass destruction still represent a threat to humanity, but cyberwar and the capacity to wage it now represent today's greatest threat to not only our quality of life but to our most basic human needs. Almost by default, we have become totally dependent upon electronics for virtually every aspect of our lives, from shelter to air and water quality to food production and distribution, and more. From the cars we drive to the sensors that we install in buildings to detect pollutants and microbes to the medical devices that have become commonplace, technology has progressed to such an extent that it now depends on electronics that were largely unimaginable decades ago but whose viability and dependability are crucial. I often wonder if we have not overextended our dependence on technology of this kind, which leads to an unintended vulnerability.

In any case, critical minerals and materials and the engineering systems constructed from them are key to our personal and national security on virtually every level today. Since the 1939 Strategic and Critical Materials Stock Piling Act, Congress has authorized the US government to stockpile "strategic and critical materials" and to develop domestic sources of their supply (as amended through Public Law 117-263, the National Defense Authorization Act for Fiscal Year 2023). Concerns associated with the kinds of materials described in this issue of *The Bridge* are prominent today, including supply chain concerns that are ubiquitous. I thank Jennie Hwang for assembling a superb issue of *The Bridge* and for her steady hand in guiding the evolution of this volume.

This issue also includes an interview with computer scientist Timnit Gebru. She is an advocate for diversity in technology and co-founder of Black in AI, a community of Black researchers working in artificial intelligence (AI). She is also the founder and executive director of the Distributed Artificial Intelligence Research Institute (DAIR) and has been recognized widely for her expertise in artificial intelligence, algorithmic bias, and data mining. She was named one of the world's fifty greatest leaders by *Fortune* in 2021, one of *Nature*'s ten people who shaped science in 2021, and in 2022, one of *Time* magazine's most influential people.

As always, I welcome your comments. Feel free to reach out to me at RLatanision@exponent.com.

Guest Editor's Note

The Future of Critical Materials

Jennie S. Hwang (NAE) is CEO of H-Technologies Group.

Significant efforts have been made in the critical materials arena on the national level, yet further holistic and amalgamated approaches are required to develop a robust and integrated national strategy and its corresponding actionable plans and to implement them in a deliberate, comprehensive, and speedy manner. This will ensure economic prosperity and national security, as well as the nation's global competitiveness.

In this context, this issue is dedicated to helping the nation ensure stable and reliable critical materials. In this issue, "material" is used broadly to refer to an element, mineral, substance, compound, or material in metallic, ceramic, organic (polymeric), or inorganic nature, encompassing end-use applications across all sectors.

This issue brings together a stellar slate of experts with diverse experiences and perspectives from industry, national laboratories, and academia. Each article focuses on a single topic or multiple aspects of critical materials. Collectively, this issue provides informative coverage of and wide-ranging views on critical materials going forward. In particular, articles in this issue discuss leveraging new and emerging technologies, desired infrastructure, innovative approaches, and a resilient supply chain to fortify US competitiveness by securing critical materials for decades to come.

In This Issue

In the opening article, "Key Issues, Approaches, and Strategies to Ensure Reliable Critical Materials," **Jennie S. Hwang** highlights the cross-cutting, concerted approach, the role of business and government, and the impact of deploying new tools such as artificial intelligence to tackle supply chain challenges. The article also offers recommendations for multifaceted strategic deliberations and implementation with the goal of overcoming the ultimate challenges by formulating preemptive solutions while not creating solutions that could be potentially worse than the problems.

The second article, "Technology and Innovation Enablers for Critical Mineral Production" by Mark E. Russell, Lindley Specht, Steve Klepper, and Alfred Pandiscio, focuses on rare earth elements (REEs), a group of materials critical to national security and the aerospace and defense sectors. The article highlights production, innovative processes, and technology-driven approaches while minimizing supply chain vulnerability and the environmental impacts of processing and using REEs.

As the electronics content in every product and service, from consumer and industrial to computer and communication to aerospace and defense, continues to increase, robust electronics manufacturing at every level of the electronics hierarchy is indispensable to all sectors of products and services. In "Critical Materials Risks to Electronics Manufacturing: Global Impacts and Actions Needed" John W. Mitchell outlines the key areas and paths forward for electronics manufacturing.

In "An Automotive View of Critical and Sustainable Materials" **Paul E. Krajewski** discusses what it will take for the automobile industry to successfully transition to an electric, autonomous, and connected future, and he offers cogent recommendations. He notes, "Automobiles are created using almost every element in the periodic table, from aluminum to zinc. A consistent supply of these materials is essential to avoiding interruptions in production."

The phenomenal innovation and advancement of semiconductor chips rely on packaging technologies and corresponding materials to connect chips to real-world end-use applications. Per- and poly-fluoroalkyl substances (PFAS) have served as key substances in semiconductor packaging. However, PFAS materials exhibit the propensity for a range of health concerns through water supply. In "Critical Needs for Non-PFAS Semiconductor Packaging Materials" Pradeep Lall presents semiconductor packaging technologies and the need for non-PFAS materials as alternatives to PFAS.

"Lithium-Ion Batteries: A New Opportunity for the Circular Economy and Recycling" by **Francisco F. Roberto** and Robert C. Dunne offers an illuminating summary of key aspects of lithium-ion batteries. The authors illuminate the circular economy with the 3R ("Reduce → Re-use → Recycle") approach, which is a crucial facet of meeting the demand for critical materials.

In "Unlocking Alternative Solutions for Critical Materials via Materials Informatics" Rémi Dingreville, Nathaniel Trask, Brad Lee Boyce, and **George Em Karniadakis** vividly present the challenges of finding viable solutions to critical materials and the merits of using materials informatics, including generative modeling, for scientific discovery and understanding.

Aluminum is listed as one of the fifty critical minerals, according to the secretary of the interior, acting through the director of the 2022 US Geological Survey. In "Sustainable Metal Production and Use in the Twenty-First Century: Challenges and a Path Forward," **Diran Apelian**, Emily Molstad, Sean Kelly, Subodh Das, Barbara K. Reck, and Alan Luo provide a comprehensive discussion of the crucial aspects of this vital metal.

Acknowledgments

My deepest gratitude goes to the authors for their insightful and forward-thinking contributions, to *The Bridge* editor Kyle Gipson for his tireless assistance throughout the entire process, and to **Ronald M. Latanision**, editor in chief, and Penelope Gibbs, production associate, for their guidance and support throughout the publication process. It has been an absolute delight to work with all authors and the editorial and production teams.

I also would like to thank the following, who have provided thoughtful input in assessing the drafts for accuracy, coverage, and substantiation: **Kevin Anderson**, Kenneth Blecker, Frank Castle, Ming Dao, Arun Devaraj, **Denise Gray**, Neal Herring, Jay Hill, **Ravi Mahajan**, Brajendra Mishra, Chris Pistorius, Greg Reed, **Anil Sachdev**, Ephraim Suhir, Jaimal Williamson, and **Matt Zaluzec**.

A holistic and amalgamated approach is essential to tackling the challenges of critical materials.

Key Issues, Approaches, and Strategies to Ensure Reliable Critical Materials

Jennie S. Hwang (NAE) is CEO, H-Technologies Group.

Jennie S. Hwang

On top of global existential geopolitical environments and changing geopolitical forces, the protracted status of the Russia-Ukraine war since Russia invaded Ukraine on February 24, 2022, has elevated the uncertainty of materials and minerals. The Hamas attack on Israel on October 7, 2023, and subsequent attacks on ships in the Red Sea added further perils to the availability, reliability, and security of the global supply chain of materials and minerals. Critical materials and minerals that are the foundation of making essential goods have been sourced from war or near-war regions or unfriendly nations, which causes high-risk concerns. High-risk uncertainties have resulted in potential hazards that have drawn intense attention across the national landscape.

From a market-demand perspective, energy use, specifically electricity, will continue to increase. This is propelled by the phenomenal growth of power-hungry data centers (some new data centers requesting grid connections are as large as 500 megawatts), the increased deployment of potent artificial intelligence (AI) tools, the need for high-performance computing, and the push

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for electrification. These market forces created a heightened criticality for some materials and minerals, such as lithium, nickel, and some rare earth minerals.

Various efforts have been made on the national level to tackle the challenges of critical materials. Yet, to create a robust and integrated national strategy and its corresponding actionable plans in a deliberative, comprehensive, and speedy manner calls for a holistic and amalgamated approach. Such an approach will ensure economic prosperity, national security, and the nation's global competitiveness.

Critical Materials and Minerals Going Forward

Critical materials and minerals include those that are crucial ingredients for making indispensable products, materials and minerals that the United States has little control over due to the lack of domestic natural resources or the absence of domestic sources, or those that are imported from high-risk regions. Additionally, critical materials and minerals may also include those required for mission-critical end uses.

According to the Energy Act of 2020 (DOE 2024):

- A "critical material" is any non-fuel mineral, element, substance, or material that the secretary of energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy.
- A "critical mineral" is any mineral, element, substance, or material designated as critical by the secretary of the interior, acting through the director of the US Geological Survey.

The 2023 final critical materials list determined by the Department of Energy includes the following:

- Critical materials for energy, including aluminum, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide, and terbium.
- Critical minerals that include the following fifty minerals (per the secretary of the interior): "Aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium." (USGS 2024)

Examples of Critical End Uses

Nickel, lithium, and some of the rare earth elements are among the top critical materials due to their importance to energy, yet they bear the most supply risk. Figure 1 depicts the criticality matrix for the next decade (period of 2025–35).

> ***AI is an effective tool that can benefit the entire ecosystem, from new material discovery to recycling efficiency.***

Take nickel as an example. Its price has been uncharacteristically volatile during recent years: it soared to an uncontrolled spike on March 8, 2022, reaching the record $100,000 per metric ton on the London Metals Exchange (LME), and its price subsequently dropped (Khan and Wallace 2023). Nickel's dramatic pricing volatility made the LME pause trading on March 8, 2022. The LME resumed trading on March 16, 2022 (the episode caused a review by regulators and the LME and subsequent litigation). It is a warning signal, as pricing volatility is often an indicator of inadequate reliability and is often associated with undue market manipulations.

Nickel is not a "fancy" metal, but it is a key ingredient for stainless steel and lithium-ion batteries that power electric vehicles, among other end-use applications. Russia is a major supplier of nickel, not to mention the role of Russia in oil and gas and other minerals. China is another significant nickel supplier, and about two-thirds of the world's lithium and cobalt—essential for electric vehicles—is processed in China. Indonesia holds one of the world's largest nickel reserves.

As a key ingredient in making batteries for electric vehicles, cellphones, and laptops, lithium demand will reportedly quadruple by 2030.

Russia is also a major supplier of precious metals, including palladium, which is an essential element being used in catalytic converters and semiconductor manufac-

FIGURE 1 Criticality matrix – medium term. Source: DOE 2019.

turing. It is reported that about one-third of the world's palladium comes from Russia.

The United States is racing to catch up on rare earth supplies with China, among other countries, as rare earth minerals are in ever-greater demand for a variety of uses, including electric vehicles, offshore wind turbines, and permanent magnets. According to estimates from the US Geological Survey, the United States has consumed an annual average of 8,300 metric tons of rare earth oxides in recent years. Despite a falling share in rare earth production (figure 2), China still enjoys dominance in rare earth processing with a 90% market share and reportedly advantageous processing technologies. China has dominated every step in the process of making rare earth magnets. It is the only nation capable of producing the magnets from start to finish at scale.

Manganese is expected to grow sixfold over the next twenty years; it increasingly replaces more expensive and harder-to-source minerals such as cobalt and nickel in lithium-ion batteries. South Africa is the world's number one producer of manganese ore (Wexler 2023), but China refines more than 90% of battery-grade manganese.

Other metals have been heavily sourced from Russia, such as titanium, which is crucial for manufacturing jet airplanes and military aircraft. Because of its high strength, light weight, and corrosion resistance, titanium is a unique metal and cannot be readily substituted. Even though some materials may not risk direct exposure, indirect impacts are expected to trickle down throughout the global supply chain.

China produces 60% of the world's germanium and 80% of gallium, according to the Critical Raw Materials Alliance. Both elements are key to manufacturing electronics and semiconductors. Germanium is used in fiber optic products, solar products for space, and night-vision goggles, while gallium is a critical material for semiconductors to make key gallium compounds (e.g., gallium arsenide, gallium nitride).

Within the semiconductor industry, some sources of production raw materials are also concentrated in Russia and Ukraine. For instance, the two countries are major sources of neon gas, which is used for making circuitry on silicon. It is estimated that about one-fourth to one-half of the world's neon supply comes from Russia and Ukraine. Although neon gas is a small fraction of semiconductor manufacturing in dollar value, a close-knit operation cannot tolerate any missing link in the chain.

A Cross-Cutting, Concerted Approach

With the criticality for some materials and minerals identified and the list of critical materials and minerals defined, national strategy should take a cross-cutting, concerted approach. Its goals should include (Hwang 2022a):

1. To verify the natural resources of the critical materials and minerals.
2. To continue defining the effective sources of critical materials and minerals.
3. To ensure the secure availability of critical materials and minerals.
4. To tackle ongoing supply chain challenges.
5. To build the key capabilities and infrastructure of critical materials and minerals.
6. To anticipate future challenges related to critical materials and minerals.
7. To continue identifying actions and approaches that the government and the private sector can take to meet the goals collaboratively.
8. To verify the relative criticality of materials and minerals in the next decade and beyond.
9. To explore and innovate alternative materials and minerals for mission-critical end uses, leveraging both theoretical modeling and experimental techniques.
10. To strike a balance between economy and environment.

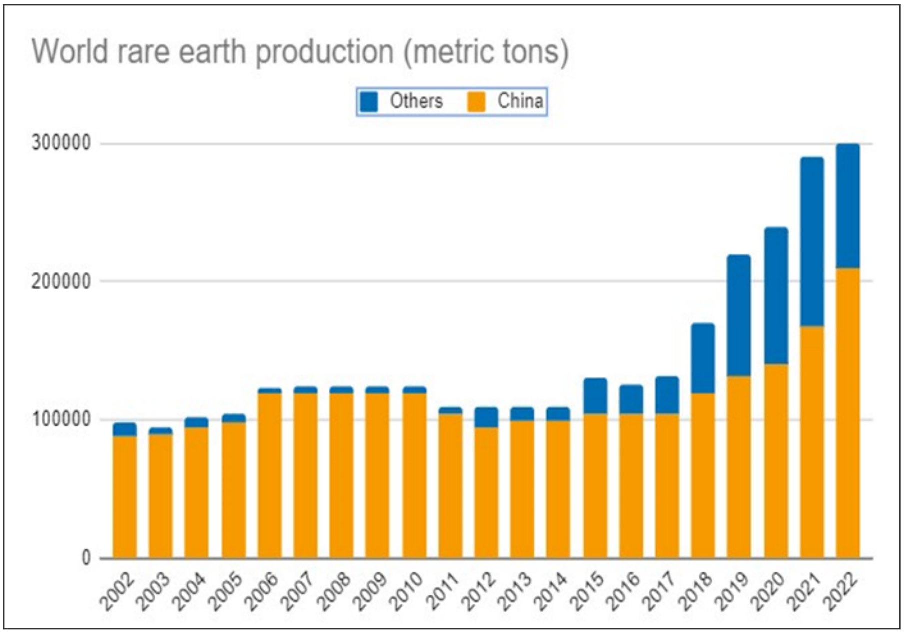

FIGURE 2 World rare earth production. Source: USGS 2024.

To fulfill the above ten multiple-front goals, it will take a concerted approach that offers a global perspective, a holistic thought process, integrated information, and collaborative action among the government, industry, and academia.

The Role of Business and Government

In business governance and management, long-term investment requires deliberations that spotlight reliable and secure critical materials. For instance, Exxon Mobil announced in November 2023 that it plans to drill for lithium in Arkansas and to start producing battery-grade lithium by 2027 (Eaton 2023). The company aiming to become a major US supplier for makers of electric-vehicle batteries by 2030 is a bright spot.

In corporate governance, critical materials should be a corporate board affair to be watched for in enterprise risk management programs.

In government and academia, the funding requirements, funding structure, and research priorities should be revisited with critical materials in mind, and actions should be taken accordingly (DOE 2019). The speed of implementation requires special attention.

Furthermore, an integrated cross-agency program relevant to the arena of critical materials and minerals is duly warranted to tackle the technologies, processes, and manufacturability effectively and speedily.

It is easier said than done, yet now is the time to act.

An Exemplar of the Concerted Approach

Back in 2013, four essential minerals were classified as “conflict,” the word generally adopted by the government as well as the industry. These four essential elements—tantalum, tin, tungsten, and gold—have been key to a variety of end-use applications for a wide array of industries, ranging from electronics to industrial to consumers to avionics to military sectors. The primary mines of these four essential elements are situated in the eastern portion of the Democratic Republic of the Congo and the surrounding countries, and the minerals have been mined under the conditions of armed conflict and severe human rights abuses in the region. The region’s armed militia groups intended to exploit the area’s natural resources. This pervasive exploitation of natural mineral resources in this high-risk area caused grave concern for the international community about the region’s activities. Accordingly, this region was deemed a “conflict region.” At that time, the companies directly or indirectly sourcing from or directly operating in this region faced a higher risk of contributing to the conflict.

These concerns have spurred much debate, which has led to substantial activities in the US Congress dealing with the issues. After concerted work and planning, the Dodd-Frank Act passed in the US Congress and was signed into law on July 21, 2010. In August 2012, the US Securities and Exchange Commission (SEC) adopted a rule mandated by the Dodd-Frank Wall Street Reform and Consumer Protection Act, which requires companies to publicly disclose their use of conflict minerals that originated in the Democratic Republic of the Congo or an adjoining country. And the first required report must be filed by May 31, 2014. Basically, the US Conflict Minerals Law contains two requirements: independent third-party supply chain traceability audits and reporting of audit information to the public and the SEC. Dodd-Frank 1502 is a disclosure requirement and places no ban or penalty on the use of conflict minerals. However, a company is required to assess whether any conflict mineral was "necessary to the functionality or production" of a product manufactured or contracted for manufacture by the company. To comply with SEC regulation, whether a company that contracts out production holds influence over the item being contracted is also to be assessed and determined. Although it is not illegal to use conflict minerals, corporate social responsibility is on the line. The goal is to be "conflict-free." On this front, some corporations are leading the way. For instance, in 2011 Apple released its *Apple Supplier Responsibility* report, detailing how it traces its supply chain—first to the suppliers that created the subcomponents of their products and then to the smelters that processed the ores (Apple 2011). Intel has conducted on-site reviews of smelters as part of the Conflict-Free Smelter program. Since then, the conflict minerals have been "managed successfully" (Hwang 2013).

The identification of critical materials and minerals is the first step, not the endgame.

The Role of Artificial Intelligence in Addressing Supply Chain Challenges

With the approach of managing "conflict minerals" as an exemplar, it is equally urgent, if not more, to rally another concerted effort to tackle critical materials and minerals. Recently, the overall supply chain has experienced unprecedented disruptions and hurdles as the result of a slew of factors. Simply put, the fundamental supply chain issues can be attributed to decades of globalization, off-shore manufacturing, and continuing and fast-paced technological changes, in conjunction with many diverse suppliers being embedded in each product. Consequently, managing today's global supply chain is a daunting task; securing reliable sources of materials and minerals requires an ongoing effort (Hwang 2024).

Take battery manufacturing as an example. The bulk of battery manufacturing occurs in Southeast Asia. Establishing supply chains for key materials, such as lithium-hydroxide, can take anywhere from three to seven years. With rising demands, multiple-front steps ranging from developing alternate supply sources to establishing strategic partnerships to innovating new materials and battery technologies should be the key path forward to ensure a secure supply chain and stable marketplace. For example, is a sodium-ion battery a viable alternative? Sodium is more abundant than lithium, less vulnerable to geopolitical challenges, and has a substantially lower cost (the price of sodium carbonate is $286/ton versus the price of battery-grade lithium carbonate, which is $20,494/ton).

AI is an effective tool that can benefit the entire ecosystem, from new material discovery to recycling efficiency. Taking one example, using AI and a supercomputer, Microsoft researchers were able to narrow down 32 million potential materials to 18 promising candidates in just 80 hours. Microsoft said, "*A new material, unknown to us and not present in nature,*" could potentially reduce lithium use in batteries by up to 70% (Microsoft 2024).

Semiconductor "chips" are another example. High computing chips (e.g., GPU, CPU, TPU) are not only hot in terms of market demands, but they are also literally hot in temperature. AI tools, to facilitate chip design and subsequent packaging, and PCB assembly, to facilitate thermal management and other performance parameters, are expected to boast the productivity and innovative products required by the continued advances in AI technology and AI tools. And AI can "reciprocally" help as an effective tool for chip design and manufacturing as well.

Developing and deploying AI tools in a timely manner to manage the supply chain will alleviate some of its bottlenecks. For example, a model that combines data with AI could predict unconventional deposits of rare earths and critical minerals.

Accordingly, to take a holistic view, the multifaceted strategies below warrant further deliberations and actions.

Critical materials and minerals will have an overarching impact on the global supply chain across all industries and all sectors. If one chain is broken, the whole system fails.

Multifaceted Strategic Deliberations

The essence of the US strategy should proactively focus on the endgame: how to become less vulnerable, more self-controlled, and more self-reliant, and how to be positioned for ready access with a competitive cost structure.

A sixteen-pronged strategy—to be further formulated, integrated, and advanced—may warrant further deliberate considerations (Hwang 2022b):

1. From supply-side consideration, a strategy to ensure a reliable supply of critical materials for which the US does not have adequate resources, especially for those materials that are abundant in countries that are or might be deemed existential or potential adversaries (Hwang 2021).
2. From demand-side consideration, a strategy to revisit and reidentify the critical materials and minerals.
3. From the perspective of a new world, a strategy to secure strategic materials and minerals by revisiting the criteria for defining strategic materials and minerals in the new world in terms of geopolitics and a new landscape in the continually changing digital era.
4. From the perspective of import-intensive metals, a strategy to "govern" the materials and minerals that essentially rely on imports (i.e., domestic production, mining, or refining is scarce or nil), particularly how to ensure resiliently cost-effective sources. This will engage the Department of Commerce, the International Trade Commission, and other federal agencies. What are deemed productive and effective policies and/or incentives to give companies that are in the position to produce the critical materials and minerals? A farsighted strategic calculus may need to be a variation of those in (1), (2), and (3).
5. From an economic standpoint, the role and positioning of technological overmatch for today and the future (e.g., five or ten years and beyond). A strategy to cultivate a sustainable ecosystem and infrastructure to transition critical materials to useful products, thus adding value to the national economic well-being.
6. From a national defense and national security standpoint, a strategy to transition the critical materials to the capabilities for national defense and national security, including combat capabilities, in the new multi-domain combat environment that the US Army and the Department of Defense have recently been focusing on.
7. From a national investment and international trade standpoint, under the increasingly clean-energy and environmentally conscious climate, a strategy for national investment to become more self-reliant or less import-dependent calls for an open debate. This requires engagement from multiple federal agencies and subordinate agencies.
8. To anticipate potentially emerging conflict minerals that are naturally abundant in conflict-affected and high-risk areas (countries, regions), the strategy to "manage" the current and potentially future conflict minerals calls for embracing both environmental and geopolitical considerations.
9. From a technology standpoint, incentivize developing game-changing technologies, leveraging both theoretical modeling and experimental techniques. One good example is the technology that enables the use of less-pure-grade (lower-cost) nickel for batteries (Hwang 2021).
10. From an alternative material standpoint, a strategy to invest in and develop technologies that are alternatives to currently defined critical materials that can meet the designated or target criteria.
11. From a competitive perspective, the plan is to leverage new and leading technologies, especially AI technology and AI tools, to speed up the discovery of new mining deposits of essential metals and minerals (e.g., Ni, Li, Co, Cu).
12. From the "*integrated bi-focus*" of environmental, climate-change, and economic standpoints with pragmatism, a strategy to revisit the priority of recycling and processing technologies to reduce import dependency and mitigate foreign-dependent vulnerability.
13. A strategy to advance recycling technology to build a true closed-loop system. For environmental enthusiasts, for example, metals such as steel and aluminum are important to advance renewable energy (perhaps counterintuitively).
14. Again, nothing can beat the relentless breakthrough innovation to either advance functions, reduce costs, or both. For example, explore the potential of nickel to be a catalyst in lieu of palladium in chemical reactions like cross-couplings. Its success will cut costs tremendously, not to mention the enhanced "security" of resources.
15. Semiconductor chips are "hot"—figuratively and literally—in terms of demands and the operating

temperature. To protect the "brain" that goes into all modern products, watch diligently for and act prudently on the materials going into chip (semiconductors) manufacturing. A sound strategy for what the role of the government should be and how it plays effectively.

16. From the point of view of the free market, a strategy to ensure that solutions are not worse than the problems is crucial to tackling the challenges of critical materials.

None of the above should be or can be viewed or attended to in isolation; the challenge is the action plan and execution to amalgamate them to reach a holistic national strategy to ensure a long-term robust economy and resilient national security.

Closing Remarks

The identification of critical materials and minerals is the first step, not the endgame; a key question is what the remedies or solutions are, both strategically and tactically, for near-term to long-term time horizons, to establish secure or alternate sources of critical materials and minerals. This calls for a decisive push forward.

Further diversifying the sourcing routes for key materials and developing alternatives to materials for industries that are highly dependent on imports from specific countries are in the works. As any alternate source of materials and minerals must go through a rigorous validation and verification process, the question is how long it takes to come up with a plan and take action, and whether it is "fast" enough. Additionally, in the long run, what kind of incentives can justifiably come from the government, both federally and locally?

Multiple initiatives to address the challenges of the global supply chain of goods are in progress. And yet, the supply chain of knowledge should be fortified in parallel. Managing today's global supply chain is a daunting task; securing reliable sources of materials and minerals requires an ongoing effort.

In a nutshell, sticking with the status quo is not an option; the reality remains the same: to deliver a holistic, all-encompassing approach by "amalgamating" strategic points 1–16 and other envisaged areas to reach a set of executable actions and to forthrightly act in a speedy manner.

The bottom line is to not rely on unreliable sources, and the ultimate challenge is to create preemptive solutions while not creating solutions that are worse than the problems.

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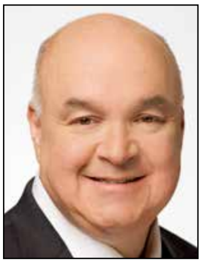
We must take steps to minimize the supply chain vulnerability of rare earth elements and the environmental impacts of processing them.

Technology and Innovation Enablers for Critical Mineral Production

Mark E. Russell, Lindley Specht, Steve Klepper, and Alfred Pandiscio



Mark E. Russell

Lindley Specht

Steve Klepper

Alfred Pandiscio

In recent years, there has been significant coverage in the general press as well as in policy circles of the challenges and risks facing the United States and allied countries regarding access to and availability of various critical minerals needed to enable the twenty-first century high-technology economy. Industries enabled by such critical minerals as the rare earth elements, lithium, cobalt, nickel, and titanium include the automotive, electronics, semiconductor, and aerospace and defense industries.

Supply chain issues around these materials have impacts spanning the domains of the economy, national security, climate, and technological competitiveness. Geopolitical tensions with nations such as China and Russia, which have significant concentrations of certain minerals and their processing,

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Mark E. Russell (NAE) is senior vice president and chief technology officer, Lindley Specht is principal engineering fellow, Steve Klepper is principal engineering fellow, and Alfred Pandiscio is vice president, defense technology, all at RTX Corporation.

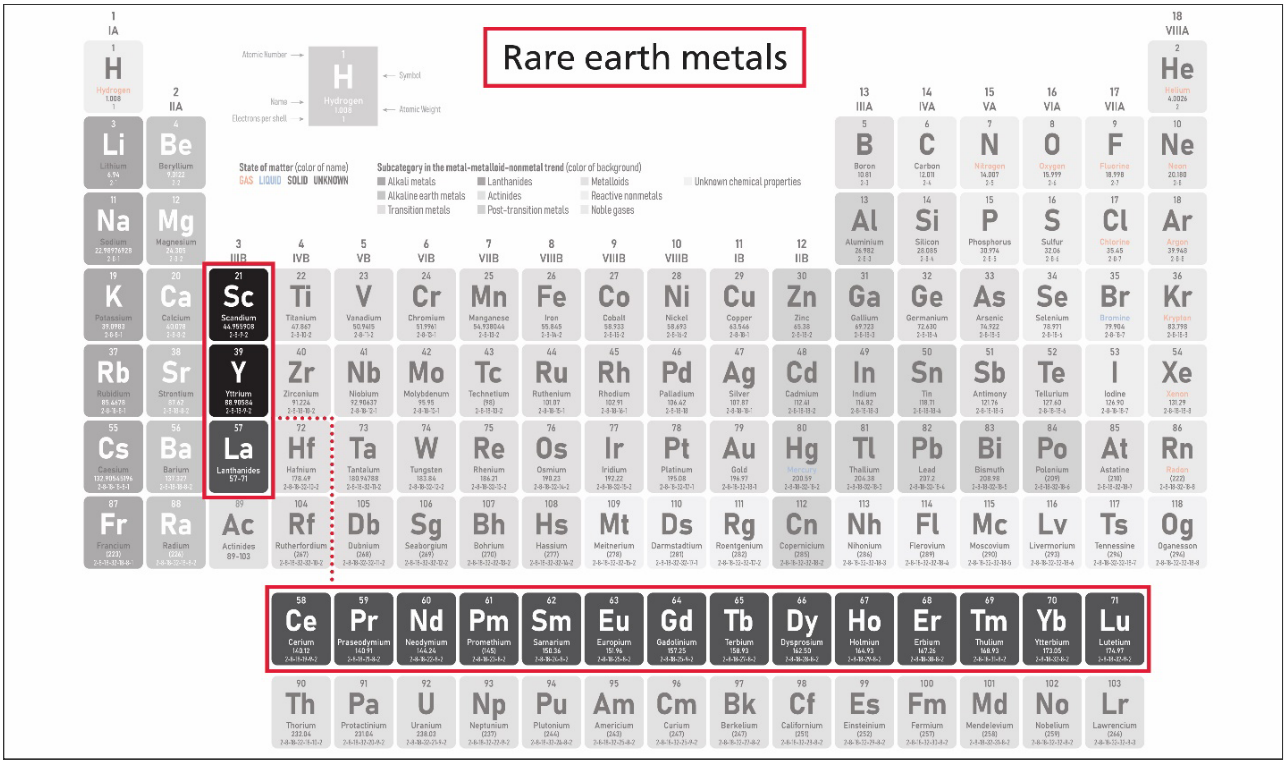

FIGURE 1 Periodic table of the elements, with the rare earth elements outlined in red.

only heighten these concerns. And the war in Ukraine, ensuing international sanctions, and Russian responses to these sanctions have served to highlight the geopolitical risks of the supply of critical minerals.

This article will focus on one subset of critical minerals, the rare earth elements (REEs), and the implications for the aerospace and defense sector. We will explore technologically driven opportunities and initiatives to reduce risks to this sector from supply chain concentration and vulnerabilities, as well as to reduce environmental impacts from the use of this class of minerals.

These technology-driven approaches include process innovations to reclaim, reuse, and recycle REE materials, which both reduce the need for newly mined and processed materials as well as mitigate the environmental impact of mineral extraction. They also include system-level efforts to "design out" or design around the need for REE materials in key applications that are a source of supply chain risk, reducing the demand for and criticality of these elements.

REEs comprise seventeen metallic elements in group 3/3B of the periodic table, including atomic numbers 21 (scandium) and 39 (yttrium), and the entire lanthanide series: atomic numbers 57 (lanthanum) through 71 (lutetium) (see figure 1). These elements are not especially rare when measured as a percentage of the earth's crust; however, they are typically widely dispersed in quantities that can be uneconomic to extract.

REE metals and alloys find uses in numerous industrial and technological applications, including in the aerospace and defense industry for applications such as communications, electric motors, guidance and control systems, and targeting and weapons (Grasso 2013). Underlying REE components used for these purposes are high-field-strength permanent magnets as well as specialty optical and electromagnetic materials, for example, in yttrium-aluminum garnet lasers. As just one example of the diverse industrial applications of REEs, gadolinium (Gd), with atomic number 64, finds many potential uses: in thermomagnetic engines and magnetic refrigeration; in a class of superconductors with applications for electric motors; as a dopant in solid oxide fuel cells; as a contrast agent for magnetic resonance imaging; as a phosphor for x-ray medical imaging; in alloys as thermal barrier coatings for hot sections of aircraft engines; and as a neutron absorber for nuclear reactor shielding.

The current production of REEs is heavily concentrated in China. Figure 2 illustrates the 1994-2022 trend

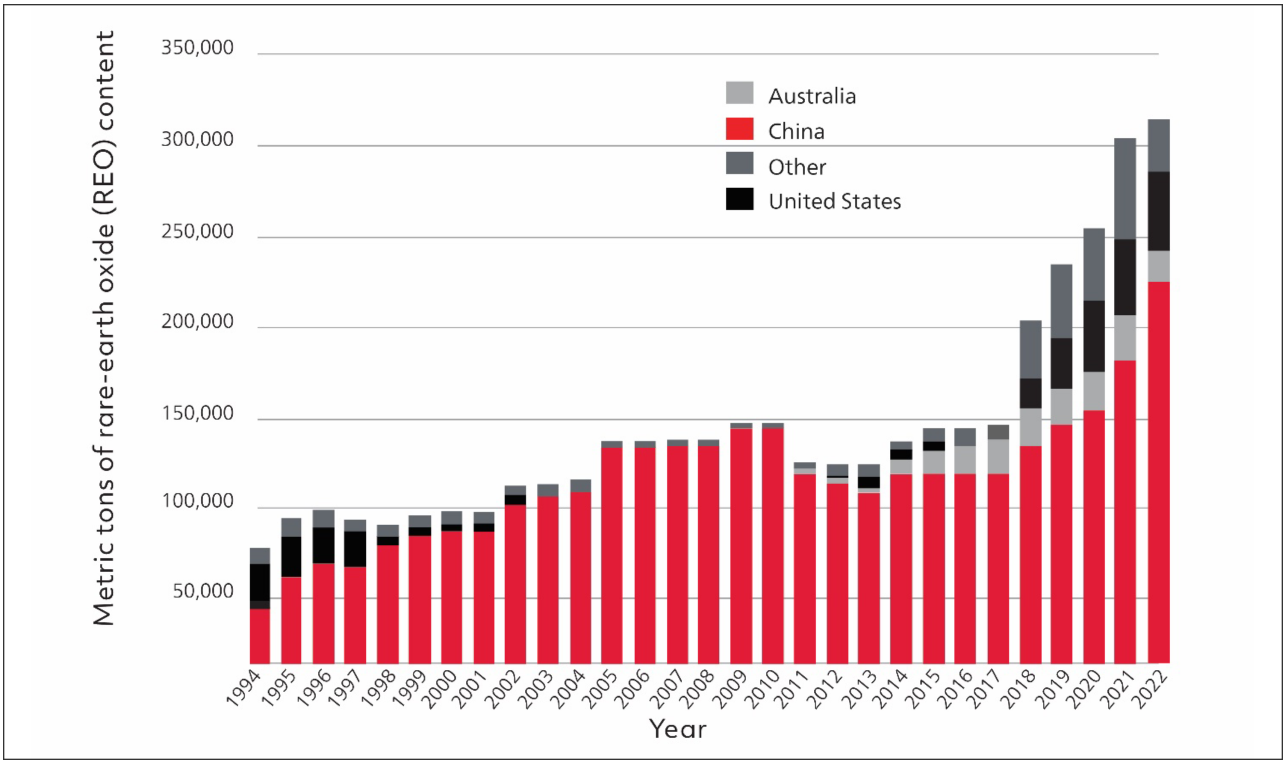

FIGURE 2 Global rare earth production (1994-2022). Source: Nassar et al. 2020.

of global REE production, illustrating the concentrated role that China has in the global supply and availability of these critical materials. As noted in a recent *Wall Street Journal* article (Zhai 2021), "Estimates of China's dominance of the rare-earth industry vary. Some analysts say China mines more than 70% of the world's rare earths and is responsible for 90% of the complex process of turning them into magnets. A White House report has estimated that China controls 55% of the world's rare-earth mining and 85% of the refining process." As a result of this concentration of worldwide REE production and the criticality of these materials to national security systems and capabilities, the US government has taken actions over the years to assess the REE supply chain and ensure the adequacy of supply.

Technology and Innovation Enablers

As most are aware, the extraction and separation of REEs from various feedstocks is a difficult yet important task in the supply chain of these materials. Also, given their chemical similarity, these elements are typically difficult to separate from one another and purify. At present, the typical method of extraction and separation from ore feedstock involves the use of strong acids (HCl, H_2SO_4, etc.) and other chemicals. While a detailed description of the various separation methods developed to date is beyond the scope of this article (Xie et al. 2014), a typical solvent extraction process might involve the use of a phosphoric acid ligand and many stages of solvent extraction to facilitate the mass transfer of the desired material (REE) between the two immiscible aqueous and organic phases. Further separation of the similar elements in this series can be realized by further exploiting small differences in their basicity or other small chemical differences.

The process results in large quantities of toxic, environmentally unfriendly waste that need to be dealt with. While the United States was a dominant player in this supply chain many years ago when these materials were introduced, its position has been replaced by China. To a large extent this transition was precipitated by the differing costs associated with the handling of this toxic waste stream and associated environmental impacts. To address this Chinese dependency, especially for defense applications, mining and processing capabilities are being established (or re-established) in areas such as the western United States (the Mojave Desert area) and the Australian outback regions in their typical mining areas. While one can co-locate the mining and processing operations, it should be noted that these current extraction and separation methods tend to require large amounts of water (and thus waste), which may not be in abundance at the actual mining location.

If the United States plans on returning to its position as a dominant supplier of these refined materials, it must both accept and deal with the higher cost of disposing of this toxic waste stream, which may also contain low levels of radioactivity due to the presence of uranium and thorium. Or the United States must develop a method of significantly reducing this toxic by-product and associated costs. Taking the latter view that reducing the total amount of waste is preferred, let's look at some of the possible methods to achieve this, of which there are at least four.

There are environmental waste considerations associated with REE processing that need to be addressed as we expand domestic production.

The first approach involves the use of higher-efficiency separation materials, such as improved ligands in the current process or improved adsorbents. One example of a novel bio-inspired separation process utilizes the REE-selective lanmodulin protein (LanM) (Dong et al. 2021). This material has shown a high affinity for REEs and can be immobilized onto porous microbeads for use in a low-pH solid-liquid extraction process. This has the advantage of utilizing a lower total solvent amount and, thus, lower waste stream generation, together with the desorption of the REE and subsequent reuse of this adsorbent media. Another advantage of increased extraction efficiency is that lower-grade feedstocks can be utilized. In the mining operation, one prefers to use the highest-grade ore available, for obvious reasons. The use of lower-grade (concentration) feedstock opens up the possibility of repurposing other "waste" supplies, such as coal ash and mining tailings. Low environmental impact work is underway in this area; however, more work is required to mature these processes enough to be economically viable.

The second approach is to take advantage of current electronic waste (e-waste) for recycling to extract the REEs (and other useful materials), either via manual disassembly, magnetic separation after processing, or other means. Apple (2022), for example, has developed robotic methods for disassembling its products and extracting the various components for recycling. Currently a significant fraction of the REEs used in Apple products come from recycling. Another process uses an aqueous copper salt-based process to extract REEs from shredded e-waste, thus bypassing the use of strong acid solutions. While much more work remains to be done, various companies (Wayman 2023) are developing these recycling approaches to add to the overall supply chain. It should be noted that, as with most recycling efforts, while they can provide a significant addition, they do not typically supplant the need for more "original" materials. Thus, while the concentration of REEs in appropriate e-waste can be high, it does remain a challenge to cost-effectively extract and repurpose these materials. Additionally, as larger market products, such as electric vehicles, reach their end of life, the source of REEs for recycling will increase along with the financial incentives.

The third approach involves the incorporation of allied countries' capabilities (in addition to those of the United States) into the US supply chain. Australia has one of the largest mining and processing capabilities[1] in the world, and Japan is one of the largest rare earth magnet fabricators (Okinaga 2022). These resources can thus augment the US supply chain to reduce dependency on Chinese raw materials and finished products. Recently, the United States, along with Australia, Canada, the United Kingdom, Japan, and other countries, entered into the Minerals Security Partnership (MSP) (Home 2022). According to the US Department of State (2022), "The goal of the MSP is to ensure that critical minerals (including REEs) are produced, processed, and recycled in a manner that supports the abilities of the countries to realize the full economic development benefit of their geological endowments."

The fourth approach involves alternative solutions that do not involve the use of REEs. Since high-field magnets, such as ones using $Nd_2Fe_{14}B$, are the focal point here, one can point to recent research (Wang 2020) into the possibility of using iron nitride ($Fe_{16}N_2$) as one possible future replacement for neodymium-based magnets.[2] For most applications, one wants a high-energy product ($(BH)_{max}$) and high saturation magnetization (M_s), along with other desirable properties. Iron nitride, while still early

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[1] For example, see lynasrareearths.com.

[2] See NironMagnetics.com.

in development, has the potential to meet these expectations. One potential limitation is the lower thermal stability of the appropriate phase of this material, which may limit applications to a lower-temperature regime (<150ºC). While much of the experimental properties of this material have been measured in various thin film forms to date, more recent work has been exploring the synthesis of this material in bulk form. This has entailed various low- and high-temperature nitridation methods utilizing, for example, nanoparticles or other starting form factors, followed by subsequent sintering or other methods to form the bulk product.

Summary

There is a recognized need to re-establish more domestic, or at least non-Chinese, supply chains for processed REEs. There are environmental waste considerations associated with REE processing that need to be addressed as we expand domestic production. Recent technological advances in the separation and extraction of these compounds and the use of alternative compounds may be able to help overcome some of these environmental (and thus cost) issues to establish a more environmentally friendly domestic capability in the near future.

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The electronics industry is moving quickly to adapt and reinvent itself for a bright future.

Critical Materials Risks to Electronics Manufacturing: Global Impacts and Actions Needed

John W. Mitchell

John W. Mitchell is president & CEO, IPC International, Inc.

Global supply chain risks associated with underlying materials apply to all of society's technologies due to the pervasiveness of electronic systems across every industrial vertical. This article will address the impacts of critical materials and rare earth minerals shortages on semiconductors, large-capacity batteries, and other technologies. This article will also explore the importance of sustainability efforts like eco-design, reuse/recycling, and legislative proclamations that drive demand for materials usage, in addition to ideas on how to change design methodologies and upgrade and then discard electronics.

From agriculture to telecommunications, every industrial vertical has grown to rely on technology, specifically electronics. From product development and manufacturing to their back-office operations and mastery of big data, the world needs electronics and electronic systems to deliver products and services. Any risks to supply chains that threaten the production of these electronics need to be understood, and where risks are unacceptably high, an alternative approach must be pursued. In the US Geological Survey "2022 List of Critical Materials" (Burton 2022) the majority of the fifty materials listed broadly apply to the entire electronics industry. From the perspective of IPC International, Inc. (IPC),[1] the global electronics industry association, critical materials for semiconductors, rare earth materials, and large capacity batteries are some of the most in-demand areas of concern. When assessing these risks, it is

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[1] www.ipc.org/

necessary to discuss ways to reduce their impact. The path described herein to minimize or eliminate risks presupposes nonviolent solutions during this time of geopolitical tensions.

While there are thousands of details involved in the design, development, and manufacturing of electronics, a simple overview of the process will be provided for consistent reference and a description of the electronics ecosystem involved. Much attention is given to semiconductors, as demonstrated by decision-makers around the globe prioritizing policies and funding towards improving the infrastructure for chips. However, semiconductors are just one part of the entire electronics ecosystem—an ecosystem that can be destabilized with the disruption of less visible supply chain segments. The electronics manufacturing process starts with design and then moves to component capabilities and creation, which in themselves can be entire systems. The parts include passive (resistors, capacitors, etc.) and active (e.g., semiconductors) components. Printed circuit boards are fabricated to establish the necessary connections between components, and then all components (active and passive) are placed on the boards and attached with various connective materials—usually solder-based materials. Each step to building the entire system is surrounded by other systems of machines and materials to build the machine or material that is needed, many of which are also wholly dependent on electronics. It takes electronics to make electronics.

Risks and Options: A Non-exhaustive List

Rare Earth Elements

While the seventeen rare earth elements (REEs) are not necessarily rare (they exist abundantly in the earth's crust), they are difficult to obtain due to their lack of large deposits and co-location with other elements. These metallic elements are used in magnets and as catalysts in both traditional and low-carbon electronics, as well as in the production of high-performance electronics, alloys, and glass. Most of the volume and production of these elements exist in China (38% [LePan 2021]). China dominates REE production and largely controls market access. The only way to change this is to discover new deposits of these materials or develop new methods of extracting deposits more efficiently to open previously abandoned possibilities. But current extraction processes create another problem: environmental impacts, in some cases devastation. Recently on the policy front, the European Union (EU) and the United States have entered into discussions to combine efforts to strengthen their position relative to China by potentially merging the EU's critical raw materials club concept with the US administration's Minerals Security Partnership (Nardelli and Marlo 2024).

Critical Minerals and Materials

Political efforts to address the scarce nature of minerals include an effort engaging four countries and the EU. The aforementioned US-led Minerals Security Partnership strives to leverage environmental, social, and governance (ESG) principles across the critical minerals sector globally.[2] In addition to the fifty critical minerals listed by the US Geological Survey, other critical materials need to be considered. Useful byproduct materials, like neon, should be added to the list of concerns, as geopolitical unrest has put pressure on base materials fundamental to the processes used, resulting in scarcity of these byproducts due to their limited location. Neon is used in semiconductor lithography lasers. Currently, integrated circuit substrates likely fit into this category, with over 95% of integrated circuit substrate production being based in Asia (Kelly and Vardaman 2021).

> ***Semiconductors are just one part of the entire electronics ecosystem—an ecosystem that can be destabilized with the disruption of less visible supply chain segments.***

Without substrate capabilities, semiconductors are useless pieces of silicon unable to connect and operate within a system. Substrate capabilities are limited by materials challenges. For example, Japan owns critical materials like Ajinomoto Build-up Film (ABF), which are necessary for substrate production for semiconductors. But substrate capabilities are also limited in terms of the expertise of a broad workforce that can manufacture them, even if materials are obtained or produced.

On a positive note, recent global investments are opening up opportunities to alleviate substrate difficulties.

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[2] www.state.gov/minerals-security-partnership/

Government subsidies have been announced in the United States, Europe, India, and other parts of the world to improve the semiconductor ecosystem, including the production of substrate technologies. Even when government funding is awarded, the reality is that most of these proposals are still five years away from reaching the technology exhibited in Asia last year.

> ***Financial and political pressures require that we make changes, and, as it always has, the electronics industry is moving fast to adapt and reinvent itself for an even brighter future.***

Water

The story around water is not new. Many do not realize that some semiconductor fabrication facilities can use five million gallons of water daily (Govindan 2022). A sobering example of the strong need for water by the semiconductor industry was reported in 2021 (Zhong and Chien), when Taiwan semiconductor factories were fighting with agricultural fields for mutually needed water. In this case, the fields went dry as technology's needs took priority over crop development. This does not include other electronics manufacturing processes that also use water in many of their production processes, like printed circuit board fabrication. It is imperative to develop three separate processes to mitigate this. The first effort, which is already underway, is the treatment of water used in electronics and semiconductor production to make sure it is recycled and returned clean. Some electronics manufacturers have wastewater treatment capabilities that enable facilities to return water cleaner than it was when received, and some semiconductor fabricators have been recycling 40-70% of the water used (Johnson 2022). Secondly, there is the process of recycling water in such a manner that you close the loop on your water needs. Water obtained stays in the factory and can be continually reused as losses are minimized. Thirdly, more efficient processes have been developed to reduce water usage in electronics and semiconductor production for over fifteen years (Goosey 2005). Improvements in each of these three areas are being explored. While this is a positive and ever-improving direction, the challenge remains as the demand and ubiquitous desire for electronics continue to accelerate.

Tin

Tin is the glue for electronics, as it is the vital material contained in most types of solder. An absence of tin would result in an absence of electronics. Many of the solutions to deliver sustainable objectives rely upon electronics to become a reality. Tin is critical for electronics to work. The forecasted demand for electronics outpaces the worldwide supply of mined tin. Estimates indicate that there may only be forty years' worth of tin left to mine at current extraction rates with known global deposits available (Jowitt et al. 2020). Again, recycling and improved processes through investments are the prescribed paths (ITA 2023).

Key Product Challenges

There are two key product families threatened by the risks described above: semiconductors and batteries. Semiconductors face several challenges from critical materials, water, and REE shortages and access. Rare earth metal oxides (REMOs) are synthesized from REEs and used in the formation of semiconductors, as well as many of the more popular electronics products in use today, such as televisions, wind turbines, LED light bulbs, and cell phones. According to Patil and colleagues (2022), "REE and their alloys have seen a surge in use in a variety of technological devices in the last three decades, including computer memory, DVDs, rechargeable batteries, autocatalytic converters, super magnets, mobile phones, LED lighting, superconductors, glass additives, fluorescent materials, phosphate binding agents, solar panels, and MRI agents." The criticality of these REEs and REMOs to the electronics products being consumed cannot be understated.

Sustainability

Solutions to enable sustainable manufacturing and address production challenges will improve the quality of life now and into the future and will address resource conservation and the need to continuously improve processes to ensure the efficient use of resources. E-waste was estimated to be around 54.6 million tons (Mt) in 2019 and is estimated to be 75 Mt by 2030 (Forti et al. 2020). These quantities of waste are also valuable resources to circularize the life cycle of products. The waste hierarchy stresses waste prevention, reduction, reuse, recycling, recovery, and, lastly, disposal—practices that can help begin to address some of the risks associated with resource management.

As production facilities, manufacturing equipment, and processes are designed to be more efficient, they can produce using less resources like water. In fact, the very water being used in more effective manufacturing facilities is reused several times over. In electronics systems production, like printed circuit board fabrication, some metals and chemicals that could be classified as waste—and, in some cases, hazardous waste—are able to be recycled at an ever-increasing rate. New reclamation systems are being developed for improved management of electronics at end-of-life, preventing e-waste; these systems look to chemical and mechanical means, and they continue to be an area of focus in the pursuit of more sustainable, or circular, electronics (Mir and Dhawan 2022).

IPC continues to dedicate its resources to various sustainability-focused initiatives, including the recent formation of the industry-led IPC Sustainability for Electronics Leadership Council, which is responsible for helping to identify opportunities to improve sustainability for electronics manufacturing and create efficiencies for the industry.[3] In June 2023, the Sustainability for Electronics Leadership Council worked with IPC's Chief Technologist Council to publish a white paper, *Electronic Design and Manufacturing Sustainability* (2023), which provides an overview of eight sustainability topics that affect the electronics industry.

Eco-design

A focal point for influencing resource needs, and the real game-changer for risk management, is found at the front end of the electronics manufacturing process: design. Design for circularity or eco-design of electronics needs to become the norm going forward. These approaches will promote modular designs and upgradability, which will make the ideals of reuse and extended life of products more realistic possibilities. The idea of using the same phone that was in use ten years ago would hamper even the most conservative mobile phone users today. But if that same phone were designed with modules that could be swapped out, upgraded, and designed so that the exchanged modules were able to have much of the metal and valuable contents reclaimed, then perhaps keeping your phone for multiple years would be a realistic prospect. New materials could be utilized, integrated into updated modules, and inserted into existing systems. While this may all seem like an obvious direction, without the upfront business decision to leverage eco-design principles and commit to a business model that does not end in the disposal of the product, this will feel more like science fiction than scientific fact.

Changing an Industry

How can companies intrinsically change their design and production business models? Historically, changing materials and product modalities has been slow to occur without there being a financial necessity. Many of these financial necessities are upon us and have been growing over the past decade. The electronics industry has found alternatives to hazardous materials like lead metal and implemented alternative materials and processes due to policy drivers such as the Restriction of Hazardous Substances in Electrical and Electronics Equipment Directive in the EU. Electronics manufacturers build for a global market—even in times of unrest. Using different materials for different markets costs more to develop, and economies of scale are often diminished. Similarly, regulatory pressures have pushed for cleaner and more energy-efficient manufacturing facilities, and the industry has continued to respond. More recent financial requirements have come in the form of ESG pressures from the investment community. Recent data also seems to indicate that the application of ESG practices to businesses attracts investors for a good reason: companies that follow them are more profitable, according to Bain and EcoVadis (Ashcroft 2023). Efforts from governments have been promoting better use of materials, or different ones. The US legislative efforts alone have amounted to over $8 billion in funding for the Department of Energy and the Department of Interior; these efforts include parts of the Energy Act of 2020, the Bipartisan Infrastructure Law, the CHIPS and Science Act, as well as the Inflation Reduction Act (Broberg and Jacobs 2023).

Financial and political pressures require that we make changes, and, as it always has, the electronics industry is moving fast to adapt and reinvent itself for an even brighter future. The development of recycling technologies, eco-design, and investigation into new materials and processes will likely result in the world having products that are operated, consumed, and maintained in ways that are very different from what the world has been accustomed to in the past.

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[3] www.ipc.org/advocacy/sustainability-electronics

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A successful transition of the automobile industry to an electric, autonomous, and connected future depends on a stable and scalable supply of critical and sustainable materials.

An Automotive View of Critical and Sustainable Materials

Paul E. Krajewski (NAE), director, GM Research and Development.

Paul E. Krajewski

Automobiles are manufactured from materials using almost every element in the periodic table, from aluminum to zinc. A consistent supply of these materials is essential for avoiding interruptions in production. The importance of a consistent supply has been known since the early days of the automotive industry. Henry Ford was very concerned about a stable supply chain and secured iron ore from Michigan and rubber from Brazil, as well as other materials critical to his vehicles.[1] The automobile industry today is much different than it was in the early 1900s, when companies were mostly vertically integrated, controlling raw materials and the production of most components and subsystems used on the vehicle. Today, most components are manufactured by suppliers and provided to automakers for assembly. As a result, materials are provided and utilized by a complex, global supply chain.

The complexity of the automotive supply chain and the resulting impact on material supply and cost have been exposed by a series of events over the past twenty years. China controls most of the magnesium production in the world (USGS 2022). As an example, prior to the 2008 Beijing Olympics, Chinese authorities ordered a halt in magnesium production, as well as steel, cement and glass production, as part of an effort to improve air quality. The result

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[1] For information on Henry Ford, see www.thehenryford.org/visit/ford-rouge-factory-tour/history-and-timeline/fords-rouge/ and www.thehenryford.org/collections-and-research/digital-resources/popular-topics/brazilian-rubber-plantations/.

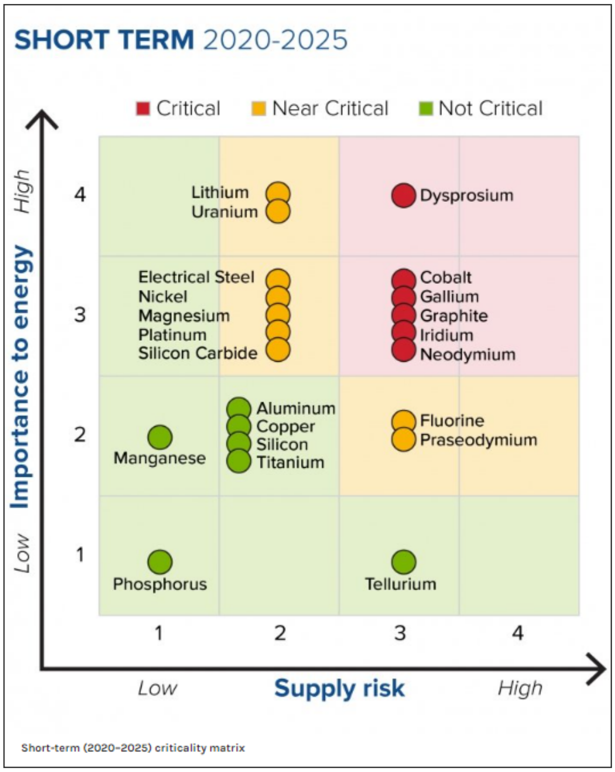

FIGURE 1 United States Department of Energy representation of critical materials showing the importance of the material to clean energy as a function of supply risk. Source: DOE 2023.

was a significant shortage of magnesium and a spike in prices (Imahashi 2021). Production was slowed again in 2021 due to energy supply issues, further contributing to uncertainty in magnesium availability and pricing (Index Box, Inc. 2021). In 2011, the Tohoku earthquake and tsunami led to shortages in electronic components and even pigments for some paints (Bunkley 2011). The 2020 COVID-19 pandemic and resulting semi-conductor chip shortage limited automobile production and even the features available on some vehicles. These events have led to detailed analyses of the automotive supply chain by automakers, including where materials are sourced, converted, and finally integrated into vehicles.

In addition to better understanding the supply chain, there is a growing desire to ensure the materials and processes used to make sure automobiles are sustainable and have a low carbon footprint. These constraints are driving new considerations and complexities in the material supply chain. This article will focus on the issues impacting how materials are viewed as critical and sustainable by focusing on two key parts of the supply chain: raw material production and conversion. Examples of critical materials as they apply to electric vehicles will be presented, culminating in a path forward emphasizing the importance of public-private partnerships to enable the availability of critical materials.

Critical Materials

The "criticality" of materials to automobiles fundamentally depends on their importance to various vehicle systems, like batteries, electric motors, sensors, or other subsystems, and how risky the supply of these materials is. The definition presented by the US National Science and Technology Council, Subcommittee on Critical and Strategic Mineral Supply Chains (NSTC 2016) is, "'Critical minerals' are those that have a supply chain that is vulnerable to disruption, and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence." Included in this classification are how easily other materials could be substituted, where in the world they are located, and whether there are multiple suppliers who could provide the material. Similarly, the Energy Act of 2020[2] defines a "critical material" as any non-fuel mineral, element, substance, or material that the Secretary of Energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy.

Recent trends in the automobile industry such as electrification, autonomous and advanced driver assistance systems, connected vehicles, and large displays have led to a change in the types of materials that are critical to the manufacturing of these vehicles. The chart shown in figure 1 is used by the US Department of Energy to designate critical materials (DOE 2023). It compares the importance of the material to future energy as a function of supply chain risk. This chart aligns well with the perspective of the automobile industry, highlighting materials critical to battery manufacturing (lithium, cobalt), electric motors (rare earth metals), and even sensors (gallium) and displays (tellurium). In addition, materials such as magnesium, which are important for vehicle light weighting but are largely controlled by China, are also represented. The chart shown in figure 1 is for the time period through 2025, but there are longer-term graphs available that capture projected future trends.

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[2] See www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals.

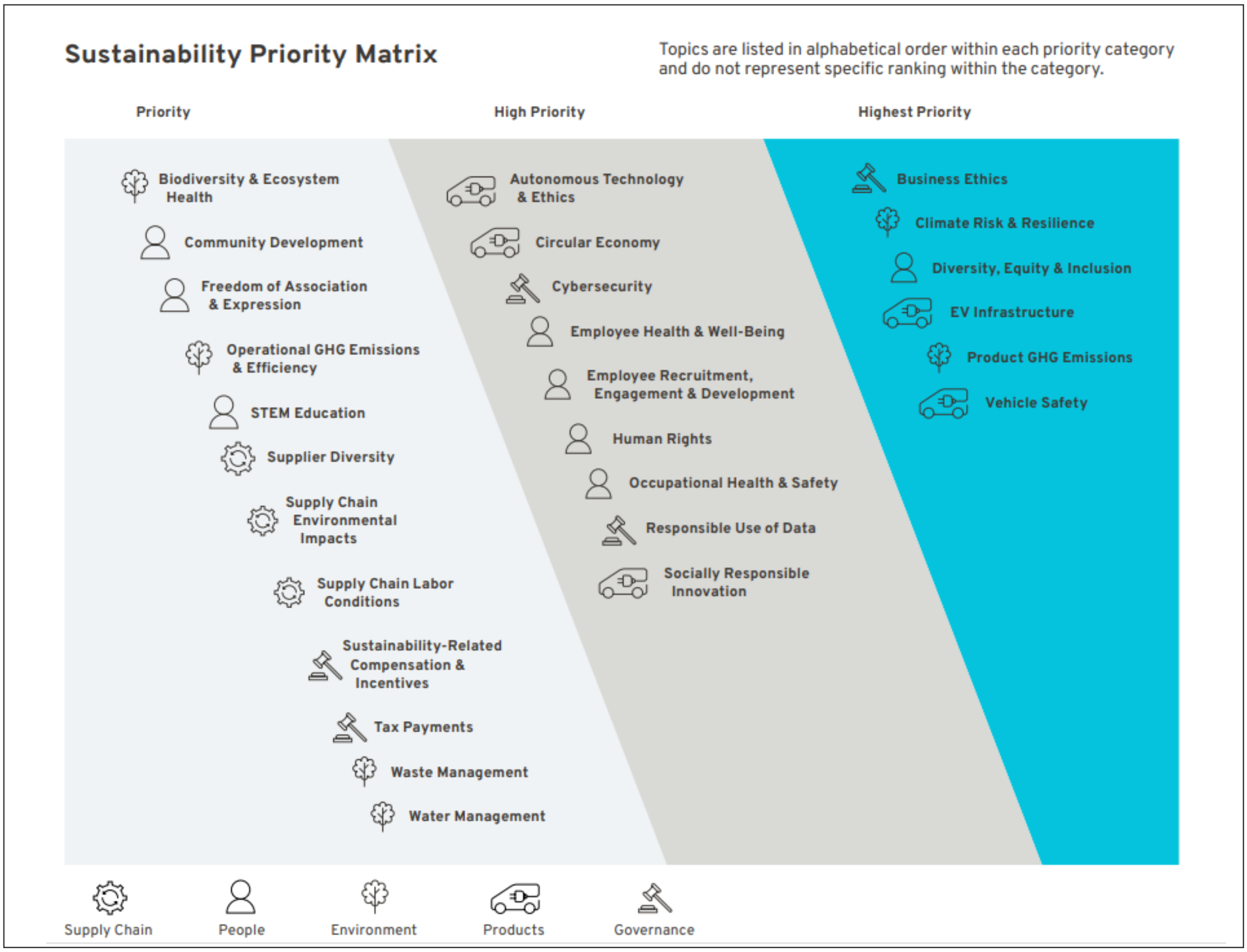


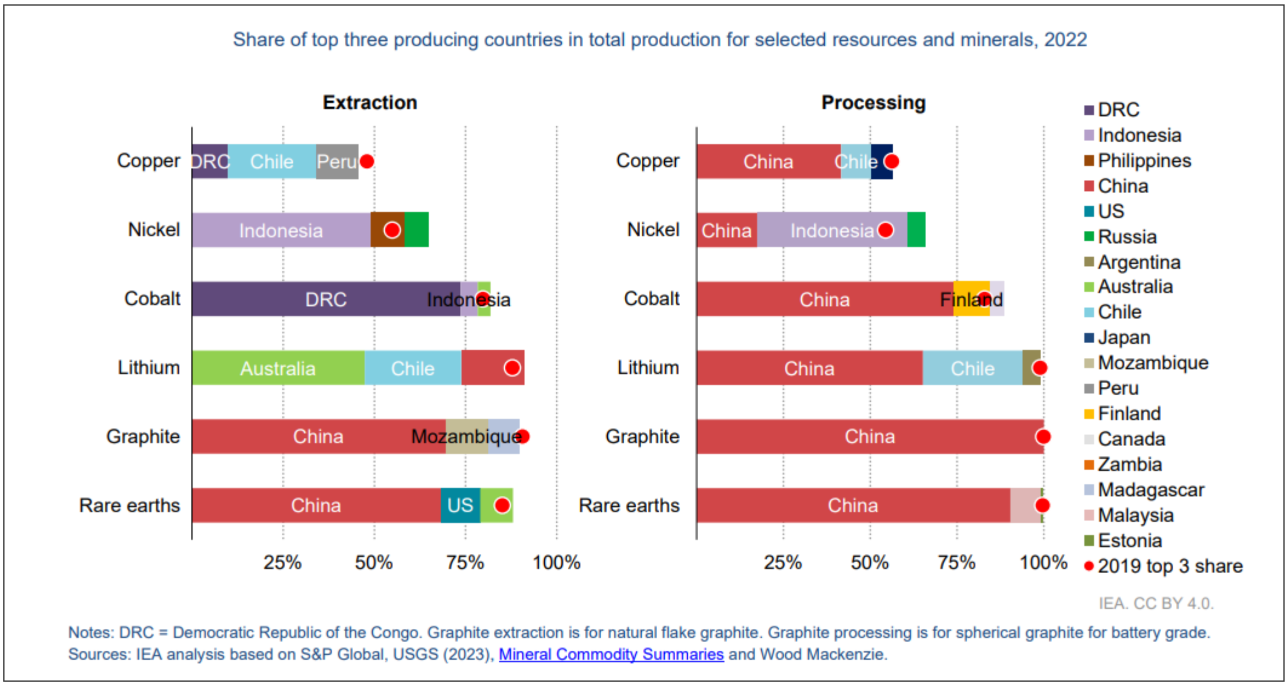
FIGURE 2 Description of key categories affecting sustainability and their relative priority to address. Source: GM 2022.

Sustainability

Automotive descriptions of sustainability cover a wide variety of issues, including safety, CO_2 emissions, programs for a sustainable workforce, community viability, and fair-trade practices, among others. An illustration of the issues impacting sustainability is summarized in figure 2, which is reproduced from the GM sustainability report in 2022 (GM 2022). There are several issues in figure 2 (GHG emissions, circular economy, supply chain environmental impacts, supply chain labor conditions, waste, and water management) relating either directly or indirectly to materials used in vehicles. Additionally, there are goals for renewable energy usage, the amount of sustainable content in vehicles, and even the packaging used for materials and components in the vehicle build process. Many of these issues directly overlap with the considerations for critical materials.

Raw Materials

Most materials used in the automobile industry are found in nature in a different form. Raw materials could reside as complex minerals or oxides from which metals are extracted, or as petrochemicals used to create polymeric materials. As a result, the location of where these materials are found and the process used to extract them are often the biggest factors driving their designation as “critical.” For example, 83% of rare earth reserves are in China (34%), Vietnam (17%), Brazil (16%), and Russia (16%) (Statista Research Department 2024). Seventy percent of the cobalt in the world is mined in the Congo (Gulley 2022). As previously mentioned, China controls most of the global magnesium supply. Alternative sources of magnesium from other countries, such as Russia, the United States, and Israel, are available, albeit at lower volumes. However, the lower cost of magnesium from China comes with a significant environmental impact as a result



Share of top three producing countries in total production for selected resources and minerals, 2022

Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite for battery grade.
Sources: IEA analysis based on S&P Global, USGS (2023), Mineral Commodity Summaries and Wood Mackenzie.

FIGURE 3 Graphical representation showing the top three countries for both extraction and processing (conversion) for select critical materials. Source: IEA 2023.

of their production methods (Pidgeon process). The same can be said regarding the production of critical materials in China as well as in other countries engaged in extraction and refinement. Thus, sustainable extraction and refinement of critical materials must be considered when sourcing materials. The regional dominance of raw material supply inherently drives risk and makes material availability subject to geopolitical issues.

The way these raw materials are extracted, the energy required, and the labor force used are some of the factors driving "sustainability." Leveraging renewable energy sources in highly efficient processes is ideal. Minimizing the amount of land and water used in the process is particularly important for the local communities. The byproducts generated by the processes and the resultant waste stream impact on the environment need to be understood. Critical throughout all these steps is an understanding of the miner's performance in terms of human rights, labor rights, safety, protection of biological diversity, and additional factors. Numerous organizations have been established to monitor these examples. The Global Platform for Sustainable Natural Rubber (GPSNR)[3] was created to address issues of sustainability, fair trade, and human rights efforts in the rubber industry. The First Movers Coalition[4] was established to help companies leverage their purchasing power to create early markets for innovative clean technologies in sectors like aluminum and steel production.

Conversion

Material conversion contributes significantly to classifying materials as critical or sustainable. The conversion process can take many forms: converting ore or minerals to usable metals or alloys; processing petrochemicals to produce polymeric materials; converting metal ingots to usable forms like sheet or extrusions; producing alloy ingots for castings; or creating textiles for fabrics and carpets, pigments for paints, or liquid crystals for displays. One of the biggest drivers affecting these conversion processes is the geographic location where they are performed. This was highlighted in the 2023 Critical Minerals Market Review (IEA 2023), which showed how the conversion of raw critical materials is dominated by China. A chart from the study is shown in figure 3. Taking a material like cobalt as an example, 70% of global production comes from the Congo, while almost 65% of the conversion occurs in China. This means the material not only has to travel through two different geopolitical regions, but it also must be shipped around the world if

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[3] https://sustainablenaturalrubber.org/

[4] https://initiatives.weforum.org/first-movers-coalition/home

it is to be used in the United States. This not only creates risk but also adds logistics costs to the materials, which is why it is deemed a "critical material."

Critical Materials for Electrification

The main reason the materials and supply chain are receiving such scrutiny is the significant transformation occurring in the global automobile industry. There is an accelerating shift from the internal combustion engine to electric vehicles powered by batteries, hydrogen, or hybrid systems. These new propulsion systems have vastly different material requirements than gasoline-powered engines. Ensuring that electric vehicles are cost-competitive requires a secure, scalable, and sustainable supply of these materials. Three examples critical to the success of electric vehicles—batteries, electric motors, and power invertors—are discussed below.

For batteries, critical materials include lithium, nickel, cobalt, manganese, silicon, and graphite. These materials are required for key battery components such as anodes, cathodes, separators, and electrolytes. There are five important steps in the supply chain to understand and secure: 1) Raw material mining or retrieval, 2) Conversion of raw materials to key compounds, 3) Synthesis of active battery cell materials, 4) Converting materials into cathode and anode powders, and 5) Assembling the components into a cell and pack. Automakers have engaged in strategic collaborations across the value chain. GM, for example, has announced that the materials required to produce 1 million vehicles of annual production beginning in 2024 were secured in 2022. In addition, the dependence on certain critical materials like cobalt has led to significant R&D to enable alternatives. As a result, the future batteries could potentially use up to 70% less cobalt than previous generations (Chevrolet 2022). As an alternative, LiFePO4 batteries are proving effective battery technology and a push toward less dependence on cobalt materials systems.

For electric motors and drive units, rare earth elements, including neodymium, praseodymium, terbium, and dysprosium, are critical to their production. These elements are essential to the high-powered magnets that are critical to converting electricity into mechanical power. The key aspects of the supply chain for electric motors include raw material extraction, conversion of the raw material to metals and alloys, creation of magnetic materials, assembling the magnetics into a motor, and assembly of the drive unit. Automakers are collaborating with materials suppliers to both secure the existing supply of rare earth elements and explore a new supply of rare earth materials (GM 2021).

Finally, power inverters are essential for electric vehicles. Inverters convert the voltage from the vehicle's battery to an alternating current (AC), which is usable by the subsystems on a vehicle. An example is the drive motor, which leverages AC to achieve smooth control during acceleration. It is also important during regenerative braking, when the AC produced by the braking motors is converted to direct current output to recharge the battery. The key material for future inverters is silicon carbide (SiC), which enables greater efficiency and operation over a wider range of operating temperatures. The value chain for inverters involves melting SiC to form an ingot, wafer fabrication, the creation of a bare die, packing the die into the power module, and then assembling the inverter. SiC is on the critical materials list due to challenges in manufacturing output and energy requirements that can lead to supply backlogs and disruption.

A Path Forward

Having a secure supply of the materials that are necessary to produce a vehicle means developing a long-term strategy and partnerships to ensure that materials will be available, with limited impact on global politics, climate disasters, or other disruptions. In addition, automobile production is considered a low-margin business, necessitating a continuing push to reduce costs. Reducing the logistics cost to transport materials from mining to conversion to vehicle assembly is critical.

> ***A successful transition of the automobile industry to an electric, autonomous, and connected future depends on a stable and scalable supply of critical and sustainable materials.***

Original equipment manufacturers have started collaborating with companies across the materials value chain to enable a secure supply. Creating the right partnerships requires a deep understanding of the whole value chain. This is especially true for materials essential to electrification.

The strategy to enable a stable supply of sustainable materials for future automobiles has four key pillars: secure, scalable, cost-effective, and sustainable, including more environmentally conscious extraction and refining of materials. This requires the private sector to work with federal and local governments to stimulate and enable success. A few examples of collaboration opportunities include:

- Incentives for production of critical materials and subsystems, ensuring consistency, speed, and transparency in compliance and permitting processes.
- Developing downstream and midstream assets both in the United States and Canada.
- R&D funding at both national labs and universities in collaboration with industry to drive mining innovation, the discovery of new materials and processes, the recycling of technologies, and the creation of sustainable solutions.
- Market access—facilitating the availability and affordability of critical minerals from asset-rich allies, such as Australia (lithium, nickel, cobalt, rare earths) and Canada (nickel, cobalt).
- Recycling and reuse—creating an electric vehicle battery recycling market at scale to secure critical mineral sources, support manufacturing and jobs, and promote energy security.
- Workforce development—measures to develop a domestic workforce with the necessary skills to support the growth and competitiveness of electric vehicle supply chains and manufacturing.

Summary

A successful transition of the automobile industry to an electric, autonomous, and connected future depends on a stable and scalable supply of critical and sustainable materials. Significant technical and business progress has been made to develop new technologies and partnerships to enable that future. A long-term vision and commitment to the transition is critical in both the private and public sectors for the transformation.

Acknowledgements

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There is a critical need for research on and development of new non-PFAS materials.

Critical Needs for Non-PFAS Semiconductor Packaging Materials

Pradeep Lall is MacFarlane Endowed Distinguished Professor and alumni professor, Auburn University.

Pradeep Lall

Environmental, social, and governance factors are used to evaluate companies to gauge their level of advancement with regards to sustainability. Sustainability has received increased attention owing to growing awareness of global environmental impact and the migration of the financial industry towards using environmental, social, and governance factors in assessing future growth potential and investment decisions. Presently, the semiconductor industry relies on per- and poly-fluoroalkyl substances (PFAS), a group of over four thousand man-made chemicals used in various consumer electronics. PFAS materials have shown the propensity to get into the water supply, linking those materials to a range of health concerns.

There is a renewed focus in several application areas on eliminating and finding suitable replacements for existing PFAS material sets. Environmental regulations seek to limit PFAS use in electronics and are divided into two types (Acquis 2023): (1) Reportable PFAS regulations that pertain to PFAS intentionally added during electronics manufacturing processes. EU REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) and the state of Maine in the United States, under the Toxic Substances Control Act, apply specific reporting requirements for reportable PFAS. (2) Restricted PFAS include long-chain PFAS, such as perfluorooctanoic acid, which are categorized as being persistent and toxic. Regulations, such as EU Persistent Organic Pollutants and REACH Annex XVII Entry 65, aim to limit the use of restricted PFAS in electronics. There is a critical need for non-PFAS material replacements that can provide similar or better properties in comparison with the PFAS counterparts presently in use. In this article, the role of PFAS in semiconductor package components is discussed, along with the specific performance enhancements enabled by PFAS for each function.

> ***There is a critical need for non-PFAS material replacements that can provide similar or better properties in comparison with the PFAS counterparts presently in use.***

The Role of Semiconductor Packaging

Bare chips require packaging in order to fulfill a number of critical functions, including environmental protection, thermal management, power delivery, fan-out of the chip pitch for compatibility with the coarser pitch of printed circuit board technologies, and elimination of the need for a high-grade cleanroom for the pick-n-place part assembly on the printed circuit boards. The device packaging can take a number of forms depending on the product architecture. The main components in a semiconductor package are the package substrate, the silicon chip-to-substrate interconnects, the substrate to the printed circuit board (PCB) interconnects, die-attach, underfills, and overmolds or lids. The silicon chip-to-substrate interconnects are called the first-level interconnects, and the substrate-to-PCB interconnects are often referred to as the second-level interconnects. The functions of these package elements include:

Package Substrate: The package substrate performs the function of fan-out of the fine-pitch chip interconnects to the coarse pitch of the printed circuit board. Substrates may be made of organic laminates or ceramic, depending on the application. Organic laminates are composites consisting of epoxy-impregnated glass fibers. Substrates are generally multilayer and use high-density interconnect wiring compared to printed circuit boards.

Si Chip-to-Substrate Interconnects: The chip can be interconnected to the substrate using a variety of interconnects, including flip-chip solder bumps, wire bonds, or tape-automated bonding. Most modern high-performance packaging uses flip-chip solder bumps, while packaging with lower I/O counts uses predominantly wire bonds for interconnection. Flip-chip solder bumps are typically formed from solder bumps termed C4 bumps or controlled collapse chip connections.

Substrate-to-PCB Interconnects: The semiconductor package can be interconnected to the printed circuit board with balls, columns, leads, or no-lead terminations, depending on the package format. Solder is the predominant material used to connect the package interconnects to the printed circuit board. The solder may have fluxes in the formulation for the wetting processes during reflow and assembly.

Die-Attach: The chip is attached to the substrate for wire-bond configurations using a chip-attach or die-attach material dispensed on the substrate or the lead frame. The die-attach is also designed to accommodate the thermal mismatch between the silicon chip and the substrate or the lead frame and to provide a thermal heat dissipation path from the chip to the printed circuit board.

Underfills: The gap between the chip and the substrate may be reinforced with underfills to provide supplemental reinforcement for the first-level interconnects and accommodate the differential thermal expansion between the chip and the substrate during thermal or power cycling. Underfills are required to bond to the chip and solder mask of the substrate in addition to encapsulating the first-level interconnects.

Overmolds or Lids: Plastic-encapsulated microelectronics packages use overmolds to protect the chip and provide ease of handling. Epoxy mold compounds, which are composites of epoxy and filler particles, are used to provide encapsulation of the chip and the interconnects. Lids are used in some applications that require high-temperature operation or higher heat dissipation. Common materials include copper or aluminum lids for attachment to heat sinks.

Semiconductor Packaging Formats

Earlier electronic architectures used through-hole packaging to interconnect the semiconductor packages to the printed circuit boards. The packages were interconnected

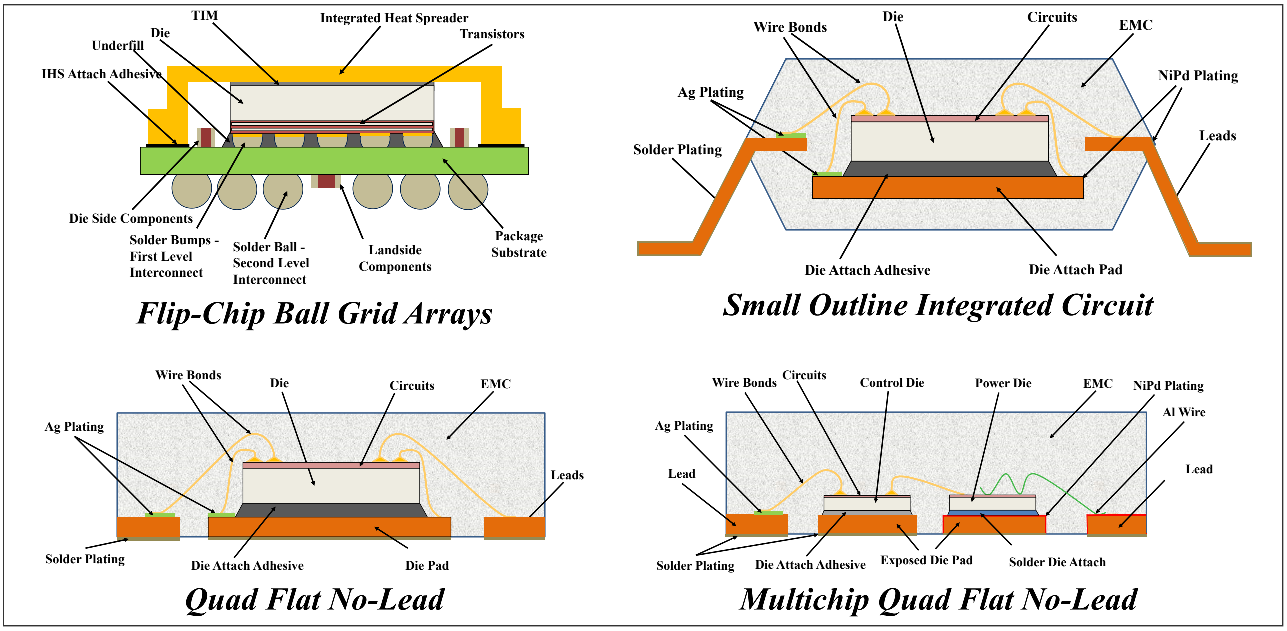

FIGURE 1 Representative package interconnect geometries.

by inserting the package leads into through holes in the PCB. The current generation of semiconductor packaging predominantly uses a surface mount format in which the second-level interconnects are attached to the surface of the printed circuit board. Some applications may have packages with copper lands that are connected to socket contacts. The sockets may themselves be mounted on the printed circuit board. The surface-mount packaging architectures may be broadly categorized into area-array, leaded, and leadless packages. Area-array and leaded architectures may use balls, columns, or punch-and-form leads (figure 1). Some examples of leaded, leadless, and area-array packaging architectures are listed below:

> *Area-array packaging*: plastic ball grid arrays, flip-chip ball grid arrays, ceramic ball grid arrays, ceramic column grid arrays, wafer-level chip scale package, fan-out wafer-level package.
>
> *Leaded packaging*: thin-small outline package, small outline integrated circuit, flip-chip small outline package, quad flat pack.
>
> *Leadless packaging*: quad flat no-lead, metal lead frame, leadless chip carrier, ceramic leadless chip carrier.

Functions Enabled by PFAS Materials

Semiconductor packaging involves the use of different materials throughout various process steps, each requiring specific material properties and quality characteristics (table 1). PFAS are known for their thermal and chemical stability. They also provide electrical properties such as low dielectric constant and loss, which are essential for high-speed and high-bandwidth communication. There are several other noteworthy properties of PFAS, including their thermal and chemical resistance, low dielectric constant, low residue transfer, improvement of surface wetting, and photo imageability. These properties help increase yield quality and reliability and enable the multistep processing required for complex packaging designs of the future. It's worth noting that PFAS have not yet been classified as regulated materials in semiconductor packaging.

Substrate Core and Buildup Layers

PFAS materials enable a number of required properties in substrate materials, including low permittivity (low-k, ε_r), low dielectric loss, low water absorption, and low coefficient of thermal expansion (CTE) (Elsherbini et al. 2022; Jiangxi Tieno Technology Co. Ltd. 2019; Shantou Ultrasonic 2019; Taiwan Semiconductor Manufacturing Co. TSMC Ltd. 2019). PFAS in buildup (or dielectric) materials within the substrate enables low-k, low dielectric loss, low water absorption, low CTE or CTE matching, high strength adhesion, improved dimensional stability, compliance or modulus matching, and reliability (Japp et al. 2008; Starkston et al. 2021; Wu C-W et al.

TABLE 1 The role of PFAS in semiconductor packaging

Packaging Component	Role of PFAS in the Packaging Component
Substrate Core	Low-k ($\varepsilon r < 2.94$) Ultra-low Dielectric Loss ($\delta < 0.0008$ @10GHz) Low Water Absorption (< 0.02 percent) Low CTE (< 20 ppm/C)
Substrate Build-Up Layers	Low-k ($\varepsilon r < 2.8$) Ultra-low Dielectric Loss Low Water Absorption Low CTE or CTE Matching between EMC and Pillars High Strength Adhesive Improved Dimensional Stability Compliance or E-matching between EMC and Pillars Improved SMT Reliability Plated Thru-hole Reliability
Flux	Diluent Media Cleaning Agent Base Resin Surfactant (0.01-1 perc by weight)
Adhesives	Release Agent Pressure Sensitive Adhesive Chemical Resistance Flexibility Bulk Thermal Properties
EMCs	Flame Retardant Dripping inhibitor Catalysts Resin Thinner Adhesive Encapsulating Gas Barrier against Water or Steam Fluorescent Polymer Compound
Underfills	Stress Reduction Semi-solid Film Formation
TIM	High-Thermal Conductivity Tear Resistance High UTS (>5-10 MPa) High Viscosity Elastic

2017). Fluorinated materials allow for high glass transition temperatures, ensuring the material remains rigid at elevated operating temperatures. Dielectric loss is a measure of the electromagnetic energy absorbed by the material. The substrate core may be required to operate in a wide electromagnetic frequency range at low voltages, making the low absorption of electromagnetic energy important for maintaining signal fidelity. Environmental exposure of electronics to moisture often results in water absorption into the substrate core and buildup layers of the semiconductor package, which can dramatically affect the dielectric properties of the substrate owing to the significantly different dielectric properties of water. CTE is a measure of the dimensional change realized per unit change in temperature. During operation, semiconductor packaging dissipates heat, resulting in the formation of temperature gradients in the structure. Large differences in the CTE of the buildup layers with the conductive traces and other semiconductor packaging materials result in warpage or loss of coplanarity. Low warpage is needed to prevent failure of electrical interconnects, cratering, de-adhesion, or material fatigue. Fluorinated polymers like polytetrafluoroethylene (PTFE), or Teflon, and related materials have low CTE, making them desirable for use in buildup layers and in the core of the semiconductor package substrates. Commercially available fluorinated buildup materials include Teflon, Teflon-FEP, Teflon-PFA, Teflon-AF, Teflon-PTFE-30, Tefzel, Halar, KEL-F, HBF-430, and Zonyl PTFE TE-3667N.

Flux

Fluxes in semiconductor packaging exist in conjunction with solders and solder paste used in chip and component assembly. Reflow during assembly typically has a ramp and soak in the time-temperature profile to allow time for flux activation and wetting. PFAS materials are used in fluxes to perform the functions of diluent vehicles or media (Cole 1981), cleaning agents (Hori et al. 2019), base resins (Arakawa Chemical Industries Ltd. 2013), and surfactants (Freescale Semiconductor, Inc. 2010; International Business Machines Corp 1973). PFAS in flux-surfactants provides the material the properties of increased heat resistance, wetting, and spreading of solder on the conductive surfaces. Flux is typically applied to the substrate prior to chip pick-and-place and reflow to allow for removal of the surface oxides. The time-temperature profile of the reflow process is intended to interact with the flux to allow sufficient time for activation of the flux prior to the liquidus zone. PFAS in fluxes are used to promote temperature stability during flux activation, prevent pre-mature flux-degradation or residue formation, and prevent voiding. Excessive solder joint voiding has been shown to degrade reliability (Arakawa Chemical Industries Ltd. 2013). Increased residue formation has been shown to degrade insulation resistance during the operation of electronics in extreme environments.

Die-Attach or Chip-Attach Adhesives

Chip-attach adhesives, also known as die-attach adhesives, serve the purpose of mounting semiconductors or silicon chips to package substrates or lead frames. These adhesives form a strong attachment and help reduce stress and control warpage during the system's operation. For semiconductors used in power management, computation, or dynamic random access memory, die-attach adhesives with a high heat transfer coefficient, low coefficient of thermal expansion, and resistance to thermal fatigue are required due to the significant amount of heat generated during operation. To achieve efficient heat transfer away from the semiconductor die, fluorinated polymers are currently used as a constituent in the die-attach adhesive, as they possess low CTE and resistance to thermal fatigue, making them ideal for enabling a high heat-transfer coefficient, low CTE, and resistance to thermal fatigue. PTFE is an essential component in certain die-attach adhesives that are used to manage the flow and bleeding of the adhesive during polymerization. The PTFE "antibleed agents" play a critical role in regulating the amount of epoxy bleed beyond the die mounted to the lead frame substrate to prevent it from spreading to other critical areas, such as wire bond pads. This is crucial because such spreading can result in product failures like wire non-stick on pads and prevent mold compound adhesion, which can lead to void and delamination on the package. In addition, PTFE helps to promote flatness of the die and uniform adhesive thickness (Marks et al. 1994; Zhang et al. 2017). Some die-attach pastes, encapsulants, and underfill materials utilize PFAS-containing chemicals as efficient surfactant agents that adjust surface energy with a low level of less than 0.1% in total weight to meet performance requirements for semiconductor applications.

Release Layer

The chip is in wafer form prior to backgrinding and being diced into individual chips for assembly into the semiconductor package. For the dicing operation, the wafer is mounted on a frame with a tape backing, also called the carrier tape or backgrinding tape depending on the operation for which the tape is used. The tapes have adhesive layers to secure the wafer to the tape. The adhesive provides the adhesion to the wafer but also may have underlying release layers for the removal of the chips through thermal, laser, mechanical, or a combination of mechanisms. Fluorinated polymers are used for anti-adhesion or release layers for carrier and backgrinding tapes (Schelcher et al. 2011). Fluorinated polymers are also used to form laser-release layers, relying on the UV sensitivity of the PFAS materials. Release layers and pressure-sensitive adhesives rely on the use of fluorinated materials to prevent the adhesion between the overlying adhesive and the underlying film of the carrier tape or the backgrinding tape (Nitto Denko Co. 2018). PFAS materials are also used as drip inhibitors during wafer processing (Inazawa and Ishada 2017).

> ***The impact of the elimination of PFAS on packaging performance, material stability, consistency, and suitability for the application relative to the PFAS counterparts is relatively unknown.***

Electronic Mold Compounds

The silicon chip is generally encapsulated using an electronic mold compound (EMC). The encapsulation is accomplished using an injection molding process or using glop-top dispense. Once molded, the part needs to be ejected from the mold for post-mold lead-forming operations for leaded parts or singulation for organic laminate parts. PFAS materials are used in liquid or film form as mold releases agents for a clean mold release while enabling thermal stability. Ethylene tetrafluoroethylene and PTFE are used as mold release agents. Materials such as silicone contaminate other parts of the semiconductor packaging process, tools, or packaging and delaminate downstream material additions. PFAS may be used as a catalyst for the cure of the epoxy mold compound. Sulfonic acids or boron trifluoride act as ion exchange resins. Fluoro compounds may be used in small percentages to thin the epoxy used for molding while maintaining the overall material characteristics (Nippon Shokubai Co. Ltd. 2013). In addition, PFAS materials are used to provide thermal stability and flame retardancy. PTFE is used to provide flame retardance (Inazawa and Ishada 2017; Teijin Ltd. 1999).

Underfills

Underfills are supplemental restraints added to the semiconductor package to reinforce the interconnects after damage during normal operation or handling. The underfill materials are composites consisting of an epoxy matrix with silica filler particles. The volume fraction of the silica filler particles is used to control the coefficient of thermal expansion in addition to the elastic modulus of the composite. Filler percentages range from 50-60 percent for most commercial underfills. The epoxy matrix is designed to have high viscosity and low volatility. The high viscosity is preferred to ensure a homogenous filler distribution in the epoxy matrix and reduce void entrapment. Reduction in viscosity of the underfill during dispense can be achieved through exposure to temperature or through shear thinning. Underfills are used to increase the semiconductor package reliability. The underfills are used in conjunction with the flip-chip joints in the gap between the silicon chip and the substrate or between the semiconductor package and the printed circuit board. Predominantly, three configurations are used for underfilling, including full underfill, corner underfill, and edge bonding. The full underfill configuration is used to completely fill the gap between the chip and substrate or between the package and PCB. The corner underfill involves dispensing the underfill in the corners of the package, while the edge underfill only involves underfilling the edges of the package. B-stage cured underfills may be dispensed as films on the surface of the chip, with the full cure achieved during the reflow and assembly process. Fluoro-propyl groups in the underfill are used to improve mechanical strength and reliability through the formation of a semi-solid film on the chip surface (Toray Industries Inc. 2018). Furthermore, stress relief of the solder interconnects may be achieved through the use of semi-solid fluorinated rubbers, including vinylidene fluoride-propylene hexafluoride copolymer and tetrafluoroethylene-propylene copolymer (NAMICS 2018). PFAS materials are used in underfills to prevent the formation of air bubbles or voids, improve high-temperature performance, and prevent resin bleedout.

Thermal Interface Materials

Thermal interface materials (TIMs) are used to fill the asperities between the mating surfaces in a semiconductor package to reduce the thermal resistance. The TIM layer needs to be tear-resistant with high tensile strength to prevent degradation during operation in which the semiconductor package is subjected to a sustained high temperature or wide temperature extremes. The addition of fillers is often used to control the conductivity of the thermal interface materials. PFAS materials such as fluorinated ethylene propylene provide unique compatibility for the incorporation of fillers, including carbon nano-tubes, metals, and ceramics, into thermal interface materials (Thomasset 2014). High thermal conductivity can be achieved through the use of fluorocarbon resins, fluoro resins, or fluorinated polyallyl ether resins. The materials enable compatibility, including adhesion to the constituents, in addition to providing the high viscosity and elasticity needed to sustain differential thermal expansion during power and environmental cycling (Cabot Corp 2016; Hermann 2012).

Summary

PFAS are widely used in the design and manufacture of semiconductor packaging. Critical functions provided by PFAS have been identified in the substrate core, substrate buildup layers, fluxes, adhesives, underfills, electronic mold compounds, and thermal interface materials. In each of the package components, PFAS in the present generation of electronics are used to perform a range of functions, including low permittivity, low dielectric loss, low coefficient of thermal expansion, mechanical strength, adhesion, chemical resistance, surfactants, dimensional stability, flame retardance, and thermal conductivity. There is a critical need for research on and development of new non-PFAS materials that provide the critical functions for each package component while ensuring reliable operation performance. A number of new non-PFAS materials have been put forth for some of the applications highlighted in this article. However, the materials and their reliability and performance are relatively unknown. Furthermore, the impact of the elimination of PFAS on packaging performance, material stability, consistency, and suitability for the application relative to the PFAS counterparts is relatively unknown. Reliability data is needed for representative use cases to mitigate the risks associated with the adoption of these materials into mission-critical applications.

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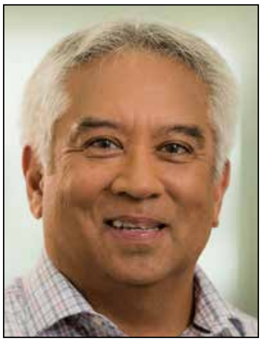
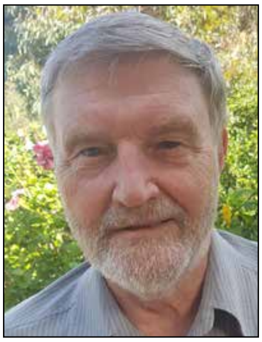
The circular economy approach is a crucial facet of meeting the demand for critical materials.

Lithium-Ion Batteries: A New Opportunity for the Circular Economy and Recycling

Francisco F. Roberto and
Robert C. Dunne



Francisco F. Roberto



Robert C. Dunne

This article considers the increasing use of lithium in electric vehicle (EV) batteries—and, to a certain extent, the primary and secondary use of lithium-ion batteries (LiBs) in utility-scale and consumer energy storage—in light of current mineral resources and mining practices, and the impact that the adoption of circular economy principles and practices could have on meeting future demand.

Curbing carbon dioxide emissions to meet the Paris Agreement (UNFCC 2015) goal of no more than a 1.5°C increase in global temperature by 2050 is dependent on many concerted efforts across the globe to shift electrical power production from fossil fuels to renewable power sources. Recently the International Energy Agency (IEA 2023) reported that the adoption of renewable energy and battery EVs was on track to meet 2030 net zero emissions targets. The 2023 IEA report also mentioned the potential for the demand in 2030 for a variety of battery metals, including lithium, to exceed projected supply and that additional work in recycling and material-efficient design was needed.

The use of lithium in LiBs is reshaping the distribution of end products utilizing this important metal. It has been reported (Bae and Kim 2021) that, with the increase in use of lithium in batteries to 65%, other uses of lithium

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Francisco F. Roberto is director of processing, Newmont Corporation, and Robert C. Dunne is adjunct professor, the Sustainable Minerals Institute, the University of Queensland.

have declined to 18%, and the IEA (2023) estimates that clean energy uses will account for 90% of global lithium demand by 2030.

Why Lithium?

Lithium has the highest electrochemical potential (operating cell voltages of up to 3.7V versus 1.2V in lead-acid batteries) and the lightest weight of the battery metals, which have traditionally included lead, zinc, manganese, cadmium, copper, and nickel, with lighter metals for electronics and vehicle applications gaining favor, including formulations containing cobalt and aluminum. The high energy densities of commercial LiBs, now approaching 300 Wh/kg, have made them the logical choice to address passenger transportation and the displacement of internal combustion engine-powered vehicles through at least 2030. For comparison, Tesla automotive batteries range from 60-95 kWh depending on the model. The Nissan Leaf, which is popular in Europe, has a 24 kWh battery, and the Ford Lightning's 98-103 kWh battery has faster charging rates and a rapidly decreasing cost of LiBs under $150/kWh (the US Department of Energy has established a target of $80 USD/kWh; DOE 2020).

Fire and explosion concerns are also leading to additional LiB formulations that contain iron and phosphorus, solid-electrolyte lithium, and alternative metals like sodium. The risk of fire or explosion has led to restrictions regarding the air transport of even consumer electronics carrying LiBs, and LiBs inadvertently or intentionally introduced into recycling streams have led to hundreds of fires at recycling facilities across the United States (EPA 2021). Nevertheless, some form of lithium-ion battery will be used in EV applications until other technologies mature. Time is of the essence with respect to achieving global carbon emissions reductions.

Mineral Security and the Geographic Concentration of Lithium Resources

Many of the metals and minerals required for renewable energy, electrification, and energy storage are not distributed uniformly or broadly. This is starkly demonstrated by the importance of the Democratic Republic of the Congo's large cobalt resources that are unequalled elsewhere around the world. The results of this concentration are manifold: only a few countries or regions may provide the bulk of global supply. This is certainly the case for many of the battery metals, including lithium, nickel, and cobalt—and the locations of these resources may be challenging for mining due to their remoteness, access to labor, distance from established utility grids and transportation, and ecological fragility (e.g., water availability).

The major lithium suppliers to the United States include Argentina and Chile (together representing 91%), China, and Russia. Globally, the South American countries that comprise the so-called "Lithium Triangle," which produces lithium from brine, include Chile, Bolivia, and Argentina. These countries are estimated to host 70% of global lithium reserves (Tahil 2008). Australia and Canada are the largest producers of lithium from spodumene, a hard rock resource. The CO_2 emissions from the primary production of lithium from spodumene are estimated to be two-to-three times higher than those for brines (IEA 2022). Unfortunately, the lower energy intensity of extraction from brines comes at a cost in terms of water lost to evaporation: an estimated 1,900 tons of water per ton of lithium recovered (Harper et al. 2019). The concentration of lithium in spodumene is about three times higher compared to that in brine by weight. The impacts of carbon emissions and water use in lithium primary production cannot be ignored in any lifecycle assessment.

Circular Economy

The underlying principles of a circular economy can be understood from the simple slogan adopted by the US Environmental Protection Agency (EPA), "Reduce → Re-use → Recycle."

> ***Some form of lithium-ion battery will be used in EV applications until other technologies mature.***

The EPA has recognized that the US recycling system is lagging behind other countries in being prepared to handle new materials and wastes (EPA 2022). As part of a ten-year program to more fully embrace the circular economy, the need for the US economy to "transition to a more sustainable, circular approach focused on reducing material use, redesigning materials to be less resource intensive, and recapturing 'waste' as a resource to manufacture new materials and products" has been identified. The authors hope to make the case that there is value in implementing and time to implement a US strategy for embracing the circular economy, with lithium contained in LiBs as both an important and technically challenging example.

There is value in implementing and time to implement a US strategy for embracing the circular economy, with lithium contained in LiBs as both an important and technically challenging example.

There are clear recycling success stories for various metals today. For example, it is estimated that over 90% of lead-acid batteries are recycled. Similarly, aluminum and copper are recycled at high rates, and the reduced energy consumption of producing new aluminum products from aluminum recycling (>40%; Gaines 2012) is a compelling argument for increasing the rate of recycling of this metal. Nevertheless, outside of the European Union (EU)—where international cooperative legislation has recently approved a new regulation requiring that 50% of lithium be recovered from waste batteries by 2027 and 80% by 2031, and 6% recycled lithium content in industrial and EV batteries (EU 2023)—the progress towards LiB recycling has been slow (only 1% according to IEA). The United States, under the auspices of the US Department of Energy (DOE) and the Federal Consortium for Advanced Batteries (FCAB 2021), has stated an objective of "creating incentives for achieving 90% recycling of consumer electronics, EV, and grid storage batteries." However, this does not constitute a proposed regulation.

Reuse

Circular economy "second use" of lithium batteries supports the adoption of non-transportation use in utility and consumer-level energy storage to maximize renewable energy storage in the case of utilities, and to permit backup power and load leveling use of electricity by consumers as a cost-saving measure. It is expected that EV batteries that may still have useful life for non-vehicle applications will be removed from service when they no longer hold 80% of their nominal charge. Second use is complicated by the need to requalify large LiBs (like those for EVs) containing large numbers of smaller cells to be safe. For perspective, the 95 kWh LiB for the Tesla Model S is reported to contain 7104 individual cells (Velazquez-Martinez et al. 2019). Reuse might also require the replacement of failed cells prior to resale and reuse. Utility-scale second use has been estimated to be 105 GWh by 2040 (IEA 2022), so the diversion of spent EV LiBs may only account for a fraction of the EV batteries available for recycling. It has been estimated that 96 GWh will be available to the reuse market in 2030 and 3 TWh by 2040 (Tankou et al. 2023).

Engineering can empower solutions to key challenges to a circular economy for LiBs: engineering can reduce the time, labor, and complexity of requalifying LiBs for second-use applications; improve the safety of handling LiBs during disassembly and recycling at end-of-life for an individual battery; reduce the cost of handling LiBs during disassembly at end-of-life to improve the economics of recycling and maximize the reuse of as many component metals and parts as possible.

The LiB Recycling Process

LiBs are complex devices at the individual battery-cell level as well as in terms of the number of individual cells required to create an EV battery module. Components include non-metals, such as the graphite anode, the liquid (and flammable), electrolyte, and plastic separator between the anode and cathode. An electronic battery management system is also required to monitor battery cell state of charge, state of health, temperature, and charging rate to shut down the battery and avoid thermal runaway if manufacturer setpoints are exceeded. A variety of Li-ion chemistries are currently used (Porzio and Scown 2021; Lima et al. 2022), which contributes to the complexity of recycling these batteries, particularly when compared to lead-acid batteries. The success of lead-acid battery recycling has been enabled by uniform chemistries and form factors (e.g., the 12V automobile starter battery). While most LiBs contain graphite anodes, the cathode may be comprised of Li-Co oxide (no longer used in EV batteries), Li-Ni-Mn-Co oxide, Li-Mn oxide, Li-Ni-Co-Al oxide, or Li-Fe-Phosphate (LFP) formulations. Most recently Li-Ni-Mn-Co oxide and Li-Mn oxide variants with a Li-Ti oxide anode have emerged. These batteries have typical charge cycle lifetimes of 1000-3000 charges, with the exception of heavier, lower-energy-density LFP (129 kWh/kg; 17) that may exceed 5000 charge cycles, which makes them more suited to heavier vehicles. Ford Motor Company's F-150 Lightning light-duty pickup truck and Mustang Mach-E use this chemistry. LFP batteries are also safer and are seeing increasing uptake in residential home use and marine recreational applications as well. An economic downside to LFP battery formulations is that they have reduced recycling value because they lack more expensive metals such as nickel and cobalt.

The Collection and Dismantling of EV Batteries

LiBs are classified as US Dept. of Transportation Class 9 (Miscellaneous) hazardous materials and as Dangerous Goods by the International Air Transport Association and International Civil Aviation Organization. The additional costs associated with the required packaging and handling requirements for land, rail, sea, or air shipment of spent batteries are anticipated to exceed 50% of end-of-life recycling costs (FCAB 2021). One consequence of these costs may be the establishment of regional or hub recycling centers to minimize transportation costs. Elimination of the flammable liquid electrolyte and modifications of the metal chemistries to avoid thermal runaway are design enhancements that could reduce the cost of recycling. As noted before, inadvertent or deliberate disposal of LiBs in waste and recycling streams has led to hundreds of fires around the world. In the United States the recycling of waste batteries would by definition constitute a hazardous waste treatment and fall under additional regulations.

The first step in dismantling LiBs is discharging the batteries. The variety of form factors and battery types with different discharge requirements and chemical compositions introduces additional hazards and complexity to handling LiBs for recycling. Discharge of stored energy into an energy storage or distribution system is ideal, since that energy can be accounted for as recovered in any life cycle analysis. It is often not feasible to do this, given the wide range of battery module designs and the potentially degraded state of the module when received for recycling. Discharge can be performed in bulk chemically using brine solutions. It is common practice to shred the individual batteries after removal from the battery assembly in an inert atmosphere to avoid fire and runaway exothermic reactions (Harper et al. 2019). If CO_2 is used as the fire-suppressing atmosphere, exposed lithium surfaces may react to form lithium carbonate. Alternatively, the shredding can take place ahead of a high-temperature furnace or smelter. The liquid electrolyte may be removed to reduce fire danger and contamination of materials to permit processing of the solid components, including the anode and cathode materials that contain metals and graphite in most cases. Recovery of the electrolyte provides additional economic and environmental value to recycling as hydrocarbon emissions are reduced.

Rosenberg and colleagues (2022) performed a systematic video analysis of the manual disassembly of a 13.5 kWh commercial battery assembly for a Mercedes EV and identified common operations relating to the removal of components and fasteners to estimate the cost per battery assembly at 80-100 euros ($85-106), depending on the size of the recycling plant. They also assessed the impacts of different fasteners, assembly techniques, and subsystem design and cabling that could be optimized for robotic disassembly.

A real-world example of a large-scale LiB recycling effort using the direct recycling approach (with Li-Co oxide cells from a computer manufacturer recall) was conducted on 2.2 Ah cells (Sloop et al. 2020). The discharge of excess power was performed chemically in a sodium bicarbonate brine solution, after which the electrolyte was extracted using liquid CO_2. After mechanical shredding of the batteries, the electrode materials were separated from other solid components. This approach was compared to careful mechanical removal of the battery case and removal of the battery components, which were then shredded to demonstrate that shredding of the intact battery yielded similar results. The cathodes were removed and hydrothermally extracted in lithium solution in a pressure vessel; graphite could be separated from the lithium-cobalt cathode. A unique aspect of this work was the downstream processing of the cathode material to regenerate ("relithiate") cathode material for reuse.

The Recycling of Battery Metals and Other Components

Four approaches have emerged at this time to recover value from LiBs: pyrometallurgical, hydrometallurgical, physical separation, and direct recovery. Each has advantages and disadvantages with respect to inherent energy use, the chemical state of the recovered materials, and cost. This topic has been reviewed extensively in considering circular economy principles in LiB recycling (Bae and Kim 2021; Harper et al. 2019; Tankou et al. 2023; Velazquez-Martinez et al. 2019).

Pyrometallurgical Recovery

In this process high-temperature furnaces combust organic components like the plastic case and internal plastic parts, binders (often polyvinylidene fluoride), electrolyte, and graphite anode and reduce the metal oxides to a multi-element slag comprised of the component metals. This slag includes the more valuable lithium, cobalt, and nickel, as well as aluminum and copper conductors and packaging. The resulting slag must undergo hydrometallurgical processing (leaching) to separate and recover the metals individually. The scrubbing of toxic gases generated during operation introduces additional operational costs and the potential environmental impact of this approach.

Hydrometallurgical Recovery

This approach utilizes acid (often sulfuric acid) or alkaline leaching in combination with a reducing agent (hydrogen peroxide) to dissolve the metals in a slurry that can then undergo solvent extraction to concentrate the metals prior to selective precipitation as various sulfate, carbonate, or hydroxide salts that can then be used directly in producing new battery cathodes. The relative lack of selectivity in acid leaching can lead to mixed-metal salts that are less desirable for reuse. This suggests an advantage in the physical separation of the anode and cathode components of the waste batteries rather than shredding. Subsequent heat treatment of residues can also generate undesirable air emissions depending on the acid used—SOx with sulfuric acid, NOx with nitric acid, and chlorine gas if hydrochloric acid is used. The scrubbing of these gases and the need for corrosion-resistant equipment can increase the capital cost of a recycling plant. The use of organic acids and non-acidic reagents may provide a sustainable alternative that reduces potential environmental impacts and capital costs and is suitable for the extraction of lithium from LFP batteries (Pagliaro and Meneguzzo 2019).

Physical Separation

After shredding of the individual cells, a variety of physical techniques, including sieving, magnetic separation, gravity separation, flotation, and filtration, can be used to separate the larger particles into enriched fractions that may include plastics, foils, and the so-called “black mass” comprised of the electrode materials (graphite, metal oxides, and binders). The latter can be further treated with solvents or high temperatures to remove the binders.

Direct Recycling

In this approach, which follows the disassembly and shredding of the individual battery cells, the anode and cathode materials are separated to permit the reuse of the cathode materials after upgrading. The upgrading process involves replenishing lithium that has been lost during discharge and aging of the batteries and restoring the structural properties of the cathode (Yang et al. 2022). This was successfully accomplished in the computer battery recall described previously (Sloop et al. 2020).

Current Recycling Capabilities and Prospects for Recycling 2023-2030

It has been estimated that with current battery technology and an estimated life of ten years, the mass of spent batteries in the United States may grow to 2 million tonnes by 2040; due to the increased uptake of EVs in China, spent LiBs will reach 640,000 tonnes by 2025 (Pagliaro and Meneguzzo 2019).

Recent reviews of commercial and proposed LiB recycling processes and operations (Tankou et al. 2023; Velazquez-Martinez et al. 2019) have led to an important conclusion: these facilities exist to profit from the recovery of other battery metals, primarily cobalt and nickel, and are not optimized to recover lithium. The Umicore process has a 7000 ton/y capacity using low-, medium-, and high-temperature furnaces to sequentially remove plastics and electrolytes, followed by the production of a Cu-Co-Ni-Li-Fe alloy and slag containing silicon, calcium, iron, manganese, lithium, and rare earth elements. The Sumitomo-Sony process has a 100 ton/y calcination to remove electrolytes and solvents, which does not recover any lithium but primarily recovers cobalt through a hydrometallurgical leach. Neither of these processes produces usable lithium.

A few examples of other existing processes include:

- Lithorec—manual discharge of batteries followed by dismantling, crushing under nitrogen, heating to evaporate solvents and electrolytes, followed by sieving and leach in a proprietary solution and calcine (2000 ton/y)
- Glencore—smelting; cobalt, nickel, copper (7000 ton/y)

Emerging processes include:

- ReCell (DOE 2020)—a testbed for battery recycling
- Li-Cycle—using a proprietary solution, batteries are shredded and discharged, and components are separated in so-called “spoke” centers that will then ship them to “hub” locations capable of large-scale hydrometallurgical extraction and processing of individual battery metals. Notable for “hub” that will process

55,000 tons/y of black mass and the recent partnerships with Glencore in Italy and various subsidiaries of LG in North America.

The complexity represented in these approaches is a result of the heterogeneous nature of today's LiBs and further supports the idea that innovation and standardization of LiBs for EVs over the next seven years would improve the efficiency of LiB recycling and promote greater circularity with respect to the various metals and other components required for their manufacture (Harper et al. 2019; Thompson et al. 2020). In addition, the hydrometallurgical processes that are integral to even the pyrometallurgical recycling approaches described here should be considered within a framework of circular hydrometallurgy (Binnemans and Jones 2023).

The Influence of Government Regulations

The International Council on Clean Transportation (Tankou et al. 2023) provided an excellent comparison of international policy relating to LiB recycling that clearly showed the leadership demonstrated by the European Union and China in developing standards and regulations to promote recycling and reuse of LiBs. The EV markets in those countries already must adhere to requirements for traceability and composition of LiBs—battery "passports" that will assist in accounting for and safely handling LiBs at end-of-life. The EU recently updated their LiB recycling regulation, specifying the required amounts of battery metals that must be recovered, including recycled content in new batteries, as previously mentioned.

At this time US standards and regulations are aspirational at best, although it should be mentioned that the California EPA (Kendall et al. 2022) has published a report providing substantive recommendations from a broad-based advisory panel comprised of state and local agencies, recyclers, automobile manufacturers and dealers, and nongovernmental organizations to support LiB recycling. Many of the federal and state regulations that must be considered in the development of recycling capabilities were also considered. Since California surpassed 1 million EV sales in 2021 and annual sales reached nearly 300,000 in 2022 (16% adoption), that state will be a major player in employing and regulating LiB battery recycling in the near future.

Future Prospects

The United States and the rest of the world are faced with existential threats resulting from climate change, accelerated by global warming, and international agreements have been signed to limit global temperature increases by 2050. The measures necessary to limit global warming are aggressive and urgent, but it is clear that the pace of decarbonizing energy generation, transportation, production, and commerce is not yet sufficient to ensure success.

The IEA recently recognized two bright spots of progress: adoption of renewable power (solar and wind) and sales of electric vehicles. For the latter, it is recognized that global mining, often constrained geographically for LiB metals, will struggle to meet increasing demand by 2050, given the existing mines and mines under development for these metals. Employing the principles of circular economy, reuse, and recycling of LiBs is a logical strategy to recover and offset some of the requirements for these metals. It has been estimated that the circular economy could satisfy up to 12% of demand by 2040 (IEA 2022), and as the inventory of spent EV batteries begins to grow after 2030, this approach might even grow to meet more than 25% of demand (Porzio and Scown 2021).

> ***The measures necessary to limit global warming are aggressive and urgent, but it is clear that the pace of decarbonizing energy generation, transportation, production, and commerce is not yet sufficient to ensure success.***

This article is not intended to be an exhaustive review of LiBs for EVs, global reserves of the metals mined to produce them, or the recycling strategies that are being developed to recover the key metals that can be recovered and reused from them. Instead, by laying out some of the approaches to reuse and recycling that currently exist and the complex challenges of developing a national ecosystem to accept, extract, and recover value from waste LiBs, we suggest that LiB recycling represents another grand challenge for engineering, for which the United States has limited time, but time nonetheless, to address.

There are perhaps six to twelve years (2030–2035) for the United States to tackle the challenges associated with LiB reuse and recycling and focus our engineering expertise on:

- Standardizing battery chemistries to reduce the range of processes necessary to recover valuable battery compounds and metals. In the near term, new formulations for solid-state electrolytes that increase energy density and improve safety, as well as non-lithium batteries such as sodium-ion batteries, are developing rapidly. Nevertheless, the development of new chemistries should be considered with regard to how they would be recycled in the same light.
- Standardizing the form factor of EV battery modules, or at least the assembly methods, so that end-of-life handling, discharge, and disassembly can be streamlined and automated.
- Refining recycling processes to incorporate green-chemistry alternatives and reduce energy consumption, offgas emissions, and liquid and solid waste.
- Developing testing equipment and protocols to streamline the assessment of LiBs no longer suitable for EV use for repurposing in energy storage applications.

The technological landscape associated with the increasing use of lithium and other battery metals in the energy transition is not by any means static. We have described a variety of supply, use, economic, and regulatory factors that can influence recycling of EV batteries in the coming decades. However, short of government regulations requiring recycling, profitability will control the broad adoption of the recycling and circular economy principles briefly described here. Key risks include:

- Labor costs—collection and battery dismantling are labor intensive and potentially dangerous operations requiring a trained and skilled workforce.
- Decreased commodity prices of the EV primary metals, which may render the current recycling processes marginal or uneconomical.
- New EV battery chemistries that eliminate or reduce the amount of more valuable metal components, such as cobalt, will impact the economics of recycling.
- Alternative power sources (e.g., hydrogen) may ultimately impact the demand for EVs and reduce the number of end-of-life EV batteries available for recycling.

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Materials informatics can have a profound impact on replacing critical materials to achieve sustainability goals.

Unlocking Alternative Solutions for Critical Materials via Materials Informatics

Rémi Dingreville, Nathaniel Trask,
Brad Lee Boyce, and George Em Karniadakis


Rémi Dingreville


Nathaniel Trask


Brad Lee Boyce


George Em Karniadakis

Critical materials are materials that are essential for a broad range of modern technologies but subject to supply risks, and for which there are no easy substitutes. The list of materials that are considered critical depends on who, where, and when you ask. This ambiguity is due to several factors, including geopolitical instability, resource depletion, and environmental concerns. In the US, lithium (Li) has become the poster child for criticality, owing to the rapid rise in electric vehicles and the dwindling domestic production. Other examples include beryllium (Be), an important material for solar photovoltaics and electric-vehicle batteries, or neodymium (Nd) and dysprosium (Dy),

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Rémi Dingreville is distinguished member of the technical staff, Sandia National Laboratories; Nathaniel Trask is associate professor, University of Pennsylvania; Brad Lee Boyce is distinguished member of the technical staff, Sandia National Laboratories; George Em Karniadakis is Charles Pitts Robinson and John Palmer Barstow Professor of Applied Mathematics and Engineering, Brown University.

because of their use in magnets (DOE 2023). A 2023 assessment by the US Department of Energy (Bauer et al. 2023) identified "the electric eighteen" critical materials, which even include materials that are viewed as common, such as copper (Cu) and silicon (Si). While their supply risk is modest, their ubiquity in the energy sector renders any disruption potentially devastating.

The quest for the discovery and manufacturing of new and innovative materials to replace critical materials remains as vital as ever. Future critical materials disruptions will likely need to be solved in a matter of years or even months, rather than the decade or more often quoted as the requisite timeframe to mature from materials discovery to commercialization. In addition to this need for agility, a broadly coordinated federal strategy across all industrial sectors must address economic viability, ease of production, domestic availability, and lifecycle environmental impact. Resistance to change within the materials industry, along with a lack of awareness about environmental impacts, can slow down this transition. Regulatory frameworks may not be conducive to promoting sustainability, and technical challenges in fabricating materials with comparable performance to their traditional counterparts can be daunting. Additionally, limited data availability, existing infrastructure geared towards conventional materials, and market uncertainties can all pose substantial roadblocks. Therefore, to meet economic, industrial, and technological needs, it is imperative to accelerate the discovery of alternatives to critical materials by developing new and disruptive methods to identify materials with the desired properties in a timely and responsive manner.

Researchers and engineers have traditionally used their expertise and intuition, in concert with ab initio and heuristic models, to guide the discovery of new materials. However, machine learning (ML) and artificial intelligence (AI) systems are now surpassing human intuition limits for complex tasks such as image recognition (Henaff 2020), materials design and discovery (Liu et al. 2017), or autonomous experiments (Bennett and Abolhasani 2023). These data-driven approaches can also compensate for predictive shortcomings in traditional models arising from assumptions, simplifications, and imperfect calibrations. As AI algorithms become more powerful and accessible, many materials scientists are increasingly embracing this emerging scientific domain to accelerate the discovery and development of new materials. Materials informatics—the amalgam of materials science, AI and ML, and advanced data analytics—holds one of the keys to addressing roadblocks to discovering alternative solutions to critical materials. The promise of materials informatics is that the discovery and manufacturing of materials solutions that will replace critical materials can be simultaneously and rapidly optimized by semi-autonomous systems, where the engineers do not have to envision all possible materials replacement solutions and then painstakingly (and expensively) test each solution with build-and-check methods. Instead, engineers can select appropriate algorithms, embed known physical laws and constraints, and assign design and materials objectives. Materials informatic approaches have already proven quite useful for certain materials problems such as broad and rapid searches across the periodic table (or more often, a rational subset) to achieve particular alloying effects (see, for example, Wagih and Schuh 2022), albeit such approaches may not be as obviously applicable for difficult-to-predict behaviors such as fatigue life, for instance.

> ***The quest for the discovery and manufacturing of new and innovative materials to replace critical materials remains as vital as ever.***

In today's fast-paced economic and technological landscape, leveraging a collaborative approach that combines human intuition with ML-guided solutions to potential alternative materials presents a promising opportunity to overcome limitations in human cognition (Boyce et al. 2023). For example, over the past decade the rapid emergence of compositionally complex "high entropy" alloys (Miracle and Senkov 2017) has highlighted the potential viability of trillions of unexplored alloy compositions—a regime of phase space that had previously been discounted as a wasteland of impractical intermetallic compounds. Trillions may be an understatement; by one authoritative account, there are 10^{177} alloy compositions waiting to be explored (Cantor 2014), even after eliminating rare, toxic, or radioactive elements. And this represents merely the compositional options; alloys also get their useful properties from the details of their processing route. To remain competitive, researchers and engineers need to explore such vast combinatorial solution spaces quickly and efficiently. One specific challenge about critical materials is that these materials often have unique process-structure-property linkages that are difficult to replicate in other materials. For example, yttrium (Y) and scandium (Sc) are critical materials used as dopants in aluminum nitride (AlN)-based piezoelectric materials because they induce an atomic structure change that enhances the piezoelectric response by nearly 500% (Akiyama et al. 2009). However, Y and Sc are rare earth elements and expensive metals, and their extraction can have negative environmental impacts. Startt and colleagues (2023) used a traditional and intuitive approach to survey twenty-three elements to identify earth-abundant alternative dopants in AlN piezoelectric materials, resulting in improved piezoelectric response. This type of paradigm, reminiscent of methods employed by Curie and Edison, is constrained by the cognitive limits of subject matter experts and engineers to select and observe relevant features based on past training and known physical and chemical principles, anticipate how those features may influence performance, and provide guidance about how to improve performance.

Materials informatics can have a profound impact on achieving sustainability goals to replace critical materials, redefining the boundaries of possibility in materials science and ushering in a new era of responsible innovation. Applications of ML and AI to materials science are now commonplace (Butler et al. 2018; Takeda et al. 2020; Zhang and Ling 2018). These approaches are being influenced by the following considerations:

- The proliferation of materials data repositories is rapidly increasing (Blaiszik et al. 2016; Dima et al. 2016; Huck et al. 2016; O'Mara et al. 2016; Pluchala et al. 2016). Researchers are exploring the automation of data and knowledge extraction from literature sources, using natural language processing techniques to populate these repositories (Jablonka et al. 2023; Lin et al. 2023). The scarcity of data repositories with relevant information on critical materials poses a challenge, necessitating new efforts to collect and curate data.

- AI and ML concepts are also reshaping both the computational and physical laboratory infrastructures used to generate materials data. Surrogate models and digital twins (Kalidindi et al 2022), trained on physics-based simulations (Montes de Oca Zapiain 2021; Oommen 2022), are actively under development, offering significantly enhanced speed while maintaining accuracy. Automation and guided high-throughput methods (Boyce and Uchic 2019; MacLeod et al. 2022) bring substantial efficiencies and eliminate redundancies in materials synthesis and characterization. In concert, orders-of-magnitude speedup in simulation and experiment are now feasible.

- In recent years, major strides have been made in using ML to synthesize multimodal data (Baltrušaitis et al. 2018; Shi et al. 2019; Wu and Goodman 2018). Disparate types of data are synthesized to exploit correlation across modalities so that they are more than the sum of their parts. While commonplace in traditional applications of ML (e.g., combining audio, video, and text), this practice has seen limited adoption in materials science, where it can serve a critical role in mitigating the sparsity of data.

- With the development of ML-accelerated models that are thousands of times faster than conventional simulations, it begs the question of what previously intractable analyses are now possible. Can we fuse physics-based models with purely data-driven modalities to identify rapidly measurable "fingerprints" of material performance? Tools from unsupervised learning could potentially enable the discovery of unconventional measurements more amenable to high-throughput collection, allowing an order-of-magnitude increase in the number of candidate alternatives to critical materials (Raccuglia et al. 2016).

Given the culmination of both advances in high-throughput data collection and scientific ML, herein we explore the gaps and opportunities in developing a candidate workflow (see figure 1) appropriate for the rapid discovery of alternatives to critical materials. While we focus here on the promise of high throughput and ML as an increasingly viable acceleration pathway, in a previous article (Boyce et al. 2023), we discussed the psychological, intellectual, infrastructural, and algorithmic barriers to adoption of such a workflow.

Data Infrastructure for Exploring Alternative Materials Solutions to Critical Materials

The discovery and deployment of alternative materials solutions require the involvement of disparate communities ranging from materials science, chemistry, physics, data science, AI, and computer science to manufacturing, economics, and sustainability. Each community has unique terminologies, requirements, priorities, and standards

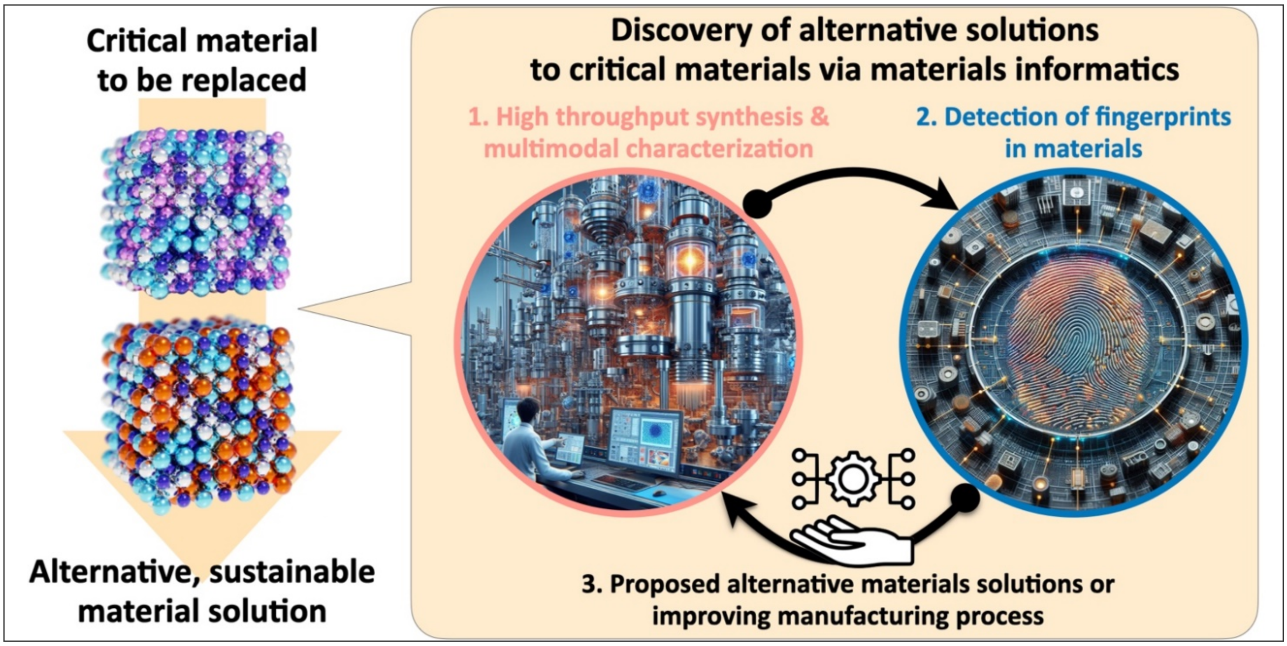

FIGURE 1 The search to replace a critical element (purple atoms) with an alternative, accessible element (orange atoms), while preserving desired performance characteristics. This search is challenging due to the massive dimensions of the candidate design space. A potential workflow to mitigate this is to: 1. Perform high-throughput synthesis and multimodal characterization over a number of initial candidate designs, potentially spanning both simulation and in-process/post-process measurements during synthesis and characterization. 2. Use ML to identify correlations across multimodal datasets, obtaining semantic clusters (or “fingerprints”), which encode distinct regimes of mechanistic performance. 3. Use generative modeling or active learning to suggest promising future designs that minimize material discrepancy, using fingerprints as input to the design process. It is an open research question to determine how to embed a sufficiently rich description of physics in (2) so that relevant mechanistic pathways may be revealed and exploited semi-autonomously, minimizing inefficiencies following from human-machine interaction (3).

when it comes to critical materials. Additionally, data on materials (whether they are critical or not) and their associated properties and physical and chemical characterization remain largely uncurated, under-explored, and not integrated, largely due to the compartmentalization of information amongst the various communities involved. The integration and standardization across these communities, along with the associated databases and data management infrastructures, are critical to an efficient discovery ecosystem for alternatives to critical materials. A number of efforts are currently attempting to federate data storage, data sharing, and data analysis in a similar fashion to existing data management workflows (Warren and Ward 2018). See, for example, Materials Data Facility (Blaiszik et al. 2016), Materials Commons (Puchala et al. 2016), Citrination (O’Mara et al. 2016), MPContribs (Huck et al. 2016), and the Materials Genome Initiative (Dima et al. 2016). The specific challenge regarding critical materials, however, is the scarcity of data. In fact, much of the corpus of data on critical materials is currently embedded in various publications and awaits conversion to standardized and interpretable (by humans or machine algorithms) knowledge via natural language processing (Tshitoyan et al. 2019). There is an opportunity today to employ such language processing tools to not only build a large repository of known (non-critical) materials but also to catalog knowledge of failures to limit and avoid redundant and unsuccessful efforts, increasing the likelihood of successful outcomes, reproducibility, and traceability when searching for viable alternatives. Such natural language processing may also help to identify and mitigate erroneous or conflicting observations. While open materials data sharing platforms are virtuous endeavors, as those data sources become increasingly commercially useful, there will be growing questions of ownership, remuneration, and intellectual property.

Rethinking Computational and Experimental Infrastructures for Rapid Explorations of Alternative Materials Solutions

Today, synthesizing, characterizing, and modeling new materials is a complex and challenging task that requires specialized knowledge and skills. Even among experts, the level of specialization required for different processing, characterization, and modeling techniques can make it difficult to explore all possible solutions for a given application. This is especially true for discovering replacements for critical materials, which often require a deep understanding of a specific class of materials. As a result, large portions of the materials space remain unexplored, not because researchers lack the ability to imagine new alternative materials with promising functionality but rather because they lack the tools and expertise to rapidly synthesize, characterize, and model these materials. Automated, high-throughput experimental methods and advanced modeling tools are, however, becoming increasingly democratized and accessible.

Combining traditional and unconventional testing methods with simulation data can accelerate the discovery of new materials and their processing routes. Unconventional, high-throughput testing methods allow for easy automated data collection and ensure that the data is collected systematically, in a way that is amenable to subsequent automated data integration and analysis while limiting human intervention and associated bias and data corruption (Bassett et al. 2023). These unconventional data sources may be particularly advantageous as surrogates for expensive and time-consuming measurands such as fatigue life, creep resistance, and even fracture toughness or tensile ductility. Synthetic data from simulation can also be used in conjunction with experimental measurements. Algorithms needed for the discovery and understanding of alternative materials solutions to critical materials cannot be simply derived or adapted from existing, "black-box" ML algorithms, because they were designed for physics-agnostic computer science applications. Algorithm inputs for materials science are often sparse and heterogeneous and can only be understood in the context of the chemical and physical laws that govern materials. Recent developments in physics-informed neural networks (Karniadakis et al. 2021) or replacing numerical solvers with machine-learned solvers (Montes de Oca Zapiain 2021; Oommen 2022) provide techniques to combine first principles physics with traditional ML—many promising applications have seen acceleration over traditional simulation by a factor of a thousand. By integrating these types of fast, experimental, and computational surrogate tools, a rapid feedback loop could be designed to synthesize, characterize, and model novel materials solutions with similar process-structure-properties linkages observed in critical materials. While some efforts in this arena aim for completely autonomous discoveries without a human in the loop, there is value in maintaining a subject matter expert engaged in the process to audit the execution, add interpretative value, mitigate pathological extrapolations, and even contribute their dexterity for rare physical tasks (Boyce et al. 2023).

Exploiting Multimodality for Accelerated Discovery

The chief hurdle in applying ML to the identification of alternatives to critical materials is the dearth of data. Experiments are slow, expensive, and classically conducted in an artisanal manner to design a precise measurement that reveals a specific property. This is antagonistic to the rapid search of design space necessary to identify alternatives to critical materials. An underutilized dimension of materials data is the broad availability of multimodal characterization (X-ray diffractograms, scanning electron microscopy, synchrotron experiments, tribological testing, etc.). There is a hierarchy of modality quality and speed ranging from information dense or slow to information sparse or fast. Additionally, there are modalities available during fabrication and characterization that are typically neglected, such as audio and video of the synthesis process. Multimodal learning aims to integrate these in a manner that exploits correlation across modalities; for instance, by combining two-dimensional images of two sides of a coin, we can understand the full three-dimensional object.

While early efforts to machine learn material responses from datasets were successful in the 1990s, they often relied upon intuition-intense feature engineering and supervised learning, whereby a human needed to empirically identify quantities of interest that exposed correlation across modalities (e.g., Atz et al. 2021, Weininger 1988). In modern unsupervised and semi-supervised learning, it is routine to autonomously identify features without human intervention. This is crucial because datasets now contain many different types of modalities, overwhelming human cognition. To grapple with this challenge of dimensionality, materials scientists have historically reduced data to low-dimensional descriptors (e.g., reducing an X-ray diffractogram to the location and height of peaks). ML-aided identification of material "fingerprints" could avoid this indiscriminate loss of information. In recent years advances from the synthesis of text, audio, and image data have provided powerful new tools that are prime for application to materials datasets: fusion of modalities through the tokens of a transformer

(Wang et al. 2022; Xu et al. 2023), variational inference frameworks for product-of-expert embeddings (Wu and Goodman 2018; Xu et al. 2021), and multimodal graph embeddings (Tao et al. 2020).

With these tools in hand, it is possible to revisit the classical problem of design of experiments and rapidly explore the space of alternatives to critical materials. If one can identify a correlation between the fingerprints of fast and slow modalities, it becomes possible to move beyond process-property maps to *process-structure-property* while maintaining high-throughput workflows. For this approach to be successful, the necessary multimodal data must not only be voluminous but also satisfy the five V's of big data: veracity ("good," clean data free from measurement errors or corruptions), value (providing the necessary information related to the objective), variety (spanning a sufficient range to allow for useful interpolations rather than extrapolations), velocity (acquired in a timely manner), and volume (lots of it for data-hungry algorithms!).

Generative Modeling for Scientific Discovery and Understanding

A comprehensive and exhaustive exploration of large-dimensional design spaces rapidly becomes combinatorically intractable (there have been estimates as high as 10^{177} for the number of potential alloys left to be explored [Cantor 2014]), necessitating intelligent iterative algorithms and an active learning approach that maximizes incremental information gain while reducing uncertainty. The proposal of candidate materials and associated manufacturing protocols can be posed as a generative modeling problem. One can use a database of materials with corresponding process-structure-property maps and use iterative and guided exploit-and-explore strategies to efficiently search for a new candidate replacement material. While classical tools like Bayesian optimization (Shahriari et al. 2015) and genetic algorithms (Tao et al. 2020) are mature, recent advances in deep learning architectures allow access to significantly more complex generative processes. Some material properties, like creep life, are difficult to predict on a purely computational basis and will require extensive investments in experimental data as part of such a search strategy, further necessitating highly selective active learning approaches.

While DALL-E and variants of Stable Diffusion (Ramesh et al. 2022) are commonplace (a prompt "cat playing basketball on the moon" yields a strikingly realistic image), there is work required to robustly produce the materials science equivalent (asking ChatGPT for a "manufacturing protocol for an alternative to gold with high conductivity" yields less impressive results). Physics must be integrated into the generative process to ensure exploitable results that are physically viable. In the graph neural network community, major strides have been made in drug discovery and biomechanics by mapping from molecular configuration to performance (Sohl-Dickstein et al. 2015; Wieder et al. 2020; Jumper et al. 2021; Bengio et al. 2021). These problems are purely geometric, however, attempting to map directly from molecular configuration to a quantity of interest with no representation of the underlying dynamic physical process is more complicated. With the vast acceleration of ML-driven surrogates over traditional simulation, there is an opportunity to integrate physical processes into generative ML architectures. Further, there is a need to advance the underlying simulation capabilities—even tasks such as predicting the yield strength of complex alloys based on individual dislocation simulations are computationally challenging. In the near future, purely computational approaches will be limited to those material properties that are more confidently predictable.

Several modern works attempt generative modeling now, using graphs as abstractions for designs. GFlowNets (Schölkopf et al. 2021), pioneered by Yoshua Bengio's group at Mila, model the generative process by traversing a graph to encode a sequence of sequential decision. In the causal ML community, cause-effect relationships are encoded as edges (AàB if A causes B) in a directed acyclic graph to build structural causal models (Richens et al. 2020). These techniques have proven very effective in bioinformatics when disentangling the root cause of diseases from biomarkers (Pavlović et al. 2024), and integrating physical models into generative processes could yield the same success when searching for alternatives to critical materials.

A Pathway Towards a Future with Less Reliance on Critical Materials

By envisioning a future with reduced dependence on critical materials through materials informatics, several pathways emerge through innovative approaches in materials science. These innovations hinge on collaborative efforts, data infrastructures, and accelerated capabilities to characterize, model, and process such data. Establishing robust data infrastructures plays a pivotal role in seamless access to precompetitive materials data, empowering both scientific research and engineering applications.

Concurrently, rethinking computational and experimental infrastructures enables rapid exploration of those databases, allowing for more efficient identification and testing of substitute, alternative material solutions. Embracing multimodality in those research approaches has the potential to accelerate the discovery process of alternatives to critical materials by providing deeper fingerprints and revealing unknown correlations, ultimately guiding us toward sustainable solutions. Additionally, leveraging generative modeling techniques, rooted in the fast-changing fields of ML and AI, offers a fresh lens for scientific understanding and discovery. These models learn from existing data to generate new candidate materials, providing the means to explore and exploit large-dimensional design spaces where new materials solutions to replace critical materials are waiting to be discovered. These integrated strategies not only expand our current understanding of the unique roles critical materials play in materials technology, but they also pave the way for tangible solutions for a more sustainable future.

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A circular economy for metals is vital to achieving sustainability.

Sustainable Metal Production and Use in the Twenty-First Century: Challenges and a Path Forward

Diran Apelian, Emily Molstad, Sean Kelly,
Subodh Das, Barbara K. Reck, and Alan Luo


Diran Apelian


Emily Molstad


Sean Kelly


Subodh Das


Barbara K. Reck


Alan Luo

In the context of materials and earth resources, sustainable development means meeting the needs of the present without compromising the needs of future generations. It is a fact that we entered the twentieth century with 1.6 billion people on our planet and exited that century and entered the twenty-first century with 6.1 billion people—a dramatic increase. And in 2024, our world population is a bit over 8.1 billion people. With such increases in human population comes increased usage of products that are made from mate-

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Diran Apelian (NAE) is distinguished professor of materials science and engineering, University of California, Irvine; Emily Molstad is chief executive officer and co-founder, VALIS Insights; Sean Kelly is chief operation officer and co-founder, Solvus Global; Subodh Das is CEO and founder, Phinix LLC; Barbara K. Reck is senior research scientist, the Yale School of the Environment, and node lead, Systems Analysis & Integration, the REMADE Institute; and Alan Luo (NAE) is Donald D. Glower Chair in Engineering and professor of materials science and engineering and integrated systems engineering, The Ohio State University.

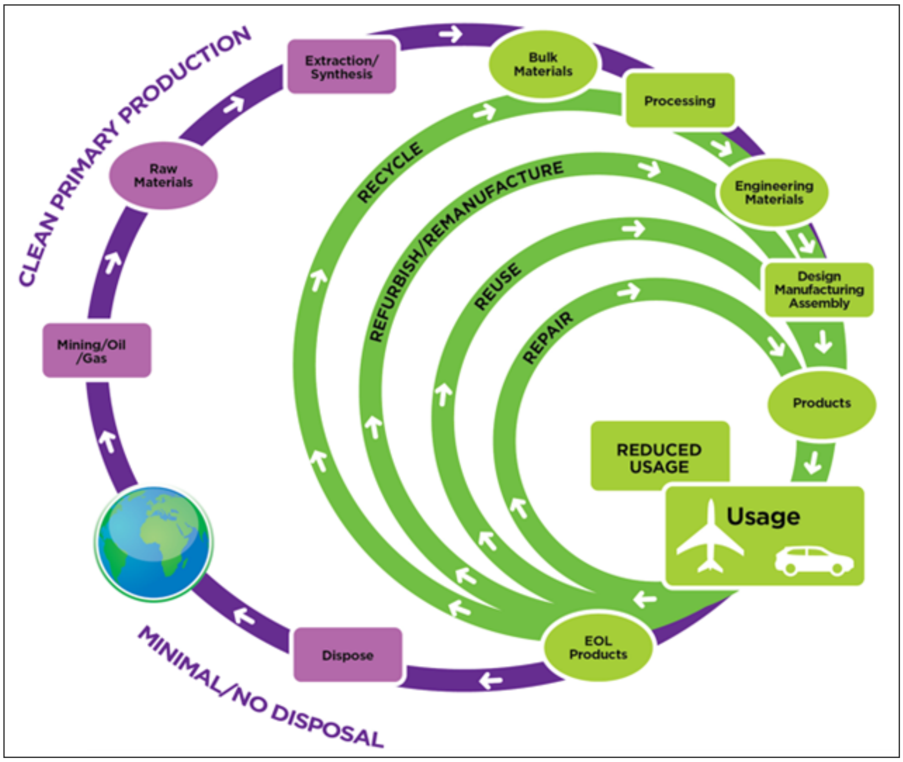

FIGURE 1 The circular economy as a new paradigm to sustain material usage in the twenty-first century (modified, based on BCAST [2023]).

rials.[1] The elements of the periodic table, with the exception of gases and inert metals, are found in the earth as ores (compounds like oxides, sulfides, etc.) that are mined and subsequently processed through various extractive operations, such as pyrometallurgy, electrometallurgy, or hydrometallurgy. However, there is substantial production waste and energy consumption, as well as a large carbon footprint associated with these extractive operations. A significant amount of energy needs to be utilized to break up the oxide bonds and produce elemental metal. Almost 50% of the global CO_2 emissions from industry are due to the production of three materials alone: steel, cement, and aluminum (Doerr 2021).

Inefficiencies exist not only at the production level but also at end of life, further countering the vision of a circular economy. A large portion of the manufactured goods in the twenty-first century are not repaired, recovered and reused, or fully recycled. Interestingly, in the 1920s, when the earth's population was less than two billion people, and there was an abundance of minerals and rich ores in the earth, manufactured goods were repaired, and there was significant effort in the recovery and reuse of materials. It was an era when neighborhood cobblers existed and were thriving, and landfills were not urban mines. It was also an era when only a few of the elements of the periodic table were used. In the last five decades we have witnessed increasing complexity of our manufactured goods in that many of the elements of the periodic table are being utilized. As one example, in the 1980s the computer chip contained eleven elements of the periodic table, in the 1990s it contained fifteen elements, and today the modern computer chip contains over fifty elements of the periodic table (Greenfield and Graedel 2013). Such complexities in our manufactured goods are also the source of the challenges we face in recovery and reuse and recycling.

To ensure that our earth's resources are also available to future generations, one of the grandest challenges of the twenty-first century is the sustainable management of those resources. A serious effort to implement the core principles of the circular economy is needed to sustain the earth's resources, reduce energy usage for the production of metals and materials, reduce our carbon footprint, and reduce waste, as well as to create value from end-of-life (EOL) consumer waste. Figure 1 illustrates the components of the circular economy, a new paradigm that has emerged over the past decade. This approach focuses on avoiding the loss of resources at EOL through repair, reuse, refurbishing and remanufacturing, and recycling (highlighted in green). To make this paradigm a reality and execute it globally will require massive efforts in three sectors: (i) education; (ii) policy; and (iii) engineering solutions and technological innovations (Apelian 2012). *Education* is needed to ensure that an informed global citizenry emerges. Issues related to earth's resources do not have any national or territorial boundaries, but rather they are global issues affecting all nations and the planet as a whole. *Governmental policies* and laws are pivotal in establishing a collective and shared

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[1] The human population figures in this paragraph are from www.worldometers.info/world-population/.

responsibility to ensure the sustainable use of resources in the twenty-first century. Designing manufactured goods for recovery and reuse will only be a reality if there is a level playing field. That requires massive political will and the voice of the consumer, which can be heightened through education. *Engineering solutions and innovations* are key to reuse and recovery and to metal/material sustainability, but by themselves they are not sufficient. All three sectors—education, policy, and engineering solutions—are needed to execute the new paradigm, as visually described in figure 1.

In this article, we set the context for how a circular economy for metals might be implemented by focusing on one metal, aluminum. We could have just as easily selected metals that are utilized in applications such as magnets, lithium-ion batteries, smart phones, etc. However, a metal like aluminum is ideal for discussing life cycle issues and how to execute the new paradigm that is needed to attain sustainability.

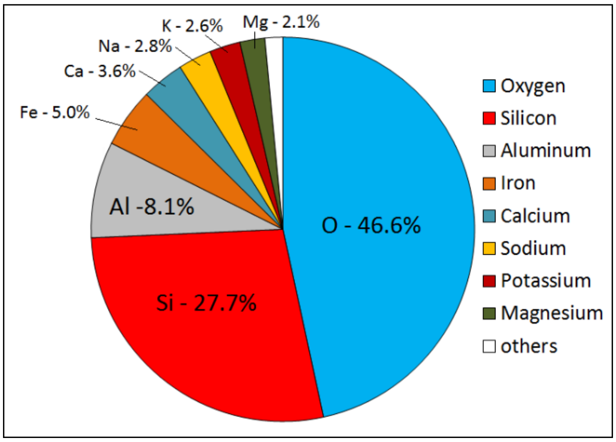

FIGURE 2 Major elements in earth's crust. Source: Earle 2019.

The Case for Aluminum: An Exemplar

Aluminum is the third most abundant element (8%) after oxygen and silicon and more abundant than iron (5%) in the earth's crust, yet it is a comparatively new industrial metal that has been produced in commercial quantities for just over 100 years (see figure 2). Measured either in quantity or value, aluminum's use exceeds that of any other metal except iron, and it is important in virtually all segments of the world's economy. Annual global aluminum production in 2023 was 70 million metric tons and is expected to grow by 80% by 2050 (IAI 2021; Merrill 2024). About 75% of current aluminum production is fueled by coal and natural gas, as shown in figure 3. This highly recyclable metal plays a critical role in enhancing the sustainability of a variety of industries through lightweighting and electrification. In the United States, transportation and packaging represented the two largest sectors for aluminum use, accounting for 35% and

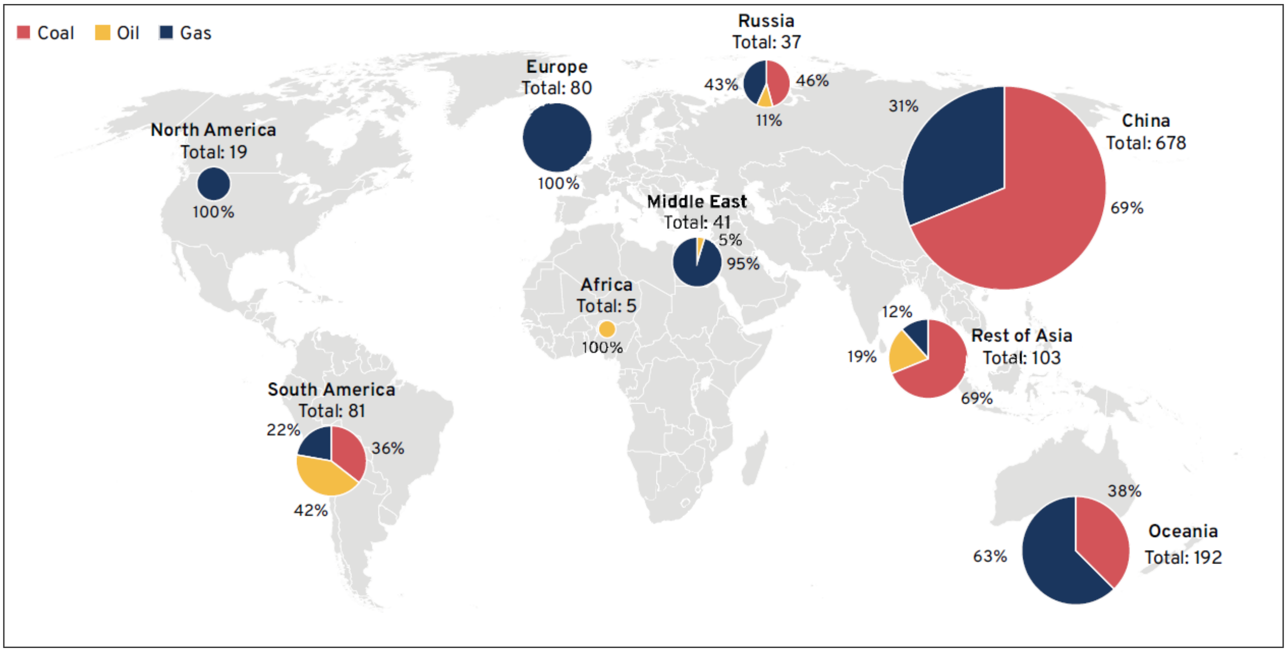

FIGURE 3 Map of 2020 energy consumption for alumina refining by region, total (in petajoules) and percentage. Source: Mission Possible Partnership and IAI 2022.

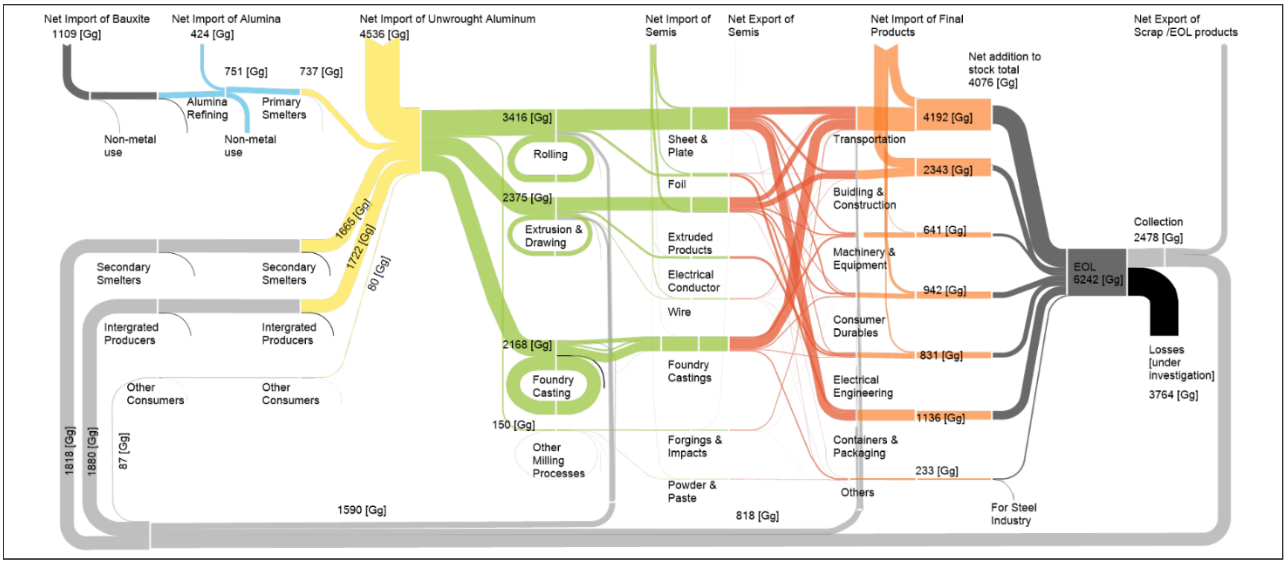

FIGURE 4 Sankey diagram showing the US aluminum cycle in 2017 from production to end-of-life management. Source: Althaf and Reck 2024. Note: About two-thirds of the “losses under investigation” were recycled.

23% of all domestic consumption, respectively (Merrill 2024).

Aluminum Production and Recycling

Primary, or virgin, aluminum currently meets roughly 70% of global demand and is produced from bauxite ore through a series of energy-intensive processes (IAI 2021). Aluminum accounts for approximately 3% of human-generated emissions, with 90% of those emissions associated with primary production (IAI 2021; USGS 2022). Additionally, the aluminum industry produces 3-4 tons of bauxite residue (red mud) per ton of aluminum, which is a serious environmental challenge. Although actively pursued, the current utilization of bauxite residues is less than 4%. Globally, some 3 billion tons of bauxite residue are now stored in massive waste ponds or dried mounds, making it one of the most abundant industrial wastes on the planet. Additionally, alumina refining plants generate over 150 million tons of red mud each year.

Secondary, or recycled, aluminum is produced from two main sources of scrap: “new” scrap, which is generated during manufacturing, and “old” or “post-consumer” scrap, which originates from manufactured goods that have reached the end of their useful life. Recycling is critical to meeting demand at a fraction of the footprint, generating roughly 80% less emissions compared to the primary production of aluminum. Current production from recycling avoids the generation of roughly 300 million tons of CO_2e, which is equivalent to taking half of all US cars off the road for a year. The US recovered 3.34 million tons of aluminum from scrap in 2022, with old scrap recycling meeting approximately 30% of consumption (IAI 2021).

Aluminum Material Flows

Material flow analysis is a powerful tool to illustrate how and at what efficiencies materials move through the economy, from production to end-of-life (EOL) management. Figure 4 shows a Sankey diagram for the US aluminum cycle in 2017 (Althaf and Reck 2022) that used the same methodologies, data sources (Aluminum Association, U.S. Geological Survey), and data frameworks as an earlier study by Chen and Graedel (2012) that characterized US aluminum stocks and flows for the period 1900-2009. The EOL collection rate for aluminum is similar to the 60% rate for steel (Reck et al. 2024), and the average recycled content in aluminum production was 40%.The use of “new scrap” from foundry alloys (castings) is significantly higher than that of wrought products (sheet and extruded).

The recycling industry plays an essential role in stabilizing supply chains, minimizing loss to landfills, and sustainably meeting demand for metals, such as aluminum. In the US post-consumer scrap has the potential to address upwards of ~45% of apparent consumption, but current misalignment between the quality of scrap material and manufacturing requirements results in the export of 2 million tons of this valuable resource (USGS 2022). There are opportunities to address this

FIGURE 5 The four pillars of action needed to hit target recycling rates. Source: Ally and Breen 2023.

gap and "leak" points, where material falls out of circulation and is not properly recovered. Along the global recycling value chain, approximately 7 million tons of aluminum is lost each year. If these leaks are not plugged, and business as usual (BAU) continues, a projected 17 million tons will be lost annually by 2050 (IAI 2022). According to the International Aluminum Institute, "a fully circular system without any (collection, process and melt) losses and no generation of new and internal scrap would deliver a 20% reduction on BAU sector emissions."

There is no one-size-fits-all solution to achieving a fully circular system, as each industry sector has its distinct set of challenges, exemplified by the challenges and opportunities facing used beverage cans (UBC) and automotive recycling. However, the one constant in all potential solutions is the need for circularity of the material chain and creating value from waste.

UBC Recycling

As reported by the Aluminum Association, about 3 billion pounds (1.5 million tons) of cans was shipped, while only 1.3 billion pounds (650,000 tons) of cans was recycled by US consumers in 2020 (Wang 2022). That calculates the unrecycled cans at 850,000 tons, with around $840 million worth of aluminum ending up in landfills. Landfill mining involves excavating landfills, and the buried resources are processed for environmental, economic, or social benefits. The vast quantities of metal buried in landfills can be suitable for use as potential secondary resources. Nonferrous metals, especially aluminum, have the maximum potential to be used as a secondary raw material after recovering from landfills and to contribute to adding value to waste materials.

That volume of aluminum cans lost to landfills could have otherwise been responsibly recycled, made into new cans, and added to the revenue stream. It will be worth more than $1 billion with the present scrap-per-ton value of UBC (about $1300/mt). The recycling rate of the aluminum can in the US stands at roughly 45%. This falls significantly short of European rates, which can be as high as 73%, or that of US transportation and construction aluminum, which is over 90% (Ally and Breen 2023). Causes of this recovery rate disparity span from collection to processing to remelting, calling for sweeping solutions across the recycling chain. If a 70% recycling rate had been achieved in 2020, 25.6 billion more cans would have been recycled. This would have generated $400 million in additional revenue for recyclers, a critical figure when considering that UBC recovery is the foundation for the profitability of most recycling facilities of municipal solid waste. A 70% recycling rate would have conserved enough energy to power more than 1 million US homes for a year (Recycling Today 2022). With these economic and environmental benefits in mind, the Can Manufacturers Institute has set a target of a 70% recycling rate for UBCs by 2030 and 90% by 2050 (Ally and Breen 2023). To achieve this goal, four pillars of action have been defined (see figure 5).

Valuable aluminum UBCs, whether from a container deposit collection or single stream material recovery facility, are comingled with materials such as paper, plastic, and steel that, when not sorted effectively, can result in the contamination of aluminum products or the loss of UBCs within other material streams. In 2022, more than 25% of UBCs were missorted at recovery facilities (Recycling Today 2022). Advanced separation capabilities such as eddy currents and optical and robotic sorting systems can minimize leakage or the loss of UBCs. The Can

Manufacturers Institute estimates that proper sortation has the potential to increase the recycling rate by 3%, which is equivalent to 3.5 billion additional cans, resulting in the avoidance of approximately 650,000 tons of CO_2e and an increase in recovery rates at material recovery facilities by more than 50% (Ally and Breen 2023).

Automotive Recycling

When one's vehicle, or even an old washer and dryer, reaches the end of its life and has been fully picked for usable parts, it will be sent to a processing facility. There it is run through a massive hammermill shredder, where in a matter of moments it is converted to a pile of fist-sized pieces of mixed material known as automotive shred, or auto-shred. A series of separation methods, including magnets, eddy currents, and density separators, remove the ferrous (steel), nonmetallic (foam and plastic), and heavy nonferrous (copper and zinc alloys, predominantly) content. What remains is the aluminum fraction of auto-shred, referred to in the industry as "twitch," which contains a variety of cast and wrought alloys of aluminum.

Unlike UBCs, automotive aluminum in the United States has a very high collection and recycling rate, in excess of 90% (Kelly 2018). However, this does not indicate a circular process; post-consumer material from a car door, or other quality stringent components, does not get converted back into a car door. Historically, twitch has been used to produce 380 and 319 aluminum cast alloys, which are lower-value cast alloys, for power train components. These alloys have a higher tolerance for compositional uncertainty and contamination associated with a mixed scrap feedstock. In this case, higher-value alloys, such as 6000 and 5000 series aluminum alloys, are downgraded, or downcycled, into lower-value materials; current practices result in the downcycling of 60-80% of the high-value wrought and cast alloys (Kelly 2018). The shift to electric vehicles has led to a weakening demand for power train components, such as the internal combustion engine, and a rising need for quality extruded, sheet, and structural cast aluminum. Downcycling perpetuates a dependence on primary aluminum that is unsustainable and uneconomical, both for the scrap processors that sell the scrap material and for the melt facilities that consume it. The combined value of twitch's constituents can be 25-120% higher than that of twitch and approximately 10% to as much as 30% lower than that of primary aluminum, meaning increased profits for both stakeholders.

To create economic benefit and reduce primary aluminum consumption, advanced technologies for the handling of automotive scrap must be implemented. Rapidly growing in adoption are advanced sortation systems that leverage compositional sensors and artificial intelligence to distinguish between and sort out alloy types. The most predominant sortation method for aluminum alloys utilizes laser-induced breakdown spectroscopy (LIBS), which has the ability to measure levels of light elements, such as silicon and magnesium, in addition to heavier elements, such as copper and iron, to create clean scrap packages down to the individual alloy. The granularity of the sort must be balanced with the throughput of the overall system. Once sorted, these scrap products are blended to deliver the desired composition and material properties. Today this is a large manual process requiring the physical sampling of both solid-state input material and the melt to create and modify melt recipes. Across the recycling value chain there are a number of opportunities to leverage availability data and Industry 4.0 capabilities, which includes advanced sensing, automation and artificial intelligence, to reduce manual processing and enhance material recovery.

New aluminum alloys are being developed to tolerate more impurities, such as iron in aluminum scrap, and to provide equivalent mechanical and corrosion properties of primary aluminum alloys for structural application. Figure 6 shows the effects of microalloying with manganese and the cooling rate on the formation of iron-containing intermetallic phases in secondary aluminum-silicon-based alloys based on computational thermodynamics and experimental validation (Cinkilic et al. 2019). Based on this study, a new recycled alloy with high iron content (about 0.5wt.%) showed comparable mechanical properties to a typical primary die cast alloy (≤ 0.2wt.%) with similar composition (Cinkilic et al. 2022).

Going forward, next-generation integrated computational materials engineering (Luo et al. 2022) and Industry 4.0 capabilities have the potential to make automotive aluminum truly circular, where the alloys of cars manufactured ten to twenty years ago are not just recovered but converted into alloys used in manufacturing today. This requires alloys and processes that maximize material quality and value across every step in the production and recycling chain.

Environmental and Policy Considerations

In addition to technology innovations, material sustainability, specifically in the case of aluminum, requires both environmental and policy considerations in primary

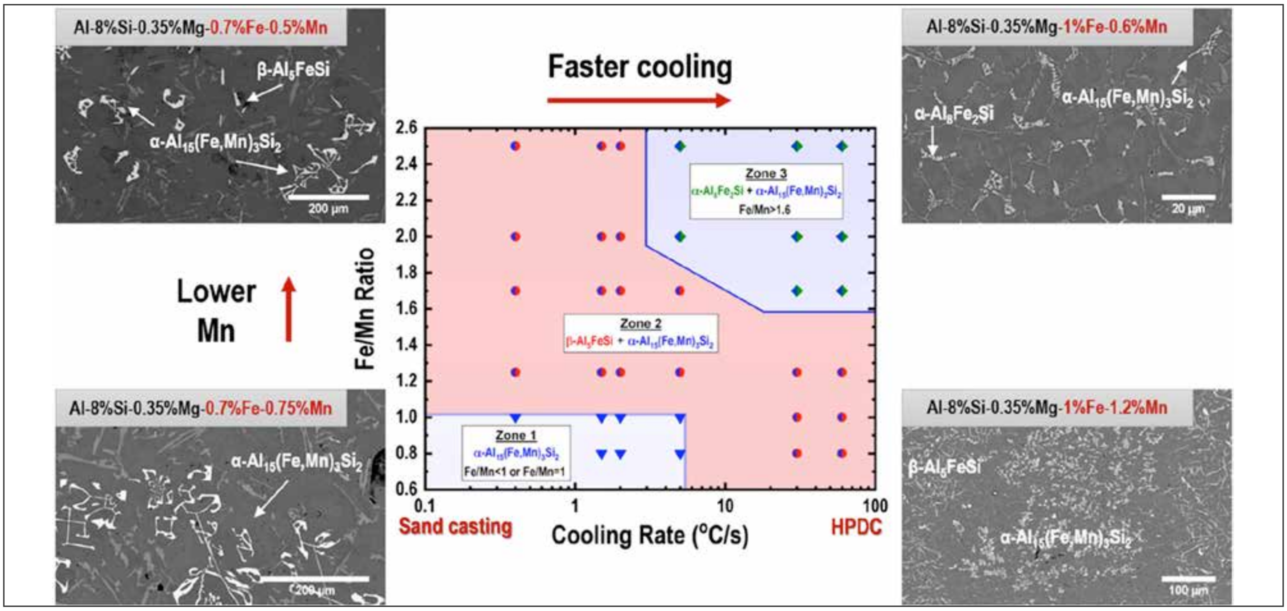

FIGURE 6 A formation map of iron-containing intermetallic phases: effects of cooling rate and iron/manganese ratio on intermetallic phase formation in aluminum-silicon-magnesium alloys with high iron contents. Source: Cinkilic et al. 2019.

production, recycling, and supply chain closure. Those environmental and policy considerations include:

- Incentivizing the use of clean electricity (hydro and other renewable energy vs. coal and natural gas) in primary aluminum production around the world via carbon calculations and economic/legislative policies.
- Rewarding beverage can recycling via nationwide legislative measures, such as return deposits.
- Promoting sustainable practices, such as bauxite residue reuse and aluminum recycling, and minimizing landfilling by offering carbon credits and tax benefits.
- Encouraging and incentivizing landfill mining projects to optimize resource utilization and further sustainability goals.
- Incentivizing manufacturers to design for recovery and reuse at EOL and have manufactured goods made in such a way that they can be disassembled for recycling.
- Adopting a circular economy model for major manufactured components, such as automobiles, wherein at EOL the manufacturer is responsible for the disassembly and reuse of the materials that were utilized in the product.
- Enhancing the role of education from kindergarten to corporate America to develop a culture of material circularity, as depicted in figure 1.

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An Interview with . . .

Timnit Gebru, founder and executive director, the Distributed AI Research Institute

RONALD LATANISION (RML): We are delighted to have you with us today.

TIMNIT GEBRU: Thanks for having me.

RML: To begin, could you introduce yourself and tell us about where you grew up?

DR. GEBRU: I was born and raised in Ethiopia. I came to the States when I was 16, and I studied electrical engineering. Electrical engineering is a very broad subject. I started out studying analog circuit design. Then I began getting more interested in device physics, so I ventured more into material science or solid–state physics, all still under the electrical engineering umbrella. And then I ventured more into image processing and signal processing. That is what led me to computer vision, which I guess is AI now. That is my educational background.

In the middle of that, after undergrad, I worked at Apple. I was doing analog circuit design. And then I went back to grad school to do my master's in the same field, but then I decided to do a PhD. At some point during my PhD, I left to work at a startup for a little bit. I did some other random stuff, and then I went back to my PhD and finished it in computer vision. I worked as a postdoc at Microsoft, and then I went to Google. Then I started my own institute called the Distributed AI Research Institute (DAIR), which is where I am now.

RML: Your history and involvement in AI are important to us, particularly given the pace at which things are changing in AI: almost daily, maybe even faster than that sometimes. My experience is that technology is at its best when it serves to help people. It does not always, and sometimes it actually does the opposite. In order to introduce a technology into the marketplace, there are usually a set of risks that people have to consider. For example, there are technical risks. Does it work? Can it be scaled up? And this applies to any new technology, whether it is AI, a new energy system, or a medical device.

There are also economic risks, which means that you want the product to be affordable for anyone. You want to make sure that there are investors interested to support the development. I think technologists have been very good at managing the technical and economic risks. But I am concerned, and I sense that you are very concerned, about the social risks.

How can new technology be introduced into the marketplace so that it is meaningful and helpful to people, but also so that the suppliers of this technology can respond responsibly and with accountability? What kind of guardrails do you think we need for new technology going forward?

DR. GEBRU: I want to go back to what you were saying about assessing risks as technologists and just fundamental engineering principles. I do not think what is happening right now in AI follows any scientific or engineering practices. That is one of the biggest problems. When you create technology, if you are an engineer, you build something and you say what it is supposed to be

Photo by Kimberly White/Getty Images for TechCrunch

used for. You assess what the standard operating characteristics are. You do tests in which you specify the ideal condition and the nonidealities.

For example, when I am designing circuits, I say what the ideal case scenario is in my circuitry and what the nonidealities are, and what is supposed to happen in the ideal case scenario. You do all these things when you create technology. And we have all of these processes to assess those things, to test those things, and to communicate those tests. And when I came to the world of AI, there was none of that. It was a shock for me to make that transition.

About six years ago, I was working with Joy Buolamwini, and we were looking at these automated facial recognition systems. We looked at these application programming interfaces from three companies for a set of automated facial recognition systems that were kinds of gender-recognition systems. We found that these are application programming interfaces that anybody could use. And we found that the error rates for darker-skinned women, in particular, were much higher than those for everybody else, and the error rates for lighter-skinned men were almost nonexistent.

The first thing I wanted to do when we were working on that is to see if they told us anything about the guidelines for what this was supposed to be used for versus not, and if there was any information about the training data or the test set, if they did any tests, and what kind of tests they did.

When I was a circuit designer, for example, if I were to choose a particular component like, let's say, a resistor, there is an idealized model of a resistor. There are equations and things like that that you learn in class. But then you know that in the real world, that is an idealized model. If you wanted to use a resistor for power generation versus audio circuitry versus nuclear power versus life support systems, those are very different kinds of resistors, even though the idealized scenario is the same. You do so many tests to see when the resistor breaks, what happens when it breaks, and so on. You have tons of pages of results on those tests. You communicate those in the form of data sheets. When I am designing in a circuit, I will look at a data sheet. I will decide whether this component is appropriate for my system or not. That is just one of the things we do in engineering.

It was so shocking for me to see that none of this was being done in the world of AI. One of the papers that I wrote was called “Data Sheets for Data Sets.” This was inspired by the data sheets in electronics. I wrote about how, similar to how we do these tests in other engineering practices, we need to do the same here. We need to document. We need to test. We need to communicate what things should be used for.

There was a follow-up paper called “Model Cards for Model Reporting.” Same thing. You ask what guardrails we should have. The most fundamental guardrail. Follow normal engineering practices that, for some reason, get a pass when someone says AI. That should not happen. That has been my approach. That is how my engineering background has grounded me.

I gave the example of face recognition or automated facial analyses. Even in that case, there are all these issues that I just mentioned of not knowing what things should be used for, documentation, and things like that.

Of course, there can still be issues with a new technology even if you write out all the documentation, endure those tests, and you don't have any disparities and error rates by different groups. It can still be super harmful because you can use it in a harmful way. You can use it to over-police already discriminated against and marginalized communities. You can follow basic engineering practices perfectly well, and a new technology could still be harmful. Before we get to that, there are the fundamental testing and documentation practices that I mentioned.

Fast forward to now. I was talking about a specific task, automated facial analyses, and a specific model that is created for that. Now, we are in a situation where people are claiming to be creating something that seems like a machine god that is supposed to be everything for everyone.

Everybody is talking about AI now, mostly because of OpenAI. They have a chatbot. If you go to the README profile, it claims to be able to do literally everything. When you read how Facebook, or Meta, advertised their system called Galactica, they said that this is a system that can write scientific papers, annotate molecules and proteins, write code, and more.

Now, let's go back to what I was talking about. How do you assess what Galactica should and shouldn't be used for? How do you test for how it is supposed to operate, the ideal conditions, what the nonidealities are, et cetera? You can't even do that because they are advertising it as a system that's supposed to be able to do literally everything. We have already lost in terms of safety because the new technology hasn't been designed to appropriately scope out what tasks it should and shouldn't be used for and the appropriate tests haven't been done.

RML: I hear what you are saying. But let's take the case of the internet. The internet was launched with the idea that it would serve as a platform for information, and it would be available throughout the world. It has served that purpose very well. We use it every day, everybody, or almost everybody, even people in some of the nonlegacy nations. However, I don't think anyone forecasted the reality that the internet could be harmful in being used to distribute misinformation and disinformation that are consumed by a public that doesn't seem to have the capacity to distinguish between reliable and unreliable information. What guardrails should've been introduced with the internet? Who should be protecting people from this? Is it a case where the people should be smart enough to figure it out for themselves, or is that utopian to imagine? How should people be protected from the abuse of the internet, which is otherwise a very helpful system?

DR. GEBRU: The internet, to me, is very different from what's going on right now. There are different protocols, Transmission Control Protocol/Internet Protocol. As someone who works in machine learning, who knows how things are trained and tested and things like that, I see how things are being advertised and how things are being created.

The very first concern right now in terms of protecting the public is the hype around AI, which is very harmful. The scientists, especially, and the academics, journalists, and politicians who are cashing in on the current hype need to be very specific about what systems are being created versus what is being advertised.

I will give an example. Sam Altman appeared in front of Congress and said that there needs to be an international agency to regulate AI akin to the one that was created for the atomic bomb. Now, what is this saying? This is saying that a company like OpenAI has created something so powerful that we don't know how to regulate it thus far. That our existing federal agencies are unequipped. We need to create this new regulatory agency because we need to regulate something that will look like "super intelligence."

> ***The very first concern right now in terms of protecting the public is the hype around AI, which is very harmful.***

Now, this statement needs to be critically analyzed because when we take this for his word, there's other stuff we are not thinking about. When you assume that a company like OpenAI has created super intelligence, for instance, you have to come back down to earth and ask what they are actually building and how. Let's look at one of their systems, like the image generation system. How did they get their data? Whose data are they using? Actually, we don't know because they are not doing the documentation practices that I mentioned earlier. We don't know whose data they are using. They are using a lot of copywritten material from artists who are not getting compensated. They are using private data, so they are breaching people's privacy. They are using exploited labor. There are data laborers who are labeling training and evaluation data sets and filtering them out all day. They are getting traumatized, PTSD, and paid less than $2 per hour to do that work. That's what, in reality, is happening. But we are talking about a digital super intelligence. We are not looking at these things that we already know about, which are data theft, labor exploitation, and huge energy costs. That's what I mean.

There are things we know how to regulate, actually. There are agencies like the Federal Trade Commission that have reminded companies like OpenAI that they are within the jurisdiction of the Commission. There's nothing new about the kinds of practices that we are talking about, and there are already agencies that can investigate these companies.

Now, Sam Altman then goes to Congress and talks about how there needs to be regulation. He's very worried about super intelligence and there needs to be something akin to international agencies, et cetera. People hail him as this Oppenheimer who is worried about his creation. His creation that he apparently can't stop building.

> ***The first thing we need to do is we need to stop talking about AI as if it is something that is developing on its own like a digital god.***

At the same time as he was saying this, there was the EU AI Act, which was dealing with some of the things that I just discussed: transparency in terms of data sets. How are you getting this data that is making you lots of money? We don't even know. When he saw this kind of very specific regulation, he threatened to pull out of the EU because he said they were going to overregulate these companies.

The first thing we need to do is we need to stop talking about AI as if it is something that is developing on its own like a digital god. We need to talk about it as if it's an artifact that is built by a bunch of different organizations using certain kinds of practices, and then we need to examine what those practices are. That's the first thing we need to do. And we already have agencies that do that, except the problem is that the hype has made our government and even scientific bodies not question the very premise of how these things are being used.

KYLE GIPSON (KG): Could you elaborate on why the general public, or nonexperts, should be worried about the hype surrounding AI and the overpromising and overapplication of AI? Why is this a problem that we as a society should be very concerned about?

DR. GEBRU: Actually, at the Distributed AI Research Institute, we have a podcast called *Mystery AI Hype Theater 3000*, which every two weeks discusses an AI hype and what has resulted because of that hype. When you talk about something that is created as something that is so powerful that it has its own its own agency, we are asking the machine to be ethical. We are not asking whether the organizations who created this thing to be ethical. We are asking whether AI be ethical. We are forgetting that there are a whole set of investors, regulators, and engineers, et cetera, who built AI, and the responsibility lies with them. You're helping them abdicate responsibility by talking about something as if it has its own agency.

Now, when you remove that discourse, which we call anthropomorphizing AI systems, we can go back and discuss exactly what is happening. For example, artists have been very vocal about what has been happening with image generators. Artists are saying that they do a lot of horrible things. For instance, style mimicry, where you can write the name of a style and say, Build me this image in the style of such and such artist. This can basically mimic the style of an artist. People who are hyping these systems will say, No. It's learning from images just like humans learn from images. The artists are like, No. That's not how humans learn from images. What you're actually doing is plagiarizing, and you're competing in the same market as me and trying to replace me, saying that you've created something that's creative. You're ascribing human-like qualities to it.

RML: Your comment reminds me of a conversation I've had with my wife, who is a professional artist. She would agree 100 percent with your comment, and she would add the copyright infringement issue to it too.

DR. GEBRU: Exactly. That's just one example of what happens when we don't believe the hype and bring the conversation back down to earth rather than if we say machines can be creative. We're not having these discussions of exactly what is happening. That's why I think the hype is one of the most important things to consider.

Then the other issue here is that the hype allows these organizations to claim that they are creating something that will save all of society. Literally just recently, Sam Altman said that if he had $7 trillion that he would create artificial general intelligence that would then solve the world's problems. Just hand him $7 trillion, and he will fix the entire world. This is what we are letting happen.

But in the meantime, what happens when you try to create an everything-machine, like what they are trying to do right now, as opposed to a task-specific model? Let's say I'm trying to build a model, and I say that the goal of this model is to identify certain kinds of diseases in plants. The scope of what I'll do is limited. I'm not going to try to have a huge data set. I will curate my data set. I'll look through it. I'll document it appropriately, and I'll see whether this model will work for this appropriate use case.

When I say that I'm trying to build a digital god, the data set is already intractable. What data set do I use to train this machine? I just ingest everything, whether it is people's private data or what the Nazis are saying on the internet. And then I repackage that and spit it out, and I can't even document or curate my data for a specific task.

What really worries me is that people are building on top of these models that we don't know anything about. Let's say, right now, OpenAI has an app store, right? People are building on top of their models and they don't even know what's in them. They can change from week to week. You can get one type of output this week, and your model can have a different kind of output next week, and you don't even know. They are not even supposed to tell you how the version has changed or anything like that. Everything we know about version control software systems, bugs, reproducibility in engineering, is not being followed right now. We are letting it happen because of the hype. They are building a digital god, so they don't have to follow these engineering practices.

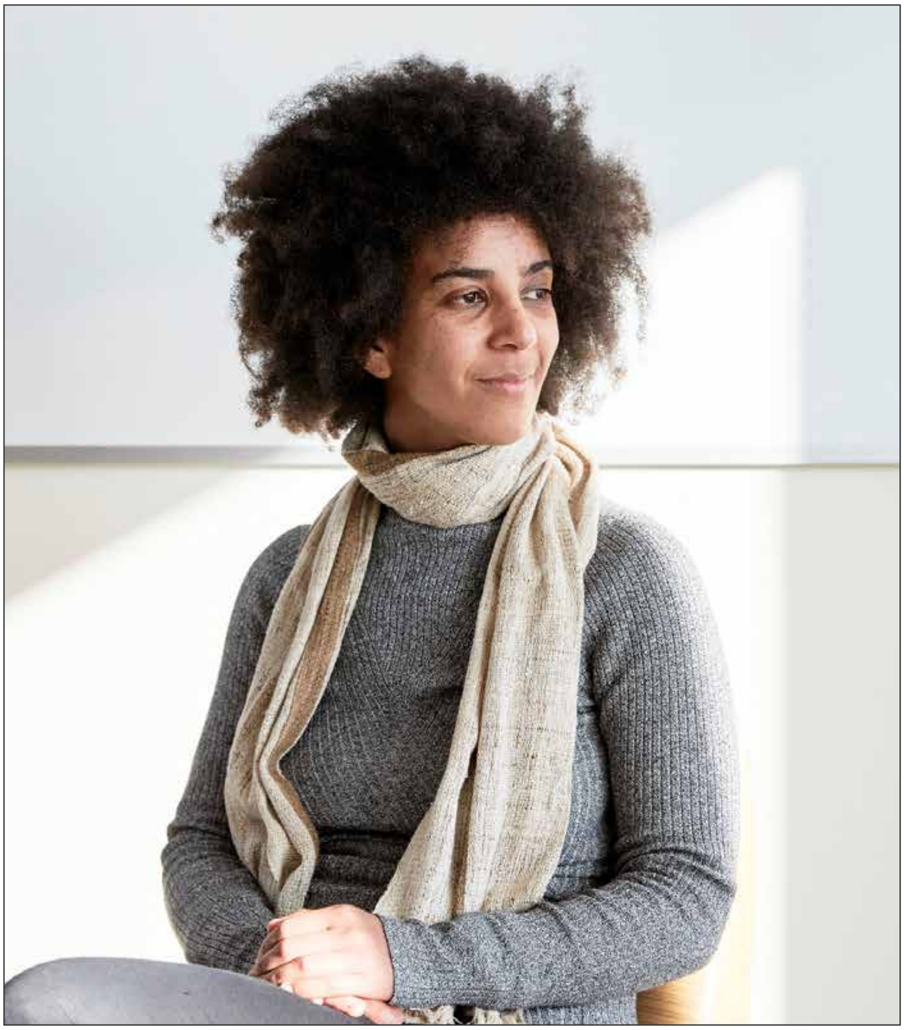

Photo by Cody O'Loughlin

RML: Let me take a step back for a moment. You said earlier that there are regulatory agencies that exist today that would in fact provide some degree of oversight. Are they not? And if they are not, why are they not?

DR. GEBRU: I think that some of them are, but they are heavily understaffed. For instance, I think the Federal Trade Commission is doing a fantastic job. But they are heavily understaffed. Let me give you an example. One of the biggest issues right now is that the onus is on these agencies to say, I think something is wrong. Or the onus is even on bodies like the EU, where we think that there is much more regulation. The onus is on me, as an individual, to say, I think my data has been used without my consent, and then they will investigate. You have these massively resourced corporations and then very under-resourced agencies, and the onus is on them to say there might be a problem, or the onus is even on individuals.

What I'd like to see is, before you put new technology out, you should have to pass certain standards. You should not be able to put something out into the world without first doing a certain number of things. For example, in electronics, we used to have the Restriction of Hazardous Substances in Electrical and Electronic Equipment Directive, which says that everything has to be lead free. Or there are certain radiation levels that you can't have. There's a whole bunch of these kinds of regulations where the onus is on the organization to prove that they haven't done harm before they put things out into the world.

> ***With research, you are able to serve as an early warning system when there are issues, and you are also able to imagine a different technological future.***

Now, imagine—I am going back to the art situation. Imagine that I'm an artist who thinks that perhaps corporations have stolen a whole bunch of my data to train their systems without compensation or consent. Let's say I wrote a book, and they want to adapt it into a movie. Nobody can just do that without telling you. There has to be some sort of negotiation for all this stuff. Right now, let's say these companies can just take whatever script you wrote and train some text-to-video or text-to-whatever thing, and I don't know as an author. But let me see. I asked them, I think you've done this. I think you've used something without my consent. And they'll say, Prove it. We have five billion data points. Go through it yourself. You can't do that. You'll say, No. Why don't you tell me that you haven't actually done that? They haven't really documented it. They don't have to document it. There's nobody that is saying that you have to have a whole database and make it easier for us to search your data set or anything like that. There are really very few requirements that they have to have in order to put these systems out there.

RML: We live in a very technologically intense world. That's a testament to what you are saying. We need regulatory agencies that have some potential power to provide oversight and accountability. What do you think of the constitution of our legislative bodies? There aren't many members of Congress who are technologists. Do you think that is a problem? We're living in a world where technology is all around us, and yet you look at the population in Congress and technologists make up a very small fraction. Should that change? Why don't you run for Congress?

DR. GEBRU: I'm too loud. There's no way.

RML: I'm actually quite serious. If people who are concerned about this don't get involved, who will?

DR. GEBRU: Two things. The number one thing that I think is a problem, even before we get to members of Congress who understand technology, is that they are too enamored with leaders of corporations. They are too enmeshed. Chuck Schumer had this AI insight forum series. It featured Elon Musk, Sam Altman. You never saw people who were negatively impacted by their systems in these kinds of forums. They are not hearing from people who have been negatively impacted by these systems. They are seeing press releases from leaders of these corporations. That's the number one issue in my opinion. Even if you are not a technology expert, you can understand negative impacts when you hear them, pros and cons. You don't have to know how a car works to see what kind of damage it could do. But if you are always just hearing from the CEO of car companies and you are not hearing from a victim of someone who was killed because of some issue or something, then obviously the way you are legislating is going to be different. That's one.

The second thing, and I think the biggest issue, is that we really don't have checks and balances. I would love to see an academia that's a check to both industry and government. I'd like to see a government that's a check to industry. We need to have checks and balances, but that's not really what's happening right now.

RML: What, in particular, would you like to see? This is a very important conversation to me in the sense that you have experience with the technology giants in your career, and you have insights that I think should be meaningful in terms of how this country goes forward, how the world goes forward. What would you do specifically, if not electing more members to Congress like yourself? I'm serious. I hope you will not disregard that completely. But what should we do? How do you change all this? It's overwhelming. Most people don't have any idea what AI is. They just know it's affecting their lives.

DR. GEBRU: Let me give you an example. The National Science Foundation (NSF) provides research funding, and it's from the government. I don't think that the NSF should need to have money from any other organization except for the US government in order to give out funding for research. But I see these calls for research proposals from the NSF that are joint calls with foundations like Open Philanthropy, which was founded by an ex-Facebook person, or with a specific type of ideology about technology. There was a joint call with Amazon, which means Amazon supplied a certain portion of the money. I should be able to have funding from the US government that is separate from Amazon and any other body. These are the kinds of things I'm talking about, so that my research can just be funded by that one entity because where your money comes from is going to determine what the goals are of your research. That's one specific thing we could do.

RML: I'm not sure I agree 100 percent with you on that. My sense would be that the NSF would put some guardrails on the money they accept from a foundation.

DR. GEBRU: If I want money from Amazon, there are fellowships at Google, or whatever. And then I want money from the NSF. I should just be able to have money from the US government.

RML: Let me give you a concrete example. I mentioned that I taught at MIT in material science. There is an initiative called the Materials Genome Initiative. The concept is to use computational materials science and engineering to develop new materials, advanced materials that meet certain advanced engineering needs. For example, if you are interested in splitting water to raise hydrogen as an energy source, you need a durable semiconductor photoelectron. MGI is federally funded. But in order to make that happen, they have to have relationships not only with universities, which produce the students and essentially the manpower going forward, but also technology companies that can implement it, that can it take from the design stage all the way through deployment. There has to be a relationship between the researchers and the folks who deploy the technology.

DR. GEBRU: The Pentagon doesn't take money from Amazon. The US government has a lot of money. There should be an agency that gives out money and does not have to take in money from corporations. Then I know that my money is coming from the taxpayers' money. There is a difference between having a relationship and undue influence. What I think right now is that there aren't enough checks and balances between government agencies and philanthropy. I wrote an op-ed about that when I founded DAIR. One of the examples I gave was: Let's say you have co-founders of Google, and then they found some philanthropic organization, and then that philanthropic organization influences government. Now, you have this one entity that is influencing everything. You can't really get away from that influence, which means you don't have any checks and balances. I think that right now what's happening is that everything is too enmeshed, and we don't have enough checks and balances.

RML: I kind of agree with that. We don't have enough checks and balances to keep all of this under some pace of evolution that is sensible.

For AI to be used ethically, it means that first we have to start with the goals of people or organizations building it and whose needs it's supposed to serve. And if AI is supposed to serve a specific group of people's needs, it should be created with their input and their goals in mind.

DR. GEBRU: And then your question about running for Congress. I'm a researcher. I still want to continue to do research. I talk to all sorts of legislators, but I'm not a politician. I'm still a researcher and that's what I do. I think with research, you are able to serve as an early warning system when there are issues, and you are also able to imagine a different technological future. Right now, we're living in someone else's imagination, and I have to constantly say don't do this, don't do that. I want to be able to institute my imagination of whatever technological future I want to live in as well. By the time we get to legislation, in some ways it's too late.

In 2021, way before ChatGPT had come to the public, I wrote a paper on large language models and the dangers of large language models. We were able to warn people because we were in research and we were seeing the early research practices that are then proliferated into the world. That's still what my skill set is, and that's still what I want to continue to do. If I'm in legislation, I've waited all this time, and now I'm acting after everything has already happened. I want to influence it before it gets to that stage.

KG: To begin to get into your vision of the technological future, I'm wondering if you could talk a little bit about what it would mean for AI to be used ethically. Are there any examples of AI being used for the good, or in ethical ways, right now?

DR. GEBRU: I think that for AI to be used ethically, it means that first we have to start with the goals of people or organizations building it and whose needs it's supposed to serve. And if AI is supposed to serve a specific group of people's needs, it should be created with their input and their goals in mind.

I have some examples of what we at DAIR are doing. There's a very recent article[1] on one of our works. To me, this is a very specific use of technology. We weren't trying to build a machine god or anything like that. We were building a specific application, and the research questions kind of came from that specific application. We were trying to examine what has changed in apartheid South Africa to analyze what we call spatial apartheid. We can look at aerial images and you can see very clearly where the townships were that were mandated during apartheid and where suburbs are. The question that we were asking was, have people's lives gotten better since the legal end to apartheid? The South African government doesn't differentiate between townships, which were created during apartheid, and other kinds of suburbs. We wanted to use computer vision techniques to segment out the townships and then ask, how much greenery is there in these townships versus elsewhere? What about different kinds of services? People know that their lives are actually worse, but they don't have the data to back it up. We could do that kind of stuff and then maybe try to force some sort of policy changes. Similar work has been done in the United States where people have used satellite imagery to analyze pollution near prisons to show that a lot of prisons are built in places that are highly polluted. We did this kind of work because the goals came from the people themselves. The person who is leading this research project is a computer vision researcher who grew up in a township. The goal of the project came from her experience.

There are other ways in which I think you can use automatic speech recognition to do automatic captioning of videos and things like that. Those could be helpful. But again, it has to start from an actual need that exists for people. That's what I think. Just because things have been done a certain way in the past, it doesn't mean they have to be continued to be done in that way in the future.

RML: We had a conversation a couple of weeks ago with Kimberly Bryant, the founder of Black Girls Code. She described herself as a social innovator. How would you describe yourself?

DR. GEBRU: I would describe myself as a scientist. I've always just tried to be a scientist and it's kind of hard to do it within the environments that I'm in. All I've been really trying to do is that. I write a paper on large language models. I get fired. I've just been trying to do the job of a scientist.

RML: But you're more than that. You are unique in the following sense. You worked for the technology giants during your very early career. You spent time at Apple, at Google, at Microsoft. These are the tech giants. You're in a position probably unlike anyone who could look at what is evolving in a technologically intense world and say, we have to step back and think about the following things in order to make sure we're not harming society and that we're serving a useful social purpose. That's a calling that's really unique and you have the capacity.

DR. GEBRU: I say that I'm literally a scientist and an engineer, whose default is something different. It means that I am centering the communities that I come from. And that's really the only thing that's different in my view. I'm not necessarily following along with what has been the default. I have a different default. Chanda Prescod-Weinstein wrote a book called the *Disordered Cosmos*, and it's a physics book, but it has a different default. It's still a physics book. It's just that the narrative is different from what we've seen before. To me, that's sort of what I think. It doesn't mean science is different. My default is doing it differently.

RML: Okay. I'll buy it. But I also hope someday I can vote for you.

DR. GEBRU: It's good to know I have your vote.

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[1] Tsanni A. 2024. How satellite images and AI could help fight spatial apartheid in South Africa. MIT Technology Review, January 19.

KG: I'm looking forward to the book. That's what I'm looking forward to.

DR. GEBRU: I'm supposed to be writing a book, but I've been putting it off. I'm hoping to write a book on my vision for a positive technological future, because I think that we are stuck cleaning up, and that goes back to the question about Congress too. I think by the time we get there, a lot has happened already, and we are looking backwards. I'd rather try to influence things early on. How do we teach the students? How are we shaping people's understandings of how technology should and shouldn't be built, what they should do, et cetera? That's where I want to be. I want to be able to shape technology before we get to the legislative process.

RML: I think that would be a genuine contribution. I really do.

KG: I'm excited for your book to be out in the world, even though it's in the very early stages.

DR. LATANISION: Thank you, Timnit. This has been a wonderful and informative conversation.

DR. GEBRU: Thank you. It's been fun.

NAE News and Notes

NAE Newsmakers

John L. Anderson, president, National Academy of Engineering, has won a **2024 LAS Alumni Achievement Award** from the College of Liberal Arts & Sciences at the University of Illinois Urbana-Champaign. The award was presented April 5 during the 2024 Alumni Award weekend.

Julia J. Brown, senior vice president and chief technology officer, Universal Display Corporation, was honored by the USC Viterbi School of Engineering with the **Daniel J. Epstein Engineering Management Award**. The award, presented April 11, recognizes Dr. Brown for her exemplary professional accomplishments and exceptional contributions to the field of engineering management.

Larry A. Coldren, Fred Kavli Professor of Optoelectronics & Sensors, University of California, Santa Barbara, has won the **ISCS Heinrich Welker Award**. Dr. Coldren has made enormous strides both in the realm of laser photonics and in developing the materials that have enabled those devices and made possible their manufacture and distribution on a scale reflected in their worldwide use in electrical devices and equipment.

Lance R. Collins, vice president and executive director of the Virginia Tech Innovation Campus, has been recognized with a **Diversity in Business Award** from the *Washington Business Journal*. The publication held its 17th annual program on March 21 celebrating diversity and inclusion in the workforce and honoring inspiring business leaders of color in Greater Washington. The awards celebrate entrepreneurial drive, creativity, and success.

Vijay K. Dhir, distinguished professor and dean emeritus, University of California, Los Angeles, has been **elected a member of the European Academy of Sciences and Arts**.

Earl H. Dowell, William Holland Hall Distinguished Professor, Duke University, received the American Institute of Aeronautics and Astronautics **Aerospace Design and Structures' Best Paper Award** in January. He shares the award with research assistant professor Jeffrey Thomas. They won for their 2023 AIAA SciTech Forum conference paper, "Using Broyden's Method to Improve the Computational Performance of a Harmonic Balance Aeroelastic Solution Technique."

Huajian Gao (NAS), Xinghua University Professor, Tsinghua University, received the **2023 ASME Medal.** The society's highest award honors Professor Gao's contributions to fundamental solid mechanics and the emerging field of mechanomaterials at the interface of solid mechanics, structure mechanics, mechanics of materials, biology, and data science.

Naomi J. Halas (NAS), university professor and Stanley C. Moore Professor of Electrical and Computer Engineering, Rice University, has been selected as the recipient of the **2024 C.E.K. Mees Medal** by Optica for "her design, fabrication, and demonstration of nanoparticles with specific optical and physical properties, the widespread application of which enables advances in fields including cancer therapy, water security, and light-driven chemistry."

Paula T. Hammond (NAM/NAS), institute professor and vice provost for faculty, Massachusetts Institute of Technology, received the **Othmer Gold Medal** from the Science History Institute on May 8. The medal is the Institute's preeminent award honoring individuals who have made extraordinary contributions to the material sciences.

John L. Hennessy (NAS), president emeritus, Stanford University, received the **2024 Vannevar Bush Award** on May 1 during the National Science Foundation Awards Gala. The award honors exceptional lifelong leaders in science and technology. Dr. Hennessy was honored for his pioneering advances in computer architecture and leadership for both academic and corporate endeavors and his dedication to supporting future leaders in the sciences.

David Huang, professor, Ophthalmology & Biomedical Engineering, Oregon Health & Science University, has been named a **2024 Oregon History Maker** for co-inventing optical coherence tomography technology. He is honored for his groundbreaking work that has revolutionized disease detection and management.

Kenichi Iga, professor emeritus and retired president, Tokyo Institute of Technology, has been named winner of the **2024 Frederic Ives Medal/Jarus W. Quinn Prize** by Optica. Professor Iga is recognized for pioneering contributions and visionary leadership in the field of semiconductor lasers and optoelectronics and a dedication to training and educating future generations.

The **IEEE 2024 Computer Pioneer Award in Honor of the Women of ENIAC** has been given to **Fei-Fei Li** (NAM), Sequoia Professor, Computer Science Department, and co-director of Human-Centered AI Institute, Stanford University, and **Leonard Kleinrock**, distinguished professor emeritus of computer science, UCLA Henry Samueli School of Engineering and Applied Science and IEEE Life Fellow. The award recognizes and honors those whose longstanding efforts have resulted in the advancement and continued vitality of the computer industry. Professor Li was recognized for leading efforts in visual recognition based on machine learning techniques and insights from human perception. Professor Kleinrock was honored for his work on the mathematical theory of packet switching, which was fundamental to the creation of the internet.

Brian McClendon, research professor, University of Kansas, received a **Distinguished Engineering Service Award** from the School of Engineering. Mr. McClendon was recognized for his dedication to excellence in engineering and to innovation in technology and, as co-creator of Google Earth, for changing the way people view and interact with geographic information.

Richard A. Meserve, president emeritus, Carnegie Institution for Science, received the **Lauristan S. Taylor Medal** from the National Council of Radiation Protection and Measurements on March 25. Dr. Meserve was selected "in recognition of lifetime achievement in radiation science." The award was presented during the Council's annual meeting at which Dr. Meserve gave a lecture entitled "Lessons from the Fukushima Daiichi Accident."

Sanjit K. Mitra, distinguished professor emeritus of electrical and computer engineering, University of California, Santa Barbara, and distinguished professor emeritus, Ming Hsieh Department of Electrical and Computer Engineering, University of Southern California, has been elected a **Corresponding Member of the Bavarian Academy of Sciences and Humanities**.

Jayathi Y. Murthy, president, Oregon State University, received the **2023 ASME Kate Gleason Award**, which honors an individual female engineer who is a highly successful entrepreneur in a field of engineering or has had a lifetime of achievement in the engineering profession. She is also the recipient of the **2023 Linn-Benton NAACP Social Change Champion** and a **2024 Women of Influence Award** from the *Portland Business Journal*.

Jorge Nocedal, Walter P. Murphy Professor, Northwestern University - Evanston, has been awarded the **2024 John von Neumann Prize**, the highest honor and flagship lecture of the Society for Industrial and Applied Mathematics (SIAM). He is honored in recognition of his fundamental work in nonlinear optimization, both in the deterministic and stochastic settings. The talk will be given on July 9 at the 2024 SIAM Annual Meeting.

Ellen Ochoa, center director and astronaut (retired), NASA Johnson Space Center, was presented the **Presidential Medal of Freedom** by President Joe Biden in a ceremony at the White House on May 3. She is the first Hispanic woman in space and the second female director of NASA's renowned Johnson Space Center. Dr. Ochoa has flown in space four times, logged nearly 1,000 hours in orbit, and continues to inspire future generations of scientists.

Julio M. Ottino (NAS), dean, R.R. McCormick Institute Professor, and Walter P. Murphy Professor of Chemical and Biological Engineering, Northwestern University – Evanston, presented the 43rd annual **Michelson Memorial Lecture** on April 17 at the US Naval Academy. Dr. Ottino spoke on "Lessons in Creativity, Innovation, and Leadership through the Nexus of Science, Math, Technology, and Art." The lecture celebrates the accomplishments of Albert Abraham Michelson, America's first Nobel Laureate in science and perhaps the Academy's most scientifically accomplished graduate.

Kaushik Rajashekara, distinguished professor of engineering, University of Houston, has been elected an **International Fellow of the Japanese Academy of Engineering**.

Junuthula N. Reddy, distinguished professor, regents professor, and O'Donnell Foundation Chair IV Professor, Texas A&M University, has been recognized by Research.com with their **2024 Mechanical and Aerospace Engineering Leader Award**, along with no. 5 and no. 8 rankings among national and worldwide mechanical engineers, respectively.

Kamal Sarabandi, Rufus S. Teesdale Endowed Professor of Engineering, University of Michigan, has been awarded an **Ellis Island Medal of Honor** to recognize his extraordinary contributions in electrical engineering, and as an immigrant to the United States.

Terrence J. Sejnowski (NAM/NAS), distinguished professor, University of California at San Diego, Francis Crick Chair, Salk Institute, and head of Salk's Computational Neurobiology Laboratory, received the **2024 Brain Prize** of the Lundbeck Foundation. He shares the prize, the world's top recognition in neuroscience, with Larry Abbott of Columbia University and Haim Sompolinsky of Harvard University and Hebrew University. They were celebrated for "pioneering the field of computational and theoretical neuroscience, making seminal contributions to our understanding of the brain, and paving the way for the development of brain-inspired artificial intelligence." His Royal Highness King Frederik of Denmark awarded the prize on May 30 in Copenhagen. Dr. Sejnowski has also been named **2024 Scientist of the Year** by ARCS San Diego for his pioneering research in neural networks and computational neuroscience.

Raj N. Singh, regents professor, Oklahoma State University, has been elected a **fellow of the American Association for the Advancement of Science**. Dr. Singh is honored "for pioneering and game-changing scientific and technological contributions to the field of materials, particularly transformative processing and manufacturing of Ceramic Composites, leading to technology insertion into commercial jet engines."

Kumares C. Sinha, Edgar B. and Hedwig M. Olson Distinguished Professor of Civil Engineering at Purdue University, was honored with an **OPAL Award** at the ASCE Gala Banquet for Outstanding Projects and Leaders (OPAL) Awards held in Chicago in October 2023 for his demonstrated excellence in furthering civil engineering education. He has mentored hundreds of civil engineers and his work has contributed to improved decision making for timely maintenance and improvement of transportation infrastructure. He has also been **elected an Honorary Member of the Institute of Transportation Engineers** (ITE) and will be inducted at the ITE Annual Meeting in July 2024 in Philadelphia. Election to Honorary Member is the highest honor of the institute.

Lisa T. Su, president and CEO, Advanced Micro Devices Inc., received the **2024 imec Innovation Award** during imec's ITF World conference held in May in Antwerp, Belgium. Dr. Su received the award for her contributions to high-performance and adaptive computing. She was also recognized for advocating for women in the semiconductor industry.

Dawn J. Wright (NAS), chief scientist, Environmental Systems Research Institute, has been named a **2024 US Science Envoy** by the Department of State. The US Science Envoy program was established by the Secretary of State in 2010 to help inform about opportunities for science and technology cooperation. Envoys travel as private citizens to engage internationally with civil society as well as government interlocutors. Each was selected to take advantage of respective expertise in key issues facing the world today: artificial intelligence, fusion energy, civil use of space, and ocean sustainability. Dr. Wright is also the recipient of the ASME/SME **2023 M. Eugene Merchant Manufacturing Medal**.

ASME 2022 honors not previously mentioned: **Horacio D. Espinosa**, James & Nancy Farley Professor of Manufacturing, Northwestern University – Evanston, received the **2022 Daniel C. Drucker Medal** for pivotal contributions to in-situ characterization and modeling of nano and meta materials, and for the creation of robust nanoelectromechanical systems. **Norman A. Fleck**, a professor of mechanics of materials and director of the Cambridge Centre for Micromechanics at Cambridge University, was honored for outstanding achievements in mechanical engineering with the **2022 Charles Russ Richards Memorial Award**. **Timothy C. Lieuwen**, regents professor, David S. Lewis Jr. Chair, and executive director of the Strategic Energy Institute at Georgia Tech, was honored with the **2022 R. Tom Sawyer Award** for outstanding contributions to the development of gas turbine combustion systems and service to the gas turbine community. **Robert O. Ritchie**, H.T. & Jessie Chua Distinguished Professor in Engineering, University of California, Berkeley, and a faculty senior scientist at the Lawrence Berkeley National Laboratory, was honored with the **2022 Robert Henry Thurston Lecture Award** for pioneering contributions to the understanding of the mechanics and mechanisms of the deformation and fracture properties of biological and engineering materials, and how those can be used to enhance the damage tolerance of structural materials. The **2022 ASME Medal** was awarded to **Katepalli R. Sreenivasan** (NAS), dean emeritus of New York University Tandon School of Engineering and Eugene Kleiner Chair for Innovation. Dr. Sreenivasan was chosen for exceptional fundamental and applied contributions to experimental, theoretical, and computational fluid dynamics, and for outstanding service as a leader in the engineering profession. **Savio L. Woo** (NAM), distinguished university professor emeritus and founder and director of the Musculoskeletal Research Center, University of Pittsburgh, received **ASME honorary membership**. Dr. Woo was so honored for a career dedicated to advancing biomechanics of synovial joints in applications including bioengineering, orthopedic surgery, and sports medicine, as well as for excellence in mentoring and being the inspirational namesake of the ASME medal for translational biomechanics.

NAE members **recently elected fellows of the American Academy of Arts and Sciences** are **Pedro J. Alvarez**, George E. Brown Professor of Civil and Environmental Engineering, and **Antonios G Mikos** (NAM), Louis Calder Professor of Bioengineering and Chemical Engineering, Rice University; **Wei Chen**, Wilson-Cook Professor in Engineering Design Mechanical Engineering, and **Mark Hersam**, Walter P. Murphy Professor of Materials Science and Engineering, Northwestern University-Evanston; **Francis J Doyle III**, provost, Brown University; and **Roderic I Pettigrew** (NAM), Executive Dean, School of Engineering Medicine, Texas A&M University, and Vice Chancellor for Strategic Health Initiatives, Texas A&M System.

The following NAE members and international member were **elected to membership in the National Academy of Sciences** at the NAS Annual Meeting in April: **Zhenan Bao**, professor of chemical engineering, Stanford University; **Supriyo Datta**, Thomas Duncan Distinguished Professor of Electrical and Computer Engineering, Purdue University; **Leonard Kleinrock**, distinguished professor, University of California, Los Angeles; **Ramamoorthy Ramesh**, executive vice president for research, and professor of materials science and nanoengineering, Rice University; **Daniela Rus**, Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science, Massachusetts Institute of Technology; and **Joseph Sifakis**, CNRS research director emeritus, Verimag Laboratory, France.

NAE Chair, Home Secretary, and Councillors Elected

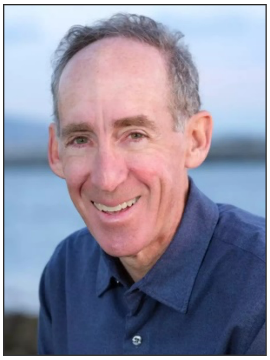
This spring, the National Academy of Engineering (NAE) elected a chair, home secretary, and four members to its council. The NAE Council is the governing body of the NAE with oversight for general policies and programs and all funds administered by the NAE. All terms begin July 1, 2024.

Newly elected to serve a two-year term as the NAE chair is **Erroll B. Davis Jr.**, a retired senior executive presently engaged with board, philanthropic, senior executive counseling, and consulting work. Davis was previously chair of the board of Alliant Energy Corporation and chancellor of the University System of Georgia, among other significant leadership roles. Davis was elected to the NAE in 2021. He succeeds **Donald Winter**, an independent consultant and former secretary of the Navy, who completes four years of continuous service as chair on June 30, 2024, the maximum allowed under the NAE bylaws.

Elected to serve a four-year term as the NAE home secretary is **Howard Rosen**, an independent consultant and adjunct professor and lecturer at Stanford University. Rosen was elected to the NAE in 2005 and has served five consecutive years as a councillor. He succeeds **Carol Hall**, Worley H. Clark Jr. distinguished university professor at North Carolina State University, who completes a four-year term as the NAE home secretary on June 30, 2024.

Erroll Brown Davis Jr.
Chair

Donald C. Winter
Chair (Outgoing)



Howard B. Rosen
Home Secretary

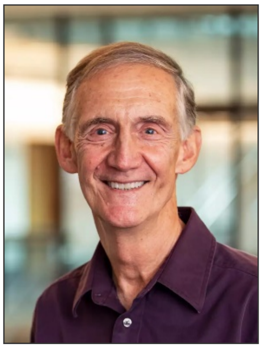
Carol K. Hall
Home Secretary (Outgoing)

Geraldine Knatz
Councillor

José G. Santiesteban
Councillor

Ellen Marie Pawlikowski
Councillor

Roderic Pettigrew
Councillor



Edward D. Lazowska
Councillor (Outgoing)

Geraldine Knatz, professor of the practice of policy and engineering at the University of Southern California and former executive director at the Port of Los Angeles, has served for one year as a councillor and has been elected to serve a three-year term. **José G. Santiesteban**, retired strategy manager for ExxonMobil, has been reelected to serve a three-year term as councillor. Newly elected to serve three-year terms as councillors are **Ellen Marie Pawlikowski**, an independent consultant and retired four-star general of the United States Air Force, and **Roderic Pettigrew**, CEO of EnHealth and executive dean of EnMed at Texas A&M University.

Retiring as councillor is **Edward D. Lazowska**, professor and Bill & Melinda Gates chair emeritus in the Paul G. Allen School of Computer Science & Engineering at the University of Washington. Lazowska will have completed six continuous years of service, the maximum allowed under the NAE bylaws.

University of Delaware Hosts NAE Regional Meeting: Clean Hydrogen for Energy Transition

By Erica K. Brockmeier

On Wednesday, April 17, 2024, the University of Delaware (UD) and The Chemours Company hosted a 2024 Regional Meeting of the National Academy of Engineering (NAE).[1]

During the public symposium, nearly 150 attendees gathered at the FinTech Innovation Hub on UD's Science, Technology and Advanced Research (STAR) Campus to hear presentations on how to tackle challenges and embrace opportunities relating to the production, storage, transportation, and conversion of hydrogen for powering clean and efficient fuel cells.

During his introductory remarks, **Levi Thompson**, dean of UD's College of Engineering, described hydrogen as a long-term choice for decarbonization, with potential uses ranging from transportation to energy storage. He then highlighted some of UD's recent achievements related to clean hydrogen, including establishing the Center for Clean Hydrogen and leading workforce development initiatives as part of the Mid-Atlantic Clean Hydrogen Hub.

Next, NAE President **John L. Anderson** provided an overview of NAE's mission, its programs, and how the organization is unique in that it brings together engineers from both academic and government research institutions as well as industry. UD President **Dennis Assanis** then welcomed the audience to UD for a day of engaging conversations and insightful presentations.

Sunita Satyapal, director of the US Department of Energy's Hydrogen and Fuel Cell Technologies Office, delivered the first keynote presentation, providing an overview of the current US energy landscape, the challenges of meeting the nation's carbon emission goals, and how hydrogen is a key element of a broad portfolio of decarbonization solutions.

Satyapal highlighted the three pillars that support the nation's clean hydrogen strategy: targeting strategic, high-impact end uses, reducing the cost of clean hydrogen, and a focus on regional networks. She also emphasized the significance of last month's DOE announcement of $750 million in funding to support clean hydrogen research as part of the Bipartisan Infrastructure Law.

Next up was Kathy Ayers, vice president of research and development at Nel Hydrogen, a company focused on the production, storage, and distribution of hydrogen from renewable energy sources. Ayers shared results from their R&D on enhancing production capacity for proton exchange membrane electrolysis, a carbon-free and renewable hydrogen production method. Ayers presented several case studies to demonstrate the technical and scientific challenges of creating materials and devices at scale.

Yushan Yan, Henry Belin DuPont Chair of Chemical and Biomolecular Engineering and director of UD's Center for Clean Hydrogen, chaired the first of two afternoon presentation sessions. First, Senator Tom Carper shared remarks via video about the importance of clean hydrogen in getting the US to net zero emissions. Then, Andy Marsh, president and CEO of Plug Power, shared his enthusiasm for the potential of hydrogen to become a ubiquitous fuel source in the future based on progress made thus far.

Tim Cortes, CTO of Plug Power, discussed his company's efforts in deploying clean hydrogen at industrial scale. With a focus on material handling applications, where fuel cells provide a clear advantage in terms of power access and productivity, Cortes described Plug Power's approach in building out the infrastructure and systems required to provide end-to-end service for their customers. Plug Power will also be involved with nine projects as part of DOE's $750 million clean hydrogen research program, which Cortes said will help accelerate the company's technology and manufacturing capabilities.

Craig Gittleman, a General Motors Technical Fellow and Engineering Group manager of fuel cell materials and analysis, discussed hydrogen's potential in transportation applications. He presented highlights of GM's fifty years of experience in developing fuel cells to power large, high-fuel consuming equipment like medium- and heavy-duty trucks. He also discussed his group's R&D on "next generation" fuel cells that are more efficient, durable, and low-cost, including efforts to find new materials for membranes and catalysts.

David Dankworth, hydrogen portfolio manager at ExxonMobil, shared insights from his group's efforts to leverage low-carbon hydrogen fuels at scale. Dankworth said that ExxonMobil is focused on leverag-

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[1] *Symposium sponsors include Chemours, ExxonMobil, NAE, and UD.*

ing their strengths in driving large-scale market solutions, with a focus on applications like carbon capture and storage, lithium, and biofuels, as well as new hydrogen projects such as the Baytown Blue Hydrogen plant ("blue" referring to the use of natural gas in a way that sequesters spent carbon). He also emphasized the importance of continued investments, infrastructure, and collaboration for successful innovations in clean hydrogen.

Ajay Prasad, engineering alumni distinguished professor and codirector of UD's Center for Clean Hydrogen, shared results from UD's fuel cell bus program, a seventeen-year, five-phase project supported by the US Department of Transportation that finished in 2022 whose goal was to research, build, and deploy a fleet of fuel cell-powered buses and hydrogen refueling stations in Delaware. Prasad presented lessons learned from this program—that fuel cells work well for urban transportation applications and provide a way to show the public that hydrogen is clean, safe, and reliable. Prasad also delved into fundamental research on ways to extend membrane durability in cerium-containing fuel cells as part of the Million Mile Fuel Cell Truck Consortium.

Timothy Hopkins, Chemours Discovery Hub and Newark Area Technology Site leader, chaired the second afternoon session. First, Representative Lisa Blunt Rochester lauded hydrogen as the "fuel of tomorrow" during a video message. Then, Gerardo Familiar, president of Advanced Performance Materials at Chemours, reminded the audience that there's no path to net zero without continued progress around hydrogen.

Andrew Park, R&D senior principal engineer at Chemours, presented results on the usability of Nafion™ membranes for proton exchange membrane electrolysis. Along with building off their current findings, Park and his team also plan to demonstrate the durability of Nafion™ over the membrane's lifetime.

Barry Sharpe, vice president of operations and general manager of the Bloom Manufacturing Center of Delaware, provided an overview of Bloom Energy's solid oxide fuel cells that enable on-site energy production. Their flexible technology platform allows for a variety of inputs, is modular and scalable, and can also be used to produce hydrogen; this includes a facility at NASA's Ames Research Center, which provides more than 2.5 tons of hydrogen per day.

Yan concluded the technical program with a presentation on his journey from laboratory research into large-scale commercialization, with a focus on anion-exchange membranes for green hydrogen generation, which Yan has worked on for the past twenty years. Yan also provided more insights into the vision and goals of UD's Center for Clean Hydrogen, including research efforts that help reduce costs by finding new materials, simpler designs, and faster manufacturing methods. He also sees UD and the Center for Clean Hydrogen as a hub for electrochemical engineering education and clean energy start-ups.

Meeting attendees, which included NAE members, industry representatives, government officials, academics, and members of the public, finished the day with a reception held at the FinTech Open Forum, with more than twenty research posters presented by UD graduate students.

Celebrating Janet Hunziker's Career and Leadership at NAE

By Guru Madhavan

Of late, I've been thinking a lot about Sir Christopher Wren, the renowned British engineer and architect. He was born in 1632. He studied optics and design principles in Latin. He invented his own instruments. He became the legendary polymath and baroque designer.

In 1666, the Great Fire destroyed two-thirds of London. The city commissioned Wren to rebuild over fifty churches. And to show that the city literally rose from the ashes, Wren redesigned and built St. Paul's Cathedral. When you go inside and stand in awe looking at the magnificent dome, you'll see the inscription, "If you seek his monument, look around you." Wren's story, if you dig just a bit deeper, has three things we can admire and apply to Janet Hunziker's thirty-five-year career at the National Academy of Engineering (NAE).

Guru Madhavan is the Norman R. Augustine Senior Scholar and senior director of programs at NAE. This piece is slightly adapted from his remarks at Janet Hunziker's retirement celebration on April 16, 2024. Collage photos by Melissa Moore-Esquivel and Guru Madhavan.

Scenes from Janet Hunziker's retirement celebration.

First, *commitment to an institution*: in Wren's case, it was the English Church. In Janet's case, it's the NAE. Second, *commitment to a community*: in Wren's case, it was the city of London he rebuilt from the ground up. In Janet's case, it's the professional network she built from the ground up. And third, *commitment to a profession*: in Wren's case, it was engineering, as it is for Janet.

But Janet didn't have to rescue our organization from any Great Fire. Thankfully, she prevented those fires. If you seek Janet's impact, go to any NAE meeting and look around you. You'll see Frontiers of Engineering. We can all recognize Janet as the gentle miracle worker, a quiet magician, an efficiency engine—but I think those descriptors are all incomplete. Her true attribute is that, much like Sir Christopher Wren, she's a *master builder*. She precisely fuses purpose, procedures, and passion, and we can all learn much from that potent mixture.

Janet, big congrats on your retirement. And importantly, my personal gratitude for your service to the institution, community, and profession. Thank you.

New Director of the NAE Grainger Foundation Frontiers in Engineering Program

Dr. Vernon K. Dunn Jr. has been appointed as director of the NAE Grainger Foundation Frontiers in Engineering program. Vern returns to the National Academies after being a research staff member at the Institute for Defense Analyses Science & Technology Policy Institute, where he provided strategic analyses and support to the White House Office of Science and Technology Policy. Vern has broad expertise in science policy areas including STEM education and workforce, space, postsecondary education, climate and energy, and health policy. He was previously a program officer at NASEM, working in the Policy and Global Affairs Division, where he managed projects under the Committee on Science, Engineering, Medicine, and Public Policy; the Committee on Science, Technology, and Law; and the New Voices in Science, Engineering, and Medicine program. Earlier, he served as program manager at the Louisiana Board of Regents, where he managed the Louisiana STEM Advisory Council's efforts to oversee the creation and delivery of STEM programs for the state. A New Orleans native, Vern received his doctorate in neurobiology from Louisiana State University and a bachelor's degree in psychology and chemistry from Xavier University of Louisiana. In his free time, Vern enjoys training for triathlons, reading, and movies. You can reach Vern at vdunn@nae.edu or 202-334-2344.

Christine Mirzayan Fellow Luis Delgado

Luis Delgado is a PhD candidate in the Department of Mechanical Engineering at Penn State. He received a BS in mechanical engineering from The University of Texas at El Paso and an MS in civil engineering with a minor in public policy from Penn State. He is an Alfred P. Sloan Foundation Minority Scholar, a Hispanic Scholarship Fund Scholar, and a GEM Fellow. He is a graduate research assistant in the Engineering Cognitive Research Laboratory and the Leonhard Center for Enhancement of Engineering Education. Luis's research expertise and interests lie in engineering education; graduate student mentoring; faculty development; and diversity, equity, inclusion, and belonging (DEIB). His doctoral research incorporates critical race theories, decision-making theories, and multiple and mixed methods techniques to help make DEIB an integral part of engineering education. In his time at Penn

State, Luis has held executive board positions in multiple organizations that strengthen underrepresented students' careers and foster an equitable and inclusive environment for graduate students. Specifically, he is actively involved with the Society of Hispanic Professional Engineers (SHPE) and the Multicultural Engineering Graduate Association. Additionally, he co-founded Penn State's Civil & Environmental Engineering Diversity, Equity & Inclusion Committee. Outside of work, Luis enjoys volunteering, hiking, traveling, and playing soccer with his friends.

Luis was the Christine Mirzayan Science and Technology Policy Fellow in the NAE Program Office from March 4 through the end of May, during which time he primarily supported the FOCUS program to help advance a couple of international collaborative initiatives underway. As a Mirzayan Fellow, Luis explored a career path in science and technology policy, learned how equity-focused research gets translated into policy, and built a network of science and technology policy experts. After graduation, Luis desires to work in government and provide engineering and technical advice to policymakers in the US Congress. We wish him well in his future endeavors.

A Legacy of Engineering Excellence: NAE Community Raises $5.3M+ in Honor of Wm. A. Wulf

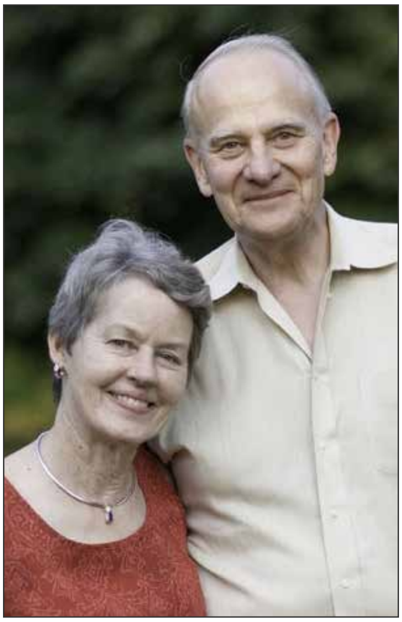
"Without diversity, the life experiences we bring to an engineering problem are limited…As a consequence of a lack of diversity, we pay an opportunity cost, a cost in designs ***not*** *thought of, in solutions* ***not*** *produced."* – Dr. Wm. A. Wulf (NAE Member, '93)

In the spring of 2023, the National Academy of Engineering lost a cherished leader, mentor, and friend.

Wm. A. "Bill" Wulf, former NAE president (1996–2007) and pioneering computer scientist, passed away on March 10, 2023, at the age of 83. Under his leadership and with the critical support of his wife and fellow NAE Member **Anita Jones**, the NAE grew into the institution that it is today.

"Bill brought creativity and thoughtfulness to the [NAE president] position. He brought strong guiding principles. He brought strategic thinking. And perhaps, most important, he brought vision." – Norman R. Augustine (NAE Member, '83, NAS Member '06)

Bill stepped in as interim president of the NAE at a time of institutional turmoil. Under his steady hand and wise statesmanship, and with the counsel of then NAE Chairman **Norman R. Augustine**, the Academy emerged stronger in its mission, programs, and stature. His vital contributions to the stability, growth, programs, and reputation of the NAE earned him the abiding appreciation and gratitude of his peers.



Bill Wulf and Anita Jones

"One trait that made Bill such an effective leader was his enthusiastic and positive approach. Instead of talking about what was wrong and needed fixing, he spoke about exciting opportunities and challenges, and sought ways to meet them." – Dr. Susan L. Graham (NAE Member, '93)

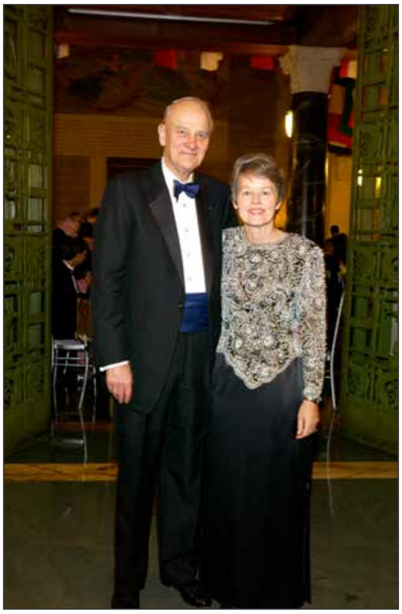
"Bill was committed to the idea that every member of the engineering community should be supportive of women and underrepresented minorities within the profession. To him, every talented person driven away from a career in engineering was a great loss because of both the injustice done to the individual and the loss of all the progress and value the individual would have made for our world." – Dr. Edward D. Lazowska (NAE Member, '01)

In honor of Bill's lifelong commitment to the engineering and computer science community, NAE President **John L. Anderson** hosted a Celebration of Life at the 2023 Annual Meeting and announced a fundraising campaign for the **Wm. A. Wulf Initiative for Engineering Excellence**. This fund ensures that

Susan Graham at the Golden Bridge Society dinner.

the programs Bill passionately advocated for that strengthen the engineering profession and emphasize diversity, ethics, and inclusion—such as EngineerGirl, the Center on Engineering Ethics and Society (now evolved into an initiative called Cultural, Ethical, Social, and Environmental Responsibilities in Engineering), and The Grainger Foundation Frontiers of Engineering—remain critical areas of the NAE's work and grow in perpetuity.

"When Bill became NAE president in 1996…he spoke very effectively about how important diversity was to the engineering design process as a whole and the engineering outcomes that resulted … as a young pre-tenure woman faculty member, one of only two in a department of over thirty, it was extraordinary to hear the NAE president speak in this way…it was really unheard of [at that time] and it changed how I felt about my department, my field and by being able to point to Bill's words and invoke his way of presenting these ideas…we were able to change how our university and how many universities approached these issues too." – Professor **Margaret R. Martonosi** (NAE Member, '21)



Bill Wulf and Anita Jones

Former NAE executive officer Lance Davis (center) and his wife Susan (left) with Bill Wulf (right)

The NAE community's response to the announcement was enthusiastic. Section 5 members **Susan Graham**, **Ed Lazowska**, and **Bob Sproull**—affectionately dubbed "The Wulf Pack"—spearheaded the fundraising effort by galvanizing the support of the NAE family to reach over $5.3 million in contributions in memory of Bill in just five short months. NAE Members **John Hennessy**, **Maxine Savitz**, **Vint Cerf**, **Janie Irwin**, and **Don Winter**, among others, also provided critical support to reach this goal.

"In addition to being a major research contributor to our field…Bill was a transformative president of NAE…He led the creation of major programs in education, engineering ethics in society, inclusion, and the importance of engineering in the modern world." – Dr. Robert F. Sproull (NAE Member, '97)

In total, 177 donors provided direct support to the initiative, while eleven supporters made contributions to other NAE funds in honor of Bill. The highest engagement came from Bill's fellow computer scientists; Section 5's annual giving participation jumped from 22% in 2022 to an impressive 36% in 2023, becoming the NAE section with the highest annual participation rate.

"This incredible man left behind a bountiful legacy of knowledge and innovation, kindness and consideration. Bill will be remembered for all that he has accomplished and for the many lives that he touched." - Dr. John L. Anderson (NAE Member, '92)

It can be said that the NAE simply would not be the respected organization it is today were it not for Bill's fearless leadership and vision. The generosity of NAE members and friends ensure Bill's legacy will continue to impact future generations across the engineering profession for years to come.

Calendar of Meetings and Events

June 5–6	Forum on Engineered AI Systems Johns Hopkins University Bloomberg Center, Washington, DC
June 17–20	2024 China-American Frontiers of Engineering Irvine, California
September 11–14	The Grainger Foundation Frontiers of Engineering Symposium Irvine, California
September 29–30	2024 National Academy of Engineering Annual Meeting Washington, DC

In Memoriam

Joost A. Businger, 99, professor emeritus, University of Washington, died December 3, 2023. Dr. Businger was elected in 2001 for contributions to the field of atmospheric turbulence transport and its applications.

Douglas M. Chapin, 83, principal (retired), MPR Associates Inc., died May 3, 2024. Dr. Chapin was elected in 2002 for improvements in reliability and the prevention and mitigation of core damage accidents in nuclear reactors worldwide.

Uma Chowdhry, 76, chief science and technology officer emeritus, E.I. du Pont de Nemours & Company, died January 7, 2024. Dr. Chowdhry was elected in 1996 for application of advanced ceramic technologies to novel catalyst structures, large-scale chemical synthesis, and multilayer electronic circuit manufacture.

Richard M. Christensen, 91, research professor emeritus, Aeronautics and Astronautics Department, Stanford University, died April 12, 2024. Professor Christensen was elected in 1987 for highly significant contributions in the technologies of polymers and composites, especially for bridging the gap between theory and application.

Jared L. Cohon, 76, president emeritus and university professor, Carnegie Mellon University, died March 16, 2024. Dr. Cohon was elected in 2012 for contributions to environmental systems analysis and national policy and leadership in higher education.

Richard W. Conway, 92, Emerson Electric Company Professor of Manufacturing, Cornell University, died March 19, 2024. Dr. Conway was elected in 1992 for contributions and leadership in the area of scheduling theory, simulation methodology, and simulation software for manufacturing.

Ghislain de Marsily, 84, emeritus professor, Applied Geology & Hydrology, Sorbonne University, died April 24, 2024. Professor de Marsily was elected an international member in 1999 for leadership in advancing the science and engineering of hydrogeology, especially in contaminant transport and nuclear waste isolation.

Robert H. Dennard, 91, IBM Fellow emeritus, IBM Thomas J. Watson Research Center, died April 23, 2024. Dr. Dennard was elected in 1984 for pioneering work in FET technology, including invention of the one transistor dynamic RAM and contributions to scaling theory.

Michele Jamiolkowski, 91, professor emeritus, Technical University of Torino, died June 15, 2023. Professor Jamiolkowski was elected an international member in 2005 for the design and engineering of major projects on difficult soils, and for international leadership in geotechnical education and research.

Clyde P. Jupiter, 95, co-founder, AZIsotopes, died March 31, 2024. Mr. Jupiter was elected in 2023 for contributions to nuclear radiation detection and advancing nuclear energy.

Herbert Kroemer (NAS), 95, emeritus professor of electrical and computer engineering, University of California, Santa Barbara, died March 8, 2024. Dr. Kroemer was elected in 1997 for conception of the semiconductor heterostructure transistor and laser, and for leadership in semiconductor materials technology.

Johanna M. Levelt Sengers (NAS), 94, scientist emeritus, National Institute of Standards and Technology, died February 28, 2024. Dr. Levelt Sengers was elected in 1992 for elucidation of the critical behavior and thermophysical properties of industrially important fluids and fluid mixtures.

John R. Monnier, 76, professor of chemical engineering, University of South Carolina, died April 6, 2024. Dr.Monnier was elected in 2017 for the discovery and development of the silver-catalyzed epoxidation of non-allylic olefins to produce 3, 4-epoxy-1-butene and other non-allylic olefin epoxides.

Thomas P. Stafford, 93, retired lieutenant general, US Air Force, and retired independent consultant, died March 18, 2024. Stafford was elected in 2014 for leadership in the development of rendezvous and docking technologies for the Apollo and Apollo/Soyuz programs.

Sven Treitel, 95, chief scientist, TriDekon Inc., died April 8, 2024. Dr. Treitel was elected in 2024 for the foundations of digital seismic exploration, for developing its applications, and for inspiring three generations of geoscientists.

Richard H. Truly, 86, director, National Renewable Energy Laboratory, died February 27, 2024. Vice Admiral Truly was elected in 2000 for leadership and personal contributions in the advancement of national civil and military space programs.

Kuo K. Wang, 98, Sibley College Professor of Mechanical Engineering Emeritus, Cornell University, died October 7, 2022. Dr. Wang was elected in 1989 for outstanding interdisciplinary research, teaching, and writing, contributing to a broad spectrum of processing technologies, benefiting the manufacturing industry worldwide.

Edgar S. Woolard Jr., 89, former chairman, E.I. du Pont de Nemours & Company, died December 4, 2023. Mr. Woolard was elected in 1992 for contributions to engineering and management of technology in the process industries, and for leadership in industry environmental responsibility.

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