STEPS

SCIENCE, TECHNOLOGY, ENGINEERING, AND POLICY STUDIES

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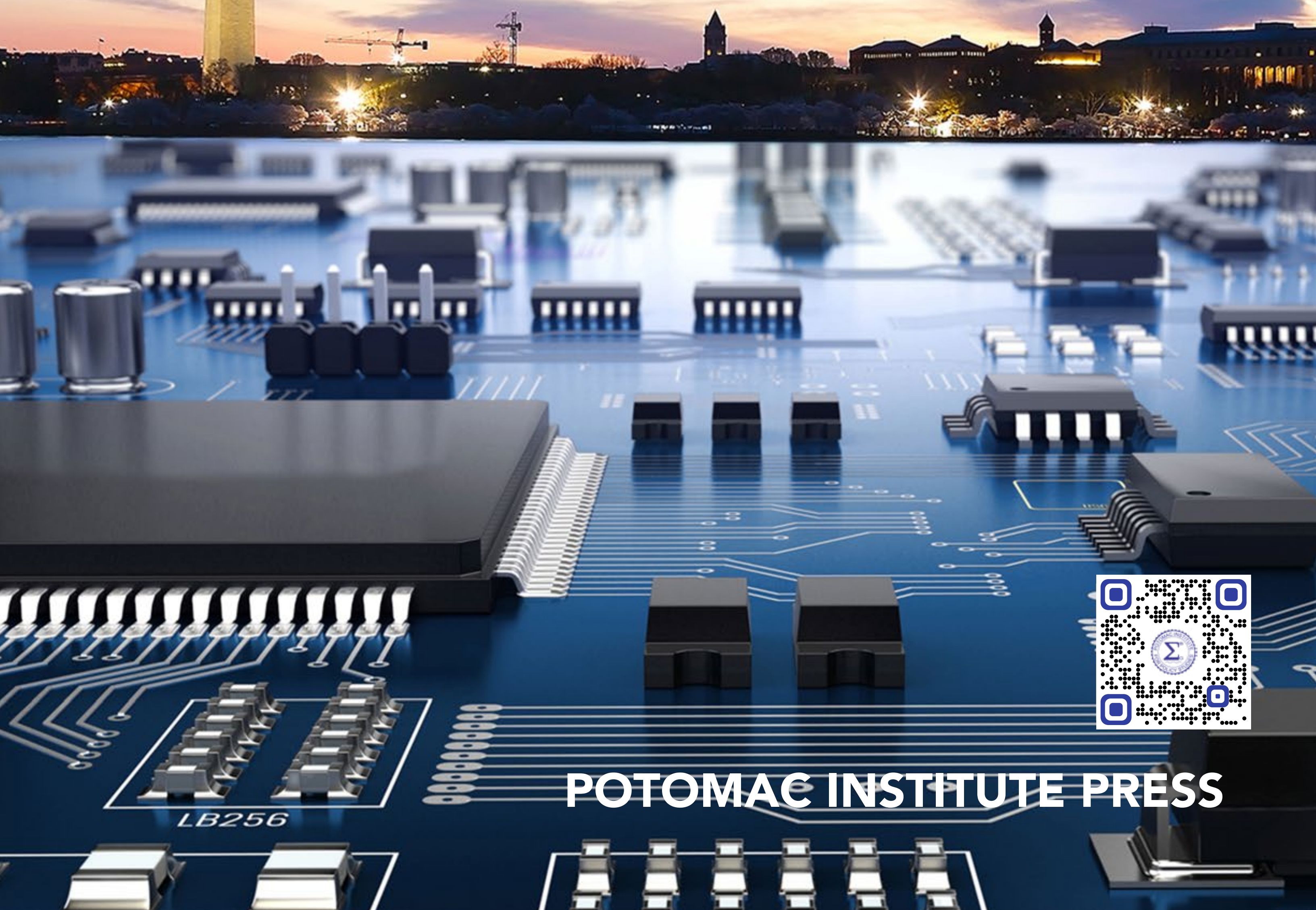
Robert (Bob) Hummel, PhD
Editor-in-Chief

IN THIS ISSUE

ARTICLES



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About *STEPS*

STEPS: Science, Technology, and Engineering Policy Studies magazine is the technical publication of the Potomac Institute for Policy Studies, where scholarly articles of broad interest are published for the policy community. We welcome original article submissions including, but not limited to the following:

- Discussions of policies that either promote or impede S&T research
- Articles that address implications and/or consequences of S&T advances on national or international policies and governance
- Articles that introduce or review a topic or topics in science, technology, or engineering, including considerations of potential societal impacts and influences
- Articles that cover historical developments in science, technology, and engineering, or related policies, and lessons learned or implications going forward
- Non-partisan opinion pieces concerning policies relevant to S&T, to include S&T research trends or research opportunities, and the role of national policies to promote or modify those trends and opportunities

STEPS promotes the mission of the Potomac Institute for Policy Studies, which fosters discussions on science and technology and the related policy issues. Policies are necessary to advance scientific research toward achieving a common good, the appropriate use of human and material resources, and significant and favorable impacts on societal needs. At the same time, the creation of effective policy depends on decision makers being well-informed on issues of science, technology, and engineering, including recent advances and current trends.

Societal changes arising from technological advances have often surprised mainstream thinkers—both within technical communities and the general public. *STEPS* encourages articles that introduce bold and innovative ideas in technology development or that discuss policy implications in response to technology developments.

We invite authors to submit original articles for consideration in our widely-distributed publication. Full articles should be between 2,000 and 5,000 words in length, and should include citations and/or references for further reading. Contributions will undergo in-house review and are subject to editorial review. Short articles of less than 2,000 words, such as notes, reviews, or letters are also welcome.

Please submit articles to steps@potomacinstitute.org **or contact us if you wish to discuss a topic before completing an article. Please refer to the** Instructions for Authors for complete information before submitting your final manuscript.

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About the Potomac Institute for Policy Studies

The Potomac Institute for Policy Studies is an independent, nonpartisan, not-for-profit, science and technology (S&T) policy research institute. The Institute identifies and leads discussions on key S&T and national security issues facing our society, providing an academic forum for the study of related policy issues. Based on data and evidence, we develop meaningful policy recommendations and ensure their implementation at the intersection of business and government.

STEPS
SCIENCE, TECHNOLOGY, ENGINEERING, AND POLICY STUDIES

CONTENTS

From the CEO

Jennifer Buss, PhD

Technology is integral to nearly every aspect of our lives—at work, in the car, and at home. Everywhere we go, we are interacting with engineered materials, digital communications, and other high-end technology and microelectronics—all powered by lithium-ion batteries. We need look no further than the recent CHIPS and Science Act to see how important these technologies are to our lives and our national security.

The reach of these technologies is seemingly infinite in our daily lives, but for society, this extends even further. The core of our infrastructure—water, utilities, the financial sector, and our medical community, for example—relies on technology. While these may seem like disparate facets of life and society, they all, along with our iPhones, smart appliances, cars, computers, and TVs, etc. rely on the same underlying technological capabilities and supply lines. In short, these technologies and their supply chains are what make modern life both modern and livable.

The ideas, raw materials, and even finished goods for modern technologies come from all around the globe. The United States is not alone, nor is it self-reliant, in the world of high technology, and it does not need to be. What is needed are strategies and mechanisms to ensure that the country retains access to essential goods and the innovative minds that bring them forward. The US has a strong network of allies and partners who share our interests. This network is a significant strategic advantage and should be leveraged to reduce US and our allies' dependence on adversarial supply chains.

This issue of *STEPS* highlights the Potomac Institute's mission to provide actionable insights for policymakers to ensure our nation continues to thrive in the science and technology fields. In this issue, our authors address some of our nation's challenges in retaining access to critical minerals and hardware components. Also considered are the emerging difficulties related to promoting the American message around the world, including the lack of a shared vision for our national future. Additionally, the authors examine the education of the next generation of leaders in science. These are not small obstacles for our nation, but the authors offer avenues for government and the commercial sector to work together to help develop meaningful solutions for the future.

The recent passage of the CHIPS and Science Act represents a major step in addressing some of the critical dependences the United States has in the microelectronics and semiconductor supply chain. Potomac Institute congratulates Congress and the Administration for this achievement, but as the final article in this issue notes, "now comes the hard work." I hope that the discussions in this issue of *STEPS* spark further thought in these areas and contribute to continued wise policy decisions and investments that benefit our nation.

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From the Editors

Robert (Bob) Hummel, PhD
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This issue of *STEPS* largely draws from the Potomac Institute's "Global Competition Project," which views the world not only in terms of a competition for military might, but also as a struggle to wield economic and political influence. In the same way that science and technology drive developments in military affairs, much of the activity in economic and political spheres is influenced by science and technology. In turn, actions in the political and economic realms can drive or inhibit the development of new technologies. In this issue, we highlight strategic communications, education, semiconductor memory chips, batteries, and critical minerals. These issues can profoundly impact the nation's economic prosperity and represent areas where competitive pressures can affect national security and seed societal discord.

With contributions by staff of the Potomac Institute and members of the Institute's Board of Regents and Fellows, *STEPS* has become a venue for amplifying the discussions that surround the Institute's activities. It has also become a resource for Institute affiliates to document bold ideas and promulgate potential solutions. In some cases, the intention is that the articles help steer policy decisions related to US national interests. In other cases, the articles are intended to inform further debate. We welcome additional contributions and participation in the discussion by those outside of the Institute's affiliates, as those contributions can lead to new activities and discussions relevant to the mission of the Institute. We find that those contributions often lead to new affiliates that continue in their participation in the life of the Potomac Institute.

The editors hope you enjoy the articles in this issue, and that you agree that *STEPS* helps fulfill a need in public dialog by combining a rigorous understand of science and technology with the many and varied US national policies revolving around ever-changing technologies.

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FEATURED ARTICLE

Reclaiming the Narrative

The US and International Communications

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Article first published online as the white paper: *Reclaiming the Narrative: The US and International Communications.*

The Shining City upon a Hill

Not long ago, the United States was universally perceived as that shining "city upon a hill"[1]—a modern nation founded solely on an idea and serving as a beacon of freedom for the whole world. For 40 years, an independent, federally-funded organization had promoted the core values of the United States, broadcasted local and international news, and shared free and open information with the rest of the world. Today, that organization, the US Information Agency (USIA), has largely ceased to exist and the world has lost a trusted, independent voice.

There Once was an Agency

The revolution in communications that connects people and nations online has placed the United States in a global competition of ideas and memes. The US is ill-prepared to compete successfully in this realm. We are losing because we are not communicating a clear, coherent narrative of our intentions and actions in ways understood and trusted by the world. We have no coordinated plan for communicating that narrative and no national strategy for communications.

Americans aspire to certain values articulated in the founding documents that provide the core constructs of the United States, namely: **justice**, **freedom**, **peace**, and the **duty** to protect those values. But today, our nation is no longer actively sharing the strong belief in those values with the rest of the world. The United States government, in particular, is no longer seen as a reliable source of truth. In 1999, the US State Department absorbed fractured parts of the USIA. It didn't take long for decision makers to realize that relinquishing an independent voice was a bad idea. Two years after the State Department took over the USIA, then-Secretary of State Madeline Albright, who had overseen the plan, expressed concern that folding USIA into the State Department might have been a mistake.[2] By 2001, the nation felt the loss of an independent and trusted voice telling our story.

The USIA's charter separated it from political bodies and provided governance that insured its independence, free from political influence. This independence, whether perceived or real, was lost when factions of USIA were absorbed into the US Department of State. Since then, the Broadcasting Board of Governors and other organizations have attempted to foster an independent voice on behalf of the United States. They have not maintained the level of trust previously held by USIA. The USIA was held in high regard and was generally believed to speak the truth concerning the United States—whether good, bad, or ugly.

Given this absence of authentic voice, we believe that our nation, and indeed the world, again needs to reconstitute an independent resource that can coordinate our messaging and relationships on the world stage, and in so doing, can earn back and maintain trust as a source of truth.

This new resource might be a new agency, like the USIA, or an independent function of an existing organization with authority and accountability to coordinate various agencies with tasking in public diplomacy and strategic messaging.

Projecting Truth and Countering Propaganda: USIA History

The desirability of a national source of public information has been recognized since the days of World War I. Various administrations created organizations designed to spread a national message to support our allies and counter our adversaries' propaganda. The Smith-Mundt Act of 1948 established the "Voice of America" as a communication outlet for foreign populations, created the Fulbright Program, and in these ways, was designed to "combat weapons of false propaganda and misinformation."[3]

Dwight D. Eisenhower had long advocated the need to conduct "psychological warfare," by countering adversary propaganda with a strategic and trusted message.[4,5] In a campaign speech in 1952,[6] Eisenhower emphasized a whole-of-government approach to strategic messaging (primarily to counter communist oppression), and the need to inspire world respect of American ideals using peaceful tools. He differentiated these strategic messaging goals from propaganda by stating that the purpose of the former is to "help free people stay free," by "winning the struggle for…minds" through a message with "spiritual strength."[7]

In 1953, President Eisenhower's "Jackson Committee" recommended creation of a separate agency for these purposes, and Eisenhower's 1953 Executive Order 10477 established the USIA.[8] Based on the now-declassified Jackson Committee report, the USIA was established for overt communications, while covert channels were established separately, with all communications coordinated through the National Security Council to the president.[9] Initially, the USIA was engaged in campaigns to support the President's "Chance for Peace" and "Atoms for Peace" proposals, both internationally and domestically.[10] During the Kennedy Administration, famed newscaster Edward R. Murrow led the USIA, and tied the agency more closely to the CIA, to receive intelligence briefings, counter insurgency training, and advice on local issues and culture, particularly in Southeast Asia. There were some indications of USIA involvement in covert operations during Murrow's tenure.[11] While there was connectivity between the overt side of public diplomacy, and covert aspects of propaganda after Murrow's departure, the USIA refused to work with the CIA in most cases, and would not release any information that did not have full and accurate attribution.[12]

Throughout the Cold War, the USIA opened libraries at embassies in closed countries, sponsored thousands of cultural exchanges, established over 200 public affairs offices throughout the world that fostered social media engagement, and provided access to world news through its Voice of America radio network; each with intent to bring truth and balance to even the most closed societies. By the end of the Cold War, the USIA had a well-connected global network of radio and television broadcasting, cultural and educational exchange programs, and open access libraries providing a wide array of knowledge—often serving as the only source of free information. The USIA adapted with changes taking place in communications technology; having a budget of around $1B per year, offices and outlets throughout the world, and a staff of over 10,000 people.

However, the agency was not free of controversy, and concerns were raised that the agency could be used to promote polemical administration policies[13] despite its charter to exercise overt public diplomacy. In 1972 and in 1985, Congressional action effectively prohibited USIA from domestic dissemination.[14] This lack of transparency may have heightened fears that the USIA was engaged in propaganda, and prohibitions were removed in the Smith-Mundt Modernization Act of 2012.

The USIA began to lose favor—and funding—in the late 1980s and '90s. The fall of the Berlin Wall and the end of the Cold War seemed to lessen the need for psychological warfare. Communist ideology had seemingly been defeated, and the desire for a "peace dividend" inspired cost cutting across the US Department of Defense and Department of State. The USIA's billion-dollar budget was an easy target. Infighting and budget cuts created dysfunction that hurt the organization, and the USIA was defunded and absorbed into the State Department in 1999.[15]

But, in this defrocking, valuable capabilities were lost. Many worldwide assets, such as free libraries, were shuttered. Perhaps most significantly, the US lost much of its ability to understand and influence real audiences within adversary and allied nations, alike.

The USIA was able to remain well-respected and trusted by demonstrating significant success in messaging, and helping to create and maintain the coalition during *Desert Storm* and *Desert Shield*. An argument can be made that the USIA was one of the organizations that helped the United States to prevail in the Cold War. The news provided by the USIA media organizations was largely of local interest to the nations where they were broadcasting, and US news was portrayed openly and honestly, inclusive of events such as civil rights issues in the '60s, Watergate in the '70s, and the political scandals of the '90s. Exchange programs, such as the Fulbright program, created generations of scholars and world leaders who had been exposed to US culture and who were educated in US institutions. A 2008 survey of USIA alumni noted the difference between public diplomacy and propaganda, and largely credited USIA with creating international understanding and support for the US and its policies.[16] The alumni pointed to values of credibility, respect, and truthfulness as the most important assets for public diplomacy professionals who are working in overseas regions. They rated public diplomacy efforts during the Cold War as having been "good" or "excellent," yet a majority felt that by 2008, US public diplomacy was marginal or poor.

Strategic Communications Abhors a Vacuum

The events of September 11th 2001 provided a harsh view of how much had been lost due to the demise of the USIA as it had been. The 9/11 Commission quoted the view of NSC staff that by spring 2001, US public diplomacy was so diminished in the Middle East that "we have by and large ceded the court of public opinion" to Al Qaeda.[17] This same lack of US public diplomacy was true in Europe, Latin America, and East Asia.[18]

Many USIA functions were absorbed into the Department of State's "Board for International Broadcasting" and the "Global Engagement Center" (GEC). These agencies still exist, but they neither have the breadth and depth that the USIA had, nor operate independently from any given administration. The GEC's mission, for example, embodies the mission of countering adversary propaganda—specifically, to "recognize, understand, expose, and counter foreign state and non-state propaganda and disinformation efforts aimed at undermining or influencing the policies, security, or stability of the United States, its allies, and partner nations."[19] But, countering foreign propaganda requires a messaging strategy, coordination with multiple information sources, and, most importantly, a source that is trusted because it operates outside of political influence. With the loss of many overseas offices and resources, the remnants of USIA lack connectivity to regional influences and knowledge and, therefore, are relatively impotent.

While the US lacked an independent strategic coordinated messaging strategy, messaging by others grew exponentially. US communications lacked overarching guidance. One communications expert has stated: "One possible reason for the cacophony of discordant messages—in addition to the sheer volume of information—is the lack of a clear, articulate strategy from the national leadership. Without this, the leaders of each department, agency, and office are left to decide what is important. In most cases the answer is to use the organization's communication efforts to advance its own interests."[20] With the proliferation of other nations' information, voices, and channels, the situation continues to worsen.

Today, there is intense competition for cognitive influence. The Internet and its ability to spread messages globally enables any individual to communicate with almost the same force and breadth as a nation. People worldwide are bombarded with competing ideas that are promulgated as "truths." The United States is not well-positioned in this competition. To regain and maintain leadership, the US should better diffuse ideas to attract populations to the ideals of democratic societies.

Both the US Department of State and Department of Defense acknowledge the need for strategic messaging. Still, responsibility for strategic communications remains fractured within these departments. In the State Department, the Undersecretary for Public Diplomacy, Public Affairs departments, as well as the Office of Congressional and Public Affairs each have responsibilities and processes for creating and executing strategic messaging within specific spheres of influence. The Defense Department has a detailed process for approving strategic messaging plans, but the substance of such messaging is left to individual departments and commands. These efforts have no unifying strategy, no executive level messaging plan, no guidance, and little evidence of coordination between them.

Regaining the Narrative

In the absence of a coordinated strategic narrative, the United States is consistently placed in a reactive posture. Control of current narratives has been ceded to others.

The need to create a coordinated, effective strategic narrative was explored in **a recent public forum** of experts in the communications field.[21] The forum discussion on strategic messaging and global competitiveness revealed that the US needs a coherent and consistent strategic messaging campaign to address global competition in the information space. Panelists emphasized that the lack of a stable strategic narrative puts the US at risk of alienating allies and driving competitors to more aggressive engagements. Uncoordinated messaging can be counterproductive. Reactions to misinformation promulgated by others and attempts to counter propaganda are not prime venues or vectors to fortify US messaging. Once one is reacting to misinformation promulgated by others, attempting to counter propaganda, it is too late to instill truth.

To illustrate the need for a national-level strategic messaging strategy, it is instructive to look at examples of messaging from the past decade.

Attempts at persuasion. Through public and private communications, over a period of years, the United States attempted to persuade the Chinese not to weaponize space. According to a 2013 study for the Department of Defense, the campaign had the exact opposite effect.[22] It pushed China into believing they needed to accelerate their programs, and prompted views of the United States as untrustworthy, in part because of what was perceived as contradictory messaging. US messaging did not consider the background and experiences of decision makers that they were trying to influence, or how the Chinese perspective would interpret and analyze the US statements and actions.

Messaging through actions. In the 1990s, the US sent China a message of support for Taiwan by running US war ships through the Taiwan Straits. On December 19th, 1995, the USS *Nimitz* transited the Taiwan Straits at the same time that the Chinese government was conducting coercive diplomacy via military exercises to influence the Taiwanese elections. The United States asserted that this transit was unplanned, and was merely avoidance of weather. But direct links can be drawn between this event and the initiation of Chinese anti-ship missile programs, which have since matured and complicated the US' ability to operate freely in the Pacific. Again, US action incurred the opposite and undesired reaction.

Messaging through publications. Because the United States is an open society, messaging can occur through public review of official documents. Recently, the US government has taken a more aggressive posture toward China in official publications. The 2018 US National Defense Strategy stated that China uses "predatory economic practices to intimidate its neighbors while militarizing features in the South China Sea."[23] The 2021 Interim National Security Strategy Guidance speaks of our "growing rivalry with China" and calls China "the only competitor capable of potentially combining its economic, diplomatic, military, and technological power to mount a sustained challenge to a stable and open international system."[24] Official publications are intended for US audiences, but Chinese government officials have equal access to them. Some official US documents treat China as a collaborator and other documents depict China as a competitor, while still others regard China a threat and adversary. It would take a cohesive narrative to reconcile these conflicting ideas so as not to foster negative reaction from China, while still making clear the US intent not to allow China to continue aggressive actions in regions that affect our allies and partners.

The current situation with Russia presents a different set of messaging challenges. Russia's objectives and motivations differ from China's. As we are seeing in events in the Ukraine, Russia has a more advanced disinformation and deception apparatus that requires that the US employ different approaches to convince the Russian populace—and the rest of the world—that democratic ideals are worthy values of governance. To be effective, a messaging strategy must incorporate understanding of history, culture, and the media environment of the target nation. In the case of Russia, the messaging strategy requires effective ways to undercut and displace false narratives promulgated by official Russian information agencies.

The United States faces mass propaganda designed to disrupt and divide societies. US efforts to counter the narratives that are controlled by others often fail because the US government lacks the global trust it once enjoyed. As a result, the United States is seen as internally conflicted and unable to control the operations of our own government.[25]

Cognitive Security: Truth Fighting its Way above the Noise

A cornerstone of a new and independent US information agency would be a focus on improving cognitive security, worldwide. Cognitive security is a new and emerging field that addresses how information provided to individuals and groups can be used to influence their beliefs and cognition, preventing them from forming their own rational beliefs based on truth and factual information.

In today's world, it is necessary to combat adversarial use of perception management, disinformation, and strategic deception. While there is nothing new about adversaries' use of these tactics, they have become far more effective given globalization and the speed of communications. Disinformation can now be targeted based on profile information concerning the recipient, rather than simply indiscriminately broadcast.

Historically, China has made considerable use of strategic deception through perception management. A 2009 study notes that they call it "psychological warfare."[26] The study states that "if China can discern its competitor's thought process through intelligence and guide it through deception and perception management, then it stands to reap considerable benefits as it pursues its own goals on domestic and international fronts." In 2013, the American computer security firm, Mandiant, revealed the extent of Chinese military cyber espionage efforts involving "Unit 61398" targeting US companies and individuals.[27]

As well, Russia has been highly effective at strategic messaging, whether via disinformation campaigns during the Cold War, through the coordinated use of diplomatic language, and/or the use of cyber-attacks. A warning was imparted to Estonia by cyber means in 2007.[28] Prior to the 2008 Russian incursion and occupation of portions of Georgia, a cyber messaging campaign was used.[29] Various financiers of the Russian Internet Research Agency and members of the Russian intelligence unit known as the GRU, are currently under US indictment for spreading cyber disinformation during the 2016 US election campaigns.[30] The recent invasion of Ukraine has been accompanied by Russian strategic messaging,[31] which reportedly continues to be quite effective in Russia as of this writing. Thus, we are seeing real-time experiments and engagements in countering disinformation through crowd-sourced intelligence and other messaging tactics.

The US has long been committed to the belief that people everywhere have the right to the truth, and to establish beliefs based on access to accurate information. Cognitive security includes practices, methodologies, tactics, and tools to defend against social engineering attempts—intentional and unintentional—to cause manipulations and disruptions to cognition and sensemaking.[32]

A reconstituted independent force such as the USIA could help establish a higher degree of cognitive security. The challenge is greater than it was a couple of decades ago, as the world—and communication technologies—have changed. The new organization could seek to establish trust through independence and dissemination of accurate information, in languages and context appropriate to the recipients. We are not advocating, nor would the population tolerate, countering disinformation with disinformation. A consistent and uniform message based on a strategy that conveys accurate and balanced information, worldwide, could replace a cacophony of uncoordinated ad hoc messages delivered by multiple agencies and multiple voices.

Such an independent function with the necessary authorities to create and manage information strategies would also require understanding the messages directed at US citizenry and proactively countering disinformation before it causes harm. Recently, in deterring Russian tactics in Ukraine, the United States pre-emptively released key intelligence information. With the increasing availability of open-source intelligence, such an approach might be effective, generally. Without stifling free speech, the agency could provide broader access to information, coordinate the messaging, and provide clarifications and access to the multiple views on events.

Reconstituting an Independent Strategic Messaging Capacity: Someone Has to Be in Charge

Reconstituting a capability similar to the USIA does not necessitate a new agency with direct control of all former USIA resources and functions, provided it has the authority and responsibility required to coordinate those functions across government agencies—it does not and cannot begin in a vacuum. USIA existed in the past, and it atrophied due to budget cuts and was absorbed into government. The Smith-Mundt Modernization Act of 2012 updated authorities in the Department of State and the Broadcasting Board of Governors (now known as the US Agency for Global Media [USAGM]) to globally disseminate information. The Voice of America still exists, albeit as a considerably reduced entity. Radio Free Europe and Radio Liberty (RFE/RL) exists as a private corporation with US government funding. The USAGM supervises the Voice of America, RFE/RL, and other media outlets. However, since 2017, the USAGM has been led by a presidentially appointed CEO rather than a bipartisan board. In forming a new organization or agency that can coordinate and guide these messaging functions, lessons learned from prior mistakes could inform existing and newly developed structures as a basis for reinvigorating US strategic messaging.

A new information agency would be different from prior iterations because the world has changed politically,

THE MISSION OF THE FORMER USIA

President Dwight D. Eisenhower drove the founding of the United States Information Agency (USIA) that led the strategic messaging and public diplomacy campaign during the entirety of the Cold War. The USIA's mission as originally constituted was to:

- Present and explain to foreign audiences US government policies and actions;
- Describe and explain American society, thought, and institutions;
- Provide objective and reliable news, commentary, and information about US and international events; and
- Provide surrogate programming where local governments curtail the free flow of information and where surrogate programming is in the US interest.

economically, and technologically. Methods of effective strategic messaging are now more sophisticated, and messaging can be better tailored to the target audiences with consideration of history and culture, and not just language. The new agency would need to draw upon expertise in messaging and regional cultures, utilizing both staff and advisors.

Enabling legislation would require careful crafting. The charter would need to ensure the independence of the organization and maintain its continuity across administration and legislature boundaries—free from political influence. Messaging should conform exclusively to accurate information, while still reflecting American core values. It would need to develop world trust, without taint of propaganda, but also proactively counter misinformation and deception that might be perpetrated by other nations and/or groups. The organization would ultimately be responsible to the American public, through budget and law.

One of the great messaging challenges is to convey the uniqueness of the US concepts of "individual freedom" and "individual rights." The US form of democratic government enables the individual to rank above the state in many instances (for example by directly voting for leaders at many levels of government, or in exercising certain constitutional rights). This idea rankles many foreign governments because it diminishes the importance of the party, castes, leaders, nobility, and government institutions. US democracy also motivates participation of individual citizens and serves as a beacon for much of the world's population. It supports ideals that include opportunities for the individual to progress up the economic and social scale. The charter of the agency should support the use of effective messaging to demonstrably relate the ideals and aspirations that make the US form of government admired.

If We Don't Control Our Narrative, Others Will

The United States is in a global information competition, where messaging is used by adversaries as a weapon against US interests. With its messaging strategies widely distributed, the United States is not effectively communicating a coherent narrative of accurate and favorable support for American ideals. Without understanding competing narratives and without contacts and strategies for countering disinformation, the US will lose the information war.

For the United States to be successful in this fast-paced societal-level competition, it must promote narratives that best support the US position in the global commons. To establish trust, the narrative should be based on our founding core ideals and the information must be presented fully and accurately, devoid of political or marketing influence.

Techniques for effectively motivating attitudes and behaviors, inspiring loyalty, and drawing people closer together have been championed by US corporations in their marketing and branding campaigns. Their techniques include developing an understanding of the audience's experiences and culture. Similar techniques can and should be adopted for a US messaging strategy.

The entity must coordinate an uncomplicated narrative that supports true goals in a strictly nonpartisan way, such that they can endure across administration and congressional change. Expertise assuring that messaging is heard and understood according to its intended effect (by the intended audiences), can be drawn from decades of advanced research and experience in regional histories and cultures.

The US must be consistent in maintaining a narrative domestically and abroad, and must be prepared to combat disinformation spread through numerous communications pathways in today's digital world. Trusted independent sources are necessary to achieve this desired level of cognitive security. The USIA was largely trusted as a defense against foreign propaganda. Given that disinformation is so easily distributed, such a trusted resource is needed now more than ever.

Endnotes

1 In his farewell address to the nation, Ronald Reagan quoted John Winthrop, a 17th Century pilgrim who came to these shores in a wooden boat.

2 Nicholas J. Cull. **"Henry E. Catto, Jr, 1989–91,"** in **The Embassy in Grosvenor Square: American Ambassadors to the United Kingdom, 1938-2008** eds. Alison R. Holmes and J. Simon Rofe (London: Palgrave Macmillan, 2012), Kindle: 270.

3 "**The United States Information Agency**," American Security Project, 2012

4 Kenneth A. Osgood. **"Form Before Substance: Eisenhower's Commitment to Psychological Warfare and Negotiations with the Enemy**," *Diplomatic History* 24(3) 2000: 405–33.

5 Sarah-Jane Corke. "**The Eisenhower Administration and Psychological Warfare**," *Intelligence and National Security* 24(2) 2009: 277–90.

6 "Text of **Gen. Eisenhower's Foreign Policy Speech in San Francisco**," New York Times, October 9, 1952.

7 Text of **Gen. Eisenhower's Foreign Policy Speech in San Francisco**.

8 Text of **Gen. Eisenhower's Foreign Policy Speech in San Francisco**.

9 Shawn J. Parry-Giles. "**The Eisenhower Administration's Conceptualization of the USIA: The Development of Overt and Covert Propaganda Strategies**," *Presidential Studies Quarterly* 24(2) 1994: 263–76.

10 Parry-Giles. "The Eisenhower Administration's Conceptualization of the USIA.

11 Gregory M. Tomlin. *Murrow's Cold War: Public Diplomacy for the Kennedy Administration* (Lincoln: Potomac Books, 2016).

12 "**Murrow at The United States Information Agency (USIA), 1961-1964**," The Life and Work of Edward R. Murrow, 2008.

13 For example, *New York Times*, "U.S.I.A.: Controversy over its Mission," November 30, 1969: 4, Sect E.

14 The Foreign Relations Authorization Act of 1973 and the "Zorinski Amendment" of 1985.

15 Nicholas John Cull. *The Decline and Fall of the United States Information Agency: American Public Diplomacy, 1989–2001* (New York: Palgrave Macmillan, 2012).

16 Kathy K. Fitzpatrick, *The Collapse of American Public Diplomacy* Public Diplomacy Alumni Association, 2008.

17 National Commission on Terrorist Attacks upon the United States. ***T*****he 9/11 Commission Report: Final Report of the National Commission on Terrorist Attacks upon the United States** (Washington, DC: National Commission on Terrorist Attacks upon the United States, US Government Printing Office, 2004).

18 Nicholas John Cull. *The Decline and Fall of the United States Information Agency*.

19 "**Counter Foreign Propaganda and Disinformation**," Global Engagement Center, U.S. Department of State, January 20, 2022.

20 Lindsey Borg. "**Communicating with Intent: The Department of Defense and Strategic Communication**." *Program on Information Resources Policy*, February 2008.

21 The Potomac Institute for Policy Studies **Forum on Global Competition: Strategic Communications and Information in Competition**, December 3, 2021.

22 "China's Space Program: Decision-Makers & Decision-Making," Phase One Communications Inc, 2012.

23 United States Department of Defense, **Summary of the 2018 National Defense Strategy of the United States of America: Sharpening the American Military's Competitive Edge**, November 2018**.**

24 United States White House, **Interim National Security Strategic Guidance**, March 2021.

25 "**Americans' Views of Government: Low Trust, but Some Positive Performance Ratings**," Pew Research Center - U.S. Politics & Policy, May 25, 2021.

26 E.C. Anderson and J.G. Engstrom. *China's Use of Perception Management and Strategic Deception Commission*, US-China Economic and Security Review Commission, November 2009.

27 Dan McWhorter, "**APT1: Exposing One of China's Cyber Espionage Units**," Mandiant, September 3, 2022.

28 Estonia planned to move a Soviet-era war memorial from central Tallinn to a military cemetery. Russia began sending angry diplomatic messages. When the work began, widespread cyber-attacks occurred all over Estonia, together with rioting by "ethnic Russians" living in Estonia. See: Ivana Kottasova. **How Russian Threats in the 2000s Turned this Country into the Go-to Expert on Cyber Defense," CNN June 18, 2021**.

29 John Markoff. "**Before the Gunfire, Cyberattacks**," *New York Times* August 12, 2008.

30 "**Grand Jury Indicts 12 Russian Intelligence Officers for Hacking Offenses Related to the 2016 Election**," The United States Department of Justice Office of Public Affairs, August 10, 2021.

31 Messages are targeted separately to the Ukrainian population and Russian-speaking separatists. See Daniel Brown, "**Russian-backed Separatists are Using Terrifying Text Messages to Shock Adversaries: And it's Changing the Face of Warfare**," *Business Insider* August 14, 2018.

32 "**What Is Cognitive Security?**" Cognitive Security and Education Forum, April 15, 2022**.**

Education of Americans Across Various Generations as a Preparation for Global Competitions

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AMERICA
MEXICO
GULF OF MEXICO
BELIZE
CUBA
BAHAMAS
HONDURAS
JAMAICA
PANAMA
ATLANTIC OCEAN

Introduction

Since the end of World War II over 70 years ago, the United States has led the world in technology development. The US spearheaded the development of capabilities (in space and with semiconductors, computers, lasers, etc.) and the education of generations of new scientists and engineers. Today, this leadership is under threat. The US needs to seriously reconsider its educational system to include both the results (outputs) and the associated research and development (R&D) investments that support and drive the system. Although the US maintains its global R&D leadership, US student performance in science, technology, engineering, and mathematics (STEM) may not be strong enough to sustain US educational leadership in the future technology competition on the world stage. The ongoing global competition for science and technology superiority has economic, military, and geopolitical consequences, and education and R&D investments are the most important levers of influence.[1]

Mega Trends in Global R&D Investment

American preeminence in science and technology has not happened by chance. Sustained commitments to education and investments in basic research have played key roles in establishing and maintaining the knowledge ecosystem and innovation driving US partnerships among academia, government, and the private sector. To compete in the global economy going forward, the US needs to renew its commitment to strengthen these key components of our national infrastructure.

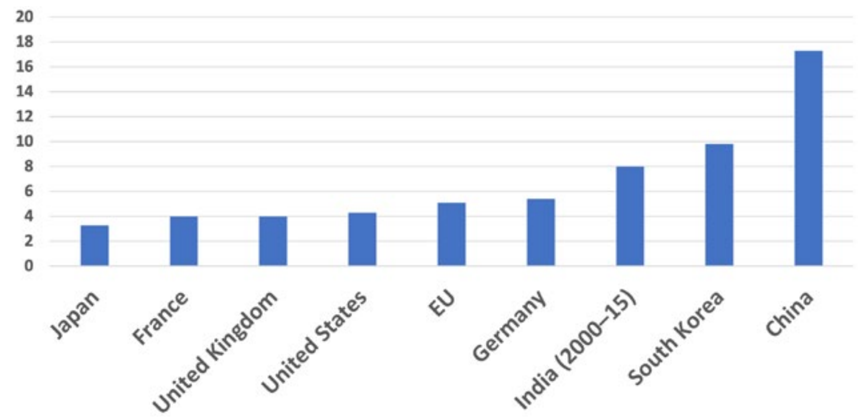
The US *share* of global investments in R&D has contracted in the post-World War II era, dropping from 70% of global R&D investments in 1960 to less than 30% in 2019. This occurred despite the fact that US federal R&D funding (in constant 2020 dollars) increased from $81B in 1976 to over $164B in 2020.[2] During the same period, total US R&D funding, including corporate and non-federal funding, rose from under $250B to almost $500B.[3] But, at the same time, the increase in total R&D investment in the rest of the world has dramatically surpassed the rate of increase in the United States (see Figure 1). For example, during 2000-2017, the Compound Annual Growth Rate (CAGR) in R&D was nearly 18% in China and about 10% in South Korea. This compares to a US CAGR of 4%. China is soon to overcome the United States in total R&D spending (see Figure 2).

It is not just total investment that has changed, but also the ratio of public to private investment in R&D. Today, public (government) investment has dropped to less than 30%; private sector (business, industry) investment continues to provide the growth in US R&D investment (see Figure 3). This shift changes the focus from scientific discovery to product development. To remain competitive, America needs to also invest in scientific discovery.

"Since World War II, advancements in science and technology have driven much of our economic growth, underpinned our national security, and transformed nearly every aspect of Americans' daily lives. New technologies built on federally-funded discovery research have led to new businesses, revolutionized health care, and created the mobile, digital world."

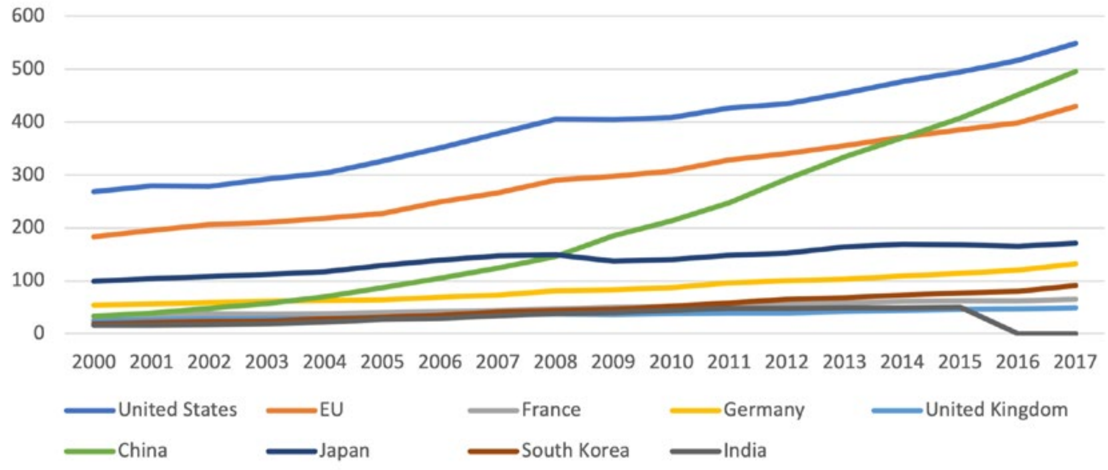
Diane Souvaine, Chair of the National Science Board,
before a Hearing of the House Committee on Science, Space and Technology on Jan 29th, 2020.

Figure 1. Compound Average Growth Rate Percentage of Domestic R&D Expenditures, by Country/Region 2000-2017.



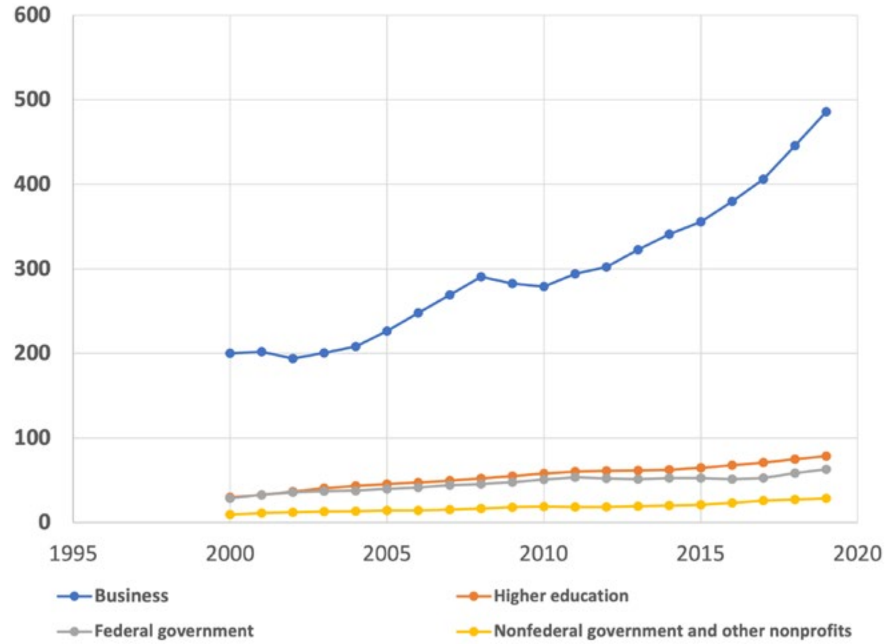
Source: NSF, National Science Board, Science & Engineering Indicators 2020, *The State of US Science and Engineering 2020*, Figure 13, p. 9. Data sourced from *NCSES, National Patterns of R&D Resources; OECD, Main Science and Technology Indicators 2019/1; UNESCO Institute for Statistics, Research and Experimental Development.*

Figure 2. R&D Spending by Select Countries Over Time. (Gross expenditures, not normalized as a percent of GDP.)



Source: NSF, National Science Board, Science & Engineering Indicators 2020, *The State of US Science and Engineering 2020*, Figure 11. *Data from NCSES, National Patterns of R&D Resources; OECD, Main Science and Technology Indicators 2019/1; UNESCO Institute for Statistics, Research and Experimental Development.*

Figure 3. US R&D Expenditures, by Performing Sector 2000-2019.



Adapted from: *NSF, National Science Board, Science & Engineering Indicators 2020*, The State of US Science and Engineering 2020, Figure 16. *Data from NCSES, National Patterns of R&D Resources*.

A strategy of fast-following is more profitable, but is not aligned with a national imperative of establishing an enduring competitive posture.

RECOMMENDATION 1

The United States must prioritize investment in basic science, R&D, and American people—particularly in scientists and engineers—to remain competitive in a global environment. This means increasing the US federal investment and developing policies that favor industrial investment.

Mega Trends in STEM Performance

Succeeding in a technological competition relies on people—scientists, mathematicians, data analysts, and engineers—in a workforce that drives the technology progress engine. Continuing signs indicate that the state of technological literacy in the US has been surpassed by other nations and is declining domestically. The impact of the shift in emphasis on R&D is manifest in student performance seen as early as middle school. The 2018 OECD Program for International Student Assessment (the PISA score) assessed the performance of 15-year-old students in math, science, and reading, and the results showed US deficiencies.[4] In fact, the US students' performance fails to keep pace with results in such diverse nations as China, Estonia, Canada, and Poland in all three assessed categories. Moreover, the US students' performance shows continued erosion over time.

How can a nation that birthed the information technology era, developed the semiconductor and computer industries, and landed the first man on the moon—and that spends so much on education—be in a competitively disadvantageous position?

RECOMMENDATION 2

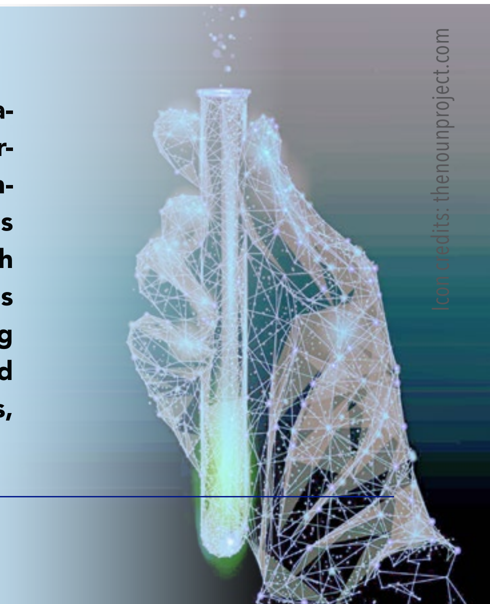
Fund the expansion of Dr. Freeman Hrabowski's University of Maryland Baltimore County model to other universities to expand the pool and diversity of domestic STEM students.

The economic incentives have not favored continued US dominance in basic (university) research in science and technology, and maintenance of US leadership in R&D globally. Culturally, we might contend that the United States has tended to value the accumulation of wealth, at least in the last few decades, over the accumulation of knowledge.

Past examples of great US scientific and engineering achievements were often accomplished with the aid of foreign-born scientists working within the United States. The making of the atomic bomb (the Manhattan project), the Apollo program to land humans on the moon, and human genome mapping leveraged basic science advances to make significant technological achievements. None of these would have been possible without non-US born scientists and engineers. The United States benefited from an influx of European physicists and mathematicians, German rocket scientists, Jewish immigrants, as well as many first- and second-generation scientists and engineers educated in the United States.

AN APPROACH TO "EXPERIENCED-BASED LEARNING"

US education needs new methods because US students are struggling with foundational studies and basic technological literacy. Dr. Freeman Hrabowski, from University of Maryland Baltimore County (UMBC) initiated a program that brings disadvantaged youth, who may not have had the appropriate preparation, to UMBC and takes the time needed to provide these students with necessary STEM skills, after which these students enter a standard engineering or STEM curriculum. This program uses "experienced-based" learning through internships and expanded lab time to bring the curriculum to life. His results have been phenomenal. Basically, Hrabowski turned the time-based 4-year college model into a skills-based approach. If it takes six years, does it matter if the United States gets a functioning engineer or scientist?[5]



Cultural differences may be reflected in graduate student demographics. Forty years ago, most hard science and engineering students were US citizens. From 1980 to 2020, the number of international graduate students in US universities rose from about 90,000 to 350,000 today—most in the hard sciences.[6] Over the same period, the total number of US university students rose by about 33%. Sources state that in 2017, 82% of electrical and petroleum engineering students were international, as were 72% of computer science, 71% of industrial engineering, and 70% of statistics graduate students in the US.[7] Yet more US graduate students are foreign-born US residents. Fortunately, stay-rates of foreign graduate students (i.e., the percent that remain in the United States after graduation) have increased, in part because of the 3-year "Optional Practical Training" program, with over half employed in STEM fields.[8]

The suggestion is that foreign cultures might value STEM education more than Americans, and that STEM fields are difficult and less appealing to US students. In a recent panel, Professor Dan Hastings from MIT said "STEM is hard, that is ok. It can also be fun." To get more US citizen students into the STEM pipeline, the United States may need to better encourage its young people to enjoy that hard work.

Cultural differences are accompanied by decreases in government funding support for R&D, which was reduced at the conclusion of the Cold War as part of the Peace Dividend. Government and military focus on global counterinsurgency after the 9/11 attacks stalled federal commitments to basic research in science and technology, in favor of more applied developments. These and other macroeconomic trends in US R&D investments were accompanied by large increases in R&D investments in science and technology by other nations, particularly China.

RECOMMENDATION 3

America has always been a nation built by bringing in the best from the world, which should remain a path forward today. The US government needs to examine how to enhance the number of H-1B visas given out to foreign students, and endeavor to bring them into US industry, academia, and select government positions.

The Economic Landscape of US Education: The Impact of Income Inequality

Education is America's key to establishing an enduring competitive advantage in science and technology. Before investments in research and development can be considered, the United States must reconsider how it invests in young people and how it funds education.

Public schools in the United States for kindergarten through 12th grade (K through 12) are largely funded by local sources: county and state. They are funded municipally by revenues gathered from property taxes (44% of total funding on average), and a portion of state tax revenues (income taxes and/or sales taxes) to account for another 48%, on average.[9]

Federal funding nationwide amounts to 8% of the sector. Public education is more likely to be well-funded in districts with valuable properties and in richer states. Conversely, schools located in poorer neighborhoods tend to have less funding, and those students who may need the most financial help are less likely to receive it.

The model of local financing of schools introduces a feedback loop. In the United States, one of the significant contributors to property value is access to "good" schools. The National Bureau of Economic Research discovered on average that "for every $1 spent on school funding, property values increased by around $20."[10] In this case, districts that have historically good schools see their funding increase, which leads to higher property values, which leads to more revenues to fund their schools. In Los Angeles, for example, homes in a "top-tier" school district sell for an average of 79% more than homes in an "average school district nearby."[11] This relationship has stratified the quality of public education across the country.

New models of financing education may be needed. Sometimes municipalities attempt to innovate entirely new systems of public education (e.g., charter schools).[12] Ultimately, the US needs a quality education system, which requires facilities and high-quality teachers. Education is costly, but it benefits the nation; the locality; and primarily, the educated person.

Private schools and private universities offer choice but are largely funded by tuition.[13] Elite universities also collect overhead on research, gifts, and endowments. State universities receive support from state resources to benefit the local population (employment, businesses, etc.). But, tuition payments (and room and board payments when appropriate) fund the administrative operations and education processes of private schools and universities.

The price of college in the United States has exploded over the last few decades. One analysis shows a constant dollar increase by a factor of 2:1 in average college costs from 1990 to 2021.[14] In a recent survey, 37% of American college applicants and 64% of parents, estimated that the costs of college are more than $100,000.[15] Total costs of attending a 4-year college can vary widely, but students who do not pay full fare are expected to take on loans. The current average federal student loan debt balance is more than $37,000, totaling over $1.6 trillion across Americans.[16] The amount of debt that a post-secondary student will incur depends greatly on the type of university, living arrangements, and the educational requirements of the program. If more than four years are required, as is often the case for STEM majors, the education will be more costly. The debt burden is not good for America,[17] but that is a separate issue. Financing models that encourage those who are not extraordinarily wealthy to take on debt greatly impact the choices made by US students contemplating their post-secondary education, which can contribute to a decline in US STEM talent.

US funding for education and incentives that influence student choice are important issues that need addressing. We also need to consider why college costs have risen so drastically.

One factor is the transition of higher education towards a competitive market landscape, where schools are incentivized to market themselves as something "more" than an educational institution. Athletics, amenities, and administrative support have broadly evolved into the leading factors in many students' decision for enrollment—including the cultural artifact of the "college experience." Given the choice between a school that offers a quality education and a school with an inferior quality but a "once in a lifetime social experience," many students choose the latter. This trend is counter to the United States' goal of cementing an enduring competitive advantage in STEM.

Another factor is that colleges and universities are incentivized to prioritize students that can pay full tuition. Today, the US can claim many world-class academic institutions that attract students from around the world who are able to pay full tuition. While most colleges state that they are "need-blind," drawing on a worldwide pool of applicants reduces the need to offer discounting (through scholarships) to qualified applicants. Since foreign students do not always stay in the US,[18] this also undermines the country's competitive advantage in STEM fields.

State funding for public universities has declined in the past decade by roughly 13% per student,[19] motivating tuition increases. Ironically, the availability of student loans contributes to tuition increases by removing some pressure for cost containment.[20] Increased access to higher education, in part due to the availability of low interest loans,[21] has increased demand on universities overall, which also results in higher tuition rates.

SCHOLARSHIP FOR SERVICE

A number of "scholarship for service" programs have funded the higher education of US students. In this model, the sponsor pays tuition, board, books, and even a stipend, in exchange for a guaranteed number of years of service to the sponsor following graduation (typically in a ratio between one or two years of service per year of sponsored education). In the US national security domain, the Department of Defense (DoD) has the Reserve Officer Training Corps program and the Science, Mathematics and Research for Transformation (SMART) program.[22] These programs provide military officers and civilian scientists and engineers advanced education for future employment in the DoD. The FBI and the intelligence community have similar programs. These types of programs could be expanded to other government agencies and industry. In addition to student service commitments, tax incentives or credits could further motivate industry to adopt such programs. In so doing, the nation could reduce future debt burdens and produce more scientists and engineers.

The Cultural Landscape of US Education

The prevailing wisdom, historically, is that one must go to a university and obtain a degree to be "successful" in life. This perception is true, based on many studies of lifetime earnings.[23] As a hiring filter, employers increasingly require a bachelor's degree.[24] The return on investment provided by a university degree is complex, and not universally accepted as a great deal; wage growth has been stagnant, and unemployment rates among recent graduates have been high.[25] Still, an undergraduate degree is undoubtedly a good deal—for both the student and the nation.

Whether due to perception or requirements, college enrollments increased rapidly from 1970 to present. In 1970, 7.4 million students were pursuing higher education in the US, and by 2010 this number had increased to 21 million.[26] (Interestingly, the number has plateaued since, with the pandemic causing further "great interruption" in enrollments.[27])

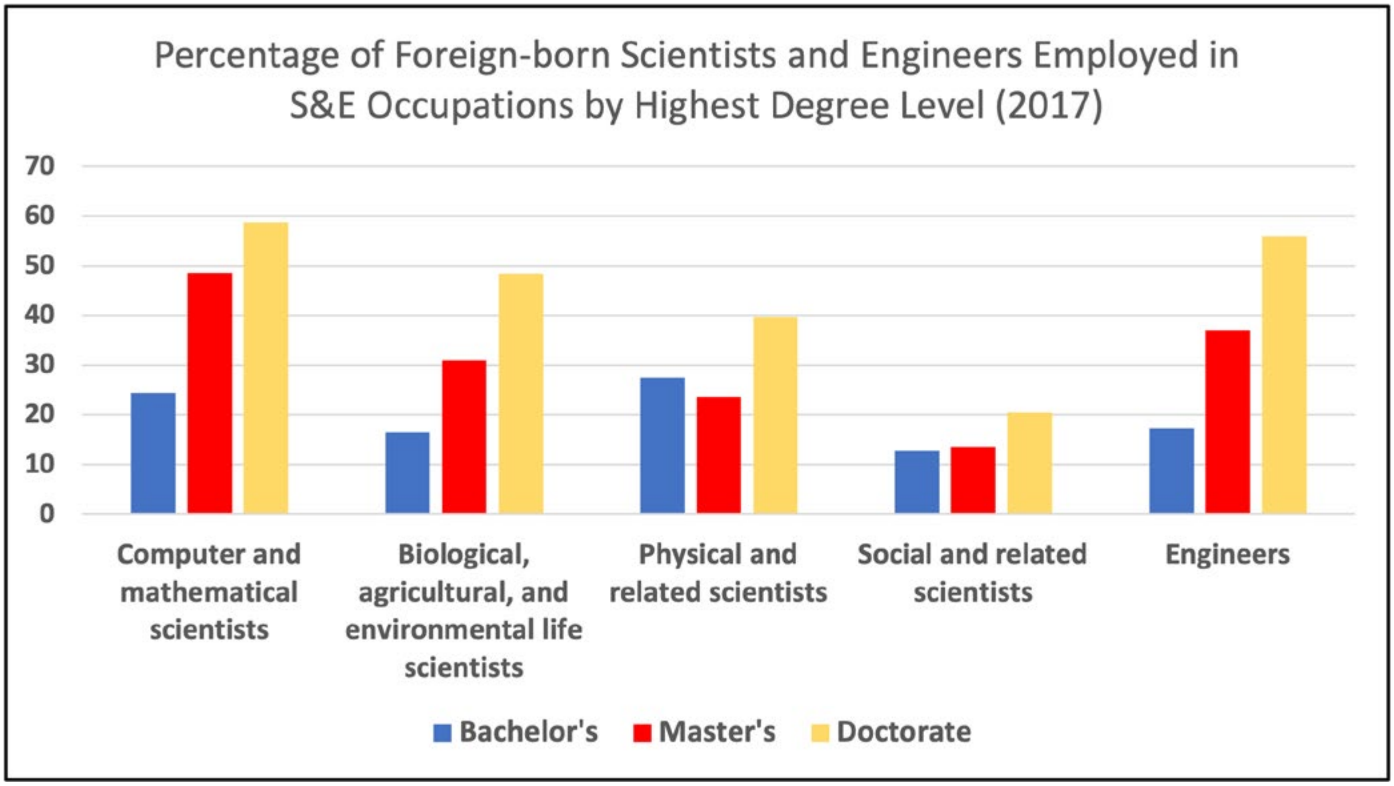
Motivations for higher education are changing. In one survey, over 86% of college first-years believed that "[being] able to get a better job" was "very important" in their decision to attend college, compared to the fewer than 60% that claimed "[preparing] myself for graduate or professional school" was equally as important.[28] Similarly, according to this same study from UCLA, the rate of respondents saying that "to make more money" was "very important" increased from 44.5% from 1971 to nearly 73% in 2014.[29] These trends in survey responses highlight a cultural shift towards an emphasis on financial rewards. Students may be highly motivated to pursue post-secondary education, but not to major in difficult STEM fields.

An education in STEM does not always translate to employment in STEM. The US Census Bureau states that out of the 50 million employed college graduates ages 25-64 in the US in 2019, "37% reported a bachelor's degree in science or engineering, but only 14% worked in a STEM occupation."[30] Graduates in STEM fields are in high demand, but not necessarily for STEM occupations. Management consulting firms and financial institutions seek students from elite institutions, observing that the talent pool is small and competitive, and "STEM professionals have become an integral part of the workforce in the finance arena… ."[31] Exceptional pay and benefits tempt graduates away from a career in the sciences to pursue other more lucrative opportunities.

The situation is slightly different for international students in the US. For visa reasons, foreign graduate students must maintain full study loads during school and are less likely to be recruited to a non-STEM career if they stay in the US with a STEM degree. Perhaps as a result, over half of US engineering and computer science workers with a graduate degree are foreign-born (see Figure 4).[32]

The cultural milieu in the United States has evolved significantly over the last half-century. Against the backdrop of the numerous economic pressures facing students and young people in the United States, there is cause for concern about the future of American competitiveness. Although rectifying the current situation is a monumental challenge, it is a challenge worth undertaking.

Figure 4. Foreign-born Individuals in Science and Engineering Occupations in US by Education Level.



Source: NSF, *National Science Board, Science & Engineering Indicators 2019, Science and Engineering Labor Force, Figure 3-24*.
Data from *National Center for Science and Engineering Statistics, National Science Foundation, National Survey of College Graduates (NSCG),* 2017.

The Factors for Migration Away from STEM Fields

In a recent forum of the Potomac Institute's Global Competition Project, panelists suggested reasons as to what could be driving the migration of American students to non-STEM fields.

The overriding reason, as suggested, is financial. The overwhelming cost of attending college in the US incentivizes students to pursue degrees outside of STEM, or to drop from STEM programs after beginning them, because they "cannot afford to fail and retake courses." Regardless of their talent or primary school experience, a STEM degree may be perceived as too risky given the burden of debt that will cripple them financially. They pivot their focus towards a subject area they believe is "easier" and less risky. One study in 2019 found that over 60% of college students dropped out of their STEM programs.[33] It is reasonable to suggest that students feel more likely to graduate with a degree in social sciences, humanities, and business.

Another factor for the migration away from STEM fields, brought up by the panelists, was the practice of introductory courses whose purpose is to "weed-out" weaker students. The suggestion is that STEM 101 courses are not designed to best prepare students for matriculation through their major but are designed to optimize the allocation of educational resources to a select few.[34] The selection process may be counter to the United States' goal of an enduring competitive advantage in STEM fields.

Class size may be another factor. In STEM disciplines, especially in introductory courses, large lecture-hall classes can be common, ranging in size from 100 to 500 students—with extremes of up to 1,000 students.[35] Quality and interactivity suffer, for efficiency. A 2021 study of the impact of class size on college students in the UK noted that large class sizes are "associated with significantly lower grades."[36] Talent in STEM may be lost as students migrate to other fields with more social experiences.

Employment opportunities and starting salaries play a role. Today, the highest paying tech jobs (those positions that demand STEM degrees) are in advertising optimization, social networking, workplace efficiency, quantitative investment analysis, payments processing, and other data analytic applications.[37] These businesses generally do not contribute to the US' competitive advantage in STEM, but they attract investments from venture capital and, thus, recruit the best STEM graduates.[38]

Today, many of the high-tech start-up companies that employ recent STEM graduates aim to be acquired by larger established companies. The start-up companies are not in the mold of large research enterprises of old, such as Bell Labs, Xerox Parc, Intel, or an early Apple. Instead, the start-ups focus on "quick wins" and demonstrations, and often do not persist at knowledge development after acquisition. STEM employees then migrate to other start-ups, or non-STEM endeavors.

To be competitive in the future economy of the world, the US cannot afford to have STEM students migrate to other fields and endeavors before their talent is discovered. The nation needs a larger cohort of students to matriculate through STEM education and to become gainfully employed in technology development for societal purposes to participate in the future economy.

A Braided River Model of Education

Today, education and career development in the US can be represented as a pipeline, i.e., a linear progression through elementary, secondary, undergraduate, and graduate education into a career. This model has been under question for some time.

An *Economist* magazine special report from 2017 proposes a changed viewpoint in the educational model.[39] Contrary to time-based block learning, where a person attends programs for a fixed number of years, the changed viewpoint constitutes a more "continuous learning" model. Many career fields operate this way already, for example, medicine, law, engineering, and accounting. In these fields, more experiential learning occurs up front with frequent refreshers, updates, and certificate credentials throughout a career.

This new model may be thought of as a braided river model (Figure 5), as envisioned by authors of a recent **EOS article** on STEM workforce development.[40] Continuous learning serves as an analog for the way we can view a typical career, with an "inclusive, responsive, and modern career development" process. The concept is to allow individuals to move along and in between multiple entry points through a STEM career, in distinction to a time-dictated "pipeline"

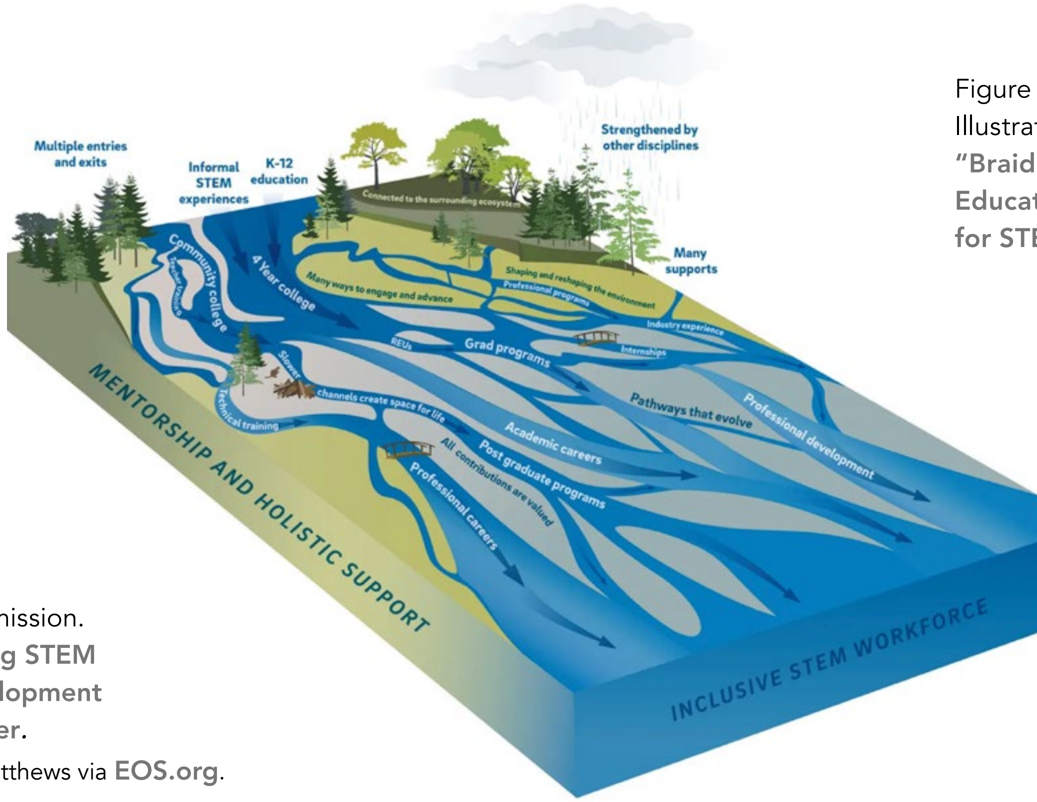


Figure 5. Illustration of the **"Braided River Education Model for STEM."**

Printed with permission. EOS, **Reimagining STEM Workforce Development as a Braided River**.
Credit: Jennifer Matthews via **EOS.org**.

that has only one main entry point, namely higher education. Partnerships among academia, government, and industry could allow for multiple entry points into STEM at any readiness level.

The model implies a very different approach to educational investments and funding. Much of the advanced education becomes the shared responsibility of the student and employer. Employment models such as the Military Reserve Officer Training Program and SMART (see **Scholarship for Service insert, page 25**) make tuition payments for advanced education. The GI bill has supported numerous college educations. Other scholarship and tuition payment service programs might accompany careers outside of the military. Government service might include student loan payments in pre-tax dollars. Mentorships, training programs, academic courses, and deployment mobility could provide greater freedom for people of all ages and career stages to pursue lifelong STEM careers and to contribute to US competitiveness in the future economy. Removing current disincentives for STEM development and replacing them with motivations and opportunities would require a major shift in investments in education and the associated funding models.

Conclusion

The United States should strive to expand its leadership on the world stage in science and technology. In the past, its position as the eminent leader in these fields provided a historically unprecedented quality of life for the average citizen and has been the foundational building block in its provision of national security. Policy-driven economic pressures should not be the reason that the United States loses its global competitive advantage. The US government needs to address the economic underpinnings of education to build a foundation for an enduring competitive advantage in STEM.

At the base of technological competition are people—the scientists, mathematicians, data analysts and engineers that drive the technological progress engine. If the US is to reestablish an enduring competitive advantage in STEM and technology, national education process reforms will be needed. Serious reconsideration of the federal government's relationship with both the private sector and state and local education will be required. The United States has the talent, universities, laboratories, and infrastructure to succeed, and to lead the world in technology development through superior research and science. However, disincentives and barriers to effective career development through STEM education must be overcome. Investments in education and career development within US enterprises of the young, talented, and motivated are necessary to establishing an enduring competitive advantage in science and technology.

Endnotes

1 Rogier Creemers, et al. "Translation: 14th Five-Year Plan for National Informatization – Dec. 2021." DigiChina. Stanford University. January 24, 2022.

2 American Association for the Advancement of Science. "**Historical Trends in Federal R&D**." October 2020.

3 The National Science Foundation. "**The State of U.S. Science and Engineering 2022**." January 2022.

4 Organization for Economic Co-operation and Development. "**PISA 2018 Results, Combined Executive Summaries**." 2019.

5 Freeman Hrabowski. "**Hrabowski: An Educator Focused on Math and Science**," Interview by Byron Pitts. *60 Minutes* November 13, 2011.

6 *Open Doors*. "**Academic Level**." Sponsored by the U.S. Department of State with Funding Provided by the U.S. Government and Supported in its Implementation by IIE. 2021.

7 Elizabeth Redden. "**Report Focuses on Graduate International Enrollment**," *Inside Higher Ed.* August 19, 2021.

8 Neil G. Ruiz and Abby Budiman. "**Number of Foreign College Students Staying and Working in U.S. after Graduation Surges.**" Pew Research Center's Global Attitudes Project. Pew Research Center, August 14, 2020.

9 Grace Chen. "**An Overview of the Funding of Public Schools**." Public School Review, March 31, 2022.

10 Lisa Barrow and Cecilia Elena Rouse. "**Using Market Valuation to Assess Public School Spending**." *National Bureau of Economic Research.* July 2002.

11 Barrow and Rouse. "Using Market Valuation."

12 Ballotpedia: The Encyclopedia of American Politics. "**Charter Schools in New York**." Ballotpedia. March 12, 2022.

13 Nathan Paulus. "**How to Pay for a Private School Education**." **MoneyGeek.com**. May 12, 2022.

14 Jennifer Ma and Matea Pender. "**Trends in College Pricing and Student Aid 2021**." New York College Board. 2021: p. 12.

15 The Princeton Review. "**2022 College Hopes and Worries Survey Report**." 2022.

16 Melanie Hanson. "**Student Loan Debt Statistics**." The Education Data Initiative. May 30, 2022.

17 Melanie Hanson. "**Average Time to Repay Student Loans**." The Education Data Initiative. December 16, 2021.

18 Xueying Han, et al. "**Will They Stay or Will They Go? International Graduate Students and Their Decisions to Stay or Leave in the U.S. upon Graduation**." PLoS One. NIH National Library of Medicine. March 11, 2015.

19 Michael Mitchell, et al. "**State Higher Education Funding Cuts Have Pushed Costs to Students, Worsened Inequality**." Center on Budget and Policy Priorities. October 24, 2019.

20 David O. Lucca, et al. "**Credit Supply and the Rise in College Tuition: Evidence from the Expansion in Federal Student Aid Programs**." Federal Reserve Bank of New York. July 2015, revised February 2017 .

21 Bhutada Govind. "**The Rising Cost of College in the U.S.**" The Visual Capitalist. February 3, 2021. Citing U.S. Bureau of Labor Statistics data.

22 Smart Scholarship Program. "**SMART Scholarship for Service Program**," May 2022; **Todaysmilitary.com**. "**ROTC Programs – Today's Military**," 2019.

23 William R. Emmons, et al. "**The College Boost: Is the Return on a Degree Fading?**" Federal Reserve Bank of St. Louis. July 17, 2018.

24 Joseph Fuller. "**Why Employers Must Stop Requiring College Degrees for Middle-Skill Jobs**," *Harvard Business School Opinion* December 18, 2017.

25 Brandon Busteed. "**The Convincing and Confusing Value of College Explained**," *Forbes Magazine* September 3, 2019.

26 Melanie Hanson. "**College Enrollment & Student Demographic Statistics**." The Education Data Initiative. April 22, 2022.

27 Bill Conley and Robert Massa. "**The Great Interruption**," *Inside Higher Ed.* February 28, 2022.

28 Catherine Rampell. "**Why Do Americans Go to College? First and Foremost, They Want Better Jobs**," *Washington Post* February 17, 2015.

29 Rampell. "**Why Do Americans Go to College?**"

30 Jennifer Cheeseman Day and Anthony Martinez. "**STEM Majors Earned More than Other STEM Workers**." United States Census Bureau. June 2, 2021.

31 Amy Meadows. "**A Sign of the Times – How the Finance Industry is Embracing STEM Professionals**" Bloomberg. August 28, 2017.

32 Amy Burke, et al. "**The State of U.S. Science and Engineering 2022**." National Science Foundation, National Science Board. 2022.

33 Student Research Foundation. "**Why Do 60%+ of College Students Drop out of STEM Programs?**" December 3, 2019.

34 Dalmeet Singh Chawla. "**Surviving Weed-Out Classes in Science May Be a State of Mind**." *New York Times* November 16, 2020.

35 The University of California Berkeley, Office of the Vice Chancellor of Finance. *Our Berkeley*, "**Class Size**." 2022. OPA – University of California Berkeley.

36 Elif Kara, Mirco Tonin, and Michael Vlassopoulos. "**Class Size Effects in Higher Education: Differences across STEM and non-STEM Fields**." *Economics of Education Review* (82) June 2021.

37 **BuiltinSF.com**. "**50 Best Paying Companies in the Bay Area 2021**." 2021.

38 Statista Research Department. "**Value of Venture Capital Investment in the U.S. 2021, by Industry**." *Statista*. April 13, 2022.

39 The Economist. "**Lifelong Learning is Becoming an Economic Imperative**." January 14, 2017.

40 R. L. Batchelor, et al. "**Reimagining STEM Workforce Development as a Braided River**" *EOS* 102 April 19, 2021, See: **https://eos.org/opinions/reimagining-stem-workforce-development-as-a-braided-river**.

DON'T FORGET ABOUT MEMORY

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Introduction

Semiconductors come in various flavors—logic, analog, sensors, memory, and others. While all play important roles in modern electronic systems, the insatiable demands of today's aptly named "data economy" make memory one of the most critical. Everything from data centers to communication networks to cellphones are dependent on large amounts of memory to safely store the information on which we rely. And while ongoing shortages of critical components remind us of the importance semiconductors play in our consumer products, we cannot take for granted the critical memory devices that make our world of instant information possible.

The US semiconductor Industry is at an urgent inflection point. Geopolitical tensions are shining a light on the growing risk from decades of declines in US semiconductor manufacturing, eroding from 37% of worldwide capacity in 1990 to just 12% today.[1] Efforts are underway to explore how the United States can revitalize growth in onshore, sustainable semiconductor production, using the same kinds of incentives that continue to tilt the playing field towards Asia.[2]

Semiconductor memory has been at the center of this maelstrom for decades. While less visible than the semiconductor logic sector, reliable access to secure memory technology is critical to the US economy and national security.

A glance at nearly any printed circuit board will reveal a sea of memory packages, both DRAM (traditional "fast" main memory) and NAND ("storage" memory). Each package often contains multiple stacked chips, most often making memory the largest ingredient of system silicon. For example, in an average cell phone, over half of the total silicon area is memory.[3] Data center servers now resemble large memory buffers—leading-edge machines can hold the equivalent of nearly three full 300mm wafers of DRAM and more than five of NAND.[4] And memory requirements continue to increase rapidly.

For example, artificial intelligence (AI) applications rely on massive stores of captured data residing in memory to hunt for the most critical patterns. Larger databases, faster networks, more powerful sensors—innovations at the core and edge—all are part of the trend demanding a need for more memory.

However, as the memory industry continues to grow in importance, it is also escalating in risk. As one of the first semiconductor segments to globalize, it has experienced a history of vicious economic cycles and spectacular bankruptcies, where suppliers often find themselves competing against entire countries. Decades of asymmetric nation-state subsidization combined with skyrocketing capital and research and development (R&D) requirements have left a dwindling number of suppliers, all with challenging margins and a manufacturing base located almost exclusively in Asia. China is now the latest in a long list of Asian countries to subsidize memory production: The "Made-in-China 2025" initiative specifically named domestic semiconductor production as a top priority[5] with a goal of protecting national security.[6] Initial efforts have focused on memory, and the emergence of two well-funded Chinese memory suppliers in 2019 demonstrates they are serious.[7]

Accordingly, the challenges of the memory industry present an urgent risk to US national security and well-being.

Today's Memory Landscape

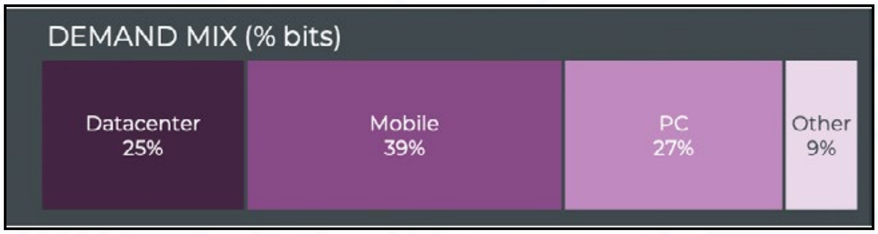
The memory industry accounts for $154B in sales in 2021, comprising 28% of the global $556B semiconductor market, and is equivalent in size to the entire category of logic (comprising CPUs, accelerators, FPGAs, etc.).[8] However, memory drives a disproportionate 34% of the industry capital expenditures,[9] yet with lower average margins than the logic industry.[10,11] The vast bulk of memory revenue is driven by product sales of DRAM and NAND into data centers, cellphones, and PCs, as illustrated in Figures 1 and 2.[12,13]

Five decades of intense, globalized competition and asymmetric state-sponsored subsidies have led to a hyper-competitive oligopoly (see **History of the Semiconductor Memory Industry** sidebar). Today, Samsung of South Korea commands roughly double the market share of the two next largest suppliers: SK Hynix (also of South Korea) and Micron Technology (of the US). These three companies together comprise 94% of DRAM revenue and 60% of NAND revenue.[14] The notables in the remainder are all single-technology NAND providers: Kioxia Memory of Japan (spun out from Toshiba Corporation in 2018); Western Digital (arising from their 2015 purchase of SanDisk and sourcing NAND from the same fabs as Kioxia in Japan); and Solidigm, the previous NAND operation of Intel (recently acquired by SK Hynix, however not yet consolidated, with fab operations in Dalian, China[15]). The most recent entrants of note are NAND-focused Yangtze Memory Technologies (YMTC), in production with competitive 128-layer 3D NAND,[16] as well as the DRAM-focused ChangXin Memory Technologies (CXMT),[17] both funded by a mixture of Chinese private equity and government sources including "The Big Fund."[18,19]

The concentration of semiconductor fabs in Asia is even more extreme for memory than other semiconductor segments (see Figure 3). Not a single advanced DRAM or NAND fab remains outside Asia due to ongoing national subsidization, expansions to existing facilities, a stable utility infrastructure, and other factors. Samsung and SK Hynix operate fabs in South Korea and China, producing memory used by their own system products such as cellphones, as well as for merchant sales. Even the advanced fabs of pure-play memory supplier Micron are exclusively located in Asia, principally by virtue of acquisition, joint ventures, and expansion over the years.[20] The lone 300mm memory fab on US soil is operated by Micron in Manassas, Virginia, and is focused on production of older-generation devices. These more mature devices are of growing interest to markets such as defense, automotive, industrial, and medical, that no longer need the most advanced, highest density devices.[21]

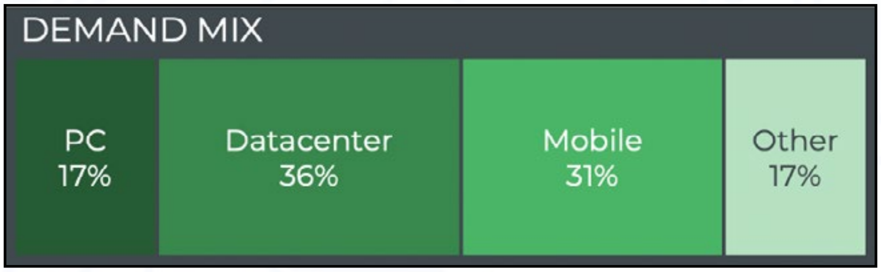
Continued page 37.

Figure 1. NAND Market Segments



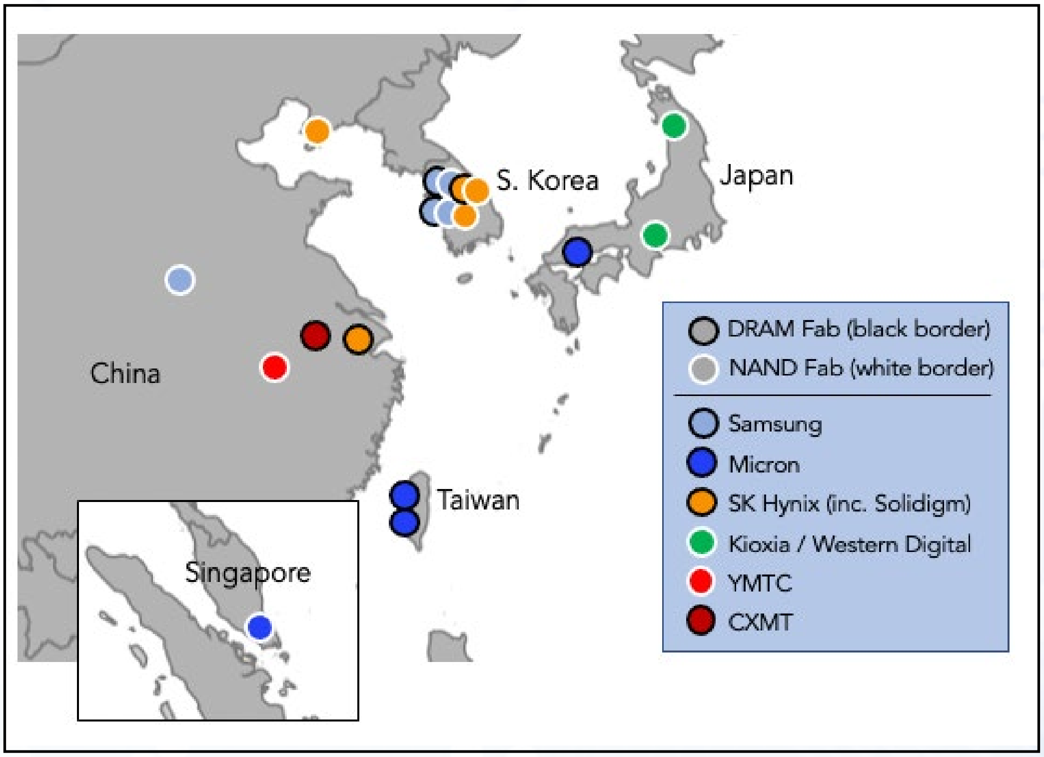
NAND Market Monitor Q2 2022. *www.yolegroup.com* © Yole Dèveloppement 2022 Reprinted here with permission from Yole Group.

Figure 2. DRAM Market Segments



DRAM Market Monitor Q2 2022. *www.yolegroup.com* © Yole Dèveloppement 2022 Reprinted here with permission from Yole Group.

Figure 3. Advanced DRAM and NAND Memory Fabs



Based on *Yole Q1 2022 DRAM/NAND Market Monitors.* Excludes fabs focused on mature/legacy technologies Solidigm included with SK Hynix based on acquisition.

History of the Semiconductor Memory Industry

The commercial memory industry dates back to the early 1970s, when Robert Noyce and Gordon Moore, in the first seminal years of Intel, helped spur the invention of the first commercially viable "Dynamic Random Access Memory" (DRAM).[22] This 1-kilobit DRAM design was Intel's first mass-produced product, conceived as a small but fast working memory between a computer's processor and the magnetic core main memory of the time, taking advantage of the recent advent of silicon metal oxide semiconductor (MOS) transistor technology.[23] The DRAM concept quickly evolved thanks to improving yields, key technical advancements from Bob Dennard of IBM[24] and others to reduce the size of the cell, and the dawning realization that silicon transistor densities had a path to continue growing exponentially at a stable cadence (the birth of Moore's Law). [25,26]

The memory industry thus became one of the key enablers of modern computing systems, helping to drive the overall semiconductor industry. Through decades of brutal, boom/bust cycles as successive Asian countries sought to dominate the market, it has never been an industry for the faint of heart. The importance of memory has only continued to grow, supplying the linchpin components critical to powering today's data economy.

The 1970s saw a dramatic expansion in DRAM densities, growing to 64 Kbit designs by the end of the decade. Demand increased with the continued growth in corporate computing and the phase-out of commercial magnetic core memories. The decade also saw an explosion of DRAM manufacturers, with system companies such as IBM, AT&T, and Motorola developing DRAMs for their own end systems, as well as several merchant suppliers joining the party, such as Texas Instruments, Mostek, and National Semiconductor. Standardization of the DRAM interface helped lower the market barriers to entry, while the easily testable, repeating patterns of DRAM arrays provided an easy gateway product to prove out production lines for more sophisticated products.[27]

The 1980s saw the memory market become both international and commoditized, with the rise of the personal computer (PC) and DRAM manufacturing by several well-funded Japanese companies driving cost competition. By the end of the decade, companies such as Toshiba, NEC, and Hitachi dominated the DRAM market, forcing out most US suppliers. [28] Intel exited in 1984, as well-documented by Intel CEO Andrew Grove.[29] IBM continued large-scale internal production for their own systems, while other merchant suppliers such as Texas Instruments pursued overseas operations with the help of partner cost-sharing and subsidies.

Urgent congressional inquiry into the declining competitiveness of US semiconductor manufacturing drove the start of Sematech, originally conceived as a national memory production center, but quickly re-chartered as an R&D consortium, initially led by Robert Noyce. Further calls for protections around US manufacturing culminated in the US Japan Semiconductor Trade Agreement of 1986, spurring Japan to significantly reduce DRAM production. However, with most US suppliers already having left the business, and with DRAM demand soaring, the moves paradoxically led to a DRAM shortage that left many system companies unable to purchase sufficient supply.[30,31]

Throughout the 1990s the demand for memory continued to skyrocket, driven increasingly by the exploding PC market and the "Win-Tel" PC cycles of Microsoft and Intel, demanding an ever-higher level of internal memory with each new product release and resultant improvements in computing power. The decade also saw a continuation of hypercompetitive boom-bust cycles. Wild price swings were caused by relatively modest supply and demand imbalances coupled with 1) the time lag to bring on new capacity when needed (due to fab construction lead-times), and 2) the unwillingness to idle capacity when not needed (due to high fixed-cost investments).

The decade also saw the emergence of South Korea as the new DRAM manufacturing powerhouse, with Samsung, Hyundai, and Lucky Goldstar supplanting many of the Japanese leaders by the end of the decade. Hyundai and LG operations merged to form Hynix after the 1997 South Korean financial crisis.[32,33] Multiple Japanese entities exited DRAM production, with NEC and Hitachi combining operations into a pure-play DRAM spin-out in 1999 named Elpida Memory. Texas Instruments likewise retreated from the memory market in 1998 by selling its DRAM operations to the United States' Micron Technology.[34,35]

The 2000s saw multiple Taiwan vendors enter the market,[36] and a push from 200mm to 300mm wafers, requiring massive capital investments for brand new fabs and equipment. The 2001 tech crash and the 2008 financial crisis drove even wilder market gyrations, with significant industry losses. Investigations of price fixing during the 2001 downturn led to guilty pleas by all five of the largest international memory vendors.[37] In 2009, Qimonda of Germany declared bankruptcy after multiple bail-out packages had been extended, drawing an end to Europe's DRAM ambitions.[38]

A new form of memory called NAND Flash was commercialized in the 2000s, loosely descended from the original Erasable Programmable Read-Only Memory (EPROM), another early Intel innovation.[39,40] Although slower speed than DRAM and with each cell able to be rewritten only a handful of times, NAND devices offer much larger densities than DRAM and can retain data without power (i.e., non-volatility). NAND flash eventually overtook large portions of the hard-disk drive market in the form of solid-state drives (SSDs). NAND memory plays a critical role in PCs, cellphones, and server systems, occupying a layer of the "memory hierarchy" between large but slow hard disk drives, and the fast but low-density DRAM main memory.[41,42]

The 2010s saw the slowing of the PC market. Demand for DRAM and NAND continued, however, driven by the consumer cellphone market and the enterprise datacenter market. By this point, the increasingly difficult technology transitions required massive annual R&D investments similar to those in the semiconductor advanced logic industry. Combined with the large capital requirements, only the largest operations were able to survive, effectively leading to an oligopoly.[43,44] Samsung retained dominant market share in both DRAM and NAND, expanding beyond South Korea into mainland China for NAND production, and benefitting from in-house consumption of memory thanks to its large cellphone and systems divisions. Similarly, Hynix of South Korea expanded production in China with their DRAM facility in Wuxi. After defaulting on its loans in 2009, Hynix was put up for sale and subsequently rescued by the SK Group, which, at that time, was the third largest of the South Korean family-owned businesses. After a Japanese government bail-out in 2009 and declaring bankruptcy in 2012,[45] Elpida Memory was purchased in 2013 by Micron, now the only combined DRAM and NAND pure-play operation left in the world.[46]

China's announcement in 2015 of the "Made in China 2025" policy initiative made clear however that both DRAM and NAND were of significant interest to Chinese national security, and that the 2020s would see the rise of indigenous Chinese memory production. Indeed, by the end of the decade, two Chinese memory companies had come forward—DRAM-focused CXMT and NAND-focused YMTC.[47]

DRAM and NAND densities have continued to increase exponentially, achieving single component densities of 16 Gigabit and 512 Gigabit respectively by 2022. Both technologies pioneered vertical fabrication well before microelectronic logic devices, in DRAM's case with a foray into deep substrate trench capacitors, and eventually with all vendors settling on narrow skyscraper-like "stacked" capacitors.[48] In the case of NAND, the push for more density first drove multiple bits per cell, leading in some cases to mere single digit numbers of stored electrons distinguishing between stored data states. Then NAND memory devices also "went vertical," with the NAND cells assembled into long vertical chains, increasing density even further, and helping surmount noise issues that had stalled any continued scaling in planar structures.[49]

Figure 4. DRAM Market Share 1970-2020

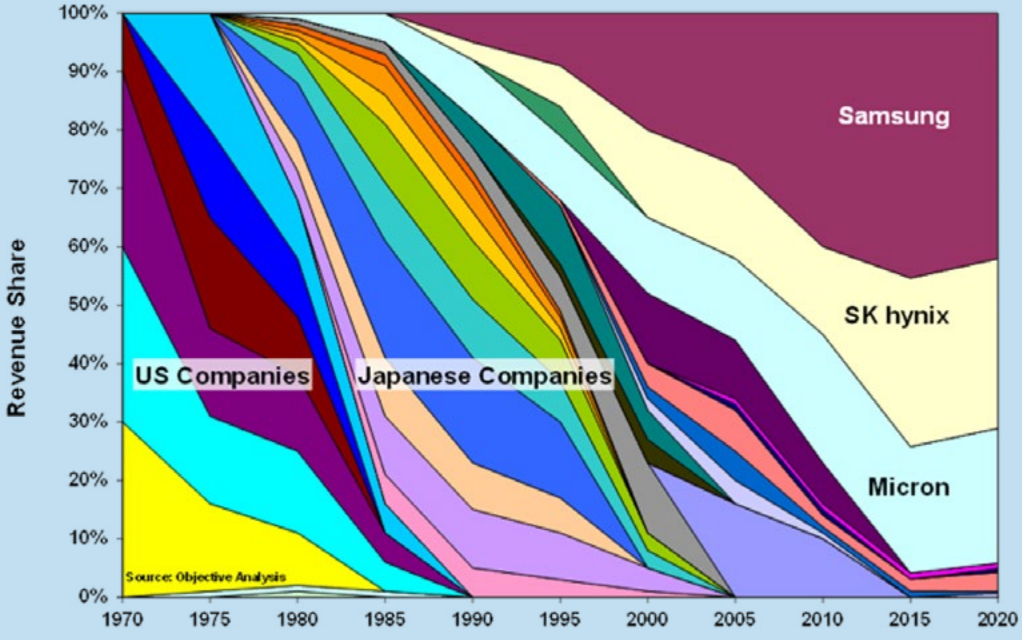
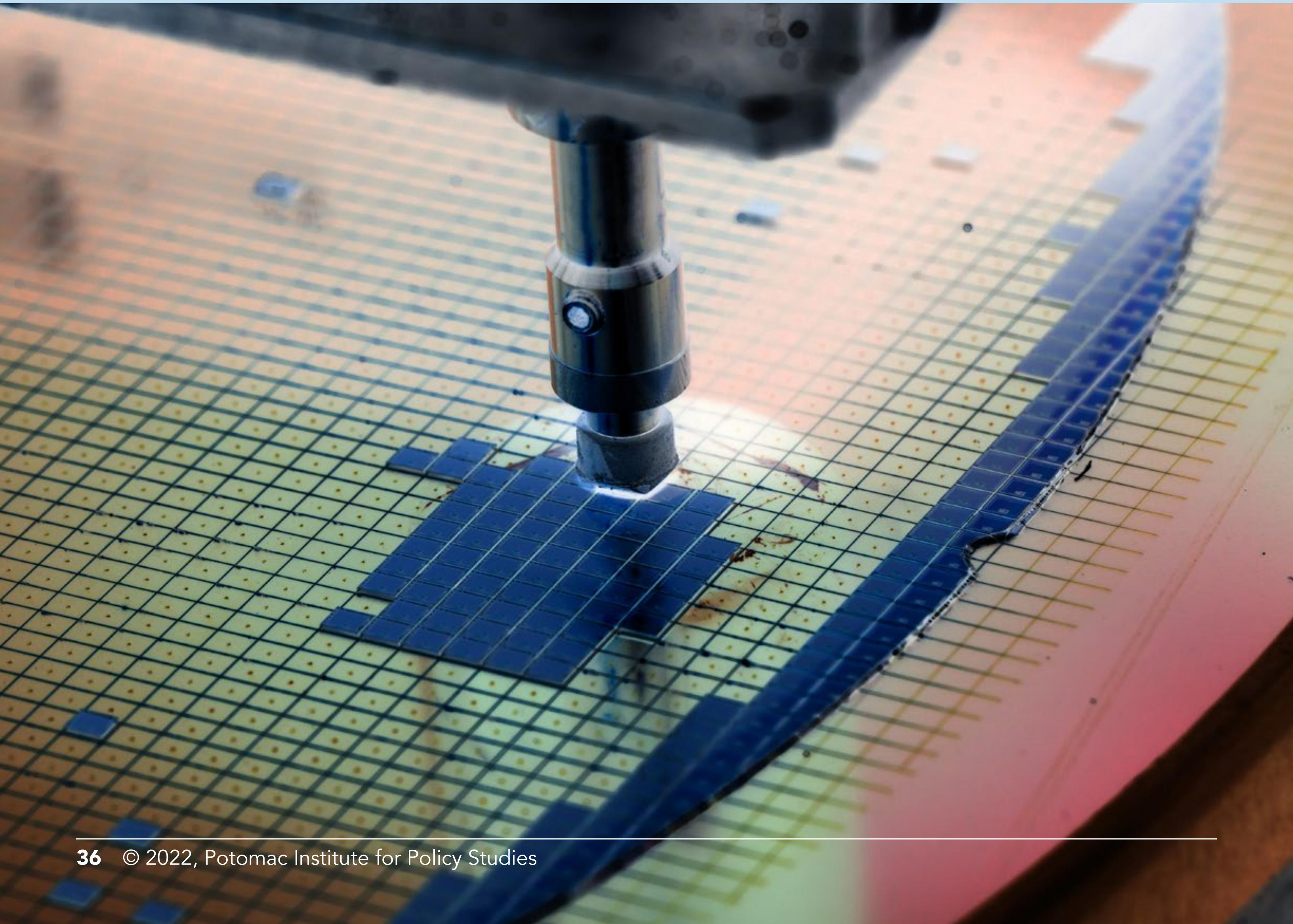


Chart Courtesy of Jim Handy, Objective Analysis **www.objective-analysis.com**.

Starting in the 1980s, it has been a recurrent drumbeat that memory "likely can only scale one, possibly two more generations."[50] These concerns also helped spur a continual search to find "the holy grail" of memory technology—a new memory mechanism that could accomplish a better set of tradeoffs in cost, scalability, speed, endurance, and non-volatility, without relying on electric charge as the storage mechanism. Massive R&D efforts and dozens of dedicated startups were committed to finding winning alternatives. Many technology concepts appeared in research papers within industry journals. A smaller number made their way to actual prototypes and an even smaller number made it to low-volume production, but very few made it to levels of production that could sustain commercial interest for stand-alone components. While the future scaling of both DRAM and NAND is as challenging as ever, it is a testament to the strength of the original concepts as well as continuing innovation over the decades that DRAM and NAND have kept barreling through every prediction of imminent demise.

Despite the technical success of the memory industry, and the increasingly critical role memory plays in electronics, the economics of the industry have always been severely challenging. The industry earned essentially zero economic value from 1996 to 2012,[51] due to significant asymmetric national investments by multiple Asian countries. Consolidation, as well as the growing technical and financial barriers to entry, helped somewhat stabilize the industry; However, decades of turmoil have left a production base for advanced memory located exclusively in Asia, and China's investments are coming on strong, driving countries such as South Korea to double-down on semiconductor incentives benefitting indigenous memory suppliers.[52,53,54] The current price tag for a new fabrication plant is around $15B and growing, with an ongoing requirement for any serious vendor to invest multiple billions annually both in R&D and ongoing fab upgrades.[55] Storm clouds are indeed growing again for memory.



Labor cost is no longer a major factor in locating fabs, given the high levels of automation common to all 300mm semiconductor operations. However, competitive cost pressures have driven a need for massive scale. New memory fabs today aim for minimum capacities of 100,000 wafers per month, which is significantly larger than most logic fabs. This drives capital and construction costs well past $15B for a new facility.[56] At that scale, and with challenging and volatile industry margins, organic funding is unrealistic. Thus, a major consideration in the industry is access to investment incentives.

The investment for a new fab is so large that any delay to the project can bankrupt the supplier. A new fab must be pulled into production as fast as possible to start generating cashflow. Suppliers drive fast ramps and minimize risk by focusing the fab on high-volume customer-qualified products. Speed of permitting and fab construction are also crucial. Countries such as South Korea, China, Taiwan, and Singapore help speed time-to-market, offering pro-business regulatory climates, as well as agencies that help with permitting and construction fast-tracking.[57,58]

Once a memory fab is operational, it must continually be recapitalized with new equipment to produce the most advanced technology, upgrading much more frequently than fabs in other semiconductor sectors. Ongoing annual upgrades can easily cost over a third of annual revenue.[59] While a steep bill to pay, especially in market downturns, these investments are necessary to stay competitive as multiple bankruptcies over the decades can attest.

The size of both the initial and ongoing fab investments, as well as China's leap-ahead investments in memory have driven other countries to continue subsidies and favorable tax treatment—notably South Korea, home to both Samsung and SK Hynix. In 2021, South Korea announced a suite of capital, R&D, and other incentives for domestic semiconductors manufacturers meant to spur total investment of over $450B through the next decade.[60]

Research and Development in the Memory Sector

The need for advanced higher density memory pushes suppliers to the edge of Moore's Law, all to continually pack more memory cells on each chip. This is notoriously costly R&D that is growing more prohibitive every year, requiring investment in new prototype equipment and dedicated cleanrooms as established technologies run out of steam. (This is true for all semiconductor sectors, with only a small handful of suppliers able to afford advanced R&D and tooling.)[61] Experiments, short-loop trials, and eventually full-flow prototype wafers must be refined through multiple iterations, pushing the limits of advanced photolithography, etching processes, and new materials, all driven by brutally competitive time-to-market pressures. While both advanced memory and logic share the same mandate to continuously shrink feature sizes, the unique specialization of each field limits opportunity for synergy or cost-sharing.[62]

Memory companies also invest R&D in product and system design enhancements to optimize for applications such as graphics, AI, and communications. Reducing power consumption is a constant priority, attempting to offset the added power from exponentially increasing chip densities and faster interface speeds. New data center interface standards such as Compute Express Link (CXL) allow larger banks of various types of memory to elegantly operate outside of traditional main memory slots.[63] Active research is attempting to move portions of logic into the memory fabric, to help reduce data movement in systems optimized for artificial intelligence, thus saving energy and reducing system bottlenecks.[64] Innovations in solid-state drives (SSDs) help deliver large performance gains to data centers and PCs, integrating dozens of NAND components together with logic controllers and firmware. These memory sub-systems also highlight the unique security risk of information storage, and the need for secure, high-integrity memory modules.[65]

Even packaging processes, once considered relatively mature, now require significant investment in both R&D and capital. Applications such as cellphones and "wearable" devices must pack multiple memory devices close together to achieve small form-factors. Techniques placing advanced DRAM and NAND packages directly on top of the processor, as well as stacking thinned layers of NAND into a single terabyte package are already in high volume production.[66,67] DRAM was one of the first technologies to achieve "3D" packaging, specifically for data center AI applications. Such "high-bandwidth memory" packages route signal connections through the DRAM stack itself, using wafers that have been thinned to less than the width of a human hair, and thousands of carefully aligned "Through-Silicon-Vias" that pass the signals through the stack, buying speed and reducing power.[68] Many of these advanced packaging processes must be performed inside the fab itself, belying the perspective that packaging is "old technology."

Taken in aggregate, the investment required to enable next-generation technology in the memory industry (adding together annual R&D and capital expenditures [capex] as a percentage of revenue), is higher or equal to other sectors, which also feature significantly larger margins. For instance, Micron (as the last remaining pure-play DRAM/NAND supplier), invested on average 50% of annual revenue into R&D and capex over 2019-2021, with an average operating margin of 23% over that time, and with all capital reinvested in existing fabs. By comparison, Texas Instruments, which is a leading US provider of analog components, invested 18% of revenue over the same time, with a 3-year operating margin of 44%. TSMC, a leading logic foundry based in Taiwan, invested a comparable 53% of revenue (of which a portion went to construction of new fabs) but with 40% operating margins.[69,70] While point comparisons across sectors always have caveats, the results highlight the steep investments required in the memory industry, despite thinner profit margins.

The Need and the Way Forward

Memory is not only more important than ever, but more difficult than ever. To be competitive, suppliers must continually invest larger sums in capital and R&D, despite challenging margins. The industry's advanced fabs are all located in Asia, with several in China already and more coming, and with the biggest suppliers using large portions of their memory production in their own systems. Organic affordability of new memory fabs is no longer feasible. The global playing field is not level, due to ongoing asymmetric subsidization in Asian countries that have recognized memory's importance. Absent appropriate attention, the US risks loss of access to the ever-growing amounts of secure memory that is foundational to the nation's critical infrastructure, and overall economic and national security health.

Recommendations

1. **ELEVATE THE PRIORITY OF ADVANCED MEMORY PRODUCTION** on US soil as a critical national security priority
2. **EXTEND INVESTMENT TAX CREDITS** competitive with Asia to drive sufficient domestic memory fab reinvestment
3. **EXTEND R&D TAX CREDITS COMPETITIVE WITH ASIA** to help defray the exploding costs for development of next-generation memory technology
4. **STREAMLINE THE SEMICONDUCTOR FAB REGULATORY PROCESS** to ensure competitive memory fab construction "time-to-market"
5. **PROVIDE INCENTIVES FOR ONSHORE MEMORY PACKAGING CAPABILITIES** necessary to complete a secure supply-chain

We thus propose a set of recommendations meant to ensure sustainable US access to advanced memory sufficient for national security.

These recommendations would help ensure US national and economic security are not at risk from multiple decades of asymmetric offshore incentives. While many argue against any form of active US industrial policy, these proposals merely level the playing field with countries that have methodically grown thriving semiconductor manufacturing environments over decades, using these same incentives for their domestic suppliers.[71] And a thriving semiconductor fabrication and R&D base drives significant, well-documented benefits in high-value job creation, driving domestic economic activity.[72]

These same incentives would also benefit other semiconductor sectors. In fact, several are now starting to confront the risks from similar asymmetric offshore incentives.[73] However, memory is the most urgent sector, given its recognized importance as the key enabler of the data economy, the exploding investments required to remain competitive, and the results from a long history of distortions. The following are comments on each recommendation in the context of the memory sector.

1. **Elevate advanced memory production on US soil as a critical national security priority.**

   The US should prioritize advanced memory production on US soil as a key priority of incentives such as those contemplated in the CHIPS bill. Secure production of memory (DRAM and NAND) in sufficient quantities for US critical infrastructure needs is crucial for enabling our digital systems. Advanced memory production remains under threat from ongoing nation-state subsidies that continue to tilt the playing field outside the US. The US cannot tolerate risk to supply-chain disruptions of such an important ingredient of critical infrastructure. Supplies of other semiconductors from on-shore facilities will not matter if supplies of memory chips are limited.

2. **Extend investment tax credits competitive with Asia to drive sufficient domestic memory fab reinvestment.**

   Such credits are critical to the memory sector, enabling crucial ongoing reinvestment in existing fabs and helping to ensure that new fabs can be built when market conditions warrant. While proposed legislation such as CHIPS could provide a "jump-start" to competitive US manufacturing, the total budgets are insufficient to offer grants to more than a few firms for new fabrication facilities, and will not help with the required ongoing upgrades. Investment tax credits would have the added advantage of incentivizing "skin-in-the-game," benefitting companies only in proportion to the investments they make in US manufacturing operations. Such incentives are common in Asia; in fact, South Korea's recent announcement highlighted 20% tax credits for all capital invested in new fab construction.[74]

3. **Extend R&D tax credits competitive with Asia to help defray the exploding costs for development of next-generation memory technology.**

   The memory industry requires an urgent level of innovation due to the slowdown in Moore's Law, while R&D necessary for next-generation memory fabrication processes becomes ever more expensive. Accordingly, tax credits for R&D activity in the US are needed to remain competitive against Asian countries that offer R&D incentives to their own domestic semiconductor manufacturers.[75] These credits help spur the purchase of next-generation advanced semiconductor tools—an industry the US still leads.[76] The institution of a competitive US semiconductor R&D tax credit would also send the message that semiconductor manufacturing is welcome in the US again, helping revitalize critical engineering training programs at US colleges that have withered as these jobs moved overseas. As a reference, South Korea's recently announced program highlights R&D tax credits of 40% (up from 30%), and provides benefit primarily to the region's indigenous memory chip suppliers.[77]

4. Streamline the semiconductor fab regulatory process to ensure competitive memory fab construction "time-to-market."

While new fab "time-to-market" is important to all semiconductor manufacturers, it is crucial to memory suppliers. Costs are at least $15B for a competitively sized memory fab, which carries the risk of insolvency if any delays forestall production. The US must streamline the regulatory process for new US semiconductor fabs to be competitive with fabs achievable in Asia. The US Department of Commerce has published an informative brief acknowledging the issue and proposing a set of recommendations.[78] Without waiving necessary regulation, the United States needs a fast-track permitting process for domestic semiconductor fabs to inject urgency into the maze of bureaucracy currently navigated when bringing a semiconductor plant to fruition.[79]

5. Provide incentives for onshore memory packaging capabilities necessary to complete a secure supply-chain.

Packaging, and the adjacent steps of printed-circuit-board fabrication and system assembly, are important manufacturing steps for all semiconductors. However, they are mission-critical for memory. Memory components and modules drive significant component and board volumes, with a need for cost-effective packaging across a variety of technologies. The US domestic outsourced assembly and test (OSAT) industry was an early casualty of offshoring (based primarily on labor cost considerations), so that today there are few high-volume factories outside of Asia. However, this critical last link in the component supply chain drives significant security and supply-chain access risk.[80] US wafer fabs would still be under significant threat of disruption if the wafer and components continue to cross the ocean multiple times for finalization. As noted above, however, recent trends are injecting more innovation into packaging, but also driving up capital requirements. Opportunities exist to leverage more advanced automation technologies in this process, which makes it more feasible to reshore. The US should consider incentives to onshore sufficient OSAT capabilities as a national security imperative.

Summary

The semiconductor memory industry needs urgent national attention. While owing its start to US innovation, the industry painfully left US shores as the first case of semiconductor globalization. Asymmetric national subsidization then led to decades of brutal economic cycles that eviscerated the supplier landscape, leading to a risky concentration of fabs based in Asia, including multiple sites in China. Vicious cost pressures require massive ongoing investment. A slowing of Moore's Law drives skyrocketing R&D costs, challenging already thin margins. These factors have caused every non-US country that still has a domestic memory supplier to double-down on subsidies. Meanwhile, China's indigenous producers are coming on strong. Memory suppliers are truly competing against the might of entire countries, while ever-present market volatility continues.

While it is not an industry for the faint of heart, these components are at the heart of every electronic system on which our data economy relies, driving performance benefits and the lion's share of system silicon content. Ensuring the integrity of these components, as well as the security of a viable, complete supply chain—from R&D to final system—is a national imperative. The US should urgently work to ensure a level playing field for onshore production and development of memory, with immediate priority on securing US supply for our most critical systems. Although there are no quick fixes, implementation of these incentives will make the US a viable home for advanced memory manufacturing again, ensuring that we have not forgotten about memory.

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Endnotes

1 "**2022 Factbook**," Semiconductor Industry Association.
2 "**CHIPS BILL**," US Congress, and "COMPLETE BILL," US Congress.
3 "Design Win for Smartphone…," SystemPlus Consulting, subsidiary of **Yole Group**.
4 Based on Yole Group Q1'22 DRAM and NAND Market Monitors – Industry average die/wafer in FQ1'22 applied to AMD EPYC 7002 2-socket server max memory of 4TB and PCIe direct attach storage max capacity of 184TB.
5 Keith Bradsher and Paul Mozur. "**China's Plan to Build Its Own High-Tech Industries Worries Western Businesses**," *New York Times* March 7, 2017.
6 Dan Kim and John VerWey. "**The Potential Impacts of the Made in China 2025 Roadmap on the Integrated Circuit Industries in the U.S., EU and Japan**," *U.S. International Trade Commission* August 2019.
7 Roslyn Layton. "**White House Report On China: Short-Term Profits Undermine Long-Term Resilience**," *Forbes* June 10, 2021.
8 "**World Semiconductor Trade Statistics**," WSTS.
9 "**Semi Capex on Pace for 34% Growth in 2021 to Record $152.0 Billion**," IC Insights**.**
10 Harald Bauer, et al. "**Memory: Are Challenges Ahead**," McKinsey & Company, March 8, 2016.
11 Kotaro Hosokawa. "**Micron Challenges Samsung's Dominance in Memory Market**," *Nikkei Asia*, May 23, 2021.
12 "**Q1'22 DRAM and NAND market monitors,**" Yole Group, www.yolegroup.com.
13 NAND is a high-density, non-volatile "storage" memory, able to retain its data without power, however significantly slower than DRAM, and of limited endurance, with each cell only able to be written a limited number of times. See: **https://www.semiconductors.org/wp-content/uploads/2021/02/Highest-Volume-Mainstream-Memory_Omdia.pdf**.
14 Results for Q1'2022, based on "Q1'22 DRAM and NAND market monitors," **Yole Group**, **www.yolegroup.com**.
15 Ryan Smith. "**Intel Sells SSD Business to SK Hynix as New Subsidiary Solidigm**," Dec 28, 2021.
16 Cheng Ting-Fang and Lauly Li. "**US-China Tech War: Beijing's Secret Chipmaking Champions**," *Financial Times* May 12, 2021.
17 Anton Shilov. "**ChangXin Memory Technologies (CXMT) is Ramping up Chinese DRAM Using Qimonda IP**," *AnandTech* Dec 2, 2019.
18 "**China Big Fund Stepping Up Investment in Homegrown Memory Sector**," China Pulse.
19 "**Taking Stock of China's Semiconductor Industry**," Semiconductor Industry Association, July 13, 2021.
20 Fabs in Taiwan, Singapore, and Japan, acquired from Qimonda, Texas Instruments, and Elpida (Micron 10K annual reports).
21 Q1'22 DRAM and NAND market monitors," Yole Group, **www.yolegroup.com**.
22 "**1-Kbit DRAM (Intel, U.S.A)**," Semiconductor History Museum of Japan.
23 George Gilder. *Microcosm: The Quantum Revolution in Economics and Technology* (New York: Simon and Schuster) 1989: 90-100.
24 Bob Dennard's DRAM innovation occurred in 1966, prior to the commercial start of the DRAM industry. Dennard then went on to publish a pioneering set of observations and rules about semiconductor scaling, later termed "Dennard Scaling," providing the industry a multi-decade roadmap on geometry, voltage, and power trends. For more information, see: **https://history.computer.org/pioneers/dennard.html**.
25 Michael Malone. *The Intel Trinity: How Robert Noyce, Gordon Moore, and Andy Grove Built the World's Most Important Company* (New York: Harper Business) 2014: 131-140.
26 Note: In the late 1960s, several firms had designed semiconductor "Static RAM" memories, much lower density, significantly lower volume, and without the commercial success that the 1K DRAM enjoyed.
27 George Gilder. *Microcosm: The Quantum Revolution in Economics and Technology* (New York: Simon and Schuster) 1989: 7, 11, 13.
28 Thomas Lueck. "**Mostek, Big Chip Maker, Shut**," *New York Times* Oct 18, 1985.
29 Andrew Grove, Only the Paranoid Survive (Penguin Random House). 1998.
30 Gilder. Microcosm, Ch. 12, pages 150-160.
31 Andrew Pollack. "**The Selling of the 256K RAM**", *The New York Times* Jun 3, 1983.
32 Leslie Helm. "**A New Force in Chip Wars: Korean Chip Exports are Growing 35% a Year, and the US and Japan are Worried**," *Los Angeles Times* Aug 17, 1992.
33 B.H. Seo. **"Hyundai, LG Complete Merger,"** *EETimes* Apr 22, 1999.
34 Staff, et al. "**TI to Sell DRAM Business to Micron**," *EE Times* June 18, 1998.
35 Laurie Flynn. "**Samsung to Pay $300 Million Fine for Price Fixing**," *New York Times* Oct 13, 2005.
36 Claire Jim. "**Analysis-Taiwan's DRAM Industry: Desperately Seeking a Future**", *Reuters* Dec 22, 2011.
37 Laurie Flynn. "**Samsung to Pay $300 Million Fine for Price Fixing**."
38 Qimonda was the DRAM spin-out of Infineon, which itself was the semiconductor products spin-out from Siemens; See: **https://www.marketwatch.com/story/qimonda-files-for-bankruptcy**.
39 "**1971: Reusable Programmable ROM Introduces Iterative Design Flexibility,**" Computer History Museum.
40 Note: Both NOR and NAND memory also benefitted from significant innovations at Toshiba in the early 1980s.
41 Jim Handy, "**A History of Flash Memory and its Rise in the Enterprise**."
42 Datacenter SSDs today are routinely rewritten so frequently as to approach cell wear-out limits, making them in some cases a "consumable" product.
43 Jim Handy/Objective Analysis, "**Why DRAM Vendors Must Consolidate; How Spiraling Fab Costs Force Vendors to Merge**," 2009.
44 Harald Bauer, et al. "**Memory: Are Challenges Ahead?**," *McKinsey&Company*, March 8, 2016.
45 Hiroko Tabuchi. "**In Japan, Bankruptcy for a Builder of PC Chips**," *New York Times* Feb 27, 2012.
46 Dylan McGrath. "**Micron Closes Elpida Acquisition**," *EETimes* Jul 31, 2013.
47 "**Taking Stock of China's Semiconductor Industry**," Semiconductor Industry Association (SIA), July 13, 2021.
48 Solid-State Circuits Society. "**The DRAM Story**", *IEEE Solid-State Circuits Society News* Vol. 13. No. 1, (Winter) 2008.
49 Maarten Rosmeulen, et al. "**How 3D NAND Flash Works, What Lies Ahead in its Density Roadmap**," EDN, March 8, 2022.
50 IEEE "**The DRAM Story**."
51 Harald Bauer, et al. "**Memory: Are Challenges Ahead?**," *McKinsey&Company*, March 8, 2016.
52 "**Taking Stock of China's Semiconductor Industry**," Semiconductor Industry Association (SIA), July 13, 2021.
53 "Q1'22 DRAM and NAND market monitors," Yole Group, www.yolegroup.com.
54 Samuel K Moore. "**South Korea's $450-Billion Investment Latest in Chip Making Push**," *IEEE Spectrum* May 26, 2021.
55 Harald Bauer, et al. "**Memory: Are Challenges Ahead**" March 2016.
56 Harald Bauer, et al. "**Memory: Are Challenges Ahead**" 2016, with cost extrapolations to 2022.
57 VerWey. "**No Permits, No Fabs: The Importance of Regulatory Reform for Semiconductor Manufacturing**," *Center for Security and Emerging Technology*, October 2021.
58 Vincent Chin. "**Sustaining Singapore's Success: Lessons of Growth and Delivery**," *Centre for Public Impact* June 11, 2015.
59 Micron 2021 10K, capital expenditures over 2019/20/21 equaled 39% of revenue.
60 Kim Jaewon. "**South Korea Plans to Invest $450bn to Become Chip 'Powerhouse'**," *Nikkei Asia* May 13, 2021.
61 Rick Merritt. "**GlobalFoundries Halts 7nm Work**," *EETimes* August 27, 2018,
62 Mark Lapedus. "**DRAM Scaling Challenges Grow**," *SemiconductorEngineering*, November 21, 2019.
63 Gary Ruggles. "**Introduction to the Compute Express Link Standard**," *Synopsys* 2022.
64 Bob Beachler. **"The Advantages of At-Memory Compute for AI Inference,"** *EETimes* January, 24, 2022.
65 Chris Stokel-Walker. "**Hackers are Now Dropping Malware into SSD Drives through Firmware Updates**," *cybernews* January 12, 2022.
66 Gary Hilson. "**Samsung Makes New Package for Smartphones**," *EETimes* Feburary 17, 2015.
Micron Aims 1.5TB MicroSD Card at Video Surveillance Market

68 Gary Hilson. "**AI Expands HBM Footprint**," *EETimes*, January 20, 2022.

69 Calculated from respective SEC 10K's and 20F forms for Micron, TI, and TSMC, using three-year weighted averages.

70 Had TSMC 2021 capex spending remained constant to 2019/20, three-year intensity would have been 45%; TSMC 20F form; See: Nick Flaherty. "**TSMC's $100bn Fab Plans to Expand Capacity**," EE News April 2, 2021.

71 "**Global Semiconductor Incentives**," Semiconductor Industry Association (SIA), February 2022: 2-4.

72 "**Robust Federal Incentives for Domestic Chip Manufacturing Would Create an Average of Nearly 200,000 American Jobs Annually as Fabs are Built, Add Nearly $25 Billion Annually to U.S. Economy**," Semiconductor Industry Association (SIA), May 19. 2021.

73 **"Taking Stock of China's Semiconductor Industry,"** Semiconductor Industry Association (SIA), July 13, 2021.

74 "**Global Semiconductor Incentives**," Semiconductor Industry Association.

75 **"Global Semiconductor Incentives,"** Semiconductor Industry Association.

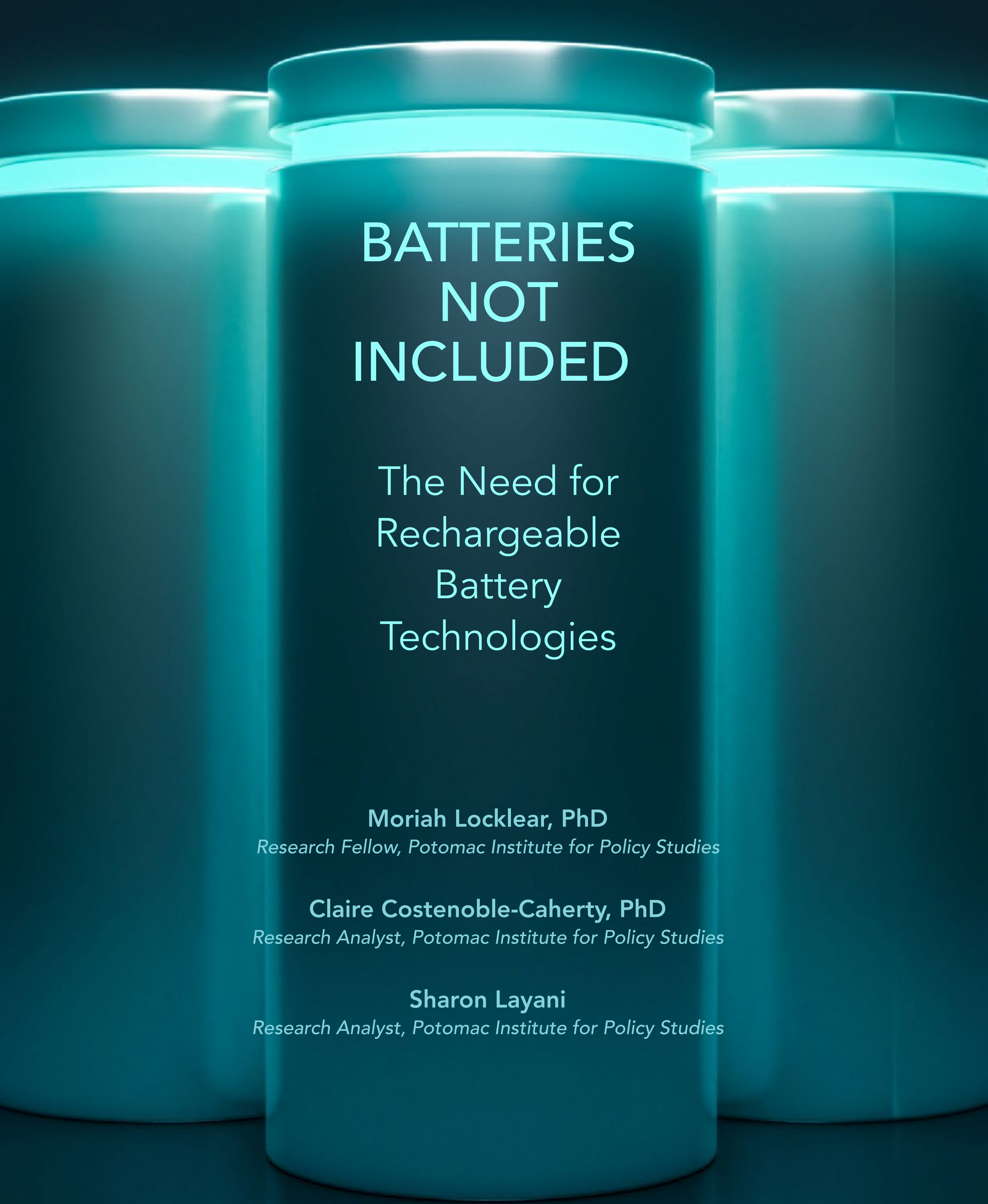
76 However, with today's uneven playing field, these tools (ironically) often help enable non-US suppliers first.

77 Kim Jaewon. "**South Korea Plans to Invest $450bn to Become Chip 'Powerhouse**."

78 "**Streamlining Permitting and Reducing Regulatory Burdens for Domestic Manufacturing**," US Department of Commerce, October 6, 2017.

79 John VerWey. "**No Permits, No Fabs: The Importance of Regulatory Reform for Semiconductor Manufacturing**," *Center for Security and Emerging Technology*, October 2021.

80 Jordan Robertson, et al. "**The Long Hack: How China Exploited a U.S. Tech Supplier**," *Bloomberg* February 12, 2021.



BATTERIES NOT INCLUDED

The Need for Rechargeable Battery Technologies

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Introduction

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

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

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

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

The Demand for Rechargeable Batteries

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

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

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

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

Meeting the Demand for Rechargeable Batteries

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

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

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

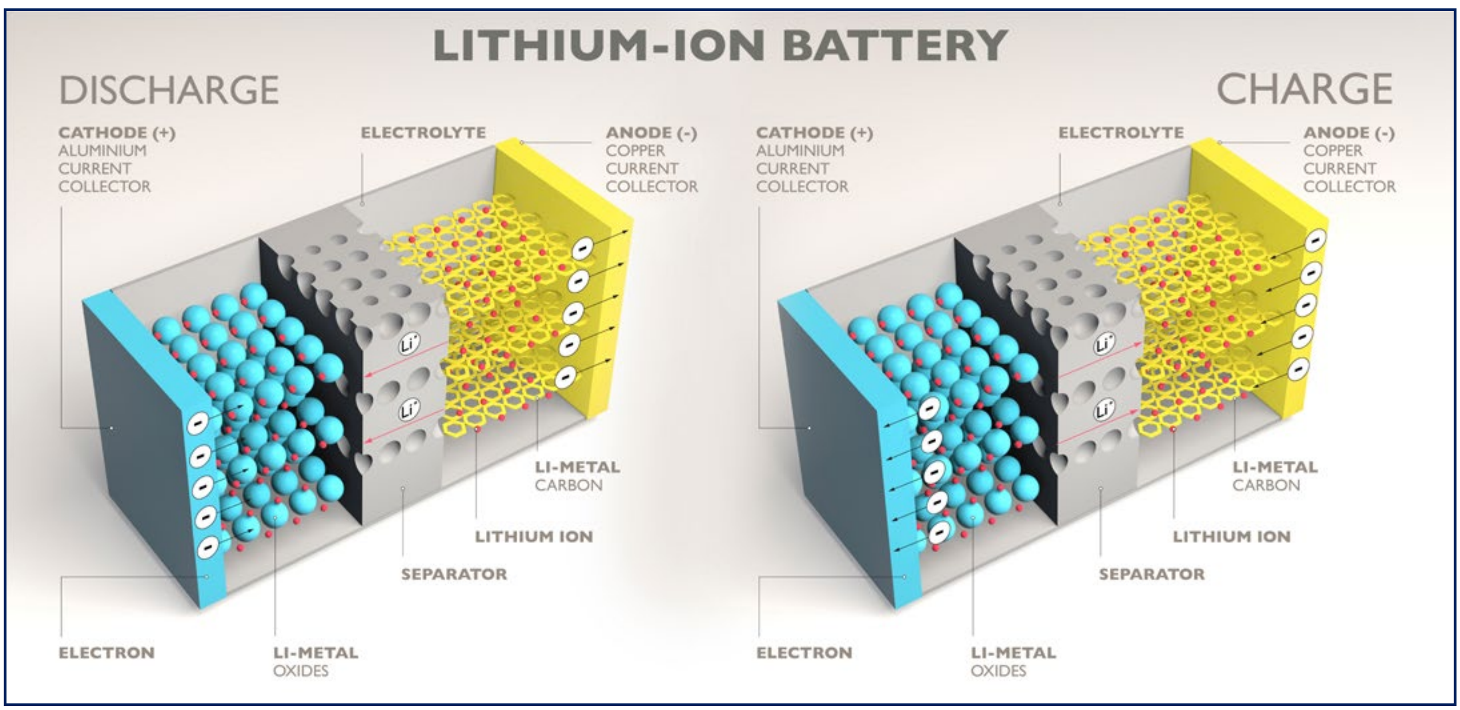
The US must secure sufficient access at all points in the supply chain to produce enough batteries for its own demand. Creating all-US onshore production for each stage is unlikely and uneconomical. But securing supplies through networks of allies and partners with global reach is possible.

What are the Prospects for New Battery Technologies?

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

Research Directions

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

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

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

An Impending Collision

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

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

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

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

Endnotes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

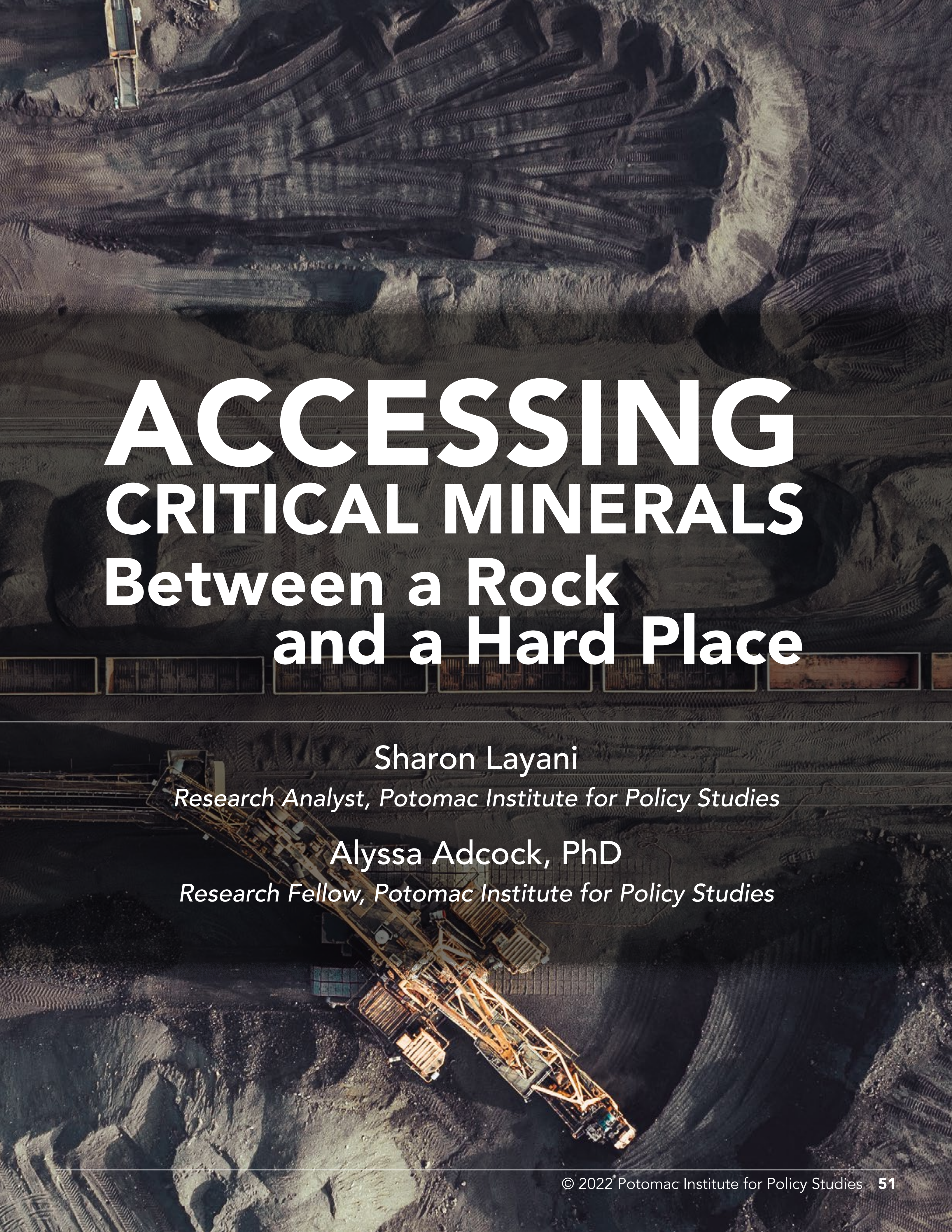
52 "**Pumped Storage Hydropower**," United States Department of Energy, Office of Energy Efficiency & Renewable Energy, April 27, 2022.

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

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

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

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



ACCESSING CRITICAL MINERALS
Between a Rock and a Hard Place

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Minerals and Civilization

Earth's natural mineral resources provide vital ingredients to the technologies that are fundamental to modern society. Epochs of civilization have long been defined by the metallurgical technologies of the time—from copper to bronze, and later iron, and most recently, steel. Over millennia, humans have extracted new and varied materials from ores, combined them into alloys, and used these naturally derived products to make the technologies of their age. Many different minerals are key constituents in today's consumer electronics, green technologies, military hardware, medical tools and devices, automobiles, satellites, and most every product of modern civilization.

Minerals have various properties that make them particularly useful for specific applications. Iron is much stronger than bronze, which in turn is stronger than copper. Chromium helps make steel non-corrosive. Lithium is useful for making rechargeable batteries. Single crystal silicon is the basis for most semiconductors. Titanium and titanium-aluminum alloys are used in jet engine fan blades due to their strength and light weight. Zirconium is used for the cladding of nuclear power plant fuel rods, sometimes alloyed with niobium. Xenon is used as a propellant for ion thrusters on satellites. An alloy of iron, neodymium, and boron has high ferromagnetism and thus makes the strongest permanent magnets. Ongoing research by scientists continues to find new alloys and mineral combinations to improve material properties and uncover new utility.

With the ever-expanding list of minerals in new products, we see how essential they are for everyday life. Consumer products, defense applications, power generation, transportation, and even food products make extensive use of minerals. Future developments in clean energy, smart cities, mobile communications, and other sectors will result in even higher demand for minerals. It is therefore critical that the United States ensure its access to these vital resources, for today and tomorrow.

What is Critical about Critical Minerals?

With the current US focus on supply chains, it is reasonable to ask whether the supply of minerals will continue to meet demand, and whether shortages may occur should suppliers become limited.

In the United States, certain materials are designated as "critical minerals." US Executive Order 13817, from 2017, defines critical minerals as non-fuel minerals resources that are of vital importance, essential to the manufacturing of products, and for which the supply chain is vulnerable. The Energy Act of 2020 directs that a list of critical minerals be revised every three years. The US Geological Survey (USGS) publishes such a list, which in 2018 included 35 critical materials.[1] The updated 2022 list has 50 minerals[2] (see list). Most minerals are simply listed by their principal metallic element, but some have been given common names referencing specific molecular materials, such as barite (barium sulfate), fluorspar (calcium fluoride), and graphite (a specific form of carbon). Criticality, and thus inclusion on the USGS listing, is a judgement call.

Stockpiling and Supply Chains

The US Department of Defense (DoD) stockpiles critical minerals for national security purposes under the National Defense Stockpile, and some minerals for clean energy technologies, per an agreement with the Department of Energy.[3] Stockpiling has a long history in the United States, from the Strategic and Critical Materials Stock Piling Act of 1939, to other programs in subsequent years such as the Strategic National Stockpile (mostly medical equipment), the Strategic Petroleum Reserve, and the National Defense Stockpile.[4] The latter, maintained by the Defense Logistics Agency,[5] contains about a billion dollars worth of metals. Reliance on stockpiling is considered by many to be problematic[6] as it requires a determination of what minerals (and materials and equipment) are critical, how much needs to be stored to provide for strategic contingencies, and the act of building a stockpile only further distorts an already constrained supply chain. Stockpiling generally focuses on defense needs rather than the needs of the civilian economy. Often, reliance on critical minerals is hidden because materials are incorporated in imported finished or semi-finished goods.[7]

Today, China has a stranglehold on many critical minerals supply lines. In 2010, China curtailed the shipment of rare earth elements (REEs) to Japan because of a maritime dispute.[8] In 2020, China similarly threatened to cut off REE supply to three US-based defense manufacturers,[9] endangering F-35 production, in response to a US defense deal with Taiwan.

Table 1. Critical Minerals with their Primary Applications*

MINERAL	PRIMARY APPLICATIONS
Aluminum (Al)	Almost every sector
Antimony (Sb)	Lead-acid batteries and flame retardants
Arsenic (As)	Semi-conductors
Barite (Barium sulfite)	Hydrocarbon production
Beryllium (Be)	Alloying agent in aerospace and defense industries
Bismuth (Bi)	Medical and atomic research
Cerium (Ce)	Catalytic converters, ceramics, glass, metallurgy, and polishing agents
Cesium (Cs)	R&D
Chromium (Cr)	Stainless steels and other alloys
Cobalt (Co)	Rechargeable batteries and superalloys
Dysprosium (Dy)	Permanent magnets, data storage devices, and lasers
Erbium (Er)	Fiber optics, optical amplifiers, lasers, and glass colorants
Europium (Eu)	Lighting phosphors and nuclear control rods
Fluorspar (Calcium fluoride)	Manufacturing of aluminum, cement, steel, gasoline, and fluorine chemicals
Gadolinium (Gd)	Medical imaging, permanent magnets, and steelmaking
Gallium (Ga)	Integrated circuits and optical devices (e.g., LEDs)
Germanium (Ge)	Fiber optics and night vision technologies
Graphite (Mineral form of carbon)	Lubricants, batteries, and fuel cells
Hafnium (Hf)	Nuclear control rods, alloys, and high-temperature ceramics
Holmium (Ho)	Permanent magnets, nuclear control rods, and lasers
Indium (In)	Liquid crystal display technologies
Iridium (Ir)	Coating for anodes in electrochemical processes and chemical catalyst
Lanthanum (La)	Helps produces catalysts, ceramics glass, polishing compounds, metallurgy, and batteries
Lithium (Li)	Rechargeable batteries
Lutetium (Lu)	Scintillators for medical imaging, electronics, and cancer therapies
Magnesium (Mg)	Alloys and for reducing metals
Magnesium (Mg)	Alloys and for reducing metals
Manganese (Mn)	Steelmaking and batteries
Neodymium (Nd)	Permanent magnets, rubber catalysts, medical and industrial lasers
Nickel (Ni)	Helps produce stainless steel, superalloys, and rechargeable batteries
Niobium (Nb)	Steel and superalloys
Palladium (Pd)	Catalytic converters and as a catalyst agent
Platinum (Pt)	Catalytic converters
Praseodymium (Pr)	Permanent magnets, batteries, aerospace alloys, ceramics, and colorants
Rhodium (Rh)	Catalytic converters, electronic components, and as catalysts
Rubidium (Rb)	R&D in electronics
Ruthenium (Ru)	Catalysts, as well as electrical contacts and chip resistors in computers
Samarium (Sm)	Permanent magnets, absorber in nuclear reactors, and in cancer treatments
Scandium (Sc)	Alloys, ceramics, and fuel cells
Tantalum (Ta)	Electronic components (mostly capacitors and in superalloys)
Tellurium (Te)	Solar cells, thermoelectric devices, and alloying additive
Terbium (Tb)	Permanent magnets, fiber optics, lasers, and solid-states devices
Thulium (Tm)	Various metal alloys and lasers
Tin (Sn)	Protective coatings and alloys for steel
Titanium (Ti)	White pigment and metal alloys
Tungsten (W)	Wear-resistant metals
Vanadium (V)	Alloying agent for iron and steel
Ytterbium (Yb)	Catalysts, scintillometers, lasers, and metallurgy
Yttrium (Y)	Ceramic, catalysts, lasers, metallurgy, and phosphors
Zinc (Zn)	Metallurgy to produce galvanized steel
Zirconium (Zr)	High-temperature ceramics and corrosion-resistant alloys

* Adapted from the US Geological Survey 2022 List of Critical Minerals
"**U.S. Geological Survey Releases 2022 List of Critical Minerals**," U.S. Geological Survey, February 22, 2022.

The Russian-Ukraine conflict in 2022 has put another spotlight how foreign policy decisions can affect global supply chains. In addition to its reserves of oil and gas, Russia is a major supplier of certain metals. As one example, the price of palladium used in automobile catalytic converters has shot up since the Russian invasion of Ukraine.[10]

Natural catastrophes, such as disease outbreaks or extreme weather events, can impact any point in the supply chain, causing reductions in available personnel or facilities.

Of the 50 designated critical materials from the USGS listing, the United States is 100% reliant on imports for fourteen of them, and more than 75% reliant on imports for another ten.

In February 2021, Executive Order 14017 launched a 100-day review and strategy development process to address vulnerabilities in the US supply chains that included critical minerals and materials as one of the focus areas.[11] In February 2022, the Administration announced a number of actions to secure supply chains for certain minerals.[12] In April 2022, the Defense Production Act (DPA) was invoked to boost critical mineral production in the United States.

The National Strategic and Critical Minerals Production Act, intended to change rules and regulations surrounding mining permitting in the United States, has been introduced in various forms several times in Congress since 2012, but has yet to pass. Hearings continue to be held on the Hill regarding critical minerals in an attempt to further secure supplies.

With growing demand and reliance on critical minerals (see box, "Anticipating Needs"), not every user will be guaranteed access. The anticipated increase in market demand for certain materials could lead to competition among end-product manufacturers.

Anticipating Needs

What are the likely critical minerals of the future? Where are the likely supply bottlenecks?

While the future is hard to predict, it is a safe bet that the future will involve a large demand for certain minerals. Overall demand for current critical minerals is increasing, with a predicted five-fold increase in use by 2050.[13] Electric vehicles will require large supplies of lithium to be used for the production of batteries, and may require other critical minerals. Electric vehicles are estimated to use six times the amount of critical minerals relative to conventional cars.[14] Until alternatives can be found, the cobalt used in lithium-ion batteries could become especially critical. Rare earth elements (REEs), such as neodymium, are expected to be increasingly important for magnets used in motors and generators. Clean energy systems are said to require, in addition to lithium and REEs, nickel, manganese, and aluminum—all in large quantities.[15] A resurgence of nuclear power sources using new technology plants might require large resources of uranium and/or thorium, boron, zirconium, and other yet-to-be-determined materials. Aerospace applications are looking at new airframe structures and more efficient engine designs, as well as stronger and lighter landing gear and corrosion resistant components, all of which will involve minerals and new manufacturing techniques involving different materials.

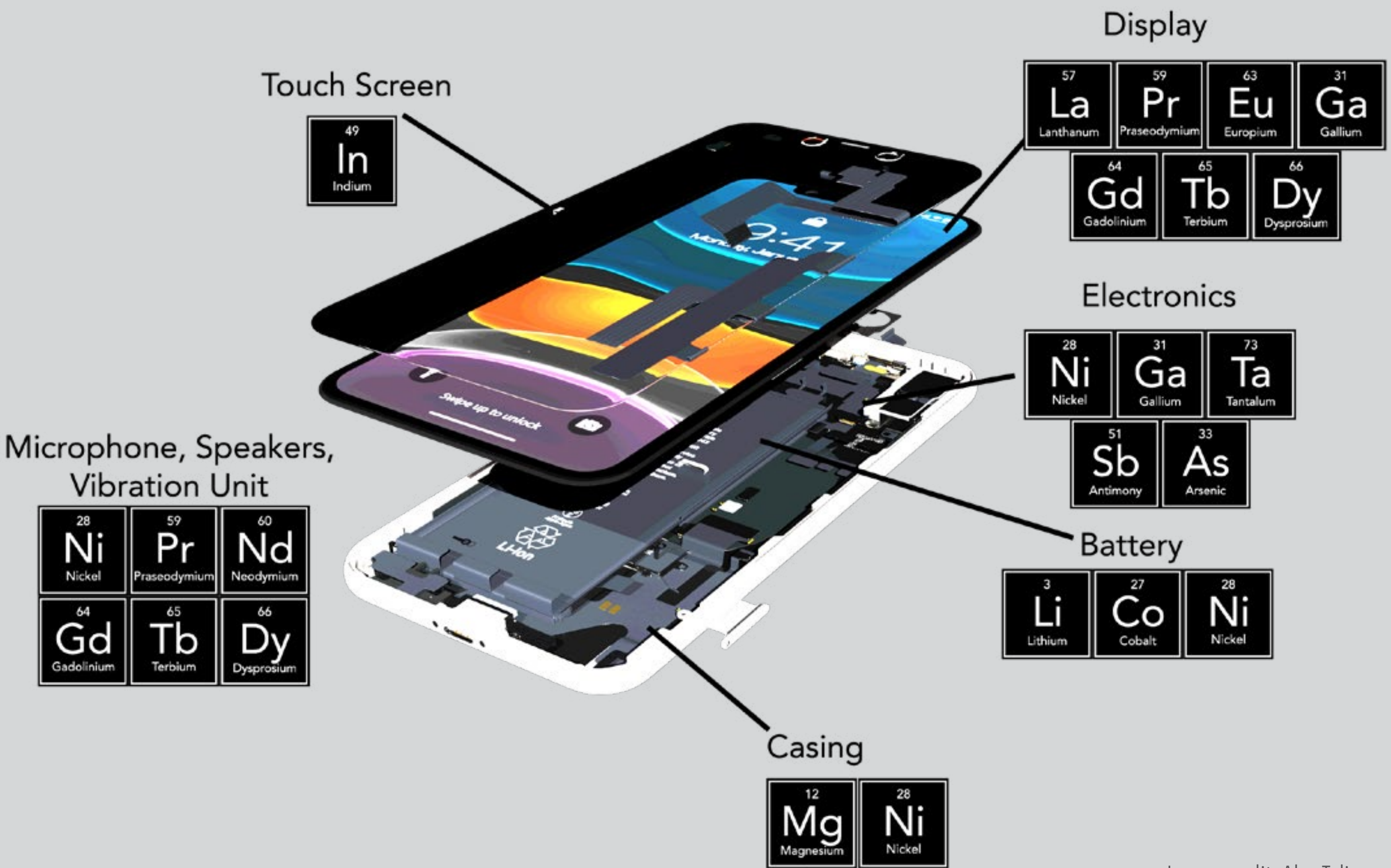


Image credit: Alex Taliesen.

It is not just the quantity of minerals required that will determine which are critical. The diversity of materials in products is increasing: the average smartphone contains something like 75 different materials sourced from minerals (see figure).[16,17] A supply chain issue in any one material might hamper production.

From Rock to Commodity

Critical minerals are generally distributed throughout the earth, embedded in rocks in the crust of the earth at varying concentrations. Certain rocks contain relatively high concentrations of particular minerals, and those ores tend to be located in small pockets in certain locations—i.e., potential mine sites.

Today, many minerals are exploited from just a few mines, and sometimes predominantly just one main mine, providing a source for the rest of the world. For example, South Africa and Zimbabwe produce 80% of the world's platinum, Australia and Chile produce 75% of the world's lithium, and 75% of cobalt is extracted in the Democratic Republic of Congo.[18]

Rare earth elements are not rare in overall terrestrial abundance,[19] but are found in low concentrations mixed in with other elements and minerals.[20] The rare earth metal neodymium (Nd), used for making strong permanent magnets and special lasers, is found in low concentrations in the ores monazite and bastnäsite. While these ores can be found in earth's crust throughout the world,[21] more than half of the known minable concentrations are found in China and Vietnam.[22]

Separating elements and minerals from rocks often requires complex chemical processes, and results in waste materials that often contain toxic and/or radioactive byproducts.[23] Further, the separation and refining process is often energy, water, and other resource intensive. Refining is often done in distant locations from the mining operation. China currently performs roughly 90% of the refining and production of REEs into magnets.[24,25] There are minerals mined in the United States that are exported to China for the processing and refining stages.[26] Similarly, more than half of all lithium extracted globally is currently refined in China.[27]

Refined minerals are then purchased and used by manufacturing firms to make products. Today, roughly 30% of the world's manufacturing of products takes place in China.[28]

Prospects for Mineral Production in the United States

The United States is not without natural resource reserves of its own. For example, the company MP Materials hopes to secure sufficient REE magnets for US needs using domestic mining, processing, and manufacturing. Berkshire Hathaway Energy is building demonstration plants to explore the extraction of lithium from Imperial Valley[29] in California and from the brine of geothermal power plants at the Salton Sea also in California.[30]

However, the mining permit process in the United States averages 7 to10 years. In contrast, countries like Australia and Canada have typical permitting processes of 2 years.[31] Mining and refining operations require a large operation and a trained workforce,[32] and it has been difficult for American companies to compete financially. The history of the Mountain Pass mining operation is illustrative of the problems facing the US mining industry (see box page 57). Similarly, the Albemarle lithium mine in North Carolina[33] shut down in 2021 because the then-depressed global lithium prices could not balance the regulatory and operating costs. A US Administration "Interagency Working Group" is developing legislative and regulatory proposals to support "responsible mining" in the United States.[34]

Mountain Pass Mine, Molycorp, and MP Materials

In the mid-1900s, the United States dominated much of the global market for REEs and related materials. From the mid-1960 until the '80s, Molycorp's Mountain Pass (MP) mine in California was considered the world's top source of rare earth oxides.[35] But environmental and financial challenges at Mountain Pass led the mine to close in 2002. In 2012, Molycorp reopened MP, only for China's increased production to greatly outpace demand, driving down prices, and causing Molycorp to file for bankruptcy in 2015. In 2017, MP Materials Corp purchased the mine. In 2020, Mountain Pass supplied almost 16% of the world's REE production. In October 2020, Shenghe (a Chinese company) was the sole buyer of the mine's rare earth concentrates, which it then sent on to China for processing.[36] The mine went public in 2021, and the Nuclear Regulatory Commission authorized the mining license to be transferred; Shenghe has about 8% ownership of MP Materials now.[37] The mine continues to face hurdles and investing complexities.[38] In February 2022, DoD announced it would be investing just over $100 million to enhance America's rare earth supply chain resiliency, including $35 million to MP Materials to separate and process heavy REEs at the Mountain Pass facility in California. It was further announced the MP Materials would be building a magnet manufacturing plant involving $700 million in investments, with the intention of providing an end-to-end rare earth magnet production capability in the United States. Ground has broken on a manufacturing facility in Texas.[39]

Bradley Van Gosen/U.S. Geological Survey

US Supplies of Minerals Going Forward

In 2019, the United States published a Federal strategy "to ensure secure and reliable supplies of critical minerals,"[40] which includes a call to "improve understanding of domestic critical mineral resources," from ores as well as from recycling. (The US Government Accountability Office has recommended that the strategy be updated.[41]) The US Department of Energy has developed an R&D roadmap[42] to diversify supplies, develop substitutes, and improve reuse and recycling, to include all aspects of the supply chain (mining, refining, manufacturing, and recycling). The US DoD was the lead for the critical minerals and materials report in the 100-day study responding to the executive order 14017 on America's supply chains, promoting sustainable production and conservation of strategic and critical materials,[43] and recommending (among other actions) "expanding sustainable domestic production and processing," which includes recycling and new mining methods. A DoD action plan and update was provided by DoD in February 2022.[44] The way forward involves securing supplies of minerals and developing alternatives that use supplies that are more easily accessed, as detailed in the strategies and action plans developed by the various US agencies.

Securing Supplies

The national interest is for more stable supply chain of resources, mitigating the risk of supply chain disruptions. The US DoD has "mapped" the sources and supply chains for critical minerals and strategic and critical materials as well, and has identified "latent capacity" of the United States to produce materials if sufficient incentives were in place.[45] The implication is that through a network of agreements and policy measures, it should be possible for the United States to ensure sufficient supplies for decades to come.

Discerning multiple pathways can help provide greater stability and help contain costs. Proactively finding multiple supply pathways is often feasible. For example, uranium is produced and exported from Canada[46] and lithium by Pilbara Minerals in Australia.[47] Japan has made headway in processing and refining REEs,[48] reducing its dependence on supplies from China compared to 2010, through investment and partnerships in other countries. Arsenic is imported to the United States from Morocco and Belgium in addition to China. There are proposals to create a "Five Eyes for critical minerals,"[49] or to establish a North American mining center based on mineral reserves.[50]

It thus may behoove the US government to exercise levers of influence though loans, subsidies, regulations, market guarantees, and tariffs to stimulate domestic production of certain critical minerals to ensure supply stability, as well as fostering agreements with allies and trustworthy sources for access to minerals. The strategy requires, however, that accurate predictions be made by government forecasters as to the likely demand and criticality of specific materials. This is a complex endeavor that is generally handled by companies for the commercial marketplace.

Invest in Research and Development for Alternatives

A complementary approach to securing supplies of critical minerals is to pursue research and development (R&D) that might uncover comparable or improved capabilities separate from today's processes or materials. Research might lead to better and more efficient end-products that make use of components with more accessible supplies. Alternative materials as well as advances in mining, processing, and recycling can relieve pressure on the current critical minerals supply chains.

New composite materials, such as carbon fiber, are finding utility in replacing metals for structural elements of products. Research in the field of materials science has explored substitute materials for materials for neodymium[51] in wind turbines and magnets.[52] Advanced Research Projects Agency–Energy (ARPA-E) sponsored a "Rare Earth Alternatives in Critical Materials" (REACT) project to study replacements for REEs.[53] Other research searches for practical superconducting materials.[54] Research involves risk, but payoffs can be large.

Research might also lead to improved extraction and refinement methods to obtain minerals. The development of new extractive techniques could shift the economic balance of mineral deposits previously deemed incapable of delivering a positive return. Offshore deep-sea mining might deliver new supplies of minerals, if additional policy issues can be overcome.[55] Some believe asteroid mining may also provide accessible reserves of critical minerals if costs can be brought low enough.

Research and development, particularly in the materials sciences area, can provide benefits for the general good. Historically, the most innovative and beneficial research begins with US government direction.

Summary

Critical minerals are essential for the composition of many consumer devices and defense applications. Demand is expected to explode in the upcoming years, but it is unclear if supplies will be available to all. The US defense and commercial sectors will be negatively impacted if access to needed materials becomes limited. The "critical mineral" designation already signals that there may be a supply chain vulnerability of these materials due to reliance on imports.

To mitigate risk, the United States is attempting to stabilize supply chains, encompassing mining, processing, refining, and manufacturing. Between invigorating domestic production and secure supply chains, and developing new materials for alternatives, the United States should be able to satisfy needs for minerals and other materials far into the future.

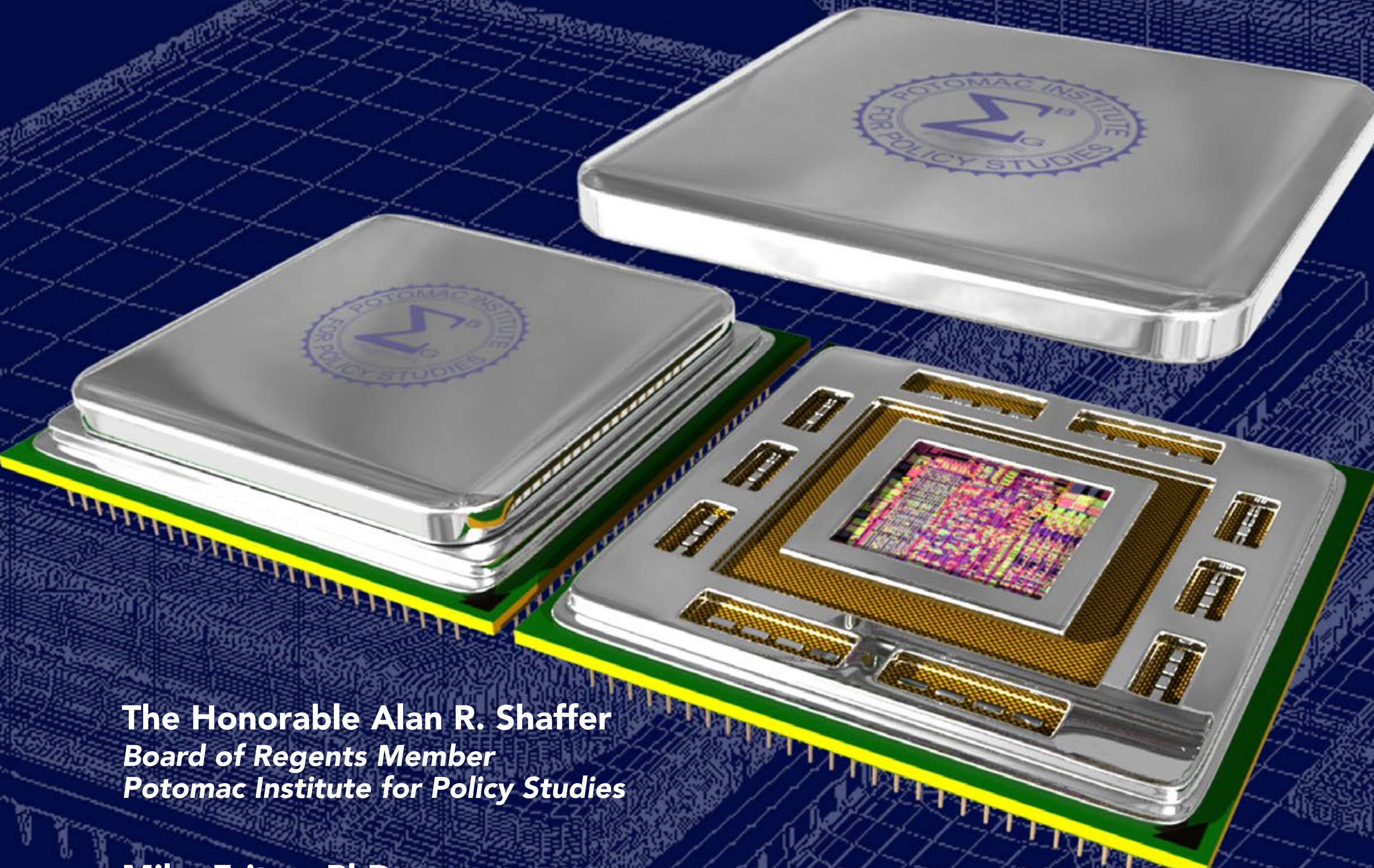
Endnotes

1 "**Final List of Critical Minerals 2018**," A Notice by the Department of the Interior, 83 Federal Register 23295 (May 18, 2018).
2 Jason Burton. "**U.S. Geological Survey Releases 2022 List of Critical Minerals**," United States Geological Survey, February 22, 2022.
3 "**US Departments of Energy, State and Defense to Launch Effort to Enhance National Defense Stockpile with Critical Minerals for Clean Energy Technologies**," U.S. Department of Energy, February 25, 2022.
4 Anshu Siripurapu. "**The State of U.S. Strategic Stockpiles**," Council on Foreign Relations, 20 April 2022.
5 "**About Strategic Materials**," Defense Logistics Agency, July 11, 2022.
6 Dolf Gielen, et al. "**Critical Minerals and Materials: Supply Bottlenecks and Risks Need International Cooperation**," Energy Post February 25, 2022.
7 Nedal T. Nassar, Elisa Alonso, and Jamie L. Brainard. "**Investigation of U.S. Foreign Reliance on Critical Minerals–U.S. Geological Survey Technical Input Document in Response to Executive Order No. 13953 Signed September 30, 2020**," U.S. Department of the Interior and U.S. Geological Survey, Open-File Report 2020–1127, December 7, 2020.
8 "**China Denies Banning Rare Earths Exports to Japan**," *Reuters* September 23, 2010, .
9 Sun Yu. "**China Targets Rare Earth Export Curbs to Hobble US Defense Industry**," *Financial Times* February 16, 2021.
10 Jim Kilpatrick. "**Supply Chain Implications of the Russia-Ukraine Conflict**," Deloitte Insights, March 25, 2022.
11 "**Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth**," 100-Day Reviews under Executive Order 14017, The White House, June 2021.
12 "**FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals**," The White House, February 22, 2022.
13 "**Climate-Smart Mining: Minerals for Climate Action**," The World Bank, July 11, 2022.
14 Nick Ferris. "**The Role Critical Minerals Will Play as the World Transitions to Net Zero**," Mining Technology, 11 August 2021.
15 Nick Ferris. "**The Role Critical Minerals Will Play**."
16 Poul Emsbo, et al. "**Geological Surveys Unite to Improve Critical Mineral Security**," EOS (102) February 5, 2021.
17 Bruno Venditti. "**Visualizing the Critical Metals in a Smartphone**," Visual Capitalist, August 24, 2021.
18 Vikas Agrawal and Shikha Sharma. "**Critical Minerals: Current Challenges and Future Strategies**," *International Journal of Environmental Sciences & Natural Resources* 27(3) March 2021: 556215**.**
19 For example, cerium is ranked 25th in overall terrestrial abundance, making it more abundant than copper or lead.
20 K. Lyon, et al. "**Enhanced Separation of Rare Earth Elements**," 2016 International Mineral Processing Congress, Idaho National Laboratory, September 2016.
21 Vladimir Alekseenko and Alexey Alekseenko. "**The Abundances of Chemical Elements in Urban Soils**." *Journal of Geochemical Exploration* 147 (2014): 245–249.
22 Nicholas LePan. "**Rare Earth Elements: Where in the World Are They?**" *Visual Capitalist* November 23, 2021.
23 Cameron Tarry and Faith Martinez-Smith. "**Supply Chain for Lithium and Critical Minerals Is … Critical**," ClearPath, June 11, 2020,
24 "**FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals**." The White House.
25 "**Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment**," U.S. Department of Energy Response to Executive Order 14017, February 24, 2022.
26 Jeffery Green. "**America's Critical Minerals Problem Has Gone from Bad to Worse**," *Defense News* May 2, 2018.
27 "**The Role of Critical Minerals in Clean Energy Transitions**," International Energy Agency, World Energy Outlook Special Report, May 2021.
28 "**China Accounts for 30% of Global Manufacturing Output: Official**," China Daily June 14, 2022.
29 "**Just the Facts: BHE Renewables–Lithium**," BHE Renewables, April 2022.
30 Beth McKenna. "**A Lithium Rush Is on at California's Salton Sea: Who Are the Players?**" The Motley Fool, June 8, 2022.
31 Jeffery Green. "**America's Critical Minerals Problem**."
32 Emma Penrod. "**As US Aims to Boost Clean Energy Supply Chain, Critical Minerals Gap Largely Human-caused, Analysts Say**," Utility Drive, June 17, 2021.
33 Amena Saiyid. "**US Mineral Mining Badly Lags Biden's Clean Energy Goals**," IHS Markit, February 8, 2022.
34 "**FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals**," The White House.
35 Marc Humphries. "**Critical Minerals and U.S. Public Policy**," Congressional Research Service, June 28, 2019.
36 Mary Hui. "**A Chinese Rare Earths Giant is Building International Alliances Worldwide**," Quartz, December 28, 2021.
37 Edward Lawrence and Tyler Kendall. "**Biden Can't Keep China Out of "Made in America.'**" Fox Business, April 15, 2022.
38 Frank Umbach. "**Rare Earth Minerals Return to the U.S. Security Agenda**," Geopolitical Intelligence Services, August 1, 2019.
39 Bob Hanes. "**Rare Earths Giant MP Materials Invests Heavily to Rebuild a U.S. Magnetics Supply Chain**," Investor Intel, June 14, 2022.
40 U.S. Department of Commerce, "**A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals**," June 4, 2019.
41 **GAO Report GAO-22-104824**.
42 US Department of Energy, **Critical Minerals and Materials, US Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains** (FY 2021- FY 2031).
43 "**Building Resilient Supply Chains,**" 100-Day Reviews.
44 US Department of Defense, **Securing Defense-Critical Supply Chains, An Action Plan Developed in Response to President Biden's Executive Order 14017**, February 2022.
45 "**Building Resilient Supply Chains,**" The White House.

46 "**Uranium in Canada: Everything You Need to Know**," Canada Action, April 2, 2021.
47 Rachel Pupazzoni. "**Australia's Lithium Miners Powering the Global Electric Vehicle Charge**," ABC News, July 29, 2021.
48 "**The Role of Critical Minerals in Clean Energy Transitions**," International Energy Agency, World Energy Outlook Special Report, April 27, 2022.
49 Dwayne Ryan Menezes. "**Launch of Report: The Case for a Five Eyes Critical Minerals Alliance Focusing on Greenland**," The Polar Connection, March 4, 2021.
50 Mary Ng. "**Canada's Vision for a Resilient North American Trade Relationship**," The Brookings Institution, February 28, 2022.
51 Neodymium Magnets Are the Strongest Type of Permanent Magnet. See: "**FAQ**," Amazing Magnets, July 11, 2022.
52 There are, however, currently no viable substitutes for REEs in magnets that offer the same performance. See: "**New Alternatives May Ease Demand for Scarce Rare-earth Permanent Magnets**," *ScienceDaily* April 2, 2019.
53 "**Rare Earth Alternatives in Critical Technologies**," ARPA-E, July 11, 2022.
54 "**New Tricks for Finding Better Superconductive Materials**," Phys.com, October 25, 2021.
55 Aryn Baker. "**A Climate Solution Lies Deep Under the Ocean—But Accessing It Could Have Huge Environmental Costs**," *Time* September 10, 2021.

CHIPS HAS PASSED

Now Comes the Hard Work



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Mike Fritze, PhD
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On July 28, 2022, Congress finally passed the "Creating Helpful Incentives for Producing Semiconductors," or "CHIPS" Act, also called the "CHIPS & Science Act." The bill authorizes $280B for technology and research and development (R&D) over five years; of that, $52B is allocated to semiconductor production and another $25B corporate tax credits. The $52B for semiconductors was appropriated, with $39B allocated for increasing domestic manufacturing, and $13B for R&D over the next five years. Already, American semiconductor manufacturers are lining up to "get their share of the pie." The CHIPS Act is critical, because the United States only produces 12% of worldwide chips, while US semiconductor consumption is estimated at 33%. The US economic well-being is dependent upon foreign entities (South Korea, China, and Taiwan) making their chips available to US industry. It may seem far-fetched that any country would restrict access to microelectronics by the United States and allies, but similar restrictions have happened before. The same was true when the Organization of Petroleum Exporting Countries (OPEC) embargoed oil to the United States and the west, creating the recession of the early 1970s. At the time, the United States produced 67% of its oil needs. If the phrase "data is the new oil" is true, then US economic well-being is critically dependent on a resource that the United States does not produce in sufficient quantities.

Now, the hard reality. The funding allocated by the government is barely a down payment. In the last year, South Korea has pledged $450B (over 10 years), China $150B, and the European Union about €40B. More troubling is that a coordinated US investment strategy has not been developed. Production of microelectronics requires multiple discrete steps. The chip must be designed (the Unted States is the global leader here), produced as dyes on wafers (the Unted States produces 12% of the global production), packaged and tested (the Unted States has about 5% of global market), then assembled in a system on a printed circuit board (PCB) (the United States is less than 5%, China dominates). If the United States focuses only on wafer production, without packaging, test, and assembly, the United States will still be critically dependent upon a product not made domestically. Without a balanced investment, developed by assessing the risk and payoff of each supply chain phase, the US investment will aid individual companies, but not overall economic or national security.

Moreover, there are many steps in the production of semiconductors. The large variety of types of chips further increases the number of facilities that are needed. The $52B will only go so far to address what the United States would need for all-domestic production. A modern, "state-of-the-art" foundry can cost $20B or more. Two state-of-the-art foundries could absorb all the manufacturing funds, and not substantially change national security, because systems would still be vulnerable to malicious actions.

We must consider the risks at all phases and all types of production and reduce risk using the available funds. People often assume that all needs will be served by "state-of-the-art" technology, and that this equates to a small node size. This is incomplete thinking. Node size matters in silicon-based semiconductors, where state-of-the-art is generally 5nm to 7nm minimum feature sizes. In general, the smaller the feature size, the more advanced the technology and the more expensive the factory. But the materials and design methodologies are as important as node size. Leading US-based research is investigating all such aspects, providing capable feature-rich parts that can be made down to 12nm. The need, however, will be for a variety of sizes, and many different types of semiconductors.

Beyond state-of-the-art chips, the majority of chips currently used in the United States and for the next decade will be between 12-45nm (as projected by the Semiconductor Industrial Association) and over 70% of the chips will be at larger sizes. The great auto constriction of 2021 occurred because of the lack of availability of 45nm chips known as micro-controllers. This shortage resulted in more than a $200B loss in worldwide auto sales—a slump expected to last until 2023. Of significance, this is the market that the People's Republic of China is targeting, with an investment of between $150-$250B. In the 14th 5-Year Plan, China targets 2030 as the year to be the dominant producer of these mid-sized nodes. Thus, the United States needs to invest heavily in the node sizes 12-45nm (and larger).

Even with the CHIPS Act, the US will not have this capability. In both package and test and PCBs, the United States has under 5% of the global market share. Unfortunately, in both of these supply chain stages, a potential adversary can introduce hardware or software elements that could allow an adversary to remotely modify or control the performance of microelectronics. Having a domestic capacity for producing chips without having secure access to package and test and reliable PCBs means the United States could be harmed by either remote attack, or more likely, serious disruptions to the supply chain. This vulnerability also needs to be addressed. PCBs are an interesting case—the United States lags in both capacity and capability. PCBs made in other parts of the world carry more advanced interconnects (traces) and subcomponents. The saying is "chips don't float," which means a chip without the final assembly steps is of little value (and conversely, a PCB without a chip is also of little value).

Without sufficient capacity in each step, the United States faces national and economic security risks. While there are promising approaches to reduce the risk of malicious

implants from potential adversaries, these approaches are currently unproven. Further, validation of the integrity of foreign microelectronics only matters if the parts are actually available to the United States. Without domestic capacity in all elements of the supply chain, the United States is vulnerable.

So, how can this problem be addressed? First, the government has to commission a risk-based strategy to identify the cost and value of all aspects of the microelectronics supply chain, and the risk of not having a portion of the chain meeting domestic demand. This would develop an investment priority (Step 1). Such a strategy could be done by short-term commission, or perhaps better, a public-private-partnership firm.

A concerted effort needs to be made to build demand to incentivize domestic production. Step 2 would be establishment of a policy or law that ensures the integrity of microelectronics used in critical national infrastructure. This means that all microelectronics used in such systems meet production standards to ensure components would be free of hidden bugs, triggers, back doors, and the like. These standards would be established by industry (similar to the auto industry), and would be audited prior to use in critical infrastructure. Critical infrastructure would include, at a minimum: weapons platforms; the electric, power, and water grids; the air traffic control network; and banking and health industries. In doing this, the nation would build the demand for secure microelectronics.

These two steps, along with the money from the CHIPS Act begin the process of restoring the US microelectronics industry. Not doing so leaves future generations of citizens at national and economic risk, and ensures the United States will continue to wane on the international stage.

Featured Authors

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Dr. Robert Hummel serves as the Chief Scientist of the Potomac Institute for Policy Studies. He is Editor-in-Chief of the Science, Technology, Engineering, and Policy Studies (*STEPS*) journal/magazine (this publication), and the author of over a hundred academic articles and Potomac Institute reports. He completed a four-year IPA assignment to the National Geospatial-Intelligence Agency in 2020. Prior to joining the Potomac Institute, he served as a program manager at DARPA for nearly nine years, managing and initiating projects in information exploitation, computer science, and sensor design. Prior to joining DARPA, he was a tenured faculty member at NYU's Courant Institute of Mathematical Sciences in the Computer Science Department, where he did research in computer vision and artificial intelligence. Dr. Hummel has a PhD in mathematics from the University of Minnesota, and he holds a B.A. in mathematics from the University of Chicago.

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Dr. Timothy Bumpus received his PhD in chemical biology from Cornell University where, as a National Science Foundation Graduate Research Fellow, he designed and implemented new chemical tools to study lipid centric cell signaling processes. Prior to Cornell, Dr. Bumpus attended Luther College where he received his B.A., majoring in chemistry, biology, and mathematics. He now brings his diverse scientific expertise to bear on the many, varied science and technology policy issues facing the country as part of the Potomac Institute for Policy Studies' research staff.

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Dr. Jennifer Buss serves as the CEO of the Potomac Institute for Policy Studies. The Institute develops meaningful science and technology policy options through discussions and forums and ensure their implementation at the intersection of business and government. She has extensive experience examining policy issues in support of NASA, and has been involved in their strategic planning processes for astronaut medical care and cancer diagnostics and therapeutics. She manages a variety of OSD programs including an outreach effort for the Department of Defense to the start-up community across the country to find innovative technologies to meet the challenges faced by the Services and Government agencies. Dr. Buss performs science and technology trends analysis and recommends policy solutions to some of the country's most pervasive problems. She has also directed and assisted research on numerous government contracts, including systematic reviews and gap analyses. Dr. Buss is an authority in her scientific field with national recognition in her area of expertise. She is responsible for major projects requiring integration/coordination across multiple scientific disciplines.

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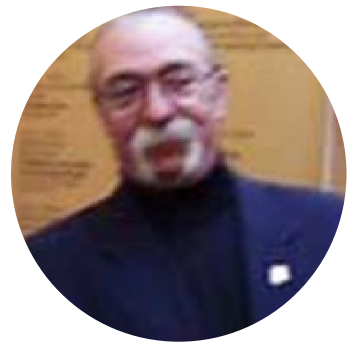
Dr. Alyssa Adcock is a S&T Policy Research Fellow. At the Institute, she has been involved with several efforts focused on providing strategic S&T recommendations and technical forecasting to government customers including ongoing work with NASA. Dr. Adcock obtained her PhD from Georgetown University in Inorganic Chemistry. Her graduate research focused on bismuth and rare earth element materials to address energy, lighting, and security needs as well as uranium chemistry relevant to nuclear waste and environmental management. Prior, she received her B.S. in Chemistry at Jacobs University in Germany and served as an intern at the Carnegie Institute of Washington's Geophysical Laboratory focusing on origin of life and geochemistry research. Dr. Adcock is a member of the Graduate Education Advisory Board of the American Chemical Society.

Jeff "Skunk" Baxter



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Jeff Baxter currently serves as Chairman of the Civilian Advisory Board for Ballistic Missile Defense. He has acted in an advisory capacity for Congressmen Curt Weldon and Dana Rohrabacher, both members of the House Science Committee, and has participated in numerous wargames for the Pentagon. Mr. Baxter was invited to serve on the Laser Advisory Board at Lawrence Livermore National Laboratory and has lectured at the University of Manitoba School of Political Science on the topic of regional conflict and missile defense. He is a world-renowned guitarist and a former member of both Steely Dan and the Doobie Brothers.

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Prior to joining the Institute, Dr. Claire Costenoble-Caherty received her doctorate in Emerging Infectious Diseases from the Uniformed Services University in 2020, and a Bachelor of Science degree in Microbiology from The University of Maryland College Park in 2013. She conducted her doctoral research in the laboratory of Dr. Ann Jerse, where she developed murine models of gonorrhea/chlamydia coinfection and upper reproductive tract infection, and studied the immune response in the context of such infections.

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Dr. Mike Fritze is a Senior Fellow and former Vice President at the Potomac Institute for Policy Studies. He is responsible for the Microelectronics related portfolio with interests and activities in the areas of secure access strategies, supply chain issues, support of legacy technologies, DoD innovation policy, outreach to Industry and strengthening the US Industrial Base. Customers have included OSD, DARPA, USAF and NNSA. Dr. Fritze is active on the NDIA Electronics Division co-chairing the Policy subcommittee. Prior to his affiliation with the Institute, Dr. Fritze ran microelectronics Programs at USC-ISI and was a Program Manager at DARPA MTO. Prior to that, he was a staff member at MITLL.

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Sharon Layani is a Research Analyst in the S&T Division. She provides assessments of emerging science and technology trends, government acquisition strategies, strategic planning, and policy recommendations. Prior to this she served as Research Associate and Research Coordinator at the International Center for Terrorism Studies. Her work focused on counterterrorism, international security, and rule of law issues. She provided research support and analysis for books, such as NATO: From Regional to Global Security Provider (2015) and The Islamic State: Combating a Caliphate Without Borders (2015), and assisted on a number of counterterrorism reports and projects. Ms. Layani served on the senior staff for Terrorism: An Electronic Journal and Knowledge Base and coordinated foreign policy and national security-related seminars. Ms. Layani graduated from the University of Michigan with a double major in Political Science and Biopsychology, Cognition, and Neuroscience, and a minor in International Studies focusing on the Middle East.

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Dr. Moriah Locklear is a Research Fellow at the Potomac Institute for Policy Studies. Prior to joining the Institute, Dr. Locklear obtained her PhD in organic chemistry from University of Nebraska at Lincoln where her graduate research focused on the study of peroxides for the construction of drug-related functionalities. Simultaneously, Dr. Locklear served as a legislative intern in the Nebraska State Legislature focusing on a variety of issues related to veteran affairs, technology policy, and green energy. She received her bachelor's degree in pharmaceutical sciences with minors in chemistry and comparative religion at Ohio State University.

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Jody Moxham is a strategic communication expert with a career focused on helping multinational corporations and government organizations measurably strengthen the persuasiveness of their global marketing strategies and communications. PhaseOne communications was founded to market a unique methodology, serving many corporate clients. After 9/11, PhaseOne dedicated a select team of analysts to work on national security projects. PhaseOne contracts spread across the IC and the DOD, for understanding target audiences, strategies for easing tensions, and understanding motivations of adversaries. In 2012 PhaseOne sold the company and Jody left in 2015. Jody was also instrumental in founding the US Marketing Communications College to help train US government personnel in private sector communication basics. She is currently a contributing faculty member for the Senior Joint Information Operations Applications Course (SJIOAC), a Senior Fellow at Potomac Institute for Policy Studies, a Senior Advisor to Parenthetic, a strategic communications company, and continues to advise and teach within the US government community.

Curits Pearson

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Curtis Pearson joins the Potomac Institute following 30 years with Northrop Grumman where he served in a variety of roles in program and system development spanning a wide range of DoD and IC technology, missions, and systems. His background includes strategic planning, mission and concept development, operational planning, technology planning and development, and mergers and acquisitions. He retired from the Naval Reserves as a CDR (O-5) after 27 years of both Active and Reserve Service with expertise in Mine and Amphibious warfare, ship systems engineering and construction, and Military Sealift Command port operations. He is a Life Member of the National Defense Industrial Association, a member of the Naval War College Foundation, and The Tailhook Association, as well as an active member in the Association of Old Crows, The Intelligence and National Security Alliance, and The Navy League. He previously served as the Chairman of the Board for the Southern Coalition for Advanced Transportation. Curtis received his bachelor's degree in Engineering from the US Naval Academy. He is a graduate of the U.S. Naval War College and completed the Darden Business School Executive Management Program.

The Honorable Alan R. Shaffer

Board of Regents Member, Potomac Institute for Policy Studies

Since January 2021, the Honorable Alan R. Shaffer has been a private consultant and member of the Board of Regents of the Potomac Institute. Previously, he was Deputy Under Secretary of Defense for Acquisition and Sustainment (A&S), confirmed in January 2019. He served as the Director, NATO Collaboration Support Office in Neuilly-sur-Seine, France after serving as the Principal Deputy Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) from 2007-2015, with two stints as acting assistant secretary. In these capacities, he is known for his service as the Executive Director of the Mine Resistant Ambush Protection (MRAP) Task Force, where he was responsible for oversight, fielding, and employment of 27,000 MRAPs across the Department of Defense. Before entering the federal government, Mr. Shaffer served 24 years as a commissioned officer in the United States Air Force and retired in the grade of Colonel. While serving, he held positions in command, weather, intelligence, and acquisition oversight with assignments in Utah, California, Ohio, Honduras, Germany, Virginia, and Nebraska. He holds a Bachelor of Science degree in Mathematics from the University of Vermont and a Bachelor of Science in Meteorology from the University of Utah, a Master of Science in Meteorology from the Naval Postgraduate School, and a Master of Science in National Resource Strategy from the Industrial College of the Armed Forces.

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Brian Shirley is a senior executive and advisor with over 34 years of broad-based experience in the semiconductor industry, including fourteen years as an executive officer of Micron Technology, a US-based Fortune 500 leader in semiconductor memory. He has been a senior consultant to the US government on topics related to the semiconductor industry and US national security. He is listed as an inventor on 82 US patents and helped drive Micron's expansion into specialized memory for servers, and mobile and networking solutions. At Micron, he drove DRAM diversification, product expansions in NAND solid-state memory and related SSD product lines, and productization of multiple emerging memory technologies. He has served on the boards of numerous joint ventures and industry organizations. Mr. Shirley retired from Micron in December 2019. In 2020, Mr. Shirley joined CTC Aero consulting with multiple departments of the US government. In addition, he is serving as a senior advisor and board member to multiple semiconductor startups, as well as serving as a member of the Board of Regents and Senior Fellow of the Potomac Institute.

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