EXECUTIVE SUMMARY

Over the past half-century, the longstanding US dominance of the global geopolitical balance of scientific, economic, and production capabilities has diminished. The United States also faces serious challenges on the home front, where economic inequality has increased and social mobility has declined. Technological change and globalization are central to all these concerns. Yet little is understood about pathways to simultaneously advance both US competitiveness in critical technologies and the well-being of all citizens.

Against this backdrop, the CHIPS and Science Act (US Congress 2022) introduced unprecedented legislation requiring the formulation of a US national technology strategy, led by the White House Office of Science and Technology Policy, to focus limited federal dollars to achieve national security, economic, and societal ends, given the interdependence of technologies and the impact of associated policies and investments across agency-specific missions. Congress charges the National Science Foundation's (NSF) Technology Innovation and Partnerships (TIP) Directorate to work in consultation with the interagency working group in identifying and evaluating societal, national, and geostrategic challenges facing the United States and investments in key technologies that could help address those challenges.

Responding to the legislative mandates will not be easy: Building the intellectual foundations, data, and analytic tools to inform NSF TIP's mission will require mobilizing, synthesizing, and integrating capabilities distributed across the country among different researchers, disciplines, and institutions. There is not a mature field of national technology strategy nor a widely agreed upon field of critical technology assessment. National investments in key technologies need to be guided by analytic and physical science expertise frequently found in academia and industry, and not easily attracted by individual agencies. National strategy in technology needs to (i) be based on knowledge that spans multiple government departments and (ii) take into account their missions. The United States lacks the data and infrastructure needed for timely situational awareness of global technology and production capabilities, rigorous methods to quantify the potential value of innovations (including considering geopolitical dynamics), and tools for quantifying opportunities across national objectives to simultaneously enhance national security, economic prosperity (including jobs), and social well-being (including health, environment, and equity).

Building the intellectual foundations, data, and analytic tools needed for critical technology assessment requires mobilizing, synthesizing, and integrating capabilities distributed nationwide among researchers, disciplines, and institutions.

In response to this gap, the NSF TIP-funded pilot National Network for Critical Technology Assessment (NNCTA) brings together leading scholars from across the nation to begin to build the intellectual foundations, analytic tools, and data needed to respond to this charge: specifically, to produce a vision for critical technology assessment that outlines (i) current capabilities (with demonstrations thereof) to help inform Congress and agency leaders on how to prioritize limited national resources—and in particular investments in research and innovation—to have the greatest impact on US societal, national, and geostrategic challenges; (ii) gaps in those capabilities; and (iii) the national investment and organizational form necessary to achieve that vision.The pilot activities highlight that there is both an art and a science to effective critical technology assessment, and that such assessment is essential to ensure that the country smartly invests and enacts necessary policies to achieve short- and long-term security, prosperity, and broad-based social well-being. Effective assessment is not top-down coordination or optimization of investments that copies competitor nations' style and approach, nor can it be solely a curiosity- (for science) or market- (for technology) driven approach that fails to acknowledge the stakes and the outcomes for the nation and its people.

Assessment is essential to ensure that the country smartly invests and enacts necessary policies to achieve short- and long-term security, prosperity, and broad-based social well-being.

As Congress recognized in the creation of TIP, something disruptive is needed in how we fund the pathway from translational discovery to commercialization. In addition, for TIP to be effective in fulfilling its charge, something disruptive is also needed in how the nation conducts critical technology assessment (CTA): the federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike. This program must embrace the accelerating pace of innovation, draw on the nation's rich variety of institutions, disciplines, and agencies, and exploit their analytic power and technical expertise. Such work will be best led by a single organizational unit charged to think across national objectives and technology interdependencies, engaging topic-specific program managers trained in the art of critical technology assessment to identify the most important problems, match methods to problems, and mobilize and orchestrate the distributed national capabilities both within and outside government.

The NNCTA pilot year activities (summarized in the next section) demonstrate that data and analytics can meaningfully inform national technology strategy, but the necessary capabilities do not sit with one discipline, investigator, or type of organization. The novel pairings and cross-disciplinary collaborations that were effective in this pilot year had to be orchestrated (a hallmark of the efforts undertaken by DARPA program managers). This orchestration is an "art" that, if done well, yields a whole greater than the sum of the parts: creating a dynamic exchange between a 30,000-foot machine-driven and a bottom-up expert-driven perspective to benefit from both; combining data across scholarly areas and institutions to transcend gaps; marshaling different disciplines and methods to solve different aspects of a policy problem; setting up different perspectives on the same policy problem to enhance understanding through complementary or contradictory insights; creating teams to combine disciplines and models in a way that produces otherwise unavailable novel findings; identifying transition partners; and transparently engaging throughout and communicating the final findings across the variety of relevant stakeholders. The analytic methods leveraged in specific fields are the frontiers of science—whether economics, computer science, sociology, political science, psychology and decision science, or engineering.

The pilot year investigations also revealed that the most appropriate methods and data are not static but closely linked with (i) the status of a technology's discovery, diffusion, and adoption; (ii) US global competitiveness in the knowledge, production, and use relevant to the technology; and (iii) the state of the policy process with respect to the technology. Understanding the most important problems to tackle in a particular area, and how to match methods across disciplines to those problems, requires deep knowledge of the industrial, technological, and policy contexts. Program managers with the talent to identify and understand national challenges as well as top researchers' activities across disciplines, and to provide the orchestration needed to address those challenges, are rare. The nation should cultivate them by investing in nontraditional educational programs and professional fellowships to build human capital with problem-oriented policy skills that leverage analytic rigor, interdisciplinary methods, and contextual and phenomenological depth—in short, to develop a community of practice in (rapid) critical technology assessment.

Based on these observations and our pilot year demonstrations, we recommend that the United States invest in a rapid critical technology assessment entity to provide the executive and legislative branches with the tools needed to inform national technology strategy. This CTA program would, as part of its primary functions, support NSF TIP in its annual roadmapping and OSTP in its Quadrennial National Technology Strategy, serve Congress and the executive branch with analytics to inform critical technology strategy across national (and agency-specific) missions writ large, and serve as a trusted source of technology assessment capability to government, industry, nonprofits, and the public. The program should focus on problems that span national missions, taking account of technology and policy interdependencies and of win-wins or tradeoffs across national objectives (or individual agency missions).

The federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike.

The CTA program would orchestrate the analytics necessary to inform national technology strategy. The program should draw heavily from the DARPA model in terms of its dynamism and the independence and discretion of talented program managers to choose problems and orchestrate top performers to address those problems. It should also, like DARPA, push the frontier of analytic capabilities, then transfer those capabilities eventually into the executive and legislative branches. Unlike DARPA, however, the program should not undertake high-risk analyses but be grounded in a simultaneously disciplined and innovative analysis process, pushing the frontier of scientific and analytic capabilities.

The core CTA function would be conducted by a program manager with both area-specific expertise (e.g., technical depth, such as in AI or semiconductors) and institutional and disciplinary breadth. Program managers would, as at DARPA, have limited terms to help keep the organization nimble and up-to-date and also to facilitate these positions as a stepping stone to follow-up leadership positions. The CTA entity would involve and draw on agency and organizational expertise across the government. It would fund problem-oriented research and also serve a business development role in supplementing nonspecific funds with matching contracts from relevant executive or legislative branches (e.g., for issues that cross departmental missions in semiconductors, involving the Departments of Commerce, Defense, and Energy; or, in the case of novel data infrastructure, NCSES, the International Trade Commission, and/or the US Census Bureau). In addition to the CTA entity's advisory board, which should include leaders from government agencies as well as from academia and industry, each program manager should have an area-specific advisory committee, and run workshops that bring together relevant thought leaders and stakeholders from academia, industry, government, and nonprofits to launch and inform analytic programs.

Overseeing the program managers, in a way similar to DARPA office directors' integrational role, would be a government director and a technical director. The government director would identify relevant national challenges across departments for which there likely is particular value in analytics, including in quantifying tradeoffs or win-wins across missions. The technical director would identify opportunities for collaboration or integration across the topic areas. The government and technical directors, along with the CTA program director, would together be responsible for one of the most challenging and important functions: where to focus the limited analytic resources—identifying the topic areas for program managers, reducing or eliminating funding of some areas as appropriate, and bringing on new program managers and funding in newly needed topics.

The CHIPS and Science Act calls for a new federal capacity to fortify the nation's leadership and ability to determine policies and investments that will ensure national security, global competitiveness, economic prosperity, and social well-being. To effectively operationalize this mandate will require something truly disruptive. This report of the pilot National Network for Critical Technology Assessment provides evidence of what analytics can accomplish, and the critical components for a path forward as effective and disruptive as legislators envisioned.

PILOT YEAR AREA DEMONSTRATIONS OF HOW ANALYTICS CAN INFORM NATIONAL TECHNOLOGY STRATEGY

Global Competitiveness

Type of critical technology assessment Situational awareness of US versus other nations' capabilities in science and technology (S&T) knowledge and production (and inputs such as funding and human capital)

Lead performers Yong-Yeol (YY) Ahn, James Evans, Joshua Graff Zivin, Cassidy R. Sugimoto

The United States today lacks sophisticated and systematic mechanisms to assess its global competitiveness in science and technology (S&T) relative to other countries in ways needed to effectively execute the country's defense, trade, commerce, and other missions (NASEM 2019). Large language models (LLMs) are revolutionizing the type of competitiveness assessments possible. At the same time, the types of on-the-ground open intelligence programs (ONR Global, NSF Satellite offices, World Technology Evaluation Center [WTEC], Asian Technology Information Program [ATIP]) needed to complement these models have been discontinued or downsized.

As an example, prior to this year's NNCTA analysis, the understanding has been that even if China has surpassed the United States in the total *number* of scientific publications, the United States is more creative and more likely to have high-impact breakthroughs like CRISPR that lead to new fields. But work by scholars in the National Network finds that China has the highest share globally of disruptive scientific papers (defined as those that initiate a new line of research in a field) and papers that lead to the emergence of new fields. That said, Chinese and US researchers also collaborate more on scientific publications than any other two nations, and this collaborative research represents a significant fraction of each country's scientific output. Causal analysis shows that both countries would substantially reduce their production of scientific knowledge if collaborations were cut off.

While these are initial measures that require further exploration with experts at field- and paper-specific levels, the findings are sufficiently concerning to deserve much greater attention. Such research will benefit from the development of a systemized approach that combines the most advanced LLM and machine learning capabilities with the knowledge of global experts in each field and, where opportunities exist (such as natural experiments), runs causal analyses to understand how policy interventions could influence outcomes in ways that strengthen US global standing in cutting-edge research.

This systemized approach should also be applied domestically to inform legislators and agencies of regional capabilities that could support US competitiveness and ways to advance them. In particular, our results show that in certain critical fields (such as computing), the United States is failing to engage the full talent base: Underrepresented female and minority scientists and technologists whose work is objectively superior are failing to get funding because of biases in the funding process. These underrepresented groups often do more interdisciplinary work and work with novel foci. Similarly, some high-risk, high-reward research is not funded in the federal peer review process. Early-stage higher-risk research may be more likely to be funded by philanthropic foundations, but their funding is not systematic and their missions do not necessarily address national needs. Tools leveraging current analytic capabilities and knowledge in decision science should be further developed and used to help mitigate federal peer review biases in real time to ensure that important innovative research is funded and domestic capability is strengthened.

Overall these results suggest that the United States needs a better system for identifying and funding underrepresented researchers and innovative, higher-risk approaches.

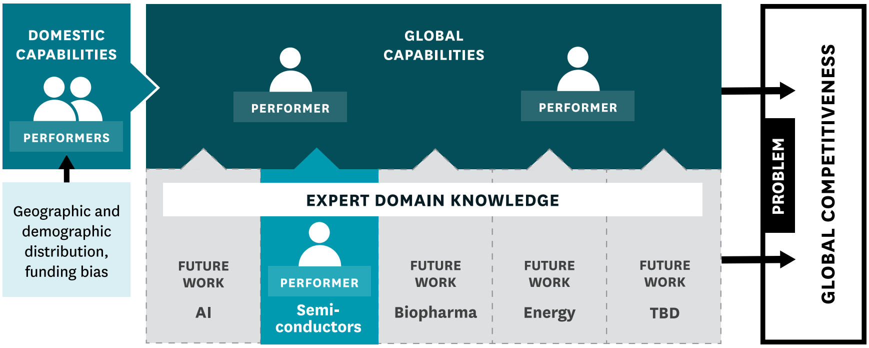
Program management Connect 30,000-foot insights from sophisticated data science models to contextual expert knowledge; red-teaming workshop; synthesis across researcher results

Methods LLMs, machine learning, end-of-program workshop to evaluate and red-team results with analytic, technology, and industry experts

Data Scientific publications, expert surveys

Criticality dimensions measured S&T competitiveness, social well-being

Challenges for future critical technology assessment Insufficient situational awareness of global technology and production capabilities (including product-level supply chains) and relevant human capital inputs



Artificial Intelligence

Type of critical technology assessment Emerging technology, high economic and security impact

Lead performers Lee Branstetter, Erik Brynjolfsson, Thema Monroe-White, Dewey Murdick, Dashun Wang

Academics, policymakers, industry experts, and the public have feared that artificial intelligence (AI) will lead to a loss of jobs, and productivity gains have proven difficult to measure. Using novel data and measurement techniques, we demonstrate that AI has the potential to substantially increase scientific discovery, productivity, output, and employment across the US economy, but the invention/diffusion process is still in early stages and not all firms, regions, demographics, or scientific fields are benefiting.

Many scientific fields are not benefiting from AI's potential to accelerate scientific discovery through machine-driven synthesis of knowledge, optimization of experimentation, and other mechanisms. Policy can support scientific and technology disciplines in discovering (through collaboration with AI experts) and training (through education) in the best uses of AI in their fields. The following measures can address gaps in leveraging AI to accelerate scientific discovery:

- Fund and facilitate cross-department collaborations between scientific and engineering disciplines and AI experts.
- Fund the development of university curriculum in the best uses of AI in their scientific and engineering fields.
- As shown by previous analyses, expand the AI-related professoriate immediately by (i) broadening opportunities for foreign graduates of related US PhD programs to remain in the United States and (ii) increasing funding and support programs that facilitate female and underrepresented groups in their graduate study in AI-related fields.

Firms that are farther ahead in AI adoption are growing in revenue and employment, but those benefits are concentrated in large firms and limited geographic regions and demographics. The United States needs to find ways to diffuse AI capabilities more broadly so that its benefits are more widespread.

- To support smaller enterprises in adopting and benefiting from AI, expand the ranks of AI workers with the skills needed to work at the disciplinary frontier, through advanced education of domestic students, attraction of outstanding foreign-born talent through immigration, and support programs for female and underrepresented groups to pursue AI-related fields.

- To enable more regions and demographics to benefit from AI, authorize funding to staff AI office and workforce support initiatives, like the National Artificial Intelligence Initiative Office for Education and Training; develop a federal framework of technical and nontechnical AI work roles and competencies; create a National AI Research Resource (NAIRR) to provide greater access to the computational resources and datasets for academics, nonprofit researchers, and startups from diverse backgrounds; and establish federal grant programs for AI industry-academia partnerships, AI-related degree and nondegree programs at community colleges and minority-serving institutions, and equipment at AI labs and related facilities.

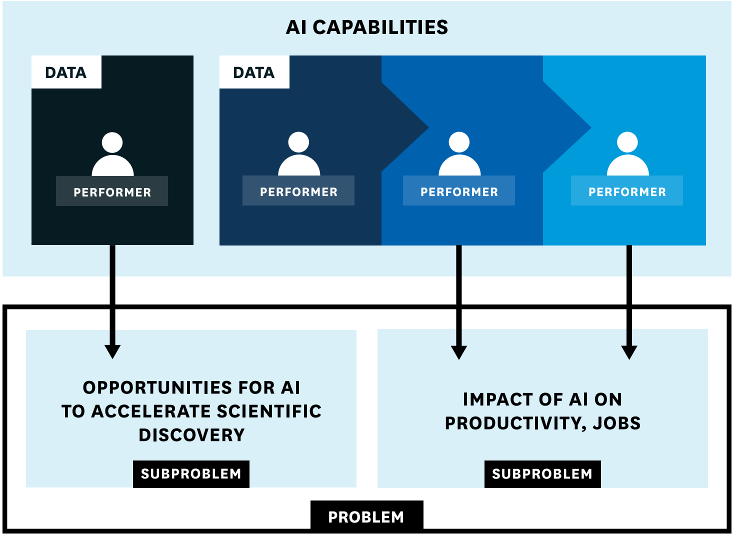
Program management Compare different datasets held by different performers to overcome sample and data limitations

Methods LLMs, machine learning, surveys, descriptive statistics, econometrics

Data Publications, patents, Bureau of Labor Statistics Survey, US Census data

Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs)

Challenges for future critical technology assessment Inadequate availability of and access to timely data—including from private sources—given the rapid rate of technology change; sharing of data and algorithms; broader geographic and demographic participation; algorithm bias



Semiconductors

Type of critical technology assessment Nascent evolving technology with high economic and security impacts; vulnerable supply chain for existing technology

Lead performers Yong-Yeol (YY) Ahn, Christophe Combemale, Hassan Khan, M. Granger Morgan, Neil C. Thompson

Regaining US competitiveness in semiconductors requires a multipronged approach. First, targeted investments in worker training will be necessary to overcome challenging labor and skill gaps in certain regions identified for new leading-edge domestic semiconductor facilities. Advanced analytic tools can and should be used to identify specific regional mismatches in skill demand and supply and inform necessary regional training and retraining programs. Second, the United States is behind competitor nations in enabling researcher access to commercial production technologies. Firms should be required to increase such access (e.g. improve their shuttle run and multi-project wafer offerings for US researchers) if receiving subsidies for US-based facilities. Last, given the stakes for the economy and security, advances by competitor nations, and insufficient funding for a broad enough portfolio given uncertainties, the United States should increase funding for next-generation (beyond-CMOS) semiconductor devices beyond that in the CHIPS and Science Act.

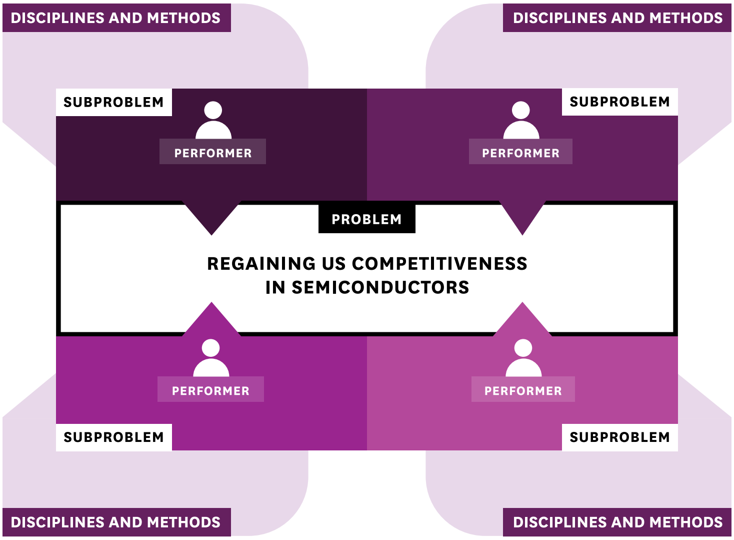
Program management Identify the most important problem and problem subcomponents, and then identify and leverage different performers with different methods and disciplines on different components of the problem; midway workshop to elicit stakeholder input and feedback from industry and government

Methods Expert elicitation, local labor skill gap modeling, productivity measurement, LLMs, engineering-economic models

Data Expert survey results, publications, O*NET data, productivity data from the US Bureau of Labor Statistics, USPTO patent data, the International Technology Roadmap for Semiconductors, and data on CPU and GPU characteristics

Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs)

Challenges for future critical technology assessment Small numbers of (i) analysts who can conduct the labor constraint analysis and (ii) nonstakeholder analysts who can pair advanced analytic capabilities with deep technical and industrial knowledge


DISCIPLINES AND METHODS
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REGAINING US COMPETITIVENESS IN SEMICONDUCTORS
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DISCIPLINES AND METHODS
DISCIPLINES AND METHODS

Biopharmaceuticals

Type of critical technology assessment Commodity product for which loss of access would have high social and security impacts

Lead performers Rena Conti, Baruch Fischhoff, Marta Wosińska

Pharmaceuticals are the most used medical care in the United States, yet their supply chains are not resilient, resulting in quality deficits and shortages that pose risks for patients and the medical system. The risks of supply deficits apply across pharmaceutical products and are concentrated among generic (off-patent) drugs, including "critical generics" used by a large fraction of the population as well as by particularly vulnerable populations. Advanced manufacturing technologies (AMTs)—such as continuous manufacturing, modular manufacturing, advanced batch processing, and digital twins—offer advantages in ensuring product quality and reliability of the manufacturing process, yet the private sector does not adopt such technologies in pharmaceuticals in general or where they are frequently needed at the generic drug level.

The public is aware of, concerned about, and affected by access issues, but appears to not be aware of quality issues. The federal government needs a multipronged approach, including revised regulation of generic drugs (and in particular the FDA production safety approval process) to facilitate AMT adoption, expanded surveillance to improve tracking and regulation of drug precursors and quality, improved public awareness of drug quality issues in fragile supply chains, and early public input on expectations around quality, price, availability, and policies to address these.

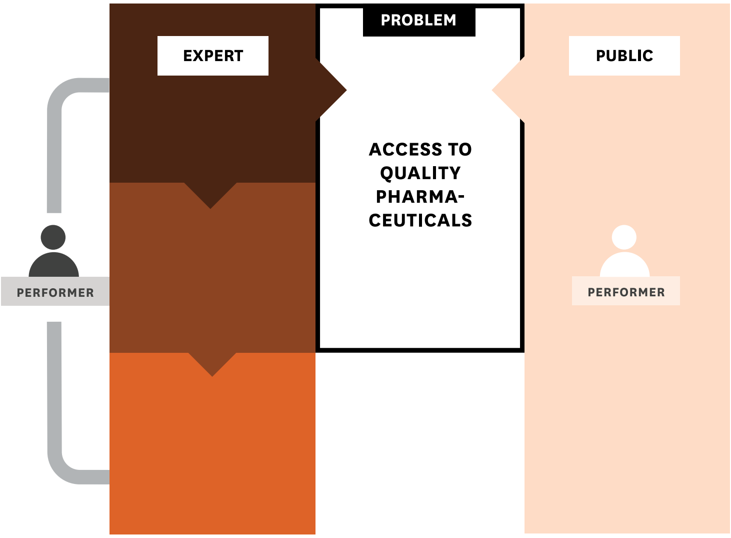
Program management Put side-by-side the results of performers with different disciplines, perspectives, and methods; workshop engaging leaders from academia, industry, and government to launch analytics

Methods Interviews, economics, descriptive statistics, expert elicitation; citizen surveys for public awareness, early input

Data Expert interviews; IQVIA pharmaceutical market data; USP data on supplier locations and drug raw materials; FDA data on drugs that have had supply shortages; expert and citizen survey results

Criticality dimensions measured Social well-being (health, demographics of populations affected)

Challenges for future critical technology assessment Limited government and nonstakeholder analyst access to product-level supply chain data in pharmaceuticals


PROBLEM
EXPERT
PUBLIC
ACCESS TO QUALITY PHARMA-CEUTICALS
PERFORMER
PERFORMER

Energy Storage and Critical Materials

Type of critical technology assessment Emerging product for which loss of access would have high social and economic impacts (and possibly security impacts)

Lead performers Elsa Olivetti, Kate S. Whitefoot

Policymakers' and industry's planned transition from conventional to battery electric vehicles (BEVs) is likely to face significant battery material supply chain risks as early as 2030. Simulations of 2030 scenarios show that lithium and cobalt supply shocks due to geopolitical disputes or natural disasters could have impacts similar in magnitude to the recent semiconductor shortage. Impacts would include significant increases in new vehicle prices (both conventional and electric), nearly a million US households unable to purchase a new vehicle, consumer surplus losses of approximately $24 billion, and significant lost wages for battery cell and pack production line workers.

The projected vulnerabilities to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries: Simulations suggest that encouraging additional supply of lithium domestically or in locations with lower risk of trade restrictions will mitigate the negative impacts of trade or other geopolitical disputes. Increasing the use of cobalt-free batteries (such as lithium-iron-phosphate) in the large majority of BEV sales significantly reduces the negative impacts of cobalt supply shocks. Immediate actions exist for increasing adoption of cobalt-free batteries and the future supply of lithium, and investments in innovations in novel lithium processing and cobalt-free battery chemistries could strengthen these alternatives.

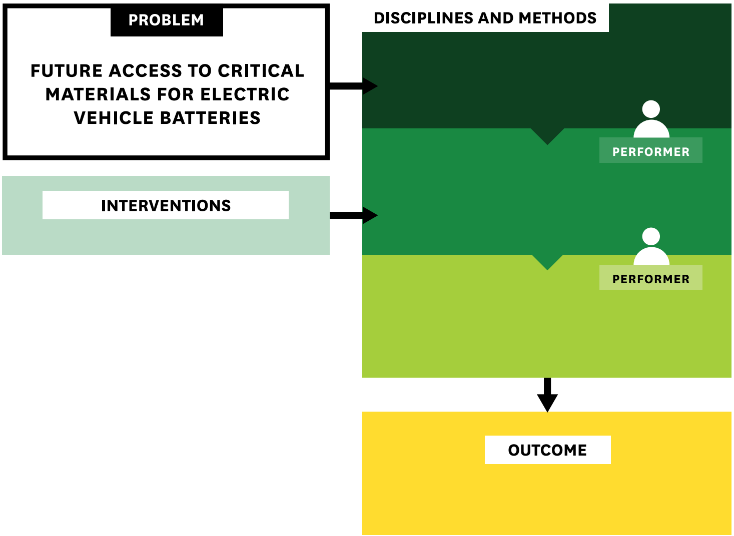
Program management Team two previously unconnected performers

Methods Industrial organization modeling, scenario modeling, supply chain modeling, engineering-economic models

Data Global mine supply data from S&P; historic data on material demand, prices, mining production, and mining costs; design, process, production, and labor hour data collected from private firms and published by Argonne National Laboratory; data on the automotive market from Ward's

Criticality dimensions measured Economic well-being, social well-being (consumer surplus losses, jobs)

Challenges for future critical technology assessment Need to bring together scholars with industrial organization economics and engineering analytic expertise, and make policymakers aware of the possibilities of such analysis


PROBLEM
FUTURE ACCESS TO CRITICAL MATERIALS FOR ELECTRIC VEHICLE BATTERIES
INTERVENTIONS
DISCIPLINES AND METHODS
PERFORMER
PERFORMER
OUTCOME

Cross-Cutting Insights for Critical Technology Assessment from the Area Demonstrations

Across demonstration areas, many scholars, government labs, and nonprofits (including FFRDCs) have a deep bench of data and models. The US government must develop a disruptive new program to tap into and integrate this expertise.

Advanced analytics today can be used to inform

- US global competitiveness in scientific funding and its collaboration networks
- US domestic funding biases that are failing to leverage the full bench of talent
- Technology commercialization pathways, including policy, investment, and other interventions—technical, human capital, infrastructure, regulatory, and citizen awareness and participation—to overcome bottlenecks. Following are examples of options identified this year to overcome technology commercialization bottlenecks:
  - Identify infrastructure gaps and increase access to that infrastructure to boost innovation;
  - Identify skill gaps in specific regions and training or worker mobility interventions to overcome these gaps;
  - Identify public, technical, and regulatory bottlenecks to the introduction of new technologies in commodity products, and opportunities to overcome those bottlenecks.
- Investment and policy interventions that could reduce supply chain vulnerabilities, and the value of that reduced vulnerability for national objectives in security, the economy, and social well-being.

US CTA capability is hampered by the following gaps:

- Building situational awareness of global technology and production capabilities is even more challenging than analyzing scientific and inventive capabilities through publications and patents: the data currently don't exist, and therefore few scholars or practitioners are rigorously addressing these problems. A CTA function must invest in these capabilities and develop a framework to determine where and how frequently they should be applied.
- The data needed for analytics to inform policy and investment in a timely fashion for rapidly moving critical technologies such as AI are lacking. Public-private partnerships must be established to create these datasets to inform critical questions in national technology strategy. There are analogous needs to coordinate data across the private sector and government in a timely fashion in certain critical technology supply chains.

The inclusion of equity in each analysis requires resources. Equity is not a single field of study, and experts with complex analytic, technical, and phenomenological knowledge are needed to address issues in algorithmic bias, energy equity, health equity, and equity and discrimination in labor and training (e.g., conscious and unconscious recruiting bias, macro- and microaggressions in STEM fields), among others. CTA leadership (the director, government director, and technical director) will also need to ensure that program managers maintain a cross-mission focus involving all three dimensions of criticality (security, the economy, social well-being), and that all analyses include the geographic and demographic implications of policies and investments.

US CTA capability will require the following institutional innovations:

- Leveraging the best of the nation's analytic capabilities to address the full portfolio of CTA challenges, opportunities, and needs will require integration of capabilities across a range of performers from academia, industry, and nonprofits such as FFRDCs.
- To scale this year's project and performer selection and orchestration activities, area-specific program managers should have deep contextual (technical and industrial) expertise in their topic area, experience in a diversity of institutions (academia, industry, and government), and an ability to understand leading analytic capabilities. There is a shortage of this type of human capital.
- To ensure policy relevance and impact of selected projects, program managers should be charged with (i) scanning globally and domestically for US challenges and gaps and (ii) scanning the nation's top talent for analytics to address those challenges, identifying multiple stakeholder agencies to partner with on specific analytic projects, and ensuring government transition partners for the outcomes.
- To simultaneously maintain relevance to policy and develop buy-in from relevant government stakeholders in the legislative and executive branches, members of Congress, the executive branch, and government agencies should be allowed to cofund analytic undertakings.
- The lack of a field of critical technology assessment means there is also a lack of human capital with the skills necessary both to perform the analytics needed for national technology strategy development and to serve as program managers of the work conducted across the country in each area. New education programs and professional fellowships are needed to invest in building this human capital.