CHAPTER 1: INTRODUCTION

Over the past half-century, the global geopolitical balance of scientific, economic, and production capabilities has shifted away from US dominance. At the same time, the United States 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. Policymakers need new tools to develop policies to simultaneously advance both US competitiveness in critical technologies and the well-being of all citizens.

Against this backdrop, the CHIPS and Science Act introduced unprecedented legislation. First, it mandated that the Office of Science and Technology Policy (OSTP) write a Quadrennial National Technology Strategy. Second, it mandated the National Science Foundation's (NSF) Technology Innovation and Partnerships (TIP) Directorate to, "In consultation with the interagency working group...identify and annually review and update a list of 1) Not more than 5 United States societal, national, and geostrategic challenges that may be addressed by technology [and] 2) Not more than 10 key technology focus areas...and evaluate the relationship between US societal, national, and geostrategic challenges and the key technology focus areas."

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 modern, 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 should both be based on knowledge that spans multiple government departments and take into account multiple departments' missions. Further, the necessary data and tools to inform NSF TIP's mandated mission are inadequate. The United States lacks 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).

In response to the legislative mandate of the CHIPS and Science Act, the NSF-funded National Network for Critical Technology Assessment (NNCTA) brings together leading scholars from across the nation to demonstrate how analytics can help inform Congress and agency leaders on strategic directions for and specific investments in research and innovation that could have the greatest impact on US societal, national, and geostrategic challenges. The goals of the 1-year pilot were to produce a vision for critical technology assessment based on current data and analytic capabilities (and demonstrations thereof), to identify gaps, and to determine the investment and organizational form necessary to achieve that vision.

Pilot Year Activities Designed to Meet the Charge

To meet the pilot year charge, the National Network for Critical Technology Assessment undertook four types of activities, as shown in **figure 1-1:** The Network (1) identified and executed selectively coupled research projects that demonstrate (i) current and prospective analytic capabilities for critical technology assessment (CTA) and (ii) how multidisciplinary lenses yield a whole greater than the sum of its parts; (2) prototyped a series of structured workshops convening experts from academia, industry, government, and nonprofits around the demonstrations' analytics for specific policy problems; (3) leveraged the demonstrations, workshops, and consensus-building sessions to build the intellectual foundations for critical technology assessment; and (4) developed a quality and communications review process to draw, from a broader base of analytic activities, recommendations for analytic and policy next steps. These activities were undertaken at a pace uncommon in academic research projects but necessary to have policy relevance (e.g., initial PI-specific demonstrations at 6 months, integration across demonstrations at 9 months), and executed in a way to make the planned and in-process work as open and transparent as possible to NSF TIP and executive branch policy decision makers.

We unpack the processes used for each of these activities below.

DEMONSTRATION SELECTION

The Network's pilot year activities include both top-down and bottom-up approaches (**figure 1-2**). A top-down "30,000-foot" view could enhance awareness of US global competitiveness and inform potential actions to improve it by assessing different countries' production of scientific knowledge and its commercialization (i.e., in the development and marketing of products), including factors such as human capital and sources of funding. A similar domestic analysis can shed light on capabilities at the regional, state, or even county level.

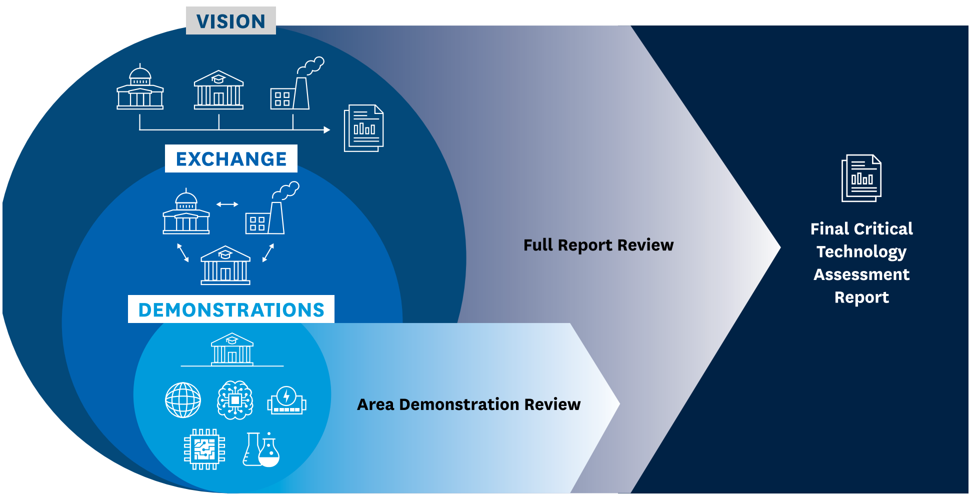

FIGURE 1-1. The area demonstrations—in situational awareness (global competitiveness), artificial intelligence, semiconductors, biopharmaceuticals, and energy and critical materials—were led by performers in academia. Their work was informed throughout by exchanges with experts in government, industry, and nonprofits. The vision for critical technology assessment drew on lessons across the demonstrations; elicited input on the data, analytic tools, and intellectual foundations for critical technology assessment during the exchange workshops; and a survey of and structured discussions and debate with network members and the Advisory Council. The area demonstrations were reviewed for research integrity and the full report was reviewed for quality and effective communication. (For process details see **figure 1-4**.)

Framework for Demonstration Selection

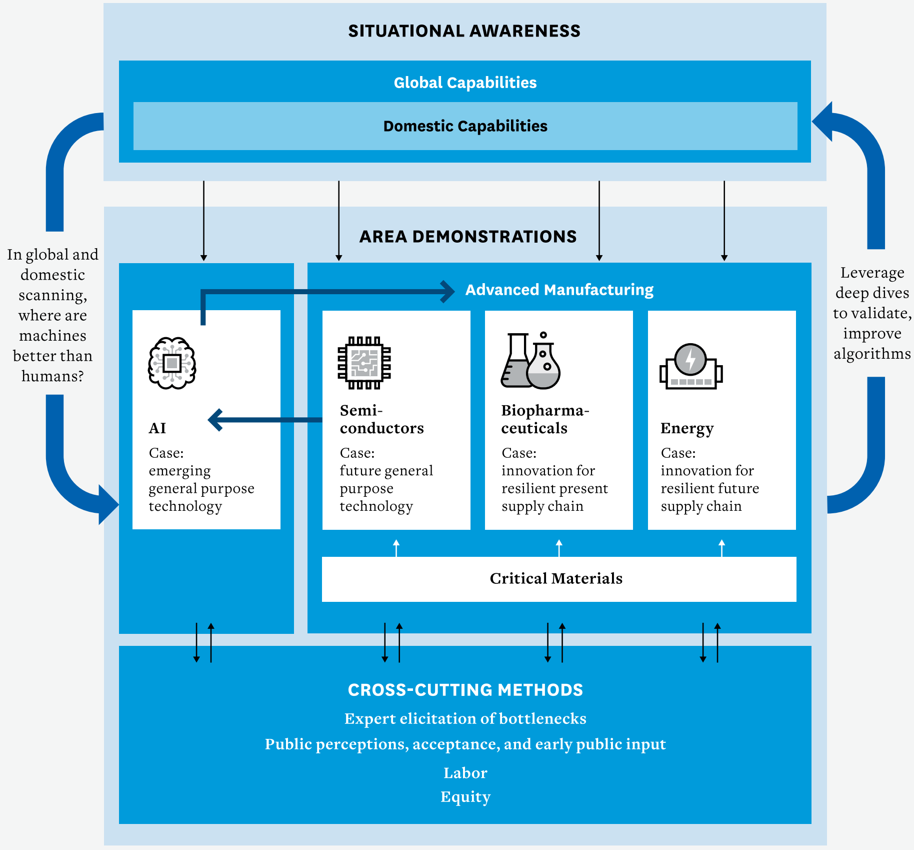

FIGURE 1-2. Framework that informed demonstration selection for the pilot year activities of the National Network for Critical Technology Assessment. The thick blue arrows show technological interdependencies explored between AI and semiconductors: advances in next-generation semiconductors are necessary to continue to advance AI, and AI holds the potential to accelerate scientific discovery, development, and commercialization of advanced manufacturing products in semiconductors, biopharma, and energy.

Situational awareness of the funding and production of scientific knowledge is matched with "bottom-up" area demonstrations in four technical areas highlighted in the list of "key technologies" in the CHIPS and Science Act and listed in a wide range of publications as "critical": artificial intelligence (AI), semiconductors (investments needed in leading-edge semiconductor device production and the future of computing devices, specifically "beyond CMOS"[1]), biopharmaceuticals (innovations in advanced manufacturing technologies for pharmaceuticals and in particular supply chain issues in generic drugs), and energy and critical materials (future battery supply chain issues with the ramp-up of electric vehicles). The area demonstrations represent different types of both technology criticality and assessment challenges.

The AI demonstration looks at the scientific discovery, productivity, and labor impacts of an emerging "general purpose technology" (GPT) with increasing but uneven adoption and with high security, economic, and social impacts. The semiconductor demonstration considers a potential future GPT, next-generation beyond-CMOS devices to advance computing performance, not yet adopted. The biopharmaceutical demonstration studies innovation and adoption of advanced manufacturing technologies to reduce pharmaceutical, and particularly generic drug, supply chain vulnerabilities. The energy and critical materials demonstration analyzes innovations in battery chemistries and critical material processing, along with potential policy interventions, to reduce future supply chain vulnerabilities.

The selected areas are important but not necessarily more so than others. Rather, they are used to demonstrate relevant methods for critical technology assessment and identify opportunities to advance US CTA capabilities. Chapter 5 explains differences in the CTA methods and data for each case.

Finally, looking at the pilot year's charge to identify gaps, it is not coincidental that three of the area demonstrations — semiconductors, biopharmaceuticals, and energy storage — involve advanced manufacturing technologies. While data are available from global publications and patents (each of which can be used to represent knowledge), data on global production capabilities (and supply chains) and on global human capital capa-bilities related to production are limited. At the same time, US manufacturing has been negatively impacted by trade and import competition and has low venture capital funding (compared to software), comparatively high R&D expendi-tures, and higher wages for high school–educated workers, and in some cases offshore manufacturing may have a negative impact on innovation (Fuchs and Kirchain 2010, Fuchs 2014, Fuchs et al. 2019, Autor et al. 2020). Commercial-ization of new technologies involving advanced manufacturing such as semiconductors, biotechnology, and energy technologies has been identified as an area of US weakness on which there is to be a particular focus by NSF TIP. Advanced manufacturing is also itself one of the key technologies listed in the CHIPS and Science Act.

DEMONSTRATION OF CROSS-CUTTING THEMES AND METHODS

The aim during the pilot year was to demonstrate in one topic area themes and analytic methods that could in future work be applied to multiple areas. Cross-cutting themes that could be applied throughout include human capital constraints (labor) and geographic and demographic diversity (equity). Cross-cutting methods relevant across cases include expert and public surveys about bottlenecks to commercialization and access.

Table 1-1 illustrates the following intersections. The situational awareness research and findings benefit by leveraging expert knowledge from the area lead in semiconductors. As shown in the "area demonstration connections" row of the table, the AI work shows the importance of assessing interactions between technologies (e.g., AI accelerating scientific discovery in semiconductors, biopharmaceuticals, and energy technologies), and the semiconductor work quantifies the potential value of next-generation (beyond-CMOS) computing devices for the economy, including advances in AI. The semiconductor area demonstrates the value of using formal expert elicitation methods to identify opportunities to overcome commercialization bottlenecks.

[1] CMOS = complementary metal-oxide semiconductor

The biopharmaceutical area illustrates the relevance of understanding public awareness and gathering early public input. The energy area clarifies the role of innovation to reduce supply chain vulnerability; in future work this lens could be applied to semiconductors and biotech.

Multiple areas demonstrate CTA methods involving labor inputs and outputs: The semiconductor area quantifies region-specific labor constraints that may prevent commercialization in this technology. The AI area considers the impact of emerging technology on labor outcomes. The energy area demonstrates the impact of supply chain vulnerabilities on labor outcomes. Multiple areas demonstrate CTA methods to quantify equity impacts: The situational awareness demonstration indicates the need for tools to help overcome demographic and geographic biases in funding. The AI demonstration shows geographic and demographic disparities in AI capabilities. The energy area explores the potential impacts of supply chain vulnerabilities on energy equity.

Limitations for competitiveness of demographic and geographic distribution of scientific funding

		ARTIFICIAL INTELLIGENCE	SEMICONDUCTORS	BIOPHARMA	ENERGY AND CRITICAL MATERIALS
Situational awareness		( )	x	( )	
Commercialization bottlenecks	Expert elicitation		x		
	Public perception & early input			x	
Labor			x		
Equity		x			
Area demonstration connections		AI's potential to accelerate scientific domains relevant to semiconductors, biotechnology, energy	Next-generation semiconductor device development limits advance in AI		Access and lack of innovation to reduce supply chain vulnerabilities in critical materials affects scale-up of electric vehicles

TABLE 1-1. Intersections of cross-cutting themes and analytic methods. See text for elaboration. x = direct intersection; () = 30,000-foot insights on competitiveness (without yet engagement with area experts)

In addition, the research questions demonstrated in one area how situational awareness could inform the area demonstration and vice versa, and in two areas how analytics could inform the relationships between technology areas. Future work should leverage analytic methods demonstrated in one area in multiple areas, as relevant to the most pressing questions in those contexts, and should draw on more disciplines and methods—including computer science, political science, and history—than could be demonstrated in this pilot year.

SELECTING QUESTIONS AND ORCHESTRATING MULTIDISCIPLINARY LENSES AND PERFORMER COMBINATIONS

Doing these analytics well is a science that should leverage the top talent across the nation. As important as this science is the art of matching of data and methods to problems, the orchestration and synthesis of insights across national analytic capabilities, and the selection of the performers and problems. The specific questions asked and the orchestration of the performers to address them are presented in chapter 4. The performers were brought together in quarterly meetings and charged in break-out sessions with identifying immediate and longer-term opportunities for integration.

MULTILATERAL EXCHANGE

NSF TIP's 1-year $4M pilot award for a National Network for Critical Technology Assessment enabled the first step of bringing together top academics from across the country to define a vision for critical technology assessment, considering current capabilities, gaps, and the national investment and organizational form needed to realize that vision. But to be successful, both the analytics and a CTA vision must also involve practitioners from industry, government, and nonprofits. Industry and government stakeholders are essential contributors who need to inform not only the data and analytics but also the questions asked. Moreover, in multiple cases industry has essential data or analytic capabilities not available in government or academia.

Network leads sought and received an award from the Sloan Foundation for a series of workshops and other mechanisms to convene or otherwise engage in a multilateral dialogue with practitioners in industry, government, and nonprofits. The workshops provided a forum to discuss the proposed demonstrations and an opportunity for the practitioners to comment on the associated data, analytics, questions, and policy problems; to potentially team up with the academics in solving challenges; and to inform the vision for the future of critical technology assessment. In total we held eight workshops: one workshop for each area demonstration, one cross-cutting workshop for labor and equity, and two workshops to engage in multilateral dialogue on the analytic results with industry and government leaders and build a cross-area vision of critical technology assessment with performers.

ELICITING THE INTELLECTUAL FOUNDATIONS FOR CRITICAL TECHNOLOGY ASSESSMENT

The Network developed a process to elicit the intellectual foundations for critical technology assessment from multiple contributors and built consensus around those intellectual foundations and a vision for critical technology assessment. Structured feedback was elicited in a 1-hour session at the end of each workshop as well as through a survey and series of exercises conducted by the Network and Advisory Council at the midway meeting. In total, there were more than 100 workshop participants spanning academia, industry, government, and nonprofits (**table 1-2**) and 25 participants in the survey of network and Advisory Council members. Based on this input, the authors identified chapters for the vision section of the report, and requested within-Network and external experts (in all cases multiple individuals per chapter) to contribute initial written content for those chapters. These authors presented their sections at the third quarterly meeting with assigned discussants, and each chapter was discussed by the full Network. The contributions were merged into a single document and each chapter draft shared with the full Network for feedback (provided both in writing and in a Zoom meeting to which all Network members were invited). Contributors to the vision chapters are listed in **appendix table 1A-1.**

TABLE 1-2. Industry, government, and nonprofit organizations that participated in multilateral exchange on the area demonstrations through area workshops, as discussants, or in meetings or conversations about the analytics.

Area demonstration	Multilateral exchange participants
Global Competitiveness	Defense Advanced Research Projects Activity (DARPA), Lockheed Martin, National Science Foundation (NSF), Office of Naval Research (ONR) Global, Office of Science and Technology Policy (OSTP)
Artificial Intelligence	Bureau of Labor Statistics (BLS), Microsoft, National Artificial Intelligence Initiative Office (NAIIO), National Science Foundation (NSF), Office of Science and Technology Policy (OSTP), OpenAI, US Department of Labor (DOL)
Semiconductors	Booz Allen Hamilton, Council of Economic Advisors (CEA), Defense Advanced Research Projects Activity (DARPA), Department of Defense (DOD), Department of Commerce (DOC), Denso, Federation of American Scientists, Ford, Global Foundries, Intel, Lockheed Martin, Microsoft, National Security Council, NVIDIA Corporation, Office of Science and Technology Policy (OSTP), President's Council of Advisors on Science and Technology (PCAST), RAND, Semiconductor Industry Association (SIA), SRI International, Western Digital
Biopharma-ceuticals	Acumen BioPharma, Association for Accessible Medicines (AAM), CMIC Group, Domestic Policy Council (DPC), Food and Drug Administration (FDA), National Commission on Biotechnology, National Economic Council (NEC), North Ocean Ventures, Office of Science and Technology Policy (OSTP), President's Council of Advisors on Science and Technology (PCAST), World Health Organization (WHO)
Energy and Critical Materials	Advanced Manufacturing Office (AMO), Defense Advanced Research Projects Activity (DARPA), Department of Energy (DOE), The Engine, Electric Power Research Institute (EPRI), LowerCarbon Capital, Office of Management and Budget (OMB), Office of Science and Technology Policy (OSTP), US House Committee on Science, Space, and Technology, Anonymous: automakers (3), think tanks and policy experts (3), mining companies (2), domestic and international government agencies (9)

REPORT REVIEW AND PRODUCTION

To cull from a number of recommendations for analytic and policy next steps we undertook two reviews: (1) of the area demonstrations and (2) of the full report. In both cases, we requested input on the research integrity, policy readiness and significance, and relevance and communication for stakeholders in Washington. For the area demonstrations, we also enlisted reviewers who were stakeholders or could otherwise comment on stakeholder response. For policy readiness, reviewers were asked to comment on whether the findings should be implemented, were an important policy-relevant finding needing support to progress to policy action, or a provocative early finding needing more research (**figure 1-3**).

The 21 reviewers across the five area demonstrations were drawn from academia, industry, and government, with at least one reviewer in each category for each area. The 23 reviewers for the full report were experts from academia, industry, government, and nonprofits with extensive experience in and knowledge of the federal policymaking process. All the reviewers generously provided thoughtful, useful critiques that helped refine the technical content and clarity of this report.

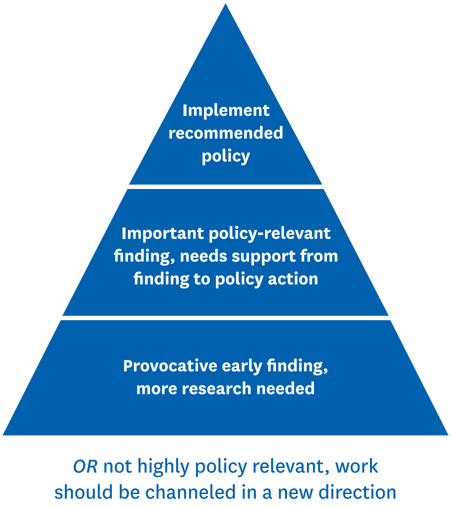

FIGURE 1-3. Quality and communications review of policy readiness.

SUMMARY OF PILOT YEAR ORGANIZATIONAL INNOVATIONS

The NNCTA pilot year activities involve six organizational innovations:

- **Project selection:** Multidisciplinary lenses on a single problem, top talent, novel collaborations, depth in specific technologies
- **Relevance to policy:** Bend academia closer to government; multilateral input from academia, industry, government (workshops, 6-month and 9-month feedback, review)
- **Speed:** Demonstrations in 6 months, integration in 9 months, synthesis and reporting at 12 months
- **Transparency:** Information shared during the analytic process with academia, industry, government stakeholders
- **Recommendations:** Quality and communications review to select from a number of recommendations for analytic and policy next steps
- **Vision for critical technology assessment, organizational form, investment:** Network consensus based on elicitations and consensus-building meetings begins to build the multidisciplinary intellectual foundations necessary for critical technology assessment, including
    - a CTA framework,
    - accommodation of different data and data solutions to different problems, and
    - Network sustainability and organizational form.

The timeline for the pilot year is shown in **figure 1-4**.

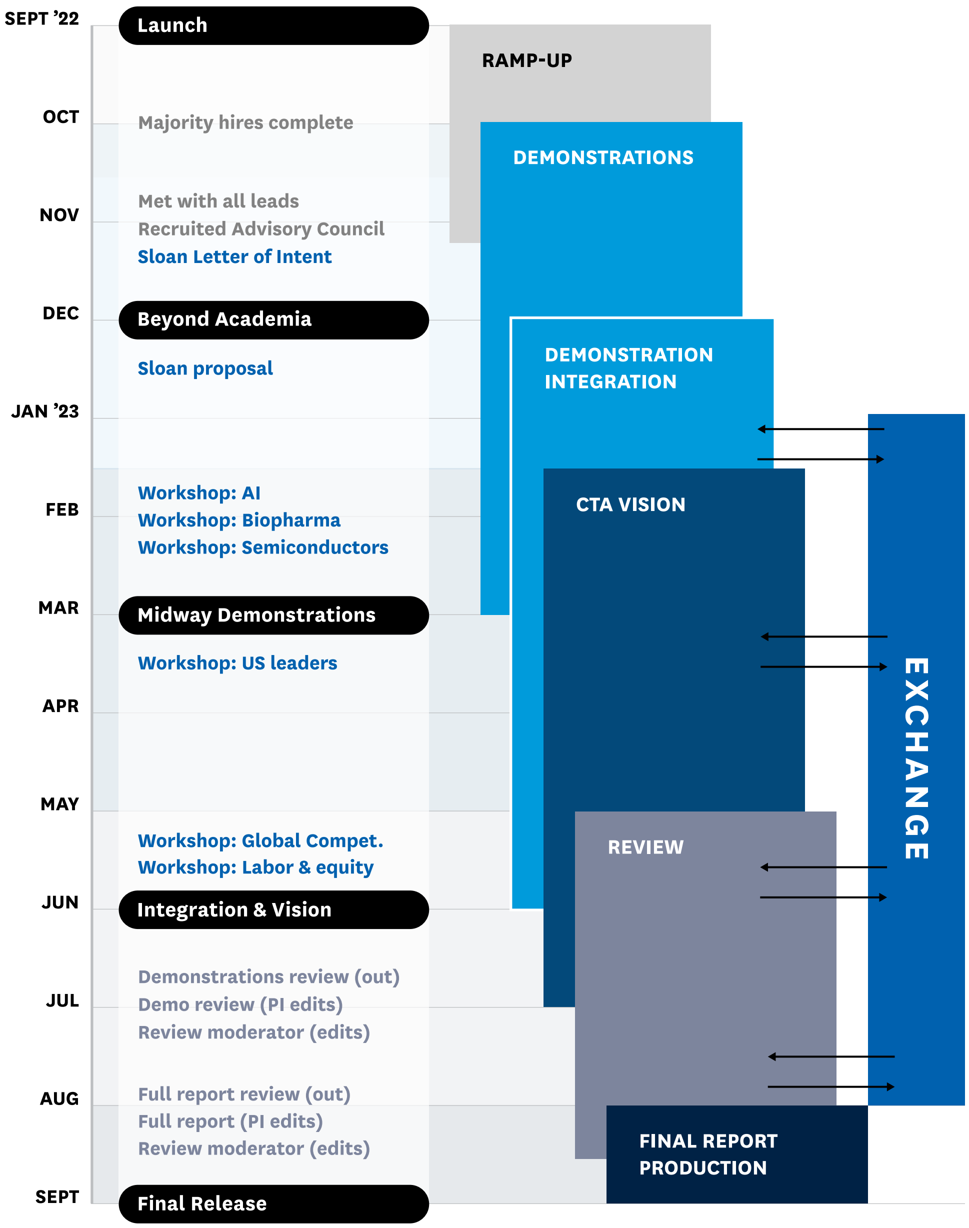

FIGURE 1-4. Timeline for the pilot year of the National Network for Critical Technology Assessment. PI = project lead