CHAPTER 5: CROSS-CUTTING LESSONS FROM THE FIVE PILOT AREAS

DIMENSIONS OF CRITICAL TECHNOLOGY ASSESSMENT

The four area-specific demonstration cases illustrate emerging scientific discoveries, technological disruptions, and vulnerabilities, all with the potential to significantly impact the United States' national security, economy, job market, and public well-being. Together the cases provide a snapshot of selected capabilities and opportunities to advance the country's abilities to assess critical technologies across a range of industries and stages of technological discovery, development, production, and use.

The area cases offer representative examples of general classes of critical technologies and demonstrate relevant methods to assess their national impact, vulnerabilities, challenges, and opportunities for policy intervention and investment. The areas represent different stages of technology discovery, development, production, and use; different positions of US versus global competitiveness; and different stages of policy development. **Table 5-1** shows these dimensions relevant to the critical technology assessment (CTA) activities. Across the selected areas, the specific technological details and (when in stages of production and use) the industrial structure shape the questions, methods, data needed, and policy solutions. Where each area demonstration sits on this spectrum and the implications for relevant CTA methods are discussed in **appendix 5A**.

The four area demonstrations also represent different types of national impact, or criticality: (i) a future evolution of a general purpose technology (semiconductors) anticipated to have significant impacts on economic growth and S&T capabilities (beyond CMOS); (ii) the current status of a general purpose technology (AI) in early stages of adoption with high impacts on economic growth, jobs, and S&T capabilities; (iii) an emerging technology (electric vehicle battery technologies) poised for rapid adoption but with anticipated vulnerabilities in supply chains; and (iv) a mature technology (the application of biotechnology for generic drugs) that is widely used but has supply chain vulnerabilities (**figure 5-1**). These different forms of criticality also require different types of assessment. We focus on these differences in types of criticality, a technology's maturity (e.g., stage of discovery, adoption, and diffusion on the S-curve), and their implications for assessment.

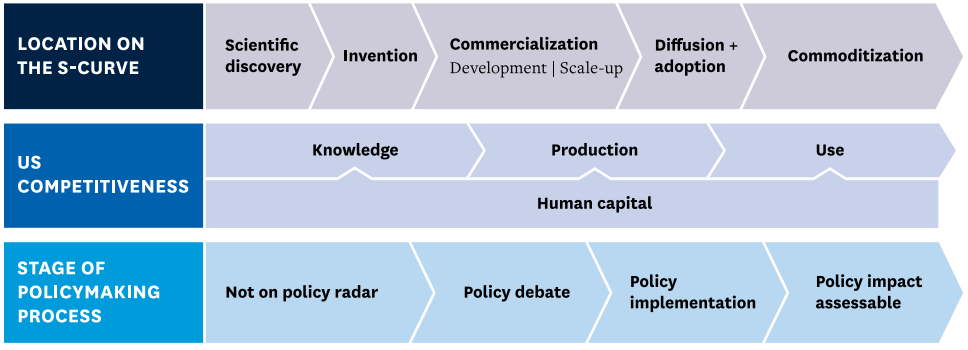

TABLE 5-1. Factors, identified from the pilot demonstrations, that shape technology assessments.

WHY CRITICAL?	CURRENT STATE	FUTURE PREDICTED
High impact (on national missions if technology advances)	**Artificial intelligence**	**Semiconductors** (next-generation devices)
Anticipated vulnerabilities (if lacking access or leadership)	**Biotechnology** (generic drug access)	**Energy storage and critical materials**

TYPE OF TECHNOLOGY ASSESSMENT

Identified bottlenecks to commercialization of next-generation semiconductor devices and potential future economic benefits	Quantified benefits—for productivity, labor, and economic growth—of greater geographic and demographic distribution	Quantified economic benefits of mitigating future vulnerabilities (e.g., through S&T innovations of policy actions)	Identified vulnerabilities in access to current products

INCREASES IN DISCOVERY, DIFFUSION, ADOPTION

FIGURE 5-1. Implications of types of criticality and stage of technology maturity and adoption (along the S-curve) for the relevant approach to technology assessment.

High-Impact and General Purpose Technologies (GPTs)

The demonstrations provide quantitative insights into the benefits of high-impact technologies, including emerging and future general purpose technologies (GPTs), in terms of productivity, GDP growth, and the geographic and demographic distribution of benefits. Additionally, the assessments identify bottlenecks to commercialization and thus US economic growth and societal well-being. The quantified benefits can inform policymakers about the value of science, technology, and policy solutions in fostering the development and diffusion of these technologies.

For instance, AI patenting leads to a 23–27% increase in labor productivity and an 8% increase in total factor productivity. The potential gains from improved semiconductors (using post-CMOS technologies) are similarly large, with the potential, if a path to commercialization is found, to yield more than $1 trillion in net present value benefits to the US economy. Each year of delay in getting these technologies forfeits hundreds of billions of dollars. In the case of post-CMOS technology, the United States lags in research output and commercialization compared to other countries. Policy interventions are needed to ensure US competitiveness in this critical area.

Technologies with Current or Anticipated Vulnerabilities

Depending on the stage of a technology's development and US capabilities compared to those of other nations, the United States may face different types of vulnerabilities. For technology areas in later stages of maturity, development, and diffusion, vulnerabilities can affect access, such as through global supply chains. The demonstrations related to later-stage technologies (energy storage for electric vehicles, generic drugs) identify priority areas and quantify the impacts of mitigating their vulnerabilities for the benefit of public well-being, including health, economic surplus, and equity considerations. In the case of energy storage technologies, the demonstration reveals that a priority area is the vulnerability of global lithium supply chains to trade disputes; addressing this vulnerability would avoid losses on the same order of magnitude as those that occurred in the automotive industry during the semiconductor shortage. For technologies with substantial national security implications (e.g., those involved in defense, economic, or health security), vulnerability may emerge from a lack of scientific or technology leadership, such as an inability to ensure privacy or failure to address ethical concerns associated with AI or synthetic biology. Such activities and vulnerabilities due to leadership were not a focus in this pilot year's demonstrations, but are very important to include in future assessments.

Quantification of potential impacts of vulnerabilities for national interests and of the potential value of interventions in mitigating such vulnerabilities can help policymakers understand the comparative value of specific science, technology, and policy solutions for mitigating potential risks.

S&T Investment and Policy Insights

Through its area demonstration analyses this report begins to contribute to a taxonomy of CTA capabilities essential for effective national decision making. The pilot year findings demonstrate that it is possible to inform targeted investments and policy interventions that promote technological progress, economic growth, job creation, and resilience in the face of a rapidly evolving technological landscape.

Among other lessons learned, the Network members recognized important synergies between the selected technical areas; for example, the recent lack of improvements in computing hardware may hamper new directions in AI, advances in AI may contribute to scientific discovery and commercialization, and investments in AI infrastructure can accelerate scientific discovery and commercial development while supporting education and training for discovery, production, and use. The members also understood that there were limitations in attempting (or appearing) to compare "apples to oranges" in identifying whether one area was more "worthy" in the US investment portfolio, given the extraordinarily different dimensions of impact of each. This dichotomy led some members to conclude that annual

lists of technologies with supporting information on their implications for national objectives might be easier for a national CTA activity to create and communicate politically (but see **box 3-1**). Such lists, to be credible and useful, would be based on quantitative and qualitative implications for national objectives, and presented with specific policy actions to advance US competitiveness in those technologies.

Finally, the Network activities highlight the importance of learning across technology and industrial contexts—from different measures of criticality to expert input to identify technology bottlenecks, public input to identify social obstacles to policy acceptance, awareness of the implications of investments for geographic and demographic participation and distribution of benefits, and the combination of scenario models with models of their impacts on industrial structure, consumers, and the economy to quantify the economic and societal implications of vulnerabilities, to name just a few. Indeed, one of the more significant outcomes of the pilot may be the start to a dynamic framework for critical technology assessment, demonstrating the types of analytic efforts that are most helpful to different types of technologies and challenges and what questions can be answered for each.

The pilot year's area demonstrations showcase the potential of the NNCTA in providing insights on US technological capabilities and vulnerabilities at different stages of the policymaking and funding allocation process: agenda setting, formulation (generic drugs), adoption (AI), implementation (semiconductors), and evaluation (energy). In some cases, policymakers are aware of vulnerabilities and policies are being implemented to address them; in these cases, the analyses identify priority areas to guide implementation. In other cases, policies have not been formulated to address the vulnerabilities, and the analyses highlight their importance.

DATA NEEDS AND TRADEOFFS

The types of data that are relevant depend on the characteristics of the selected technology, the technology's stage of the S-curve, the research question being asked, and where that question lies in the critical technology assessment framework. Data on the inputs (e.g., human capital, funding) and outputs (publications) of scientific discovery are more likely to be publicly available, although they may require sophisticated analysis to extract and interpret correctly. Scientific publications are perhaps the easiest form of data to access publicly, given their very nature of making knowledge public. But access to granular data on who and what is funded (e.g., the full portfolio of funding and associated outcomes of individual researchers) and on funding sources (e.g., foundations) can be challenging. In contrast to the generally public nature of scientific discovery, data on technology development, commercialization, production, and use are more likely to be privately held and difficult to access unless required by government (although government may be limited in its ability to compel firms to provide data or to validate the accuracy of data reported) or negotiated by individual researchers.

Because firms and governments have different objectives (firms to maximize profit, governments to ensure security, the economy, and societal well-being), they may need different data to inform their decision making. Moreover, government decision making is diffuse and disjointed, spanning federal and state levels and agencies with different missions. The data collected to support that decision making are similarly diffuse and unlinked, complicating assessments across federal and state or agency datasets.

As a consequence of these challenges, many Network members expressed a desire for more accurate, frequent, complete, granular, and timely data in their demonstration projects and expertise area. That said, data collection, sharing, and storage have costs, and thus face tradeoffs in their design and use.

We identify the following dimensions of data: *timeliness and frequency, accuracy and completeness, granularity, privacy requirements,* and *ease of access and cost of collection, storage, and validation* (these are described in **appendix 5A**). **Appendix table 5A-1** shows the intersection of data types and dimensions for the four pilot year demonstration areas (semiconductors, AI, energy storage and critical materials, and biopharma-

ceuticals). Below we consider potential tradeoffs between these dimensions; why, given these tradeoffs, more of one dimension is not always better; and how procedures and incentives for data disclosure can influence all six dimensions.

Tradeoffs in Dimensions of Data

There are often tradeoffs between the different dimensions of data. For example, publicly available data may be timely but unvalidated and thus less accurate or complete. Other data (e.g., from the US Census Bureau) may be highly accurate and complete but more costly (in terms of both time and money) and less frequently updated or timely. Differential privacy protections can also impair data access or quality. For example, companies may be unwilling (and indeed unable without compromising their competitiveness and security) to share supplier data openly, but willing to share the data with a neutral third party to provide insights into supply chain vulnerabilities that would not be identifiable from single-firm data.

These examples emphasize the importance of tailoring data collection to the context and the question of interest. This necessary tailoring raises questions about the contexts and problems for which data collection should be institutionalized, and with what frequency the data should be collected.

Matching Data Solutions to the Question Posed

Network members discussed the suitability of a variety of solutions to different types of questions and data challenges. They distinguished between (i) cases that may need a high-quality data collection process (e.g., for a data science observatory or critical product supply chain), associated infrastructure (such as that of NCSES or the US Census Bureau), and/or high-frequency collection (e.g., for rapidly changing technologies or industries or on production capacity for essential products during a crisis); and (ii) cases for which data are best collected in time to answer a particular pressing question (e.g., for technology commercialization pathways, early public input, or institutional or worker response) (**table 5-2**).

There was general agreement among the Network members that the United States requires better infrastructure for data on the scientific enterprise globally and on the relationship between scientific inputs and outputs. Some scholars have called for an improved and people-centered federal science policy data infrastructure to measure scientific inputs and outputs and enhance the effectiveness of investments (Hausen et al. 2023). Erik Brynjolfsson (**box 5-1**) explains, in the context of rapidly advancing technologies and technology capabilities, why data collection may need to be more frequent to be relevant to policy decisions, and how improving researchers' access to these data will improve the quantity and quality of the insights available to policymakers. Recognition of certain data as a public good and their accessibility to academics can also expand the geographic and demographic population of researchers looking at and asking questions of the data. And data accessibility to the general public may enhance public awareness and inform public opinion.

Farther out the S-curve, it can be very challenging to track technology development and production activities and capabilities, human capital requirements, and at times use; aspects of these challenges are illustrated by Rena Conti in the context of the pharmaceutical industry (box 5-2). A technology in the commercialization, scale-up, and production phase is typically housed in private enterprises, where such data are often proprietary. Data that can be particularly difficult to access (e.g., on capabilities in China or supply chains) can also be costly to obtain—and confer a competitive advantage, whether for a nation or for an individual researcher or organization in the context of analytic enterprise.

For contexts where data may be highly proprietary, Dewey Murdick cites the need for a robust data infrastructure and suggests a data trust (box 5-3). For supply chain data, Valerie Karplus and Erica Fuchs make the case for a strategic roadmap to (i) determine what technologies are sufficiently critical to monitor regularly and (ii) establish institutional capabilities with public-private partnerships for near-real-time knowledge sharing during crises (**box 5-4**). With expert or public surveys (e.g., to identify commercialization bottlenecks), individual confidentiality can be protected while ensuring the value and public availability of anonymized data in an interactive format.

Stage of S-curve	Data availability	Data solution
Earlier	More public data	Observatory
Later	Less public data	Trusted 3rd parties, public-private partnerships, data trust

TABLE 5-2. Different types of data solutions can be needed for scientific discovery—which tends to happen in the public domain—and for technology commercialization, adoption, and use (including production and supply chains)—which often involve private and confidential information.

BOX 5-1

Timely Access to High-Frequency Data for Academic Researchers

Erik Brynjolfsson

Academia plays a critical role in furnishing nuanced and comprehensive analyses to fortify data-driven decision making. However, rapid technological advances, as in AI, pose significant challenges for academics, policymakers, and the general public. The pace of change requires academics to be more time-sensitive in their work, which requires access to high-frequency data on the economy, workforce, and AI technology. Publicly available datasets are often several years old by the time of academic publication. Private datasets offer valuable insights into real-time developments in skills, innovation, and the workforce, but their accessibility often comes at a high cost. Therefore, it is crucial to take measures that promote access to high-quality, high-frequency data for academic researchers.

In other contexts, such as identifying commercialization pathways, private firm design or production or worker task data may be useful to inform simulations. Public access to both the modeling tools and the collected aggregate or generic industry data has precedent both in academia and the national labs, and can be of high value for use by other academics, firms, and government agencies. Such access typically does not require a complicated data infrastructure. In addition, retaining the raw data (and the right, when possible, for aspects of the data to eventually be incorporated in a data trust or the public domain) could be valuable in retrospective evaluation of these activities, to (i) improve efforts to assess and predict technology commercialization pathways and (ii) expand knowledge of potential relevant policy interventions. That said, given the sensitivity of much design and process data to firms' core competitiveness, such data are typically shared with a single trusted party under strict confidentiality agreements. Making the model public with aggregate data is an essential negotiation in such agreements for the public good.

Regardless of a technology's state of diffusion and adoption, interpretation of data to inform critical technology assessment frequently requires deep knowledge of specific scientific, technology, and industrial contexts to determine meaningful and tractable policy options. How different types of data were used in the demonstrations for different research questions is described in the appendix and captured in **appendix table 5A-1**. The dimensions of data across the pilot year topic areas—situational awareness, semiconductors, AI, energy storage, and biopharmaceuticals—are explored in **appendix table 5A-2**.

BOX 5-2

Data Needs in Pharmaceutical Products

Rena Conti

To be sold in the US market, prescription drugs must meet or exceed stringent regulatory standards for safety, purity, and efficacy set by the Food and Drug Administration (FDA). But international trade disruptions, military actions, or global outbreaks of disease may threaten US drug quality or supply without anyone realizing it until it's too late. The federal government's knowledge of the complex and often foreign-based supply chain of prescription drugs is limited. Pharmaceutical companies may manufacture their own active pharmaceutical ingredients (APIs) or final dosage forms (FDFs, also called drug products; e.g., tablets, capsules, ointments), or they may choose to transfer the manufacturing process to a company affiliate or outsource it to domestic or foreign facility contractors. Statistics on the relative importance of domestic compared to foreign manufacturing are limited. Several reports indicate that increasingly the manufacture of excipients, APIs, and generic FDFs intended for US consumption is done abroad and is highly concentrated among a handful of companies. In 2017 almost 90% of sites manufacturing API for generic drugs and about 60% of FDF manufacturing sites were located outside the United States (Berndt et al. 2017a,b). The United States is the largest source of FDF production (41% in 2019), India is second (21%), and China is third (8%). But from 2013 to 2019 the number of US API sites declined by about 10%, with dwindling supply largely located in regions vulnerable to interruptions from severe weather and in the Rust Belt states.

The required labeling of prescription drugs sold in the US does not disclose the name or location of the FDF, API, or excipient manufacturer, and contract manufacturing of prescription drugs and base ingredients remains completely hidden from public view. Nonpublic data provided by the FDA do not indicate the formulation types (e.g., oral, injectable/infusible, or other) manufactured at a site. No information is available about the volumes of a drug manufactured in a specific time frame nor the capacity of a site to manufacture that product. And the FDA does not systematically collect the identity, use, or potential deployment of new technology related to the production of new products or the manufacturing of base active and inactive ingredients. Knowing the identity of manufacturers, and their capacity and volume of prescription drug production, is increasingly valuable to stakeholders interested in maintaining competition in the prescription drug market, for assessing vulnerabilities to climate change–related events and potential geopolitical conflicts and their consequences for supply adequacy and affordability. More information is needed to determine which factors are amenable to change based on potential investments in new technology and domestic production, and their tradeoffs and alternatives.

BOX 5-3

A Data Trust: Shared Core Data Infrastructure for Critical Technology Analysis

Dewey Murdick

In critical technology analysis, experts tackle a wide range of analytic tasks. They aim to optimize R&D portfolios, pinpoint vital innovation partners, manage risks from "bad actors," prevent undesired tech transfers, evaluate supply chain vulnerabilities, monitor skilled talent movement, assess the economic outcomes of different scenarios, and gauge the disruptive potential of emerging technologies. A robust data infrastructure, built and continuously refined, is crucial for these analytical explorations. Often, new analytic initiatives miss the chance to capitalize on previous projects, especially in terms of enhancing and connecting the underlying data. Governmental and other users of this analysis should support the creation of a shared infrastructure that is updated and improved over time. Such an approach would integrate AI and advanced analytical tools, prioritizing data security, privacy, and accessibility across teams. It's essential to tailor this resource to address foundational research questions common to a broad range of critical technology analysis challenges. One way to address this need could be to build a "data trust," envisioned as a collaborative platform.[1] Organizations would merge their data assets, fostering both innovation and shared advantages. Appointed "trustees" would play a pivotal role, navigating data collection, licensing intricacies, and data management and ensuring ethical data use. A data trust would anticipate and proactively manage the vulnerabilities associated with data use through a commitment to professional data stewardship. The trustees would advocate for the interests of the trust's members as well as individuals from society whose information is captured in the data.

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[1] Consider, for example, the 2022 report by the Global Partnership on AI, *Enabling Data Sharing for Social Benefit Through Data Trusts,* https://gpai.ai/projects/data-governance/data-trusts/.

BOX 5-4

A Strategic Approach to Data Collection and Management

Erica R.H. Fuchs and Valerie Karplus

When the COVID-19 pandemic hit the United States in March 2020, decision makers lacked information on the ability of domestic manufacturers to provide critical medical supplies on short time frames with high confidence. The US Economic Census collects information on all businesses only every 5 years, and annual surveys (such as the US Census Survey of Manufactures [now the Annual Integrated Economic Survey]) are tied to this sample. Moreover, firms were neither prepared nor incentivized to respond to such a low-probability (e.g., in the case of COVID, once per 100 years), high-risk event. Although a number of domestic manufacturers from nonmedical product industries entered or pivoted into medical products and were able to expand US domestic capacity in critical products, many new entrants noted that their efforts were slowed by barriers in knowledge, shipping, and regulatory approvals.

Network research identified two gaps that if closed could provide the framework and incentives for appropriately ramping up domestic production to meet national need in a crisis: (1) a roadmap that defines

the roles of the White House and various federal and state stakeholders in data collection and information flows both in normal and crisis conditions, and (2), for the most essential "critical" products, US Census collection of business and production capacity data with greater depth and frequency.

To implement (1), the Department of Commerce could identify critical products and intermediate inputs for which these costly but important efforts have sufficient expected value, based on the probability of various future crises, and at what scale and frequency. To implement (2), the Department of Commerce could work with relevant agencies (e.g., in the case of the pandemic, FEMA, HHS, CDC) to conduct cost-benefit analyses to quantify the value of tracking different products and their intermediate inputs and with what frequency, again bearing in mind that data collection is costly.

To augment this capability as needed, the White House should develop mechanisms for the US Census to (i) share business data with government crisis response teams and (ii) integrate data on domestic manufacturers and their capacity with data from the Bureau of Industry and Security on US international trade to support analysis of geopolitical dependencies, as there may be concerns about intermediate input availability from different parts of the world. Also in support of (2), the United States should invest in an integrated, secure, near-real-time public-private data architecture to maintain high-frequency production capacity data for firms that produce (or demonstrate the willingness or potential to produce) some critical products. During crises, these products would be prioritized for collection and analysis, with a focus on both domestic production and the international footprint of their upstream supply chain. The administrators of this architecture should also consider maintaining a council whose members represent selected critical producing industries and can provide expert guidance on appropriate equity metrics for White House supply chain officials to use when evaluating potential crisis response policies and sourcing strategies.

This discussion is drawn from Fuchs and Karplus (2021).