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Emerging Industrial Policy Approaches in the United States

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The federal government has long avoided industrial policies outside of its defense sector. But now, facing competition from China, it is pursuing a series of new programs at a scale never tried before. The effort will require careful, system-wide planning to bear fruit.

KEY TAKEAWAYS

- U.S. industrial policy approaches trace back to Alexander Hamilton's attempts to spur a manufacturing sector. But while the defense sector has long applied industrial policy, interventions have been limited in the civilian economy.
- Mainstream economists have long opposed industrial policy approaches, favoring reliance on markets instead, and there have been definitional debates over what industrial policies actually entail.
- Four previous periods of industrial policy efforts have included the Cold War challenge, the competitiveness challenge with Japan, the energy technology initiative starting in the 2000s, and advanced manufacturing efforts starting in 2012.
- Now, spurred by bipartisan concerns about the competitive threat posed by China, major industrial policy programs are evolving at an unprecedented scale and magnitude.
- Programs now underway cover semiconductor production, development of critical technologies, energy demonstration projects, secure domestic supply chains in critical fields, and speeding domestic vaccine development and production.
- These programs require new supporting infrastructure and operating mechanisms.
- These include: a new talent base; integrated research connections; strong manufacturing foundations and supply chains; testing and demonstrations; technology certifications; flexible contracting; financing; and procurement.

CONTENTS

OVERVIEW

Long reluctant to pursue industrial policies outside its defense sector, the U.S. federal government is now pursuing a series of new approaches at a scale not tried before. This effort has been driven politically, largely on a bipartisan basis, by concern over China's extensive industrial policy system, which has enabled it to surpass the United States as the world's leading industrial power. China is also starting to out-invest the United States, long the leader, in research and development (R&D) in critical technologies, directly taking on a role that has been central to U.S. innovation and, therefore, economic growth and national security. Growing concern about climate change has also been a driver for these new policies. This paper:

- places these new policy approaches into a historical context both in the postwar and in a series of subsequent periods,
- reviews the definitional and economic debates over industrial policy,
- catalogs and summarizes the current main thrusts of the new industrial policy efforts,
- describes the major elements, as well as gaps in these approaches, and
- reviews the new mechanisms and supporting infrastructure we will need to make them operational

THE EARLY HISTORICAL CONTEXT

Like many topics, this one starts with Alexander Hamilton. The first American leader to back a federal role in industrial policy, in his report on manufacturing to Congress and subsequent work he advocated nurturing American industries through protectionist tariffs and direct support of industry.[1] Later, he joined President George Washington in supporting government-owned industries through creation of military arsenals to produce weapons for the army.[2] Hamilton's tariff-based trade policies became a mainstay of federal industrial policy for more than a century. The system of military arsenals was expanded a few years later to include government-owned shipyards that built the early American Navy. The arsenals and shipyards marked the federal use of a defense justification for industrial policy. The arsenals at Harpers Ferry and Springfield subsequently developed the first system of interchangeable machine-made parts in making muskets; this system spread across early factories in the northeast in the 1840s and was a critical step in enabling American mass production.[3] But Hamilton's plans were opposed by agriculture-oriented southerners led by Thomas Jefferson and James Madison, and more direct support of civilian manufacturing was not taken up by the federal government. Instead, Hamilton launched this branch of his industrial policy approach through state support to a corporation developing waterpower at the Passaic Falls in Patterson, New Jersey, which supported a network of factories built around that power source.[4] These patterns of federal support for industrial policy—support for trade policy and for military R&D and industrial facilities, but not for direct civilian sector industry involvement—proved long-lasting.

During the Second World War, Vannevar Bush, as Franklin Roosevelt's science advisor, led the creation of a highly connected system for technology advance. The federally funded research university was initiated at scale, and these universities were closely linked to industry, the military, and government agencies. The federally funded R&D centers (later called FFRDCs) were created as well, and these elements led to critical wartime technology advances at the Rad Lab at MIT and the Manhattan Project. It was an intense system of industrial policy designed by Bush and other technology leaders to win the war. Immediately following the war, however, Bush led the dismantling of much of this extremely successful connected system. In his famous policy tract, *Science the Endless Frontier,* he recommended to President Truman a focus on basic research and a disconnected system.[5] Why? With the war machine being dismantled in the expectation of world peace, Bush likely was trying to salvage some parts of the system. He saw the power of the federally funded research university and advocated federal support for basic research that could sustain that creation. Basic research is far cheaper than applied development, and he likely thought the government could still support that basic stage amid the postwar cutbacks. He also was concerned that science, like Icarus, was "moving too close to the sun"—science had become too tied to government, with all its intense political and military power, and he wanted to shield it, reclaim its independence. Bush advocated what was later called the "pipeline model" for innovation, with early-stage research as the federal input into the pipeline, with the later pipeline inputs relying on industry. The model disconnected the actors in that innovation system. Like with Humpty Dumpty, the United States has never fully managed to put the pieces together again.

The Definitional Debate

A preliminary question concerns defining industrial policy. After delineating other discussions of the term, British economist Ken Warwick, in 2013, broadly defined industrial policy as, "any type of intervention or government policy that attempts to improve the business environment or to alter the structure of economic activity toward sectors, technologies or tasks that are expected to offer better prospects for economic growth or societal welfare than would occur in the absence of such intervention."[6] More recently, Information Technology and Innovation Foundation President Robert D. Atkinson defined industrial policy as "a set of policies and programs explicitly designed to support specific targeted industries and technologies."[7] In this sense, there can be industrial policies for a variety of goals. Atkinson argues that the goal should be U.S. international competitiveness, especially in advanced technology sectors.

Others have taken the term "industrial policy" and tried to apply it largely social policy goals. Mariana Mazzucato, Rainer Kattel, and Josh Ryan-Collins have advocated "mission-based innovation" as the basis for industrial policy, taking up Warwick's "societal welfare" element.[8] They identify mainstream, neoclassical economics and its reluctance to employ the power of the state as a cause for societal ills, including growing economic inequality, economic stagnation, a succession of financial crises, and climate change. While others have made these critiques, Muzzucato and colleagues seek to apply technological innovation not only to technological challenges but to societal missions such as reducing economic inequality and building sustainable development. They hold up the Apollo Moonshot project as an organizational model for how to get there.

Political economist Suzanne Berger argues that they reach too far.[9] Technology programs such as the Apollo mission or the Manhattan project were organized around technology goals, not broad societal goals—rocketing to the moon or creating atomic weapons, not solving economic inequality or other societal goals. In effect, she is suggesting that the term "industrial policy" has to emphasize "industrial." Going beyond that, she argues, requires not simply a technical dimension but a major political dimension, requiring public consensus for long-term, sustained political change. Warwick's definition, when it tries to embrace "societal welfare," and

Muzzucato's and her colleagues' pursuit of solving social ills appear to be too-long of a stretch for most technology-based efforts.

We should note that growth economics has long established that technological and related innovation is the largest factor in economic growth—which, in turn, is a major enabler of societal economic well-being. Vannevar Bush himself argued that investment in research would yield societal gains—a "war against disease" and "public welfare."[10] But some societal goals are more in range of a technology strategy than are others. For example, a program to implement advanced manufacturing technologies may not only make the manufacturing sector more competitive, it may enable manufacturing job retention. Or, as we have recently witnessed, a breakthrough vaccine technology development program may achieve a societal goal of reducing deaths and hospitalizations. Much, then, depends on the nature of the societal goals and how directly they can be connected to a technology development effort.

Of course, the technological advances can enable societal gains as well as technical impacts. But this broader notion drifts into the debate over technological determinism—and we don't need to travel that far for a practical and working definition of industrial policy.[11] Often driven by external crises, the federal government has periodically and actively sponsored industrial policy approaches. Societal welfare has typically not been the stated goal, although it can be a by-product. Instead, narrower sectoral or technology targets, or economic goals, such as improving economic competitiveness, are usually the public goal. Technology development, national security, economic advance, and competitiveness are the most workable goals for industrial policy, and, given the mixed record of past social engineering projects, a focus on applying technology advances for broad societal ills could prove a diversion from these economic fundamentals.

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Berger's critique, then, rings true in many cases, as does her point about societal goals demanding political consensus. And from an industrial perspective, industrial policy needs more definition beyond Warwick's phrase "any type of intervention"—as this phrase simply doesn't tell us much about the nature of the interventions that might fall within the scope of industrial policy.

Another approach would be to define industrial policy in terms of the well-known stages through which a technology must advance: research, development, technology prototyping, testing, demonstration, product development, production financing, market entry, and expanded market creation. Industrial policy entails government intervention in a series of these stages in order to further a technological advance. The science and technology organization of World War II, for example, knitting government, industry, and universities together with interventions at all these economic stages, was clear industrial policy to meet wartime needs.

Although Mazzucato and colleagues have called for another "moonshot" solution, that specific approach followed a relatively straightforward government-contract model: The government issued contracts to firms and organizations for the technology to get us to the moon. Many industrial policy approaches, however, require not simply government contracts, but for new technologies to be developed, adopted, and imbedded in the significantly larger private sector, a much more complex technology organization and system that requires major public-private collaboration. Energy and climate challenges, for example, fall into this category. We also need to keep in mind that industrial policy can involve a range of implementation approaches.

Opposition From Economics

Strong opposition to industrial policy has come in the past, as noted, from neoclassical economists. Certain governmental interventions are permissible when there is "market failure"—wherein, for example, the risks or costs of an activity are too high for the private sector to manage, or there is a problem of collective action. These permitted interventions include public education, transportation infrastructure, and early-stage research. But technology implementation is not on this list.

A focus on markets continues to reign in American economics with a corresponding dread regarding industrial policy.

Part of the reluctance of mainstream economists to allow government to intervene is because of the limits of their tools. They have long emphasized mathematical modeling, and have therefore focused on the efficiency of markets that are amenable to modeling. But they have been hampered by their inability to model and therefore understand innovation and the complex systems behind it. Robert Solow, who won a Nobel Prize for developing an innovation-based growth theory, felt his theory was "exogenous," that there were too many variables to predict innovation from neo-classical economic models. Paul Romer, another Nobelist, later countered with his own "endogenous" growth theory, trying to place growth theory back into neoclassical economics, but the metrics-based tools of economics have made this a largely unfinished project. Innovation requires the consideration of many complex elements outside of scientific advance, such as culture, traditions, vested political interests, change agents, governmental infrastructure, public expectations, collective action, and organizational management, that are not readily amenable to economic modeling.[12] So a focus on markets continues to reign in American economics with a corresponding dread regarding industrial policy. This has been more intense in U.S. economic circles than in other nations. For example, in 1983, Charles Schultze, who was head of Kennedy's and Johnson's Bureau of the Budget and Carter's Council of Economic Advisors, in a well-known piece, attacked interventionist federal policies aimed at responding to Japan's quality manufacturing innovations in the 1970s and 1980s as counterproductive, and even denied that the United States had been de-industrializing.[13]

The Evolving History

Despite the long-standing outcry from mainstream economists against industrial policy, since the end of World War II, the federal government has moved through four subsequent periods of industrial policy approaches. In each, it has tried to partially reconnect the different actors in its innovation system in industrial stages beyond research.[14]

The first period was the Cold War, which began in earnest with the Korean War in 1950, and featured the military working to reconnect the key actors. For example, new nuclear weapons labs, including Lawrence Livermore and Sandia, pushed atomic development, and the need for an air defense system accelerated real-time computing through the Whirlwind and SAGE (Semi-

Automatic Ground Environment) projects. The 1957 Sputnik crisis led to the creation in 1958 of the National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency (DARPA). The Defense Department (DOD) could not work with a disconnected system, so it returned to its connected model of World War II. It built a system that supported not just the research but the development, prototyping, testing, and demonstration, and often created the initial market. In contrast, the civilian R&D agencies supported research only through early-stage development. This meant that the United States had been running two very different innovation systems in parallel—a disconnected civilian system and a connected defense system. DARPA exemplified this defense difference. Its "right-left" approach identified potential breakthrough technologies on the right side of the innovation pipeline and then went back to the left side of the pipeline to nurture the science to get there. It was not interested in incremental advances, only revolutionary ones. Its reach across both science and technology was a dramatic contrast to the curiosity-driven basic research supported by Bush's model.[15] NASA's push for moon landings through the Apollo Mission was another form of industrial policy in that era, creating a major space technology and satellite communications sector that has since been commercializing at large scale. This system of defense support for technology development and follow-on product procurement played a central role in most of the major innovation waves of the second half of the 20th century: aviation, space, nuclear power, electronics, computing, and the Internet.[16] But defense spending as a percent of national's GDP is considerably smaller now than during the Cold War so its spin-offs are inevitably less impactful on the broader economy.

The second period was the era of competition with Japan in the 1970s and 1980s. Japan made technology and process advances in production that the United States missed, leading to its quality production system. U.S. policymakers became concerned that although the United States was originating the leading innovations, the country was limited due to its disconnected innovation pipeline, in its ability to commercialize them.[17] Japan used its quality manufacturing system to capture industrial leadership in automotive and electronics sectors previously led by the United States. The result was the "rustbelt"—declining Midwest and Northeast United States industrial areas. In response, the United States played catchup, taking years to understand the quality production advances.

NASA's push for moon landings through the Apollo Mission was another form of industrial policy in that era, creating a major space technology and satellite communications sector that has since been commercializing at large scale.

In this period, the U.S. also launched a series of new policy elements aimed at helping its innovators get across "the valley of death" between research and technology implementation. The Bayh-Dole Act of 1980 assigned ownership of federally funded research results to the universities where the research was executed, giving universities a stake in its commercialization.[18] Typically, the universities shared these rights with the researcher inventors on their faculties and in their labs, incenting them to implement their ideas. It has proved particularly useful in supporting an emerging biotech sector, wherein biotech companies frequently spring out of university research.[19] The Manufacturing Extension Partnership (MEP) program was authorized in 1988 to bring the latest manufacturing technologies and processes to small manufacturers around the nation, as small firms play such an important part in U.S. manufacturing output.[20] It was directly designed to bring Japan's quality manufacturing approaches—often called "lean manufacturing" in the United States—to small and mid-sized firms. The MEPs have worked with thousands of manufacturers, and MEP studies maintain that, in the past 30 years, the centers have delivered some $18.8 billion in cost savings and $111.3 billion in increased or retained sales per year to small manufacturers.[21] The Small Business Innovation Research (SBIR) program began in 1982 and was a another successful "valley of death" program model.[22] It offers competitive R&D grant funding to small and start-up companies, and there is a related program, the Small Business Technology Transfer (STTR) program that focuses on university-originated start-ups. These two competitive programs attempt to make small, high-tech, innovative businesses a part of the federal government's R&D efforts. Twelve federal departments and agencies participate in the SBIR program through required set-asides from their total R&D funding, and five participate in the STTR program. SBIR and STTR award over $3 billion to small businesses annually.

The R&D tax credit was enacted in 1981 to incentivize innovation by U.S. companies, rewarding them for increasing their investment in R&D in the current tax year. It was available to firms for developing new, improved, or technologically advanced products or processes.[23] Another program, Sematech, was the U.S. response in the 1980s when the U.S. semiconductor industry faced a massive challenge from Japanese competitors that began to dominate market share through lower-cost, higher-quality chip production systems. The program focused on semiconductor equipment makers to improve chip manufacturing processes. DARPA matched Sematech funding from 1991 until 1996; the effort reversed many industry production problems and the U.S industry returned to being the world's technology leader, which lasted until recently.[24] Together, SBIR, STTR, Sematech, and DARPA stood for targeted federal economic interventions in the innovation process that resulted in spurs to particular sectors or segments, such as innovative smaller firms and small manufacturers, to improve their competitive posture. The general success of these programs encouraged subsequent efforts.

A third period was around efforts to tackle climate change through energy innovation at the Department of Energy (DOE) during the Clinton and the Obama administrations. DOE shifted from an agency organized around fossil fuels, nuclear power, basic physical science research, nuclear stockpiles, and nuclear cleanup to much more of a new technology innovation organization. The older pieces remained, but added to DOE was an Advanced Research Projects Agency–Energy (ARPA-E), major renewable energy programs at an expanded Energy Efficiency and Renewable Energy (EERE) agency, an Advanced Manufacturing Office, a Loan Programs Office (LPO) for new energy technology projects, Energy Innovation Hubs, SunShot, Energy Frontier Research Centers, and a Technology Transition Office.[25] Regulatory programs were expanded to drive technology shifts, with energy efficiency standards reaching new sectors. ARPA-E was emblematic of the new approaches.[26] It embraced the DARPA "right-left" model of envisioning needed new energy technology advances on the right side of the energy innovation pipeline and then pursuing the R&D breakthroughs on left side of the pipeline to get there. But DOE lacked a procurement program such as DOD's to drive its technologies into markets, which meant ARPA-E lacked an implementation partner. Its designers originally planned to use the robust U.S. venture capital system to get there, but in 2008–2009, venture capitalists backed out of energy technology because they considered it too risky and long term. So ARPA-E had to get creative, funding only those projects with a reasonable roadmap toward market acceptance, using DOE applied programs to help with scale-up after ARPA-E's initial investments, and establishing a "Tech-to-Market" team in the agency with private sector expertise to develop commercialization plans for each project. DOE did have applied programs that could fund companies for technology development, and it had a loan program. For example, loans helped scale up numerous renewable energy start-ups (with one notable failure discussed below), and saved Tesla from bankruptcy in the 2008 recession, thereby allowing it to become the leading producer of electric vehicles.

A fourth period has been attempted in recent years around advanced manufacturing. U.S. manufacturing never fully recovered from its problems in competition with Japan. And when China arose in a remarkably short period to displace the United States as the world's largest manufacturer, U.S. manufacturing experienced a disastrous decade from 2000 to 2010.[27] Manufacturing employment declined by one third in that period, mostly due to global competition from China, not higher productivity; the United States only recovered a fifth of the nearly six million jobs it lost by 2019.[28] Manufacturing fixed-plant investment declined during that period, and U.S. manufacturing output only returned to its 2000 level in 2018. Today, U.S. manufacturing productivity growth has fallen to historically low levels, lagging behind its major competitors.[29] It runs an enormous trade deficit in goods, reaching $911 billion in 2020, including a $191 billion deficit in advanced technology goods.[30]The result over the past decade and a half has been extensive social disruption, with an increasing portion of the American working class losing middle-skill jobs for lower-end service-sector jobs, thus creating rising income inequality.[31] While, in the postwar period, the United States both innovated and produced here, realizing the gains of innovation at every stage, it increasingly shifted to an "innovate here, produce there" approach, outsourcing its production to lower-cost producers abroad. Manufacturing needs to be seen as part of the innovation system—the stage at which technology advances enter markets—and it requires highly creative engineering, particularly for new technologies and products, and often requires rethinking the underlying science inputs for meeting design and cost requirements. If manufacturing is part of innovation, then "producing there" runs the risk of "increasingly innovating there."

While, in the postwar period, the United States both innovated and produced here, realizing the gains of innovation at every stage, it increasingly shifted to an "innovate here, produce there" approach, outsourcing its production to lower-cost producers abroad.

U.S. policymakers were very slow to see the implications of U.S. production decline. But by 2012, they began to pay attention to the innovation side of manufacturing. Taking a page from both Sematech and Germany's Fraunhofer Institutes, the United States created 16 manufacturing innovation institutes.[32] Each is organized around a particular strand of advanced manufacturing technology, including additive manufacturing, digital production, robotics, power electronics, biofabrication, flexible electronics, and photonics. The institutes are a consortia of large and small producers, area universities and community colleges, and government, with industry, state, and regional support matched by federal government funding. They undertake collaborative applied research around their advanced manufacturing technologies with universities and industry, engage with regional manufacturing ecosystems, and provide workforce education. In short, they a return to a more "connected" model of innovation, incorporating post-research innovation stages previously outside the federal purview and tying the innovation actors together in a way not previously undertaken in the federal government outside the defense sector. It is a complex model requiring diverse interests to partner and collaborate, but the institutes have made significant progress. Of the 1,900 member organizations in the institutes, 61 percent are manufacturing firms, 70 percent of which are small and medium-sized manufacturers with 500 or fewer employees.[33] Total institute expenditures in FY 2019 were $488 million, including $133 million in base federal program funds and $355 million in institute-generated funds from industry, academia, economic development, state government, and competitive federal funding.[34] This represents a 2.7-to-1 investment ratio in matching funding to base federal funding. These funds are invested in technology R&D, capital investments such as facility or manufacturing equipment purchases, institute operations, and education and workforce development programs. But the total federal funding to the institutes represents an underinvestment in the levels needed for a manufacturing transformation—it's difficult for some $133 million in annual funding to leverage major change in a $2 trillion manufacturing sector. And there are other programmatic gaps as well, including the inability to help test and finance the new production technologies in companies that are ready to take the risk of experimenting with and adopting them.[35]

Why was the manufacturing funding modest given the size of the problem? One reason was a major setback for industrial policy approaches that occurred in 2011. A thin-film solar cell manufacturing company in California, Solyndra, obtained $535 million in government-backed loans from the Department of Energy.[36] However, Chinese manufacturers had been dumping low-cost crystalline solar panels in U.S. markets, driving prices down, and Solyndra's more advanced thin-film technology could not compete. Solyndra declared bankruptcy and a partisan outcry and congressional investigations ensued. The episode resulted in a black eye for federal entanglements with industry outside of its traditional R&D role, forcing retrenchment for a time from industrial policy approaches. Solyndra remains a cautionary tale for future programs.

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In summary, the United States has engaged in a series of elements of industrial policy since the end of World War II, and by far the most significant has been through its defense system, wherein it built a series of innovation agencies and linked them to follow-on defense procurement investments. While the investments were made for defense reasons, many of the technologies were "dual use," creating new sectors in the overall economy, including space, nuclear power, computing, and the Internet. Most of the post-war innovation waves have come out of this connected system. Other efforts outside defense were smaller in scope and scale, but have still been noteworthy and often successful. These include various programs created in response to competitiveness pressures from Japan, new energy technology efforts to address climate change, and, lately, an effort to create public-private consortia to develop advanced manufacturing technologies. All have generally fit within the industrial policy definition of governmental policy interventions that alter economic activity in sectors, technologies, or tasks to improve economic prospects in ways non-interventionist market forces cannot. All have tended to share three general characteristics: to build on strong U.S. R&D capacity, to intervene to support particular technology sectors, and to take advantage (when available) of federal follow-on procurement funding or financing. But problems like Solyndra remain a warning light for future federal industrial policy attempts.

THE NEW INDUSTRIAL POLICY APPROACHES

A series of new industrial policy efforts are now taking shape that are dramatically different in size and scope than what has been attempted previously.[37] A major shift in fiscal policy approaches enabled this rather abrupt outpouring of billions of dollars for industrial policy. In March 2020, when it became clear that Covid-19 would unleash a worldwide pandemic, stocks fell almost as deeply as they had in 1929 and 1987. At a low point on March 23rd, U.S. stocks lost 30 percent of their value and globally, equities lost $26 trillion.[38] An even more ominous development was that the Treasury market was becoming illiquid and dysfunctional. The situation appeared even more dangerous than the 2008 crash. The Federal Reserve led other central banks in a rapid response, unleashing three prongs of attack: It created a loan facility to back up credit card, auto, small business, and student lending; it took the unprecedented step of supporting direct credit to large employers by buying debt or loans directly from corporations; and it supported the public debt markets for state and local governments. Once investors understood the scale of these dramatic steps, markets rapidly stabilized. Trillions were involved, and trillions were seen to be needed. Supplementing the Fed's efforts, the Trump administration backed a $1 trillion Covid relief bill in 2020 and the Biden administration $1.9 trillion. In general, fiscal restraints were lifted in the face of the emergency, and other areas of federal spending were opened up in the name of recovery, including for industrial policies thought to be required for competition with China. And China's massive spending on industrial policy efforts themselves served as a spur for major investments.[39]

The following discussion attempts to summarize and catalog five major recent efforts and identify their underlying approaches. The sheer size of the efforts and their variety of approaches is far beyond anything previously attempted outside the defense sector. Many elements listed are in still-pending legislation, but if they become law and are adequately funded, they could constitute a fifth and more systematic industrial policy period. They would signal a major policy turning point, marking a more widespread acceptance of these approaches.

The Semiconductor Industry

Semiconductors have been recognized for decades as a foundational technology, on which all software operates and data is processed. They are essential for defense technologies and systems, and for upcoming generations of advanced technologies such as artificial intelligence (AI) and quantum computing.[40] And, of course, they are core to a host of societal services, such as computing, the Internet, and broadband, upon which the daily economies and functioning of societies are based.

The U.S. government is now undertaking its second intervention into the sector; the first was in the late 1980s. Although transistors, integrated circuits, and a host of semiconductor advances were developed in the United States, in the mid-1980s, the U.S. semiconductor chip industry was falling behind Japan's leading firms, Nikon and Cannon. In response, Robert Noyce, CEO of Intel, led the creation of Sematech in 1987 as a consortium of 14 semiconductor companies.[41] He persuaded the Reagan administration to back a public-private partnership effort to restore U.S. technology leadership. DARPA provided $500 million over five years, which was matched by the industry partners.[42] The problem identified by the group was in chip manufacturing, and a major joint effort turned around the speed and quality of chip production systems, focused on improvements by chip equipment makers. Sematech is generally acknowledged to have played an important role in the return of technology leadership in semiconductors to the United States. But by 2020, the United States faced a loss in chip leadership.

Although the United States has offshored much of its electronics production, in 2019, semiconductors were its largest electronic product export and its fifth-largest export product, amounting to some $42 billion. In 2018, 44 percent of U.S.-headquartered firms' front-end semiconductor wafer capacity was located in the United States. American companies—including those with production abroad—held 45 percent of the global semiconductor market in 2019.[43] Despite those impressive-sounding numbers, the United States have only 12.5 percent of global semiconductor manufacturing facilities (fabs). They are located in 18 states and employ 240,000.

The world has become largely dependent on one semiconductor maker: TSMC in Taiwan.[44] It produces the great majority of the world's high-end, sophisticated chips as well as lower-end chips, which are in virtually all electronic products from computers to iPhones, and in platform technologies such as automobiles or aircraft. With the world's largest fabs, TSMC, as the manufacturer, provides the foundry for many well-known companies that design their own chips, such as Qualcomm.[45] TSMC passed Intel in recent years as the most important semiconductor maker and has become the world's 11th-largest company. As the first to reach the 7 nanometer (nm) scale, TSMC makes 92 percent of the newest cutting-edge logic chips (an indication that it has assumed technology leadership over U.S. firms).[46] But TSMC is located on an island that is vulnerable to Chinese interference; and China is making massive investments in semiconductor technology in a systematic effort to dominate the sector.

Certain aspects of the semiconductor ecosystem also require mention.[47] Concerning semiconductor materials—particularly rare earth materials—China dominates, and is making major investments in tools for assembly and packaging. In the area of manufacturing equipment, the United States shares leadership with Japan and the Netherlands. At the semiconductor manufacturing stage, as noted, Taiwan's TSMC leads, with Korea's Samsung in second place and Intel now in third. The most challenging production issue from the perspective of technology leadership is in high-end, state-of-the-art manufacturing at the 7 nm level and evolving toward the 5 nm level. Here, TSMC, as noted, now leads while Intel has fallen behind. The state-of-the-art production sites are now overseas—not in the United States—in foundries that manufacture chips designed by and for other companies. This shift in production capacity in large part has been due to financing subsidies provided by foreign governments, which the U.S. government has been unwilling to undertake. A major signal of U.S. decline came in November 2020 when Apple, after having contracted with Intel for processors for 15 years, but wanting access to improved chip performance at the smallest nanometer scale, switched from Intel to TSMC for its chips.[48] So the United States now faces significant gaps in manufacturing. While its R&D and design capabilities are still solid, it is not translating them into production leadership in this area, as it has in so many other areas. And since, as noted, production needs to be seen as part of innovation and is deeply tied to it, production erosion leads to innovation erosion.

There is an additional and oncoming set of challenges around design and technology leadership. Start-ups play a potentially significant role in future innovation capability. But while U.S. venture capital has been available to U.S. start-ups in semiconductor fields at the seed stage, at the scale-up stage, when start-ups need to bring technologies into implementation, foreign capital has dominated. In terms of innovative U.S. firms in the semiconductor field seeking to raise Series B- and C-stage capital, a review of available capital from 2015 through 2017 shows they had to rely on foreign sources 66 percent of the time.[49] U.S. advances, then, are increasingly controlled, and can be shifted, abroad, leading to the familiar "innovate here, produce there" story.[50]

Alerted to the security and geopolitical implications of these developments, in 2020, bipartisan leaders on the Senate Intelligence Committee introduced major legislation designed to restore U.S. semiconductor technology leadership. Known as the CHIPS (Creating Helpful Incentives to Produce Semiconductors) Act, the legislation authorized $53 billion for a series of interventions into the semiconductor sector.[51]

R&D and technology development:

- Directs the White House Office of Science and Technology Policy, through the National Science and Technology Council and its Subcommittee on Semiconductor Leadership (responsible for the development of a national semiconductor research strategy) to ensure U.S. leadership in semiconductor technology and innovation, which is critical to American economic growth and national security, and to coordinate semiconductor R&D.
- Authorizes funding for DOD to execute research, development, workforce training, testing, and evaluation for programs, projects, and activities in connection with semiconductor technologies and direct the implementation of a plan to utilize Defense Production Act (DPA) Title III funding to establish and enhance a domestic semiconductor production capability.
- Creates new R&D streams to ensure U.S. leadership in semiconductor technology and innovation.
- Provides $2 billion to implement the Electronics Resurgence Initiative of DARPA.
- Provides $3 billion to implement semiconductor basic research programs at the National Science Foundation (NSF).
- Provides $2 billion to implement semiconductor basic research programs at DOE.

Supply-chain review and support:

- Directs the secretary of commerce to complete a report assessing the capabilities of the U.S. industrial base to support national defense needs in light of the global nature of the supply chain and significant interdependencies between the U.S. industrial base and that of foreign countries related to microelectronics.

Financing for new production fabs in the U.S:

- Creates a 40 percent refundable investment tax credit (ITC) for qualified semiconductor equipment that is placed in service or for any qualified fab investment expenditures through 2024. The ITC is reduced to 30 percent in 2025 and 20 percent in 2026, and phases out in 2027.
- Directs the secretary of commerce to create a $10 billion federal program that matches state and local incentives offered to a company for the purpose of building a semiconductor foundry with advanced manufacturing capabilities.

Advanced semiconductor manufacturing and packaging:

- Creates a new National Institute of Standards and Technology (NIST) semiconductor program to support advanced manufacturing in the United States. The program's funds will also support STEM (science, technology, engineering, and mathematics) workforce development, ecosystem clustering, U.S. 5G leadership, and advanced assembly and testing.
- Establishes a $5 billion Advanced Packaging National Manufacturing Institute under the Department of Commerce (DOC) to establish U.S. leadership in advanced microelectronic packaging and, in coordination with the private sector, to promote standards development, foster private-public partnerships, create R&D programs to advance technology, create an investment fund ($500 million) to support a domestic advanced microelectronic packaging ecosystem, and work with the secretary of labor on establishing workforce training programs and apprenticeships in advanced microelectronic packaging capabilities.

Cooperation with international programs:

- Establishes a trust fund of $750 million over 10 years to be allocated after an agreement is reached with foreign government partners to participate in a consortium in order to promote consistency in policies related to microelectronics, greater transparency in microelectronic supply chains, and greater alignment in policies toward non-market economies. To incentivize multilateral participation, a common funding mechanism is established to use this fund to support the development of secure microelectronics and secure microelectronics supply chains. A report to Congress is required for each year funding is available. This is particularly aimed at competition with China's state-directed semiconductor strategy.

The legislation engages at a series of technology development stages, consistent with our definition above: at the R&D stage to attempt to secure semiconductor technology leadership, at the supply chain level with an assessment of supply vulnerabilities, at the production financing level to assure location of fabs for producing advanced chips in the United States, in the development of advanced manufacturing technologies for both chips and related packaging areas, and with a fund to attempt to secure Asian and European cooperation in the face of massive Chinese subsidies of its semiconductor sector. It is clearly an industrial policy approach. The authorizing legislation for the program passed Congress in 2020 and full appropriations funding for the program is now pending before Congress.

The Endless Frontier Act

First introduced in May 2020 by Senate Majority Leader Charles Schumer (D-NY) and Senator Todd Young (R-IN.), with a similar version introduced at the same time in House, the "Endless Frontier Act" legislation aimed "to solidify the United States' leadership in scientific and technological innovation through increased investments in the discovery, creation, and commercialization of technology fields of the future."[52] In April 2021, they introduced a revised version of the bill (S.1260) with 12 Senate cosponsors from both parties. That bill was renamed the "Innovation and Competition Act" and was amended during a May 2021 Senate Committee mark-up and again during Senate passage in June 2021, when it was passed by a bipartisan vote of 68 to 32. It is, as of this writing, in conference with House legislation of narrower scope.[53]

With the final version unlikely to emerge until this fall, the version of the bill as passed by the Senate illustrates its new technology and industrial policy approaches:[54]

- Authorizes over $100 billion in funding for NSF, DOC, and DOE over five years, for both basic and applied research, and related programs—although approximately half of this total is for extensions of current programs, as opposed to new funding.
- Focuses on advancing 10 advanced technology areas, including AI; quantum computing; new high-performance computing and semiconductors; robotics, automation, and advanced manufacturing; biotechnology; cybersecurity; advanced materials; advanced energy technology; and advanced communication technology.
- Creates a new advanced Technology Directorate at NSF with $29 billion over five years for applied R&D in the 10 advanced technology areas, largely through the new centers and other programs listed below.
- Directs the new Technology Directorate to fund University Technology Development Centers, which could be single universities or consortia between universities and industry.
- Instructs the new Directorate to apportion its budget between Technology Development Centers, innovation institutes, testbeds, lab-to-market initiatives, student and postdoc awards, other NSF directorates, and EPSCoR (Established Program to Stimulate Competitive Research), which provides R&D to less-established regional universities.
- Provides for regional scale-up of advanced technologies through "at least 10" Regional Innovation Hubs, run by consortia of industry, state, and local government and education institutions, selected and supported by DOC's Economic Development Administration (EDA) and NIST programs.
- Appropriates full funding of $53 billion to implement the CHIPS Act, the major semiconductor initiative.

These are just highlights of the legislation, as it includes many other provisions. For example, to satisfy NSF's university basic research constituency, there is funding in the10 technology areas not only for applied research but for basic research at NSF. The bill also increases the annual budget of the rest of NSF—largely basic research—from the current level of $8.5 billion to $12 billion over five years. DOE research is also raised by $17 billion to satisfy its large lab constituency.[55]

The overall aim of the bill is to put the United States in a position to compete with major ongoing applied technology initiatives in China—an important reason behind its bipartisan support. Although the bill was significantly watered down in the course of markup and Senate passage, it does mark a shift from the long-standing U.S. basic research emphasis advocated by Vannevar Bush in 1945 to include more applied research.[56] Indeed, the bill's initial name, the Endless Frontier Act, is ironic, since it moves away from Bush's basic research emphasis in his Endless Frontier treatise toward applied R&D. NSF has long been the bastion of U.S. basic research, but the bill adds a major applied R&D directorate into the NSF basic research mix. NSF is America's one major, broadly focused R&D agency not tied to a specific, and narrower, mission.[57] But the nation's current problem is technology, not simply basic science—many argue it needs a new technology development thrust, and this has not been NSF's job. So the approach of this legislation is to form a technology focused subunit within the agency—the proposed new

Technology Development Directorate. Some have argued this will create a culture clash within NSF. Yet, we have a long history of basic and more use-inspired, applied research working in tandem, and the cultures can be complementary: DARPA works alongside the Naval Research Lab, and ARPA-E alongside the DOE's Labs and Office of Science. Critics of the bill have argued the other side of this point, that the problem won't be applied research spoiling basic, but that the long-standing basic research emphasis at NSF will limit technology development.[58]

Optimally, the Technology Directorate could form part of a larger system. Getting to new technology, as opposed to new science, requires moving through a series of post-research stages: development, prototype, testing, demonstration, scale-up/piloting, initial markets, and full production. The proposed legislation attempts to recognize this, with organizational elements aimed to match the process:

- **R&D in critical technology areas:** Earlier-stage research elements would be performed at existing NSF directorates, and later-stage research as well as development would be performed through the new Technology Directorate.
- **Development and prototyping:** The University Technology Centers could perform this role, and importantly, they can be consortia, including industry participants.
- **Testing and demonstration:** New test beds are called for to prove and demonstrate the new technologies so they can get into the risk range industry and supporting forms of capital can work with.
- **Scale-up:** DOC-designated Regional Innovation Hubs, while designed to spread innovation capacity to more U.S. regions, could also support this stage of scaling-up toward production and preparing the regional technology ecosystems and infrastructure for introduction.

Creating and linking these new organizations will be a major challenge, but non-defense legislation that recognizes a need for an innovation system is a new step.

The Regional Innovation Hubs called for in the bill, to be funded and set up through the Commerce Department's EDA and NIST programs, is a new programmatic element that could be a way to encourage regional innovation. How could these regional innovation approaches work?

This issue has been studied for years. Michael Porter's work on innovation clusters dates back over two decades.[59] There has been much regional experimentation; we have had many regional kitchens trying many ingredients, and there is no exact recipe. Different regions can make different recipes work. Imposing innovation tasks on struggling regions, however, often does not work. Yet, there are examples of places that have become hubs of innovation activity not simply by accident but through concerted effort. To summarize a large literature in a few words, most believe we need regional ecosystems for innovation to thrive.[60] Typically, such an ecosystem includes an area education and research institution as an anchor for technology research and talent. Ecosystems also seem to need an organized public sector engaged with the private sector—including companies and area business groups—all pursuing a joint strategy.[61] Solid larger firms linked to solid supply chains of smaller firms are another ingredient. Regions need to build on their existing regional strengths—not every area is going to be a biotech hub. Workforce education has become an increasingly significant component of a solid regional ecosystem so a number of regions are now encouraging companies and start-ups to come because they offer a trained and skilled workforce that's tied to employer needs. This mean strong workforce programs for new skills at area community or technical colleges are also a component. Another feature of the legislation is grants to communities to help them build strategies for their regional assets. To summarize a few key points, there needs to be a broad engagement in innovation—a big tent—not a narrow, single-innovation focus; strong locally-based firms need to be engaged as "anchor tenants;" a connection is needed to the talent pipeline—state university and skills education programs, for example—which will be key to companies; and state and local governments need to strongly support the effort.[62]

If the Regional Innovation Hubs anticipated in the legislation take on the innovation scale-up role in addition to the regional innovation capacity role, they will need to be located in regional ecosystems that can pull together existing assets such as those listed previously. To effectively compete for these, they will need to involve firms interested in implementing new technologies, and the Hubs should be able to muster their regional actors to show how they can help implement them. The Regional Hubs, then, are broader in purpose than the NSF University Technology Development Centers the bill will create, which will primarily support development through prototyping stages. More than prototyping is needed for successful innovation; additional actors are needed to move from those research-to-prototyping stages to work on the scale-up of new technologies. Not only universities are needed but regional industry associations, with both small and larger firms and their supply chains, community and technical colleges, and support from area government and economic development organizations. The Hubs could be the mechanisms to bring this additional combination of actors together. The Development Centers hopefully could be participants in the Hubs.

The Endless Frontier Act is full of experiments, as the nation begins to think about industrial policy approaches. Some will work, others may not, but, assuming much of this legislation becomes law, there should be important lessons learned.

Demonstration Projects for New Energy Technologies

On August 10, 2021, the U.S. Senate passed a major bipartisan $1 trillion infrastructure funding package supporting highway and transit infrastructure, water and power infrastructure, and broadband Internet access. While it was a major political victory, the bill is less than half the $2.6 trillion version the White House originally proposed, and it does not include some $600 billion President Biden originally wanted to spend on R&D and related initiatives, including efforts to combat climate change.[63] However, the bill includes significant funding for advancing clean energy technologies, including electric vehicles and efforts to trap carbon dioxide produced by power plants before it enters the atmosphere, and related R&D.

The bill includes support for a wide range of energy projects:[64]

- **Carbon management projects:** regional direct air capture hubs, $3.5 billion; carbon capture demonstration and pilot programs, $3.47 billion; carbon storage commercialization, $2.5 billion; industrial decarbonization demonstration projects, $500 million; carbon utilization programs, $310 million; and direct air capture prizes, $115 million
- **Clean hydrogen programs:** regional clean hydrogen hubs, $8 billion; clean hydrogen electrolysis demonstrations, $1 billion; clean hydrogen manufacturing and recycling programs, $500 million

- **Renewable energy programs:** waterpower, $146 million; battery recycling R&D and demonstrations, $125 million; wind energy, $100 million; geothermal energy, $84 million; solar energy, $80 million; energy storage demonstration projects, $505 million
- **Nuclear energy:** advanced reactor demonstration program, $2.48 billion; industrial research centers, $550 billion
- **Critical minerals and materials projects and demonstrations:** mineral security project, $802 million; U.S. Geological Survey earth mapping initiative, $320 million; USGS energy and minerals research facility, $167 million; rare earths demonstration facility, $140 million; USGS geological data preservation program, $24 million

To highlight some examples of the programs and projects funded on the above list, the bill would greatly expand DOE's hydrogen R&D and demonstration activities, allocating $8 billion to establish four regional clean hydrogen hubs, $1 billion to support hydrogen electrolysis demonstration projects aimed at reducing production costs, and $500 million for a clean hydrogen manufacturing and recycling program. It also would provide new funding for projects to remove carbon emissions directly from the atmosphere, including $3.5 billion to establish four "regional direct air capture hubs." It also provides $2.5 billion for a carbon capture demonstration program and close to $1 billion for carbon capture technology pilot projects. Importantly, it includes $500 million for industrial decarbonization programs in heavy industry, a neglected sector to date yet a major source of emission.[65] The Office of Nuclear Energy would receive $6 billion for a new Civil Nuclear Credit Program that would subsidize economically ailing nuclear power plants, and there would be support for the recently formed Advanced Reactor Demonstration Program. And there would be support for a range of renewable energy projects.

There is a strong emphasis in the legislation on the demonstration stage of technology implementation, providing $21.5 billion in funding for a new DOE Office of Clean Energy Demonstrations. DOE has long had a need to build technology demonstration capability for projects where the commercial sector lacks the incentive to carry out on its own. This is particularly the case for projects that meet climate change goals. While DOE has one of the world's largest armies of physicists, with some 12,000 in its labs, it historically has had very limited expertise in large-scale project engineering, project management, and project financing—the skill sets required for the massive new technology demonstrations it will be required by the new legislation to conduct.

The record of government-funded and government-run large-scale energy demonstration projects in the past has been mediocre. Projects such as the Clinch River Breeder Reactor, the Barstow Solar Power Tower, and two DOE-run synthetic fuel plants faced large cost overruns due to collapsing oil prices four decades ago, and conveyed only limited technology information to the private sector.[66] In more recent years, there has been a record of unsuccessful carbon capture and sequestration demonstration projects.[67]

Former Energy Undersecretary John Deutch draws three lessons from the past problems with government demonstration projects.[68] First, indirect incentives (production payments, tax credits, loans or loan guarantees, and guaranteed purchases) for demonstrating the possibilities of new technology deployment to the private sector have important advantages over stand-alone, government-dominated demonstrations not well connected to potential users. Second, because large demonstration projects with large cash outlays attract congressional interference, creating a quasi-public corporation to manage the demonstration provides insulation against congressional intervention.[69] Third, it is important to build flexibility and resilience into the economic model, which the private sector is better able to do, so that the executors of the project can react to changing market conditions and not make the mistake that plagued a number of projects: designing the demonstration solely around the assumption that current economics will always continue.

Deutch also argues that managing a commercial demonstration requires management expertise that the private sector has and the government doesn't. Since DOE lacks such expertise, a public corporation could be a means to recruit people that do have it. A public corporation would also be able to operate outside the limits of government procurement systems in an environment more comparable to that of a commercial firm. This private-sector expertise—in both major project financing and commercial-scale engineering—should be backed by the kinds of financial incentives previously described and by access to a sufficient multiyear stream of assured funding to permit the efficient execution of a demonstration project. Cost sharing with industry can provide a further incentive to cost control and commercial discipline.

While this legislation has not yet passed the House of Representatives, it is likely to. DOE faces a significant capacity problem in its ability to take on a major new demonstration role at this scale. These are significant industrial policy programs, and will not work unless the government builds the management capacity to handle them.

Assuring Secure, Domestic Supply Chains

In June 2021, the Biden White House, after 100 days in office, issued a major report in response to a prior presidential executive order, on "Building Resilient Supply Chains, Revitalizing American Manufacturing and Foster Broad-Based Growth."[70] The departments of Commerce, Energy, Defense and Health and Human Services all cooperated in the report's development. The report examined domestic supply chain gaps in four areas—pharmaceuticals and ingredients, advanced batteries, critical minerals, and semiconductors—making a long series of recommendations for bolstering supply chains in each area. In each of the four areas, some of the key findings and recommendations are summarized below.[71]

Pharmaceuticals and Pharmaceutical Ingredients

Key findings: The United States experienced serious supply problems for personal protective equipment and other needed medical supplies during the coronavirus pandemic, which led to a new awareness of supply chain issues in the medical sector. The report finds that the United States is dependent on imports for a range of key pharmaceutical products and Active Pharmaceutical Ingredients (APIs) —the primary ingredients of generic drugs—which represent 90 percent of all prescription medications filled. About 87 percent of API facilities for generic drugs are located overseas, which has left U.S. supply chains of essential medicines vulnerable. China and India control substantial parts of the supply chain where there are shortage issues. The drive by U.S. hospitals and medical systems to lower costs, as well as unfair trade practices, have led to a hollowing out of domestic production. More resilient supply chains, including improving supply transparency, building emergency capacity, and investing in domestic production, are all required.

Policy recommendations:

- The Department of Health and Human Services (HHS), using the DPA, plans to establish a public-private consortium for advanced manufacturing and onshoring of domestic essential medicines production. The consortium's initial task is to select 50–100 critical drugs, drawn from the Food and Drug Administration's (FDA) essential medicines list, for a production onshoring effort.
- HHS will commit $60 million from the DPA appropriation in the American Rescue Plan to develop novel platform technologies to increase domestic manufacturing capacity for APIs to reduce threats of future shortages.

Advanced Batteries

Key findings: Advanced, high-capacity batteries are integral to technologies that are needed for a clean energy transition and national security capabilities, from electric vehicles to stationary energy storage to defense applications. Demand for these products is set to multiply as supply chain constraints, geopolitical and economic competition, and other vulnerabilities continue to increase. The United States reliance on the importing of inputs for fabricated advanced battery packs from abroad exposes the nation to supply chain vulnerabilities that threaten to disrupt the availability and cost of the technologies that rely on them. With the global lithium battery market expected to grow by a factor of 5 to 10 by 2030, investment in scaling up a secure, diversified supply chain for high-capacity batteries is required. The full lithium battery supply chain, including the sourcing and processing of the critical minerals used in battery production through to end-of-life battery collection and recycling, needs attention.

Policy recommendations:

- DOE will release a National Blueprint for Lithium Batteries that will codify the findings of the battery supply chain review in a 10-year plan to urgently develop a domestic lithium battery supply chain.
- DOE's LPO will use the approximately $17 billion in loan authority in the Advanced Technology Vehicles Manufacturing Loan Program to support the domestic battery supply chain.
- DOE's Federal Energy Management Program (FEMP) will launch a new effort to support deployment of energy storage projects by federal agencies. It will begin with a federal government-wide energy storage review that will evaluate the current opportunity for deploying battery storage at federal sites. The resulting projects will help build markets for materials supported in other efforts.

Critical Minerals

Key findings: China, using state-led, non-market interventions, has captured large portions of value chains in a series of critical minerals and materials needed for energy, electronics, and national security applications. China also accounts for an outsized share of the world's refining capacity, so that even if the United States diversified sources of critical minerals or increased domestic extraction, it would still be reliant on China for processing before use in end-product manufacturing. The United States needs to work with allies to diversity supply chains and invest in sustainable production, refining and recycling capacity domestically.

Policy recommendations:

- The Department of Interior (DOI) will establish a working group of agencies, including the Environmental Protection Agency (EPA), to identify sites in the United States where critical minerals could be produced and processed.
- An interagency team of staff from agencies including DOI, USDA, EPA, and others with expertise in mine permitting and environmental law will identify gaps in statutes and regulations that may need to be updated.
- DOD will deploy DPA Title III incentives—including grants, loans, loan guarantees, and offtake agreements—to support sustainably produced strategic and critical materials, including scaling proven R&D concepts and emerging technologies.
- DOE's LPO, through its Title 17 Renewable Energy and Efficiency Energy Projects solicitation, will have more than $3 billion in loan guarantees available to support efficient end-use energy technologies, such as mining, extraction, processing, recovery, or recycling technologies of critical materials.
- The U.S. Development Finance Corporation will expand international investments in projects that will increase production capacity for urgently-needed products, including critical minerals and other products.

Semiconductors

Key findings: As reviewed in more detail in the previous discussion of the CHIPS Act, the United States has fallen from 37 percent of global semiconductor production to just 12 percent over the last 20 years. The United States also lacks production capability at the most advanced technology levels. For leading-edge logic chips, the United States and its allies rely primarily on facilities in Taiwan, which produces 92 percent of such chips. This reliance on imported chips introduces new vulnerabilities into the critical semiconductor supply chain. The United States produces only 6 to 9 percent of the more-mature logic chips, where there is a major current shortage affecting many product sectors. The loss of production capacity threatens all segments of the semiconductor supply chain as well as overall economic competitiveness.

Key policies:

- The administration supports the provisions of the CHIPS Act to provide dedicated funding for semiconductor manufacturing and R&D at the level of $50 billion.
- DOC will expand its partnership with industry to enable information flow between semiconductor producers, suppliers, and end users and support common strategies.
- The administration will strengthen engagement with allies and partners to promote fair semiconductor chip allocations, increase production, and promote increased investment.

This report contains numerous additional findings and recommendations, but these are just highlights. The report also makes clear that this was not to be the only supply chain effort. The administration is establishing a new Supply Chain Disruptions Task Force across agencies to address near-term supply chain challenges to the economic recovery, led by secretaries of commerce, transportation, and agriculture. It will focus on areas where supply/demand issues are a problem: homebuilding and construction, semiconductors, transportation, and agriculture and food. It will convene public and private stakeholders to evaluate problems and review solutions to bottlenecks and supply constraints. In addition, DOC will bring together data from across the federal government to improve the federal government's ability to track supply-and-demand disruptions and to facilitate information sharing between federal agencies and the private sector to more effectively identify supply chain risks and vulnerabilities. The administration also plans to examine the ability of the EXIM Bank to use its existing authorities and lending ability to support domestic manufacturing of products—both production facilities and infrastructure.

Operation Warp Speed

Unlike the pending policy approaches previously listed, Operation Warp Speed (OWS) represents a new industrial policy approach that has been implemented and fully acknowledged as a major accomplishment, thereby showing the potential of this approach. Rather than listing a series of abstract policy recommendations, a review of this project allows characterization of its actual major thrusts. Nearly all of the historical industrial policy approaches from 1957 through 2018, described in the four periods above, were crisis-driven, and OWS faced a crisis on steroids: the sudden 2020 pandemic. It offers important lessons for other industrial policy efforts. A recent article by David Adler has described some of the program's elements.[72]

At the beginning of 2020, when COVID-19, a virus that was both highly infectious and deadly, landed in the United States, the public health system was dangerously unprepared for the scale of the assault, and most of the nation's vaccine and medical supply industries had been outsourced. OWS was a partnership between HHS, DOD, and other agencies to develop, manufacture, and distribute effective vaccines against COVID-19. It was a public health triumph, delivering hundreds of millions of doses of new vaccines at unprecedented speeds—in a year not a decade—saving hundreds of thousands of lives. Organizationally, it was not a public-private partnership, it was a wholly governmental, cross-agency partnership, but directed at and with participation from the private sector.

The team: Since there is no substitute for talent, the mix of talent and agency expertise involved in OWS was an important indicator of its success. It was conceived by Dr. Robert Kadlec, assistant secretary for preparedness and response (ASPR) at HHS, joined by Dr. Peter Marks, director of the FDA's Center for Biologics and Research.[73] Kadlec had been an Air Force physician, biodefense official, and biotech executive and earlier developed the legislation creating the Biomedical Advanced Research and Development Agency (BARDA) in HHS, which had powers somewhat akin to DARPA's to advance biodefense and disease therapeutics and diagnostic tools. Marks is a medical doctor and cell and molecular biologist with experience in the pharmaceutical industry and in medical centers who led the regulation of vaccine products at the FDA. His Star Trek fandom led him to name the new organization "Warp Speed." Jared Kushner helped push the idea through White House approval, and it was formed on May 15, 2020. OWS was led by an experienced pharmaceutical vaccine executive, Moncrief Saloui.[74] He was aided by defense logistics expert, General Gustav Perna.[75] This group and their OWS colleagues operated as change agents at an accelerated speed to address a national crisis, cutting across bureaucratic lines and taking advantage of diverse agency expertise and legal authorities. OWS resembled a company, with an interagency board, but was a government operation, bringing in officials from key health agencies such as the FDA, the Center for Disease Control and Prevention (CDC), the National Institutes of Health (NIH) as well as DOD agencies, such as the Army Corps of Engineers and DARPA, and HHS agencies such as BARDA and ASPR, as needs arose. Dr. Matthew Hepburn, a former DARPA program manager and OWS's DOD lead for vaccine development, has said that "Warp Speed was inspired by DARPA but with a focus on scaling and implementation. OWS was DARPA at scale."[76] He was referring to DARPA's reputation for sponsoring technology breakthroughs, finding top talent, providing fast implementation, and avoiding bureaucratic lethargy. OWS exemplified a series of industrial policy approaches.

Portfolio approach: OWS had the great advantage of many years of prior research on mRNA applications. Researchers Katalin Karikó and Drew Weissman at the University of Pennsylvania had discovered ways to increase mRNA's therapeutic potential in 2005. Dr. Dan Wattendorf, as a DARPA program manager, launched a DARPA project to rapidly develop vaccines, and focused on mRNA, funding new biotech companies, including $25 million to Moderna, to advance it. Moderna completed phase one clinical trials in an mRNA vaccine by 2019. Work in nanolipids for delivery, and by Barney Graham and Jason McLellan through NIH on the structure of the Covid-19 spike protein, also led to advances. By the time COVID-19 arrived, mRNA was approaching scientific readiness. But mRNA had never received the resources needed to scale. OWS didn't want to rely solely on mRNA, which had not yet led to an approved vaccine, so it took another page from the DARPA playbook and decided on a portfolio approach. It surveyed over 100 pending vaccine projects, decided on four different types of vaccine technology platforms—some new, such as mRNA, and others more established—and then picked two companies to support each platform approach. It developed a portfolio to manage the technology risk, selecting a range of technologies and firms.[77]

Guaranteed contracts: Once the firms were selected, OWS began targeting them with support. Key was the issuance of contracts for the production of their vaccines, even though the vaccines had not yet received emergency-use approval from the FDA. The OWS concept was that further vaccine development and clinical trials would proceed in parallel with actual vaccine production so doses would be ready for distribution as soon as they were approved. The government's guarantee that it would purchase the vaccine at scale enabled the firms to take the risk of ordering supplies and developing production facilities. It was a crucial tool that enabled rapid production scale up.

Manufacturing was a major challenge because the United States had offshored so much of its medical production capability. It had nearly stopped making masks, personal protective equipment, glass vials, swabs, and diagnostic tests. When the pandemic hit, the country was completely unprepared, and had to start reinventing production for those products in the face of exports from other nations collapsing as they moved to meet their own needs.[78] CDC, with responsibility for disease control, was more of an academic institution and had never focused on supply chain problems. CDC's early failure to a develop a sound test for the coronavirus and get it produced became a notorious signal of the nation's lack of preparedness. In vaccine production, the number of U.S. vaccine makers had declined from over 30 to just 4 firms because vaccines are such a poor market—selling a medicine that has to be taken daily for years is a sound market, preparing a vaccine that is used only during, or to prevent an, epidemic is not. Companies want blockbuster drugs people must take for life, not a vaccine that's taken once and solves the problem, and only has a large market if much of the population is facing a disease disaster. Much of vaccine production had shifted abroad, with India becoming the largest vaccine producer and China growing fast and hoping to dominate the sector. Pfizer had production capacity that, once it had a federal guaranteed contract of $2 billion for 100 million doses if emergency approval was granted for its vaccine by the FDA, could be shifted to the mRNA vaccine developed with the German BioNTech. But the smaller biotechs had limited manufacturing experience. So OWS intervened, building or refurbishing production plants, purchasing and fitting out equipment, hiring staff, enabling raw material supplies and purchasing vials, syringes, and needles in bulk.[79]

Active companies: Effective industrial policy requires both an active and creative governmental role and willing and energetic company participants. If companies are neither committed to the project goals nor ready to invest in them, it will not work. In OWS, the government was able to work with committed leadership at committed companies such as Moderna and Pfizer, and partnering with BioNTech.[80]

Flexible contracting mechanisms: OWS made extensive use of *Other Transactions Authority* (OTA), which was first developed by DARPA and used by DOD agencies, and offered a much faster and more flexible way to contract outside the glacial process of normal federal procurements. Contract agreements using OTA could be reached in days, not months, and were key to working with biotechs and smaller suppliers unaccustomed to complex federal contracting. The DPA dates back to the Korean War and allows the federal government in national emergencies to require suppliers to supersede serving their customers in order to meet security needs. It proved key to lining up supplies and resources for vaccine makers to avoid production delays. It can be a double-edged sword, however, and needs to be applied carefully to avoid disrupting other important markets.

Technology certification: The FDA's *Emergency Use Approval* (EUA) was another key to speed—the FDA could use this approval to meet emergency health needs as opposed to having to wait for full and permanent approval that often takes years of reviews. This FDA step was vital: It amounted to a certification and validation of the technology, assuring instant market acceptance. FDA approval is the gold standard for medical products worldwide, and signifies that those products work. The majority of the American public immediately accepted the vaccines as soon as they received the FDA's EUA. Such a technology certification is completely unavailable for U.S. technologies outside the FDA's role in health technologies, but it shows the potential importance of technology certifications.

Mapping supply chains: The DPA enabled OWS to intervene into supply chains, but key to that was an in depth understanding of every facet of relevant supply chains. DOD, under General Perna, was used to supplying U.S. troops in Middle East wars, had a strong emergency logistics capability, and knew the importance of supply chain reliability and flexibility and how to map them. It sprang into action, helping the companies with these supply issues and working to manage the application of the DPA to get key supplies to vaccine makers while not disrupting other needed markets.

Integration of federal personnel with companies: OWS put federal agency personnel into certain companies to help them with the complex regulatory approval processes and to assist with project management and supply access. The Army Corps of Engineers oversaw construction to expand company production facilities.[81] While OWS was a government-run enterprise, it integrated its staff with private sector companies to speed development, approval processes, and production. This integration did not compromise the process—the federal employees remained federal personnel—but they cut bureaucratic barriers and accelerated processing.

Distribution systems: OWS took on the task of not only supporting the production of vaccines but also getting the doses shipped to states based on a state population-based formula. Considering that the two mRNA vaccines had to remain frozen and required special complex handling, the logistics were remarkable, with only a tiny amount of vaccine ending up spoiled in shipment. But vaccine distribution did not mean actual administration of shots. While OWS originally decided that the military would create mass vaccination sites and administer the shots, the state public health bureaucracies insisted that administration was its role and OWS acceded. But the state health bureaucracies were not ready, and doses administered initially lagged far behind doses delivered. Exacerbating the problem, CDC set vaccination priorities in an impractical way, allowing the most elderly to go first since they were most at risk of dying, but then created a second priority that bundled together most of the rest of the population, combining social equity concerns with risk. This created a disorderly administration process in most states, with countless individuals jockeying with each other on state and local online sites trying to set vaccination dates. But after these initial rollout problems, which the Biden administration made it a priority to fix, by March, the doses administered scaled up to meet the demand. In the end, the United States led vaccine development and distribution, many weeks ahead of its EU developed nation counterparts.

OWS was just that: an operation. It was not about science research. The work on the science and the technology development behind it had been undertaken in the years before the pandemic. OWS was about scaling up a technology into manufacturing and getting it to users rapidly. Except in defense areas, the federal government simply never does this. It has systematically ignored American manufacturing decline; it has paid little attention to processes for scaling up new technologies and their related products; and it has developed few tools to undertake these steps. OWS worked only because military approaches to scale-up were systematically applied by a flexible new organization that reached across agencies. As Dr. Michael Hepburn, DOD's vaccine director, has pointed out, it was like a DARPA for scale-up. It revived interest in the United States in industrial policy, lifting it out of its long-dormant status as the whipping boy of mainstream economists. It represented a strong and remarkably successful industrial policy approach. The tools previously listed—diverse talent, guaranteed contracts, flexible contracting mechanisms, committed companies, technology certifications, mapped supply chains, federal officials integrated with companies, and distribution systems—need to be considered for other critical national needs, including but not limited to future medical emergencies.

GUIDING PRINCIPLES AND OPERATING MECHANISMS FOR A NEW INDUSTRIAL POLICY INFRASTRUCTURE

All of the programs listed meet the definition for industrial policy discussed at the outset. They involve governmental interventions at a range of various innovation stages aside from early-stage research—from development to prototyping, testing, demonstration, product development, production financing, market entry, and expanded market creation. Different programs operate at different stages, but all reach a number of post-research stages.

All face a challenge of public support. Will they be effective and resilient enough to become politically accepted? Programs that operate at various innovation stages are not enough. For an industrial policy program to work, it will require applying a number of guiding organizational principles—really, new operating mechanisms that amount to a new kind of infrastructure. When tried in the past, industrial policy approaches outside the defense arena, particularly energy technology demonstrations, have sometimes failed. Getting these new programs to deliver on their promise requires applying a series of new operational mechanisms. This is an unstable area, where we haven't built the foundations to form strong projects, nor the talent base that will understand how to implement them. Examining our menu of five industrial policy examples, critical operational mechanisms and guiding organizational principles are delineated below that should be applied to each of the new programs. They amount to prerequisites for industrial policy programs to work.

Teams of change agents: Because innovation doesn't just happen, change agents are critical to complex innovation.[82] Even if the elements of an innovation system are assembled, a catalyst or group of catalysts is needed to force the changes and connections required, just as a conductor is required for an orchestra. The team creating and leading OWS provides a good example of this change-agent role. Clearly, change agents and the leadership they can bring will be needed for industrial policy projects. There are other parts of the talent team that must be built as well. Although talented researchers are needed, since industrial policy stretches beyond research, a series of other skill sets belong in the talent team. As discussed in the section on DOE demonstration projects, project management, project engineering and project finance expertise will also be required. And those with bureaucratic know-how and understanding of the legal and contracting authorities could also prove vital, as OWS demonstrated. Understanding of regional innovation could also be key as projects called for in the Endless Frontier Act illustrate. The point is that a new set of skill sets is going to be required by these kinds of projects—not simply R&D skills, but a panoply of tech development, tech scale-up, tech financing, and tech production skills. Sticking traditionally trained scientists and engineers into leadership positions will not work; new education efforts will be required to create the needed change agents. We do not have this talent base in place outside the defense department, and it must promptly be built.

Connections to strong research foundations: While industrial policy projects focus on stages after initial research, a strong research foundation is critical that is connected to the follow-on stages. OWS was the beneficiary of vital research work on the mRNA and nanolipids that enabled rapid vaccine scale-up. Similarly, the applied technology advances called for in semiconductor advances, the Endless Frontier Act, and DOE demonstration programs will all require extensive foundational research. Industrial policy is not only about application, it must also integrate with earlier stage research. Ensuring "connected research" will be critical to ongoing and longer term applied efforts.

Rebuilt manufacturing foundations: A weakness of most of the industrial policy-type programs previously cataloged is that they lack a manufacturing element. Any industrial policy is going to be dependent on a strong manufacturing system; unless this system is strengthened, initiatives will tend to collapse like a house of cards in slow motion. As noted in the section discussing recent manufacturing initiatives, U.S. manufacturing productivity has fallen to historically low levels over the last 15 years, with investment in capital plant and equipment declining in parallel. They indicate that U.S. adoption of advanced manufacturing technologies and processes is lagging behind its major competitors, which are doing better on productivity. Manufacturing needs to be seen as part of the innovation process, a step the United States hasn't taken, although its leading industrial competitors have. Many of the five initiatives previously discussed focus on implementing advanced technologies, yet the United States is running, as noted, a massive and growing $191 billion deficit in advanced technology goods.[83] They are indicators that a number of these pending advanced technology industrial policy programs will simply not achieve their aims. They signal that renewed focus on advanced manufacturing as a foundation for these programs will be critical if they are to work, although these programs, such as the advanced manufacturing institute program, have received limited attention from the Biden administration to date. This is a critical gap that must be filled. Strengthening the manufacturing sector in general and implementing advanced manufacturing technologies and processes will be a critical foundation for industrial policy programs; without this strengthened foundation, they will not work.

Mapping supply chains and paying attention to gaps: In building an innovation system through industrial policy approaches, there can't be gaps in the system, as strong connections are required throughout the system. The exercise of mapping supply chains can be vital to an operational system. This supply chain mapping, and corresponding efforts to fill in gaps, was vital to OWS. It is already proving central to the effort to secure domestic supply chains for critical technologies and materials, and will be required in semiconductors, and for the technologies called for in the Endless Frontier Act.

Technology testing and demonstration: While many prototypes often evolve, only some will ultimately work well. Testing and demonstration are therefore critical innovation stages. DOD, which has long followed industrial policy approaches, builds them into virtually all its technology development programs, but they are often missed in civilian agency efforts. Testing and demonstration are also crucial to commercialization—firms and users will not be interested in a technology unless it is tested and proven. This is why developing testing and demonstration capability at DOE is so critical if new-battery, advanced-nuclear, and renewable technologies and processes for industrial decarbonization are to be developed and adopted.[84] This is the rationale for the DOE demonstration program. It will also be key, and so is built into, the Endless Frontier Act for the new technologies it will support.

Integration between agencies, industry, and universities: All the innovation efforts reviewed herein require implementation in the private sector. None are about Manhattan or Apollo technology projects conducted solely for the government. Therefore, they will all need to be fully integrated with industry efforts. This is the connection pathway semiconductors, Endless Frontier Act technologies, DOE demonstration projects, and secure domestic technology and material supply must follow. OWS provides a good example of the government closely integrating with private sector vaccine makers to the point where government personnel were located at firms to speed regulatory review and understanding. It is important for implementation success that industry partners be *actively engaged* and committed—if they are not, the projects will inevitably fail. Industry leadership is thus a significant aspect of successful industry engagement.

In programs that will move technologies from research through implementation, such as with semiconductor advances and the new technologies called for in the Endless Frontier Act, integration between university research, government agencies, and industry will be required. And the other projects will have important researcher aspects as well. These collaborations are complex, and there is not enough space here to spell out operation rules, but close integration between the three main actors—industry, universities, and government—will be vital. OWS, as discussed, provides examples.

Technology certification and validation: While the health sciences sector has a technology certification process (its FDA approval process) that is fully accepted and recognized, no other sector has a similar mechanism. It amounts to a widely accepted technology validation system. FDA approval guarantees immediate market acceptance, making it a very powerful innovation tool. It commands markets. The FDA's preliminary step to full approval, EUA, was a technology certification that proved vital to the success of OWS in limiting the effect of the pandemic and helping the adult population reach an over 70 percent vaccination rate. As noted, no equivalent certification is available outside the health sector, but its utility suggests that comparable technology certification or validation mechanisms should be considered as the government pursues industrial policy approaches.

Financing: Initiatives for industrial policy may grind to a halt unless financing is available for the technology projects required. There are a variety of financing types that may be appropriate for particular projects, including lending, guaranteed contracts, tax incentives, and procurement for initial market creation. Guaranteed contracts were crucial to OWS's ability to rapidly scale-up vaccine production, for example. The DOE demonstration program relies on authority from DOE's LPO, as do the critical materials and minerals-development efforts called for in the initiative to secure critical domestic technologies and materials (The latter also suggests that the EXIM Bank, which has some $80 billion in lending authority, develop a domestic lending capability to meet domestic manufacturing requirements for these supply needs.

The semiconductor initiative uses ITCs as a financing tool to enable domestic fab and foundry creation. While the Endless Frontier Act does not specify a financing system, a section in the legislation calls for this authority. If advanced manufacturing is to be spurred as a foundational element for industrial policy initiatives, financing for new advanced manufacturing equipment, particularly at small and mid-sized manufacturers, will be needed. Recognizing this gap, Sen. Chris Coons (D-DE) and six colleagues have introduced legislation to create an Industrial Financing Corporation to invest in innovative manufacturing.[85] All these points underscore the importance of financing as a cornerstone of successful industrial policy initiatives.

Procurement: Most of the above mechanisms for implementing industrial policy efforts operate on the supply side in promoting technology development. What about the demand side? Government has an additional tool: its large procurement programs, which can be applied for innovative new products and technologies. If government can act not simply as a technology-development supporter but as an initial market creator, as it frequently does with new defense technologies, then it can help assure scaling and acceptance of new technologies and systems. Federal procurement and programs play a massive role in defense-related and health sectors—the accelerated vaccine procurement effort behind OWS is a good example. The character of demand also shapes the new industrial production processes, and the federal government can use its leverage over demand. For example, while defense production accounts for only a modest portion of total manufacturing output, a surprisingly sizeable proportion of manufacturers rely on some defense contracts. Defense procurement therefore can leverage significant advances in production processes through requirements for its contractor base to adopt advanced manufacturing technologies. Effective use of federal procurement can play a significant role in creating initial markets for new technologies in a number of areas, helping shape the demand that will be key for new technologies to scale.

Flexible contracting mechanisms: These go hand-in-hand with procurement approaches. The DPA provides authority for intervention into manufacturing supply chains to assure rapid production scale-up of critical goods related to national security. This authority proved critical to the success of OWS in rapidly developing and producing vaccines. Application of DPA authority is cited in the initiatives for DOE demonstrations and to secure critical technologies and materials. Another example of flexible contracting authority is the "Other Transactions Authority," developed initially by DARPA to enable rapid contracting outside the cumbersome procedures of standard federal procurement, and then applied by other agencies as well. These and other examples of flexible contracting authority may prove critical to industrial policy approaches, as OWS indicates.

CONCLUSION

While DOD has long operated an industrial policy system with economic interventions at many stages of the innovation process, this is largely a new road for government in the civilian economy. There are, of course, historical precedents, including the programs developed to respond to Japan's development of quality production technologies and processes, development of energy technologies in the 2000s, and the effort to create advanced manufacturing institutes after 2012. But the plethora of new industrial policies proposed in 2020 and 2021 summarized herein is unprecedented. While only some will likely go into effect, these could amount to a fifth and larger-scale period of industrial policy approaches. This report has attempted to catalog them in some detail, and also to delineate key operational mechanisms—in effect, a new supporting infrastructure—that will be required in organizing these approaches to make them fruitful. Industrial policy is a complex process with many actors, and it requires a careful plan, strong foundational programs, and a spirit of enterprise to accomplish it. As the Pentagon has long since discovered, you can't just build the pieces, you have to build the system. This work has attempted not only to review the new programs but to set out the foundational infrastructure they will require.

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