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Encompassing the Innovation Panoply

As US science policy shifts toward a new model intended to stimulate economic growth, the country must create an institutional infrastructure for federal industrial policy.

US policymakers from both parties have long avoided "industrial policy," but a new set of drivers—competition with China, confronting climate change, and the COVID-19 pandemic—is forcing a shift in attitudes. These three challenges amount to a crisis that is likely to induce a major change in US science policy.

Following the Trump administration's vaccine development effort, the Biden administration and Congress have proposed a series of major technology initiatives that are moving the federal government toward what can only be called industrial policy. An injection of more than a hundred billion dollars over the next decade into targeted programs could completely revamp the model of US science policy that has been in place since the end of World War II.

Many high-income nations, including Germany, Japan, Korea, Singapore, and lately China, have long placed bets on industrial policies to accelerate their economic growth. By contrast, the United States, outside its defense and energy sectors, has taken only modest steps, largely aimed at the golden goose of free markets: innovation. Indeed, beyond a history of generous tax breaks to energy companies, civilian industrial policy in the United States has been mostly limited to research and development subsidies and tax incentives. This approach fits with a sense, in both parties, that government intervention should be used only to fix "market failure"—activities such as the provision of national defense or scientific research that, without government support, would not be provided by the private sector at levels considered equal to the national interest. Thus, the new direction of US industrial policy reflects a broader government intervention beyond R&D to support technological development from ideas to markets, including prototype testing, demonstration, and product introduction.

Bush versus Steelman

To understand what industrial policy has done for US innovation, and the transformative steps legislators currently are considering, it is instructive to recall the policy debate that shaped our current research enterprise.

Vannevar Bush is widely considered the architect of American science policy. As President Roosevelt's de facto wartime science advisor, Bush created an integrated innovation system that linked industry, universities, and government agencies around projects that used research to gain an edge on the battlefield. It was textbook industrial policy.

Yet at the war's conclusion, Bush sought to return the reins of innovation to the private sector. In his famous *Science, the Endless Frontier* report, he proposed concentrating federal support on basic research, to be conducted at universities. In practical terms, Bush sought to establish an independent agency, a foundation, to centrally administer all federal research funding.

It is crucial to understand that Bush was no less brilliant an engineer than he was a policy entrepreneur; he grasped the power of simple ideas that captured the imagination of policymakers. His design for the organization of US research was undergirded by a mental model of innovation that Bush himself might have considered a caricature, but that was easy to present, to defend, and to use to garner political buy-in. Today it is known as the linear model of innovation. In Bush's design, the federal government injects funds for research on one end of the innovation pipeline, and after transferring that new knowledge to industry, the private sector shepherds it through subsequent stages of maturity—development, prototyping, testing, demonstration, and product implementation—all the way to

the marketplace. Bush did see, from his industry and military experience, that the transfer of public research to private enterprise would be neither automatic nor unproblematic.

Like all policy proposals, Bush's design met political and practical challenges. His most formidable detractor was John R. Steelman. A professor of sociology and economics at Alabama College, Steelman was recruited in 1934 to the Department of Labor's Conciliation Service and soon became its director. In that position, he helped President Truman resolve disputes with coal miners and railroad labor. In 1946, Steelman became assistant to Truman, a position that in later administrations evolved into the White House chief of staff.

Bush's original proposal was passed by Congress in 1947. However, Truman vetoed the bill, not wanting the new foundation to exist outside control of the executive branch. At the president's behest, Steelman led a group of former New Dealers in producing a four-volume study of federal support for science, a much more comprehensive study than Bush's. The Steelman report proposed much more government involvement and funding for R&D, with far more emphasis on public funds for development. While Steelman placed the proposed funding agency under executive branch control, it was not to be the main actor; other federal agencies would fund development projects in addition to research aligned with their missions.

As the Bush and Steelman designs collided, political forces demanded a resolution, in no small part because science had become an instrument and symbol of hegemony between the Cold War superpowers. The National Science Foundation Act was finally passed in 1950, although the agency didn't receive significant funding until after the Soviet Union's launch of the Sputnik satellite in 1957. Although NSF was the brainchild of Bush, it never became the central hub of federal research he had envisioned. Rather, Steelman's decentralized model, including a modest-sized NSF and other, more generously funded research agencies, set the framework for the US federal research enterprise.

Steelman more than Bush may thus be the true architect of American science policy, except for one thing: Bush's linear model of innovation has remained firmly entrenched in the minds of policymakers. Basic research became the core focus not only at NSF but at other federal civilian science agencies. The linear model's intuitive appeal—that innovation is produced like a car or a toaster, along a conveyor belt of sequential stages—may be why this model continues to inform the role of government in science. It may also have kept policymakers from implementing full-scale industrial R&D policy. That may be about to change under the pressure of today's brewing crisis.

Seventy-five years of piecemeal industrial policy

The US government has purveyed piecemeal industrial policy for at least three-quarters of a century. By far the most significant part of it has been channeled through the national defense apparatus, which built a series of innovation agencies and programs and linked them to follow-on defense procurement investments. Although these investments were justified in the interest of national security, many resulting technologies were "dual use" or "spillovers" that created new sectors in the civilian economy. These include space, nuclear power, computing, and the internet. Arguably, the fountainhead of postwar innovation is the generously subsidized defense innovation system.

Since the end of World War II, industrial policy approaches have occurred within four somewhat discernible periods. The first period firmly established defense industrial policy but did not do the same for civilian industry. The Cold War imbued a sense of national peril in the political class, which rushed to re-erect a formidable national security enterprise. This enterprise needed a technological edge, and, to that end, it included a defense innovation and production system modeled on the war mobilization effort.

Starting around 1950, the military worked to integrate key innovation actors—industry, university, and government—in service of the defense mission. The 1957 Sputnik crisis further accelerated the effort, leading to creation of the National Aeronautics and Space Administration and the Defense Advanced Research Projects Agency (DARPA), both in 1958. The Department of Defense (DOD) had low tolerance for uncertain timelines and outcomes, so it returned to the integrated wartime model, building a system that supported not just research but also development, prototyping, testing, and demonstration. DOD often created the initial market by becoming a major customer. In contrast, the civilian R&D agencies supported research only through early-stage development. This means that the United States has been running two very different innovation systems in parallel: a distributed and disjointed civilian system and an integrated defense system.

The second period was the era of competitiveness with Japan in the 1970s and 1980s. Japan's economy advanced in leaps with the modernization of its industrial production process, the total quality management revolution. Combined with just-in-time inventory and precision machining technologies, Japan seemed poised to outperform the United States in the full range of high-value-added manufactures. Although the United States remained the leading innovator, its industry was comparatively disadvantaged by a lack of government coordination of innovative activities and actors. Evidence of Japan's edge became apparent as its cars and electronics penetrated US markets, and the public and the political class attributed rust belt manufacturing declines to Japanese ascendence. US industry was forced to play catch-up as it climbed the steep learning curve to embrace total quality production.

In that period, the United States launched a series of

Illustration by Shonagh Rae

novel policy attempts to try to help small firms and startups at the cutting edge of technological innovation grow and compete in global markets. These programs included streamlining technology transfer with the Bayh-Dole Act in 1980, which gave universities rights to patents that resulted from federally funded R&D, and the Stevenson-Wydler Act, also in 1980, which introduced similar incentives for federal laboratories. It also included the Manufacturing Extension Partnership to bring new processes to small manufacturers and the Small Business Innovation Research program to support small firms and startups in developing technologies from their research. Other policy initiatives sought to support those businesses seeking to gain a competitive edge via innovation. The programs included the Advanced Technology Program to support technology development at companies; SEMATECH to restore US semiconductor leadership through manufacturing quality and efficiency improvements; and the R&D tax credit to encourage companies to invest in research and development.

A third period, starting around 2001, comprised policy efforts to mitigate climate change through energy innovation at the Department of Energy (DOE). As implemented, the new policy translated into new offices and tasks added to the department rather than modifying its existing functions. The new elements included the Advanced Research Projects Agency-Energy (ARPA-E), expanded renewable energy programs, advanced manufacturing institutes, a Loan Programs Office for new energy technology projects, and Energy Frontier Research Centers. Regulatory programs were also expanded to drive technology shifts.

A fourth period has evolved in recent years around advanced manufacturing. When US manufacturing began relocating production overseas, old industrial towns never fully recovered their lost jobs and status. China arose in a remarkably short period in the early 2000s, displacing the United States in 2011 as the world's largest manufacturer. Simultaneously, US manufacturing experienced a steady decline. Manufacturing employment shrank by one-third between 2000 and 2010, and 60,000 factories closed as production shifted to China and other countries ready both to operate at a fraction of the labor cost and to introduce new efficiencies.

In response, between 2012 and 2017, the federal government created a network of 15 manufacturing innovation institutes (the sixteenth was added in 2020) called Manufacturing USA, supported by DOD, DOE, and the National Institute of Standards and Technology (NIST). Each institute was organized around a particular advanced manufacturing technology, ranging from 3D printing to photonics, digital production, and robotics. While past manufacturing policy focused on trade or tax incentives, the institutes aim to accelerate introduction of productivity-enhancing manufacturing technologies to enable the United States to better compete. They bring together industry and universities, with support from three federal agencies and from state and local governments. The institutes undertake technology R&D, offer shared equipment centers for new technology prototyping and testing, and provide education and workforce development programs.

The success of industrial policies over these four periods has sometimes been mixed. Take, for instance, the industrial policy programs motivated by energy policies: government-funded large-scale energy demonstration projects have a mediocre record. Projects such as the Clinch River Breeder Reactor, the Barstow Solar Power Tower, and two DOE-run synthetic fuel plants faced massive cost overruns because they failed to anticipate collapsing oil prices four decades ago. The projects conveyed only limited technology information to the private sector. In more recent years, there have been unsuccessful large-scale carbon capture and sequestration demonstration projects. The most visible recent setback occurred when DOE made a $535 million loan guarantee to Solyndra in 2011 to scale advanced solar technology. But the new technology could not compete with low-cost, subsidized solar panels put into the US market by Chinese firms, and Solyndra went bankrupt. This highly publicized episode was an embarrassment for industrial policy approaches and it serves, along with these other energy projects, as a useful reminder of their complexity.

The new direction of US industrial policy reflects a broader government intervention beyond R&D to support technological development from ideas to markets, including prototype testing, demonstration, and product introduction.

New industrial policies

A series of new industrial policy efforts is now taking shape. In size and scope, they are dramatically different from previous approaches.

The US government in 2020 abruptly shut down much of the economy to mitigate the impact of the COVID-19 pandemic. To adjust to the pain caused by these shutdown orders, stimulus packages were enacted, flooding the economy with an unprecedented $3 trillion in federal expenditures, with a follow-on $1 trillion infrastructure bill in 2021. The resulting industrial policy consists of a suite of initiatives, some funded through these stimulus actions. They include the following:

Operation Warp Speed (OWS) dramatically accelerated development and distribution of COVID-19 vaccines to within ten months, in contrast to the usual four to ten years required for vaccine development and approvals. Using multiple policy tools and authorities—including guaranteed contracts for production scale-up, flexible government contracting mechanisms, a diversified portfolio approach backing several vaccine technologies, extensive supply chain management, and government-organized transportation delivery systems—OWS delivered vaccines to mass markets in record time. It likely saved countless individuals from illness and untimely death. OWS is an example of industrial policy with unqualified success, a fact that underscores the potential of its approach.

The CHIPS for America Act was passed by Congress with bipartisan support in 2020. A $53 billion appropriation is now pending to finance new fabrication plants and foundries for US chip manufacturing. It will also support research, technology development, and scale-up programs in advanced chip technologies and strengthen manufacturing and production supply chains. The global share of US-produced semiconductor chips has fallen to 12% and, as the technology moves down the nanotechnology scale, US firms have lost technological leadership to Taiwan and Korea.

The Endless Frontier Act (now called the Innovation and Competition Act) passed the Senate in June 2021 and is now in conference with a comparable but narrower bill passed by the House. It creates a new Technology Directorate at NSF with a $29 billion budget for applied R&D in ten key advanced technology areas. The new directorate will fund University Technology Centers, which can include consortia with industry, and will also support testbeds and lab-to-market activities, as well as Regional Innovation Hubs that could help with scaling up technology advances.

Demonstration projects for new energy technologies were included as part of major infrastructure legislation approved in a bipartisan compromise. The projects include carbon management, clean hydrogen, renewable energy, nuclear energy, and critical minerals and materials. In addition to over $20 billion in funding for the demonstrations, the legislation creates a new DOE Office of Clean Energy Demonstrations.

Strengthening domestic supply chains was a focus of a major White House report in June 2021. The report examined four areas—pharmaceuticals and ingredients, advanced batteries, critical minerals, and semiconductors—and made recommendations for new policies as well as funding to secure supply chains in these areas.

These programs all meet a definition of industrial policy because they are governmental interventions beyond research. All face a major challenge of finding public support and political acceptance, and all go well beyond previous efforts presented as fixes for market failures. And while this is clearly new territory for US policymakers, simply bringing such initiatives into existence does not guarantee their success.

A new institutional infrastructure

For these programs to be effective, they will require a network of new supporting and coordinating institutions—a type of institutional infrastructure that the United States has not previously attempted. Past industrial policy approaches outside the defense arena, particularly energy technology demonstrations, have sometimes failed precisely because of missing support institutions.

A review of the supporting infrastructure in defense R&D over the past decades, as well as what has been missing in civilian R&D, makes clear that three broad categories of mechanisms and support systems are needed to ensure an agency's capacity to carry out industrial R&D policy. First, there is a need to build foundations to form strong projects and the talent base to implement them. Second, the country will need infrastructure to scale up these projects. And finally, policy initiatives will need support going forward. Understanding these three categories can help administrators at implementing agencies ensure they have the appropriate capabilities, while enabling them to signal to Congress and the White House that insufficient resources will likely lead to failure.

Foundational elements. The first category of necessary infrastructure contains elements necessary to establish new projects, including connections to research foundations and a talent base. Industrial policy is not only about application; it must also effectively integrate the various tasks of innovation that, contrary to the linear model, are rarely timed sequentially. Ensuring research is plugged into innovation networks will be critical to ongoing and long-term applied efforts. OWS was the beneficiary of vital research work on mRNA and nanolipids that enabled rapid scaling up of vaccine production. Similarly, applied technology advances in semiconductors (per the CHIPS and Endless Frontier Acts) and DOE demonstration programs will require extensive foundational research.

Furthermore, outside of the defense sector, federal R&D and technology agencies typically lack experience in implementing industrial policies. In particular, these agencies lack trained and experienced managers to coordinate integrated portfolios from development to deployment. Program managers currently overseeing civilian research projects have an entirely different job: they judge scientific merit and promise independent from considerations of application and commercial use. In turn, in industrial policy programs, project managers are central nodes of innovation networks, articulating the work and simultaneously coordinating production of knowledge and commercial products. In the current system, program managers are virtuoso pianists; under industrial R&D policy, project managers are orchestra conductors.

For example, the team that created and then led OWS had a wide range of experience and expertise, including from the private sector and across different agencies. Complex DOE demonstration projects are another example, requiring expertise in project management, engineering, and finance. People with bureaucratic know-how and understanding of legal and contracting authorities could also prove vital, as OWS's use of innovative contracting demonstrated. Understanding regional innovation may be key as well, as illustrated by projects called for in the Endless Frontier Act. The point is that these kinds of projects require new skill sets: not simply R&D skills, but a panoply of tech development, tech scale-up, tech financing, and tech production skills. Outside DOD, this talent base is not in place, and it would have to be trained promptly to support the new programs.

Scaling up. The second category of infrastructure enables agencies to scale up efforts to bring R&D out of the research stage to develop prototypes, verify technology, determine how to manufacture the product, and see where it fits into supply chains. In contrast to the foundational efforts, all scaling efforts must be integrated tightly with the private sector; none are like the famed Manhattan or Apollo projects with the government as the sole customer. Therefore, all will need strong public-private partnerships that open up markets.

Again, OWS provides a good example of close integration of the government with private sector vaccine makers, to the point at which government personnel were located at firms to speed regulatory understanding and review. To succeed, industry partners must be actively engaged and committed. Industry leadership is thus a significant aspect of successful industrial policy: pending legislation needs not only the buy-in of politicos but of industrial and financial leaders as well.

One of the first steps to scaling requires testing and demonstration to produce working prototypes. DOD, with its long-standing industrial policy approaches, builds testing and demonstration into its technology development programs, but civilian agencies often do not. Testing and demonstration are also crucial to commercialization. Firms and users will not be interested in a technology unless it is tested and proven. Testing and demonstration capability at DOE, for example, will be critical for the development and adoption of new battery, advanced nuclear, and renewable technologies, as well as industrial carbon capture and sequestration and carbon dioxide removal technologies. Testing and demonstration are built into the Endless Frontier Act, but their effective implementation should not be assumed.

Although the health science sector has a technology certification procedure through the Food and Drug Administration (FDA) approval process, there is no formal and fully accepted process for validating other technology. However, this mechanism is a very powerful innovation tool: FDA approval guarantees immediate market acceptance. FDA's preliminary step to full approval, emergency use authorization, was a technology certification that proved vital to the success of OWS in limiting the pandemic's effect, helping the adult population reach a vaccination rate of over 70%. 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.

A particular weakness in most industrial policy programs is the lack of manufacturing integration. The new industrial policy must interface with national manufacturing, or innovation will suffer from supply chain insecurity. This is particularly hard given that US manufacturing productivity rates have fallen to historically low levels over the last 15 years, with plant and equipment investments declining in parallel. It's a catch-22 situation: industrial policy gives innovation a push with the intention of reinvigorating US manufacturing, but a vibrant manufacturing sector is the necessary pull for research-based innovation.

Building more supporting infrastructure is necessary in part because government-financed R&D will not be taken up by a still-depressed manufacturing sector. The government needs to boost manufactures to give its R&D programs a chance to succeed, but boosting manufactures is best done via innovation in production processes and technologies. What's more, while these initiatives focus on implementing advanced technologies, the United States is running a $191 billion (and growing) trade deficit in advanced technology goods. This imbalance suggests that the proposed advanced industrial policy for R&D programs will only achieve partial success domestically, with the residual effect realized in overseas manufactures. Consequently, renewed focus on manufacturing is critical for industrial policy to have its desired effect on the US economy.

Enhancing the US innovation system via industrial policy also means integrating it, bridging gaps between its actors, and establishing redundant routes to build supply chain resilience. Within such efforts, mapping supply chains itself seems a vital task for policy success. Such a mapping was pivotal to the success of OWS. It is already proving central to the effort to secure domestic supply chains for critical technologies and materials, and it will be required in semiconductors and for technologies targeted by the Endless Frontier Act.

Support. Initiatives for industrial policy may grind to a halt unless financing is available for scaling up technology projects. A variety of financing mechanisms may be appropriate for different projects, including lending, guaranteed contracts, tax incentives, and procurement contracts for initial market creation.

Guaranteed contracts were crucial to OWS's ability to rapidly scale up vaccine production. The DOE demonstration program relies on authority from DOE's Loan Programs Office, as do the critical materials- and minerals-development efforts called for in the initiative to secure critical domestic technologies and materials. The semiconductor initiative uses investment tax credits as a financing tool to enable domestic fabrication plant 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. All these points underscore the importance of financing as a cornerstone of successful industrial policy initiatives. Creating a banking institution comparable to the Export-Import Bank for domestic manufacturing, with the private sector fully sharing the risk, may facilitate such financing.

The government cannot simply act as a technology development supporter. It must be an initial market creator, as it frequently is with new defense technologies, helping new technologies reach commercial feasibility scale. Federal procurement plays a massive role in the defense and health sectors: the accelerated vaccine procurement effort in OWS is a good recent example. The federal government can also apply its leverage over demand. For example, although defense production accounts for only a modest portion of total manufacturing output, a surprisingly sizeable proportion of manufacturers pursue (and obtain) defense contracts. Defense procurement could, in principle, require its contractors to adopt advanced manufacturing technologies by which they would help improve production efficiency and drive down federal costs. Effective use of federal procurement can also 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 go hand in hand with procurement approaches. The Defense Production Act, for example, provides authority for intervention into manufacturing supply chains to ensure the sufficient supply of goods critical to national security. This authority proved instrumental to the success of OWS in rapidly developing and producing vaccines. Application of this act 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 circumvent the lengthy standard federal procurement process and since applied by other agencies as well. These and other examples of flexible contracting authority could be key factors in the success of pending industrial policy.

The task ahead

The United States has been undertaking industrial policy projects in the defense sector for a long time, and advances in aviation, space, nuclear power, computing, and the internet owe their inception largely to those policy efforts. On the civilian side, the government has been gradually undertaking more such policies in areas such as energy and manufacturing.

As a new industrial policy accelerates in response to the series of initiatives proposed by the Biden administration and Congress, we must change not only policy and outcomes, but also the way we conceive of the innovation system itself. The new policies are geared toward integrating the innovation system not as a linear production chain but as a network of interacting economic agents taking differentiated tasks of innovation beyond prescribed sequences. This has been called a "systems of innovation" approach, in contrast to Vannevar Bush's linear view of innovation as a conveyor belt. This new approach is a multidirectional system, not a one-way street, where technology development influences R&D as well as vice versa.

The new wave of industrial policy implies we must understand innovation in a more dynamic way, in terms of its components, flows, organizations, and underlying policies. In consequence, the proposed policy instruments target barriers and bottlenecks in innovation flows, with agencies engaging in "boundary spanning" to broker connections and implement solutions beyond their traditional jurisdictions. This will not be enough. We have long thought R&D was innovation, but we need to expand our perspective to encompass the full innovation panoply, from development through production and application. A concerted effort to build an institutional infrastructure to support industrial policy will be needed.

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RECOMMENDED READING

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"The Next 75 Years of Science Policy" has been made possible through the generous support of The Kavli Foundation.