RECLAIMING AMERICA'S LEADERSHIP IN ADVANCED MANUFACTURING

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MForesight: Alliance for Manufacturing Foresight serves as the voice of the national advanced manufacturing community, providing government, academia and industry with information and insights about emerging technologies, cross-cutting challenges, workforce training, and opportunities for public-private partnerships that strengthen U.S. competitiveness. MForesight is funded by the National Science Foundation (NSF) and the National Institute for Standards and Technology (NIST).

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Foreword

This report is a complement to MForesight's 2018 work, Manufacturing Prosperity: A Bold Strategy for Wealth and Security. Based on input from the national manufacturing community at multiple roundtable discussions held around the country, *Manufacturing Prosperity*, identified specific challenges facing U.S. manufacturing and recommended bold solutions. The response to that report and discussions and developments in the year since its publication prompted the current volume. For example, analysis of the defense industrial base by the Department of Defense in response to Executive Order 13806, the release by the NSTC of, “Strategy for American Leadership in Advanced Manufacturing,” and NIST’s Green Paper, “Return on Investment Initiative for Unleashing American Innovation,” all released in the past year, addressed issues in the U.S. manufacturing sector and proposed steps to strengthen both defense and civilian manufacturing. With this additional context, this report strives to highlight concerning patterns of performance in U.S. manufacturing, such as the alarming lack of productivity growth, and opportunities that demand greater attention to build the industries of the future.

Like its predecessor, this MForesight report identifies fundamental weaknesses in U.S. manufacturing and the risks these weaknesses pose for long-term wealth and security. It emphasizes the need for concerted national action to rebuild and restore manufacturing skills, capabilities, and productive capacity. The problems have developed over decades but have become worse with time, now reaching the point where we have lost the ability to scale emerging technologies because of a weak industrial commons, lost supply chains, and lost production knowledge.

The implications for the country are profound. Despite spending roughly $150 billion on science and technology, the nation had a record trade deficit in manufactured goods of nearly $900 billion and a deficit in advanced technology products of more than $125 billion in 2018. Filling the gaps in our innovation pipeline could convert the results of this large R&D investment to high-value products that will capture domestic and global markets. One such gap is investment in translational R&D, the applied engineering research necessary to advance technology and manufacturing readiness levels. High-wage, advanced economies such as Japan, German, and South Korea, spend 3-8 times as much as the United States on translational research, and maintain trade surpluses in manufactured products.

Solutions will require long-term, substantial, coordinated government action to support the private sector in rebuilding the national innovation ecosystem for hardware. Just spending more on the same programs is unlikely to yield different results. The United States needs a strategic, coordinated, and comprehensive approach that mobilizes both public and private resources to restore U.S. manufacturing competitiveness. The areas that need strengthening—translational research, training and skill development, increased investment capital for hardware start-ups, and support for small and medium-sized manufacturers—were outlined in*Manufacturing Prosperity* and again here. We refer to this comprehensive national effort as a National Manufacturing Initiative. How this Initiative is implemented should be determined by policymakers. Our objective is to reinforce national understanding of the challenges facing U.S. manufacturing, the solutions proposed by the manufacturing community, the nation’s waning ability to generate wealth from its massive investment in research and development, and, most importantly, to motivate the needed bold action. Competitors are not standing still. The onus to act is still on us.

RECLAIMING AMERICA'S LEADERSHIP IN ADVANCED MANUFACTURING

In 2018, MForesight documented the challenges facing U.S. manufacturing as decades of globalization have resulted in serious losses of production capacity, gaps in manufacturing know-how, and growing dependence on foreign producers for advanced technology products. Driven by short-term profit U.S. manufacturers adopted a strategy of "invent here, make there." For individual companies, this strategy has been wildly successful, but for the nation's ability to maintain a strong, diverse manufacturing sector and a defense industrial base free of critical foreign dependencies, the strategy has been extremely damaging. **In many respects, with the exception of aerospace, the United States is no longer an advanced manufacturing economy, focused more on mid-tier industries than the advanced, high-technology sectors needed to maintain high living standards and superior military capabilities.** Even worse, many U.S. manufacturers have discovered that domestic capabilities have eroded to the extent that "invent here, manufacture there" has become "invent there, manufacture there."

The United States must take bold steps to rebuild its capabilities and production capacity in advanced manufacturing to reinvigorate wealth creation and strengthen the defense industrial base across all tiers of the supply chain. Rebuilding the national innovation ecosystem in hardware will be a complex and long-term undertaking, but the nation has no choice if the United States is to reclaim its leadership in advanced manufacturing.

To focus resources on this critical national need, the federal government should implement the necessary structural and budgetary steps that will mobilize and augment existing programs and create new ones to fill gaps. Consider these efforts a National Manufacturing Initiative (NMI), a term to capture the substantial, coordinated, long-term government action needed to support the private sector to restore high-value manufacturing in the United States. Specifically, this NMI would:

1. **Invest in translational research and manufacturing innovation,**
2. **Encourage domestic pilot production and scale-up,**
3. **Empower small and medium-sized manufacturers to deploy advanced technologies, and**
4. **Grow domestic engineering and technical talent.**

Positive national impacts will justify the needed investments. The United States will:

1. **Regain foundational manufacturing capabilities,**
2. **Ensure a return on federal investments in R&D,**
3. **Capitalize on technology changes broadly affecting manufacturing,**
4. **Establish leadership in new industries of the future, and**
5. **Restore the broad-based supplier networks that are essential to economic and national security.**

Creating a National Manufacturing Initiative is a necessary step, one commensurate with the importance of manufacturing to long-term national wealth and security. If supported financially and managed effectively, the result will be a manufacturing sector that produces high-value defense, industrial, and consumer products with broad-based supply chains, diverse industrial clusters, and the foundational support for high-paying services that depend on strong manufacturing.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

"If high tech is to sustain a scale of activity sufficient to matter to the prosperity of our economy and not shrink down to a marginal research activity, America must control the production of those high-tech products it invents and designs…. production is where the lion's share of the value added is realized....High tech gravitates toward the state-of-the-art producers.[1]

– Manufacturing Matters, 1987

U.S. manufacturing competitiveness has been debated since the 1980s. Although significant changes have occurred in both the national and international economies, most importantly the rise of the internet and the explosive growth of China, the concerns raised in *Manufacturing Matters* and other analyses 30 years ago have largely come to pass. Offshoring production in broad swathes of manufacturing, not just labor-intensive industries such as apparel but also computers and telecommunications, consumer electronics, industrial equipment, and many other sectors, has resulted in the loss of over 5 million manufacturing jobs and a large drop in the number of U.S. factories in the last two decades. Offshoring has been so successful, at least in financial terms, that conventional wisdom holds that manufacturing should be done in China. It's cheaper, quicker, more flexible, and more effective as the community of Chinese suppliers, engineers, and production experts has expanded, much of it as a result of American offshoring. Instead of manufacturing, so the argument goes, the United States should embrace its "post-industrial economy" and focus on research, software, and finance while offshoring production.

Over time the real national costs of this strategy have become apparent and, to a great extent, evolved just as predicted in the 1980s. First, offshoring of parts, assemblies, and final production has worked well for large multinational companies driven by quarterly financial performance, but has devastated the small and medium-size manufacturers (SMMs) that comprise the nation's supply chains and are the foundations of geographically dispersed industrial clusters. While the share of SMMs in the total population of U.S. manufacturers has risen, their absolute numbers have dropped by nearly 100,000 since the 1990s. Second, as Cohen and Zysman predicted, innovation in manufacturing gravitates to where the factories are. U.S. manufacturers have learned that the applied research and engineering needed for new product introductions, design enhancements, and production process improvements are best done near factories. As more engineering and design work shifted offshore, many U.S. companies lost their capability to perform those tasks here. Besides, Chinese engineers are cheaper, thereby extending the shift of value-adding activities offshore to reduce costs. Over time, "invent here, make there" has become "invent there, make there."

The impact on U.S. national capabilities has been profound, and may finally be receiving long-deserved attention. Recent analyses of the defense industrial base have identified specific risks to weapons production—fragile domestic suppliers, dependence on imports, counterfeit parts, and material shortages, for example.[2] In commercial sectors, manufacturing imports continue to set records, despite recent tariffs. Dependence on imports has virtually eliminated the nation's ability to manufacture large flat screen displays and next-generation flexible displays, smartphones, advanced materials, and packaged semiconductors. Perhaps most importantly, the loss of production capabilities in advanced industries has severely diminished the nation's ability to manufacture the results of its large investments in research and development (R&D). Without that ability, the United States is failing to generate sufficient return on that R&D investment, failing to generate the wealth that invention should create, and effectively subsidizing R&D for foreign competitors.

1. Stephen Cohen and John Zysman, *Manufacturing Matters: The Myth of the Post-Industrial Economy*, New York: Basic Books, 1987, p. 8.
2. U.S. Department of Defense, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," Report to President Donald J. Trump by the Interagency Task Force in Fulfillment of Executive Order 13806, September 2018.

Technological innovation is distinctly different from both scientific **discovery** and engineering **invention.** Innovation is about transforming a promising discovery or an invention into a new product or process at scale to meet societal needs through world-class engineering and manufacturing know-how. It is not sufficient to excel at basic research. To create wealth and support national security, the United States must innovate. Otherwise, the federal government's large investments in R&D are simply subsidizing R&D for other countries that manufacture and make profits from the results. Foreign companies and governments are aggressively targeting U.S. intellectual property (IP), not only through forced technology transfer and industrial espionage, but also through generous licensing agreements and company buy-outs. In too many cases, competing offers from American licensees and investors cannot match the attractive terms offered by foreigners. The costs to the U.S. economy are significant.

Some policymakers will argue that the United States remains a large manufacturer and that these concerns are overblown. A closer look, however, reveals serious weaknesses. For instance, manufacturing output as a share of GDP was actually somewhat lower in mid-2018 than during the recession in 2009. Recovery since the recession has mostly been in just a few industries: transportation equipment, food, and fabricated metals. Productivity growth, a key indicator of competitiveness, has been falling since 2005 and now is close to zero. Meanwhile, the gap between finished goods prices and Chinese import prices continues to widen. **In many respects, with the exception of aerospace, the United States is no longer an advanced manufacturing economy, focused more on mid-tier industries than the advanced, high-technology sectors needed to maintain high living standards and superior military capabilities.**

Clearly, continuing on the current path is not sustainable, at least if the United States intends to remain an advanced economy. Government action is needed that will shift these long-term trends. Past initiatives, such as the Hollings Manufacturing Extension Partnership (MEP), various Department of Defense (DoD) programs, Manufacturing USA institutes, and the National Science Foundation's (NSF) Engineering Research Centers, have all made—and continue to make—a contribution, but have been insufficient to arrest the long-term negative trends. Most recent programs, such as the Department of Energy's Technology Commercialization Fund and DoD's Defense Innovation Unit, nibble the edges of the problem. All of the existing programs are scattered across multiple federal agencies, none of which have U.S. manufacturing competitiveness as their core mission. Recent history has proven that this approach does not work. If, as a nation, we finally recognize that manufacturing matters, then we need to take bold steps commensurate with its importance. Strategic, significant, coordinated, and sustained government action is essential to rebuild the industrial commons, restore lost capacity to innovate, and strengthen the capacity to manufacture at scale so the nation can establish and lead the industries of the future. Although the mechanics of implementation can take many forms, best determined by policymakers, the overall effort can be considered a National Manufacturing Initiative (NMI) that sets rebuilding U.S. manufacturing as a national imperative.

Establish a National Manufacturing Initiative

Just as the creation of NSF indicated strong national support for science and provided a clear mechanism to support basic research, the federal government should provide similar focus to advances in manufacturing and hardware innovations. Through a combination of strategic agency coordination, modification and augmentation of existing programs, and creation of new programs as needed, an NMI will provide a renewed national emphasis on manufacturing. Similar in concept to but more ambitious than other federal initiatives, such as the National Robotics Initiative and the National Nanotechnology Initiative, the NMI would engage the entire federal government. Specific aspects would include:

1. Fund Translational Research: The United States must ensure that breakthroughs in research are commercialized and manufactured here. Additional funding for translational research is needed to advance both technology and manufacturing readiness levels (TRLs and MRLs). Too many research results languish as prototypes in academic and national laboratories, or worse, are commercialized abroad. The NMI would include the resources needed to create a series of **Translational Research Centers** (TRCs), strictly focused on advancing TRLs and MRLs, that would continue development of research results to increase the flow of commercial products produced here. The TRCs would be based at, though separate from, research universities, would be structured as public-private partnerships, and would be subject to clear metrics used to gage success and eligibility for continued funding. The TRCs would also have the flexibility to generate financial benefit from supported technologies that are successfully commercialized, either through equity stakes in start-up companies, sharing of licensing income, or some other mechanism.

2. Fund Applied R&D and Technical Training: To recover and upgrade technical know-how lost to offshoring, the NMI would provide increased funds for both engineering and manufacturing R&D, as well as technical training on foundational industrial capabilities and technical issues common to multiple industrial applications. Examples include application of machine intelligence in varied production environments, cybersecurity, use of technology to decrease environmental impacts, and both production and implementation of multiple technologies needed to address other national priorities.

3. Create Manufacturing Investment Funds: The NMI would mobilize resources to form public-private partnerships to create investment funds that would raise the availability of capital for hardware start-ups. These funds would fill a gap in the venture capital markets and allow hardware start-ups to scale production in this country beyond pilot plants. They would complement the technical support provided by the TRCs with financial investments to rapidly increase the number and likely success of hardware start-ups. The current Small Business Investment Company (SBIC) program in the Small Business Administration could be one method to create these funds. Several states already have small funds that could serve as models. State investment banks, commonly used in Europe, could also provide insights.

4. Strengthen Support for SMMs: Significantly more financial and technical support is needed for SMMs to rebuild domestic supply chains and strengthen manufacturing clusters. In particular, SMMs need help to accelerate their implementation of smart manufacturing technologies and to access the skills required to utilize these technologies effectively. A combination of technical assistance and financial support, in the form of loans, grants, loan guarantees, and tax incentives, would be included in the NMI, augmenting the work of existing programs such as the MEP and technical assistance offered by DoE's national laboratories.

Funding and Implementation

As previously documented in *Manufacturing Prosperity*, the national manufacturing community strongly supports these multiple elements of a National Manufacturing Initiative. The argument for an NMI is not based solely on the need for greater funding for translational research and the other priority areas listed above, but also as a national rallying point for the public and private action needed to rebuild advanced manufacturing in the United States. Effective implementation will be critical. Achieving the desired outcomes will require cooperation between public, private, and academic resources; coordination across existing government agencies and programs; clear metrics to determine effective use of funds, replicate successes, and implement course corrections; and strong leadership to maintain national focus. The NMI would become the touchstone for the strategic goal of restoring U.S. manufacturing competitiveness, regardless of the legal and administrative mechanisms chosen to implement it.

With its mission focused on holistic rebuilding of national manufacturing capabilities, the NMI should be funded commensurately. At least 5 percent of total federal S&T funding is appropriate. This amount would still be less than competing nations, such as Germany, Japan, and South Korea, that spend 7-30 percent of their federal S&T budgets on translational research. To put this in perspective, **the U.S. Intellectual Property (IP) Commission has estimated that the cost to the U.S. economy of IP theft, counterfeit goods, and pirated software by Chinese actors could be nearly $2 billion per day!**[3] It is important to note that this NMI budget should be additional funding without taking funds away from basic research, which is critical to national competitiveness.

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3. White House Office of Trade and Manufacturing Policy, "How China's Economic Aggression Threatens the Technology and Intellectual Property the United States and the World," June 2018, p. 5.

A start-up period would be needed to establish an effective operational model that includes not only administrative structures and talent, but also draws in experienced engineers and business leaders. These experts would engage with researchers to identify promising technologies, design and conduct the necessary translational research, and build the financial, legal, and technical mechanisms needed to establish production at U.S.-based factories.

Although funds are needed for fellowships, loan guarantees, and support services, the majority of funds should be used for funding engineering and manufacturing R&D, to bridge the gap between research and manufacturing, and to make needed advances in technology and manufacturing readiness that will reduce the risk of commercialization to domestic manufacturers. The NMI would engage multiple federal S&T agencies to maximize the impact of funding by setting technology priorities, maturing promising product and process technologies, accessing relevant expertise, and leveraging procurement opportunities to meet defense mission requirements and other national priorities. (See Figure 15 on p. 33.) In addition to the S&T agencies, the NMI would also engage with other agencies that provide key services to manufacturers, such as the International Trade Administration and the MEP.

With the overall objective to strengthen foundational manufacturing and to advance full-scale manufacturing in the United States of new hardware technologies emerging from federally funded R&D, metrics should be devised to determine progress toward meeting those objectives. Metrics to consider include the number of technologies successfully reaching commercial-scale production; private sector job creation; new manufacturing facilities built in the United States; domestic availability of critical defense technologies; exports of advanced hardware technologies; and return on investment for both public and private stakeholders. Consistent tracking of metrics will allow for timely assessments and course corrections to ensure that the NMI remains focused on the success of U.S. manufacturing and NMI funds provide a return on investment to taxpayers.

The NMI would provide a focal point for the federal government's efforts to strengthen civilian manufacturing, a necessary condition for strong defense production. DoD would work within the framework of the NMI to support translational research in technologies important to defense. The NMI would also facilitate connections between hardware start-ups and other federal agencies, especially the DoD, to leverage federal purchasing power as a lead customer. Government purchase orders can be used by new manufacturers to get financing for plant and equipment to scale production.

The most important aspect of any actions supported by the NMI would be intense focus on the success of domestic manufacturing. Procedures should be implemented to limit the possibility that the technologies, products, and processes supported through the NMI leak to foreign competitors. After all, the guiding mission of the NMI is to coordinate national resources to strengthen domestic manufacturing and to build the industries of the future in the United States.

Finally, if managed appropriately in collaboration and partnership with the private sector, the NMI should accelerate technology commercialization and domestic production without the specter of "picking winners and losers." Government has played an indispensable role in American industrial development throughout history. Government mandates in areas such as emissions control and vehicle safety, government mission priorities in space and defense, and long-term technical support in agriculture and electronics are all ways that the U.S. government has supported industrial development and global leadership. In fact, the leading U.S. manufactured exports are aircraft and weapons, two areas with significant government R&D investment.[4]

Establishing a National Manufacturing Initiative is commensurate with the importance of manufacturing to long-term national wealth and security. By leveraging the discoveries and inventions emerging from existing R&D programs with a commitment to strategic, sustained investment in manufacturing, the NMI would help to establish the hardware industries of the future in the United States. The result will be a manufacturing sector that produces high-value defense, industrial, and consumer products with broad-based supply chains, diverse industrial clusters, and the foundational support for high-paying services that depend on strong manufacturing.

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4. Between 2013 and 2017, the U.S. accounted for 34% of global arms exports. See: https://www.graphicnews.com/en/pages/38243/MILITARY-Sales-of-U.S.-weapons-soar

CHAPTER 1
CURRENT STATUS OF U.S. MANUFACTURING

U.S. manufacturing competitiveness has been part of the national debate since the 1980s. Back then, Japan posed the biggest challenge, as Japanese cars, machine tools, and consumer electronics rapidly built U.S. and global market share. But large investments by Japanese firms in U.S. production capacity and the widespread adoption by U.S. companies of Japanese production techniques embodied in lean manufacturing fended off the challenge.

Today, the challenger is China, but the nature of the challenge is far more complex than the comparatively straightforward competition from Japan. For more than 20 years, China has been the preferred location for U.S. manufacturers moving offshore to reduce production costs. Especially in the 1990s and early 2000s, China was not considered to be a competitor but an extension of U.S. production capacity, an integral part of many American firms' manufacturing strategy. U.S. firms took advantage of China's low wages and lax regulations to cut production costs drastically, first on relatively low-value, low-technology products, but eventually on more high-technology products and components, especially in electronics. The loss of 5 million manufacturing jobs in the last two decades is primarily due to offshoring and the increase in imports from China, not automation.[5]

This strategy has been so successful that **conventional wisdom among many American managers and investors holds that manufacturing is best done in China**—it's cheaper, more flexible, and more effective as the community of suppliers, engineers, designers, and production experts has expanded. In many industries, this set of resources—a broad-based industrial commons—is simply no longer available in the United States, forcing companies to produce in China. This situation has been widely accepted and frequently drives investment decisions and strategy. To maximize profits, U.S. companies should focus on innovation while producing those innovations offshore: invent here, make there.

As MForesight previously documented in *Manufacturing Prosperity*,[6] this massive shift of production capacity by American firms to China has continued up the value chain. With production facilities in China, manufacturers realized that engineering of production processes for new product introductions, design enhancements, or efficiency gains was best done near the factory. As more engineering and design work shifted to China, many U.S. companies have diminished capability to perform those tasks here. Besides, Chinese engineers are cheaper, thereby extending the shift of value-adding activities offshore to reduce costs.

5. D. Autor, D. Dorn, and G. Hanson, "The China Shock: Learning from Labor Market Adjustment to Large Changes in Trade," Cambridge, MA: National Bureau of Economic Research, Working Paper 21906, January, 2016, and S. Andes and M. Muro, "Don't Blame the Robots for Lost Manufacturing Jobs," Washington: Brookings Institute, April 29, 2015 at https://www.brookings.edu/blog/the-avenue/2015/04/29/dont-blame-the-robots-for-lost-manufacturing-jobs/
6. Sridhar Kota and Thomas Mahoney, *Manufacturing Prosperity: A Bold Strategy for National Wealth and Security*, MForesight, June 2018.

In recent years, this cost-cutting process has progressed to include invention and innovation, driven by research and development (R&D) that U.S. manufacturers increasingly do in China, and thereby encompassing the entire value chain.[7]

Old assumptions that the United States would specialize in high-value industries and activities, and continue to move up the value chain over time, have proven false as more and more high-technology, R&D-intensive industries are offshored to China. By some estimates, the share of manufacturing value added contributed by high-technology industries in the United States is only a little more than half, compared to nearly 70 percent for Germany and South Korea.[8]

The situation is exacerbated by the rapid advances of indigenous Chinese firms and by China's remarkable progress in science and engineering. For all of these reasons—lost industrial commons in the United States, offshoring of high-technology industries, advances in Chinese science and engineering capabilities, and the cost-cutting focus of American industry—the old paradigm of "invent here, make there" has increasingly become "invent there, make there."

The ramifications of this fundamental shift, not only in production capacity but also in skills and capability, may finally be recognized by both public and private decision makers. In national security, the recent report by the Department of Defense (DoD) in response to Executive Order 13806 identified multiple specific cases of critical defense technology that is dependent on foreign producers or, in too many cases, few and fragile producers in the United States. Examples include solar cells, flat-panel aircraft displays, printed circuit boards, and semiconductors.[9]

In commercial production, the negative ramifications of massive offshoring—on communities, supply chains, and innovative capacity—are being recognized across the economy. The challenge posed by China to the technological innovation and intellectual property of the United States has been recognized at the highest levels of the U.S. government.[10]

The situation has been building for many years, but it may have finally reached the tipping point that demands the political will to do something about it. Fortunately, a number of factors are aligning to create opportunities to rebuild American manufacturing, engineering, and innovation. First, at more than $150 billion, the United States continues to lead the world in R&D spending, creating a rich supply of inventions and potential innovations that can form the basis of new wealth creation. Second, application of digital technologies to production—referred to as Industry 4.0, smart manufacturing, or the industrial internet of things (IIoT)—creates opportunities to vastly improve efficiency and gain competitive advantage through local, distributed production of customized products. Third, new production technologies, including but not limited to pervasive automation, will eliminate any remaining cost advantages from low-wage labor, provide difficult-to-copy competitive advantage, and create the potential for the United States to regain global market share in a wide variety of industries.[11]

Finally, with wise policies and investment decisions, both public and private, the United States can take advantage of its strong R&D capabilities to create industries of the future with production anchored in this country.

Taking advantage of these opportunities will require a focused national strategy dedicated to restoring the nation's manufacturing strength. Although a tax regime that is internationally competitive is necessary, as are the steps being taken to ensure fair trading relationships and effective protection of intellectual property, these are not sufficient to reverse decades of

7. From 1997 to 2016, R&D performed abroad by foreign affiliates of U.S. parent companies more than tripled to over $53 billion. Although Europe accounted for 58 percent of that total, R&D in China (including Hong Kong) increased 31-fold during this time to surpass Japan. Source: NSF, S&E Indicators, 2018 and https://apps.bea.gov/iTable/iTable.cfm?ReqID=2&step=1

8. J. Wubbeke, et. al. *Made in China 2025: The Making of a High-Tech Superpower and Consequences for Industrial Countries*, Mercator Institute for China Studies, December 2016. x https://www.merics.org/sites/default/files/2018-07/MPOC_No.2_MadeinChina2025_web.pdf

9. "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," U.S. Department of Defense, September 2018, p. 41.

10. "How China's Economic Aggression Threatens the Technologies and Intellectual Property of the United States and the World," White House Office of Trade and Manufacturing Policy, June 2018.

11. McKinsey estimates that only about 18 percent of global goods trade is now driven by labor-cost arbitrage. See, https://www.mckinsey.com/featured-insights/innovation-and-growth/globalization-in-transition-the-future-of-trade-and-value-chains?cid=other-eml-nsl-mip-mck&hlkid=0c-823927be10461681597b702d11f4a6&hctky=10424165&hdpid=061101a9-35af-42ab-9f48-92747f862bb6

offshoring. Cost differentials remain daunting, at least in some industries. Worse, decades of offshoring have left gaps in supply chains, engineering talent and production skills, machinery and infrastructure, skill availability, and process know-how. Filling these gaps and rebuilding a broad-based competitive manufacturing sector will require clear assessment of existing incentives, business practices, and national priorities in areas such as research, education, and investment that created the current dilemma in the first place. **Most of all, decision makers, both public and private, need to focus on the long-term competitiveness of manufacturing, in products and industries of the future, not recapturing lost industries of the past.**

Specific actions for positive change, however, require clear understanding of the current status and recent history of U.S. manufacturing, patterns of research spending and technology transfer, trends in skill availability and workforce training, and other critical factors that will make or break the long-term success of the U.S. manufacturing sector. Many recent reports have documented troubling trends in the domestic manufacturing sector.

Obviously, national statistics provide a broad picture of the state of industry and cannot account for individual companies, or even regions, that continue to thrive. Recognizing that superior manufacturers have found success in the global market does not avoid the unmistakable conclusion that U.S. manufacturing has performed poorly in recent decades, creating what McKinsey has called "the lost decades."[12]

To illustrate, consider:

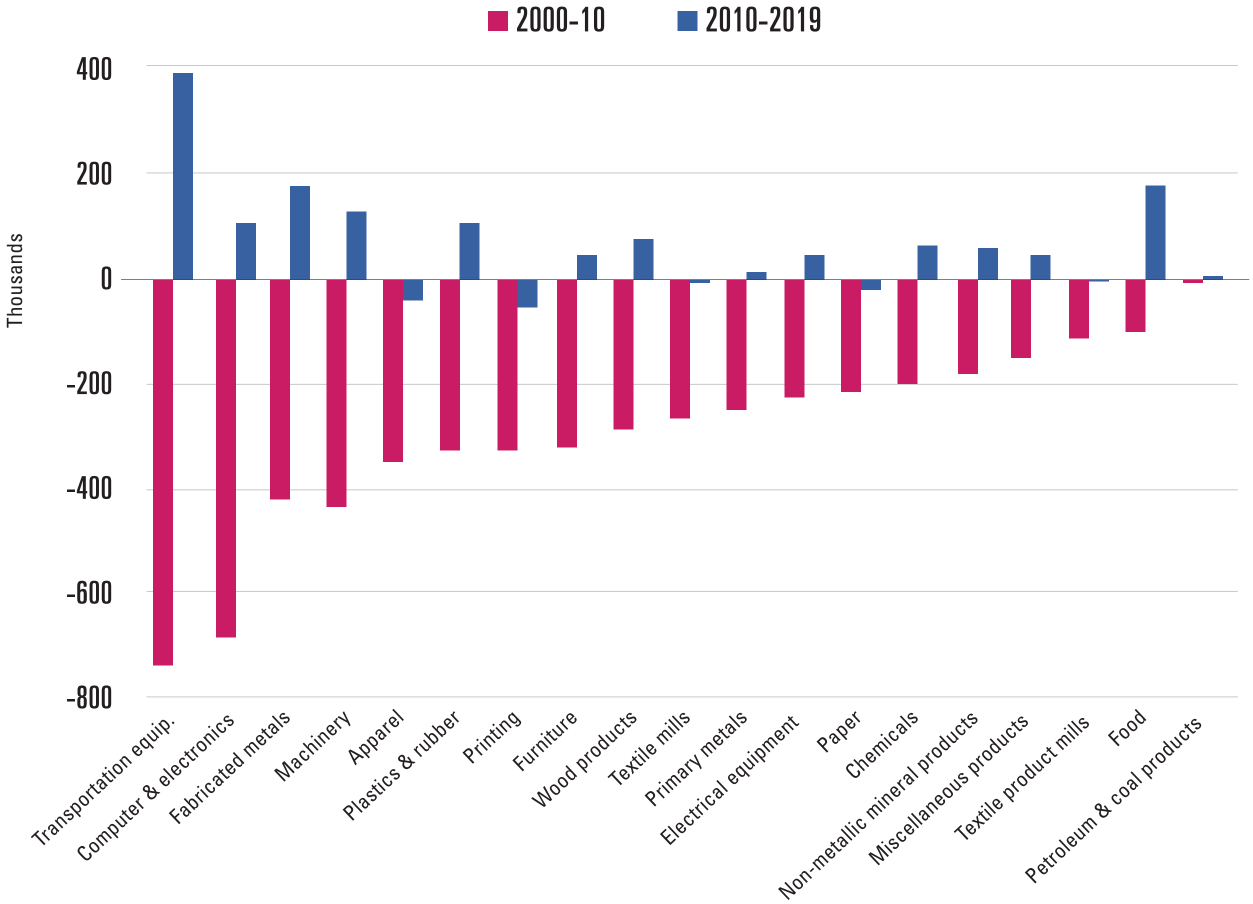
- Manufacturing output as a share of GDP was 11.4 percent in mid-2018, somewhat lower than 11.7 percent during the Great Recession in 2009.

- In 2016, the largest manufacturing industries by output were transportation equipment (18 percent), chemicals (13 percent), food (13 percent), and petroleum and coal products (11 percent). Industries typically considered to be high-technology or advanced comprise a small proportion of national output: computers/peripheral equipment (1 percent), communications equipment (1 percent), medical equipment (2 percent), semiconductors (2 percent), engines/turbines/power transmission (1 percent), industrial machinery (1 percent), and electrical equipment (1 percent). The major advanced manufacturing industry is aerospace (4 percent),[13] which is one of the high-priority industries identified in China 2025 and has been aggressively pursued by China through acquisition of multiple U.S. aerospace firms and large state investments in its domestic civilian aircraft industry.[14]

- At the end of 2018, manufacturing employment was 12.8 million, a 34 percent drop from its peak, but at least an increase of 1.4 million since the end of the Great Recession in 2010. Multiple studies have indicated that this employment drop has primarily been caused by offshoring and a surge in manufactured imports, not automation.[15] Although the loss of manufacturing jobs between 2000 and 2010 was distributed broadly across industries, the gains since 2010 have been concentrated in relatively few industries, mostly transportation equipment, food and beverages, and fabricated metals (Figure 1).[16]

12. McKinsey Global Institute. "Making it in America: Revitalizing U.S. Manufacturing." November 2017.
13. Bureau of Labor Statistics. Note that aerospace products are included in transportation equipment.
14. U.S. Senate Committee on Small Business and Entrepreneurship, "China 2025 and the Future of American Industry," February 2019, p. 25.
15. D. Autor, D. Dorn, and G. Hanson, op. cit.

Figure 1: Net Change in U.S. Manufacturing Employment

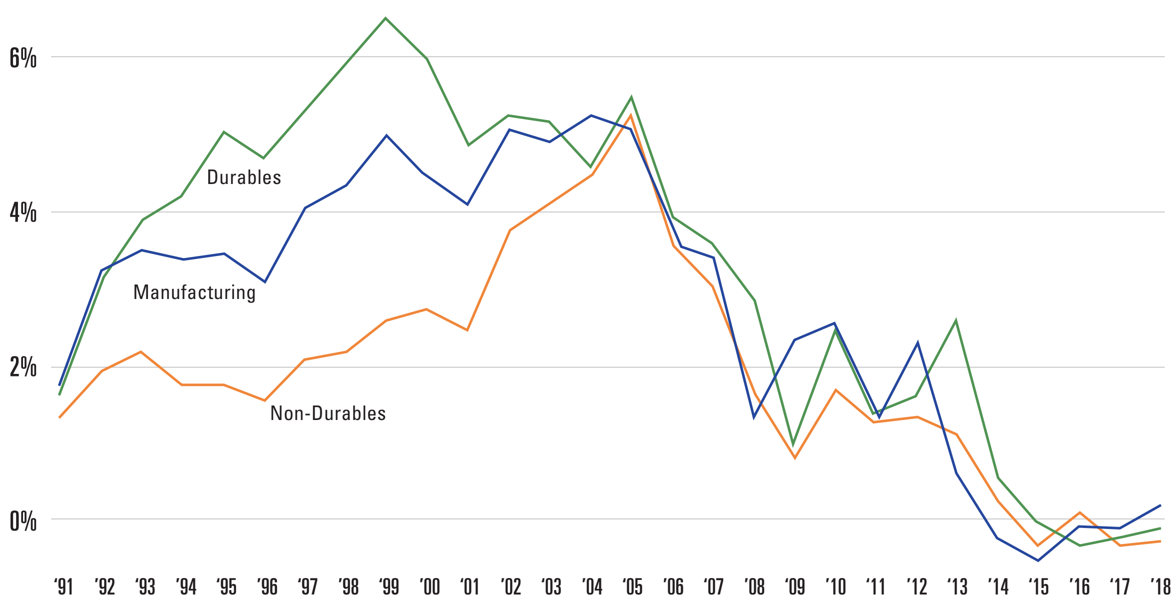


Source: Bureau of Labor Statistics

- Between 2006 and 2016, some of the largest reductions in output were in advanced industries: pharmaceuticals shrank 3.1 percent, industrial machinery declined 2.9 percent, communications equipment was down 2.5 percent, and computers and peripherals shrank 2.3 percent. Imports increased in all of these industries.[17]
- Productivity growth in manufacturing has virtually disappeared, as Figure 2 illustrates.[18] Since 2011 labor productivity has risen by a total of 0.7 percent; worse, total factor productivity fell 5.8 percent between 2011 and 2015.[19] The negative impact on U.S. manufacturing competitiveness is difficult to overstate.

16. Jaison Abel and Richard Deitz, "The (Modest) Rebound in Manufacturing Jobs," Feb. 4, 2019 at https://libertystreeteconomics.newyorkfed.org/2019/02/the-modest-rebound-in-manufacturing-jobs.html
17. Ibid.
18. Michael Mandel, *The Rise of the Internet of Goods*, MAPI Foundation, Aug. 2018, updated with Bureau of Labor Statistics data.
19. Peter Coy, "American Factories Have One Very Big Problem," Bloomberg BusinessWeek, May 9, 2018, at https://www.bloomberg.com/news/articles/2018-05-09/american-factories-have-one-very-big-problem.

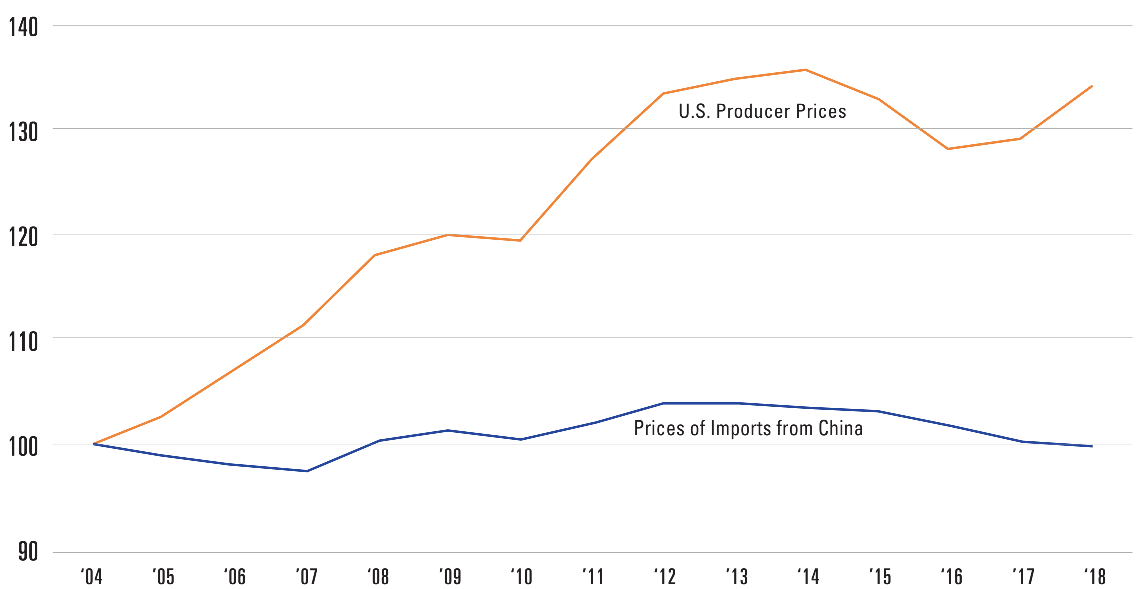
Figure 2: Dramatic Decline in Manufacturing Productivity Growth



Source: Bureau of Labor Statistics

With this productivity performance, it is unsurprising that the gap between U.S. producer prices of finished goods and the price of Chinese imports is widening (Figure 3).[20] Based strictly on price, U.S. manufacturers continue to lose competitiveness to Chinese producers.

Figure 3: Widening Gap Between U.S. Producer Prices and Chinese Import Prices



Source: Bureau of Labor Statistics

20. Michael Mandel, *The Rise of the Internet of Goods*, MAPI Foundation, Aug. 2018, updated with BLS data.

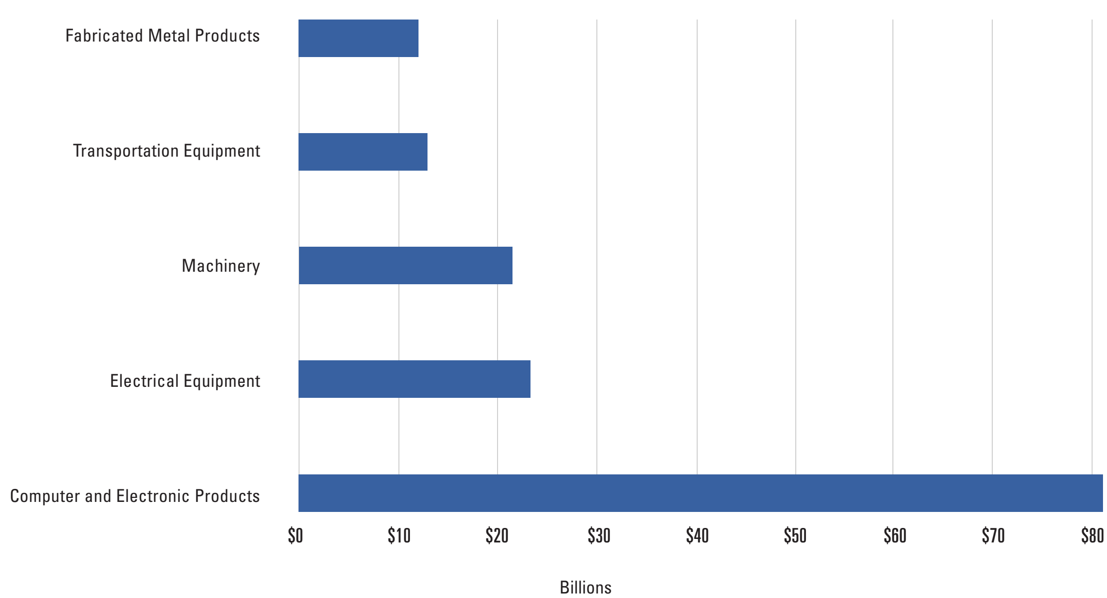
In the face of this price gap, it's not surprising that imports of manufactured goods continue to set records. Imports of manufactured goods from the 14 largest low-cost trading partners in Asia surged by $55 billion, nearly 8 percent, in 2017. Since 2013, imports from these countries have increased 19 percent, while U.S. manufacturing gross output has grown only 1 percent.[21]

Note that roughly 40 percent of Chinese exports are produced by affiliates of foreign companies or joint ventures between Chinese and foreign firms. Foreign firms produce 87 percent of the electronics and 60 percent of the machinery made in China.[22] This accelerates China's "learning by doing," aids Chinese innovation and competitiveness in high technology, and poses increasing threats to America's remaining advanced industries. **Of the products targeted by U.S. tariffs, over 85 percent are produced by wholly foreign-owned enterprises in China, many of them American multinationals.**[23]

- The Chinese exports to the United States that have grown the most since 2009 are primarily in technology-intensive industries (Figure 4). Total imports grew by more than $200 billion, with five advanced industries accounting for over 70 percent of that growth.[24]
- Despite expectations to the contrary, there is no evidence that U.S. manufacturers are reshoring production. A.T. Kearney's annual Reshoring Index fell in 2017.[25] Often, because of sunk investment costs, reshoring occurs only when the manufacturer realizes that offshoring was a mistake, indicated by loss of production control, poor quality, shipping delays, and loss of intellectual property.[26]

Contrary to popular reports of a strengthening manufacturing sector, this sample of data paints a stark picture of the state of U.S. manufacturing, especially in advanced technology. Despite several years of national economic growth since the Great Recession, manufacturing has not grown much at all. **Growth has largely been concentrated in three industries, transportation equipment, petroleum products, and food, but offset by stagnation or declines in advanced industries** such as

Figure 4: Largest Manufactured Import Growth from China, 2009-2017



Source: International Trade Administration

21. The 14 trading partners are China, Taiwan, Malaysia, India, Vietnam, Thailand, Indonesia, Singapore, the Philippines, Bangladesh, Pakistan, Hong Kong, Sri Lanka, and Cambodia. https://www.atkearney.com/operations-performance-transformation/article?/a/reshoring-in-reverse-again
22. MGI, "Trade in Transition," Jan 2019, p. 10.
23. Mary Lovely and Yang Liang, "Trump Tariffs Primarily Hit Multinational Supply Chains, Harm U.S. Technology Competitiveness," Peterson Institute for International Economics, 2018.
24. U.S. International Trade Administration
25. https://www.atkearney.com/operations-performance-transformation/article?/a/reshoring-in-reverse-again
26. Ibid.

pharmaceuticals, communications equipment, and computers.[27]

Employment has recovered somewhat, but without stronger productivity growth, U.S. manufacturing firms will continue to have compelling incentives to manufacture in Asia and import that production to the United States. This pattern will continue to have long-term adverse consequences for the overall health of the U.S. economy and the strength of the defense industrial base.

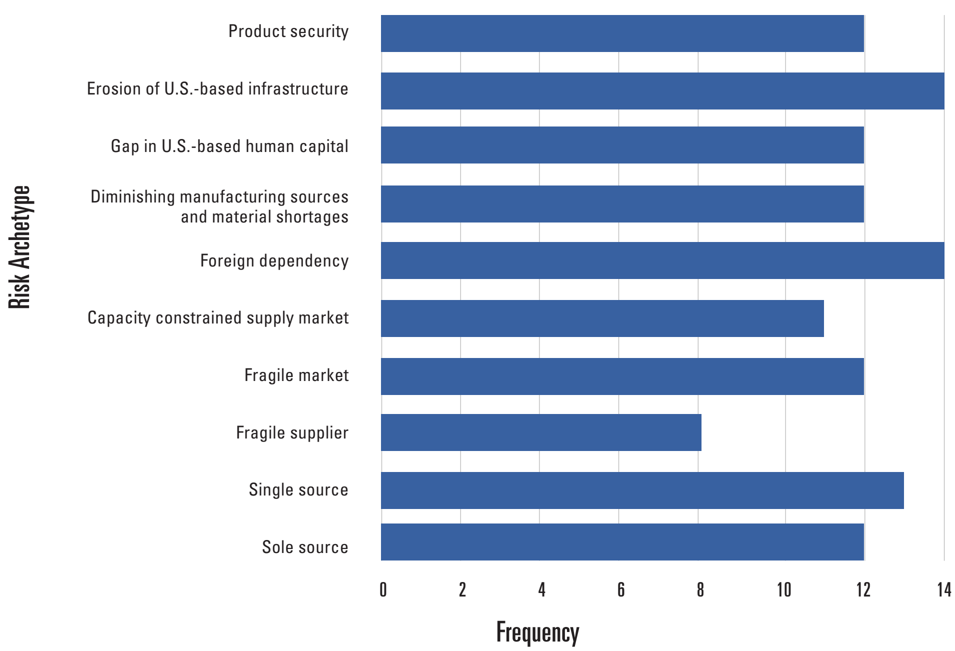
Issues in the Defense Industrial Base

These adverse trends in U.S. manufacturing have had negative impacts on the defense industrial base throughout the "lost decades" that are at last beginning to be documented. In September 2018, the DoD released an unclassified summary of its response to Executive Order 13806, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States."[28] The effort provided a comprehensive assessment of the risks threatening the U.S. defense industrial base, as shown in Figure 5.[29]

Within each of these risk archetypes, the assessment provides specific instances of key parts, components, and technologies of which reliability of supply is threatened. Examples include:

- There is currently only one domestic production line capable of manufacturing large caliber gun barrels.[30]
- The single domestic source for large thin-wall castings for rotary wing gearboxes filed for bankruptcy in 2016, putting programs such as the AH-64E Apache, the V-22 Osprey, and the CH-53K Heavy Lift Replacement Helicopter at risk.[31]
- Since 2010, the number of vendors in key defense systems such as ammunition, weapons, and missile and space systems has fallen, even as spending has been stable or increased.[32]

Figure 5: Risks Threatening the Defense Industrial Base



Source: U.S. Department of Defense

27. The United States fell from 9th to 11th in the Bloomberg Innovation Index, largely due to declines in output and employment in communications and computers, only partially offset by continued leadership in aerospace and pharmaceuticals. See, https://www.bloomberg.com/news/articles/2018-01-22/south-korea-tops-global-innovation-ranking-again-as-u-s-falls.
28. U.S. Department of Defense, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," Report to President Donald J. Trump by the Interagency Task Force in Fulfillment of Executive Order 13806, September 2018.
29. Ibid., p. 14.
30. Ibid., p. 47.
31. Ibid., p. 23.
32. Ibid., p. 26.

- Especially in electronics, counterfeit parts, insufficient quality control, and lack of part traceability have been identified as vulnerabilities in the defense supply chain (as well as commercial supply chains such as automotive). Most counterfeits come from China.[33] A 2012 study by the Senate Armed Services Committee found that 84,000 counterfeit electronic parts were supplied by just one Chinese company.[34] Since then, DoD has taken numerous initiatives, in management practices and technology, to mitigate the risk and prevent the introduction of counterfeit parts.[35]

- Despite its centrality to electronic devices of all types, the U.S. printed circuit board (PCB) industry is shrinking and failing to keep pace with technology developments in rigid and rigid-flex printed circuit board production capability.[36] Dependence on foreign sources for advanced PCBs has implications across multiple defense and civilian industries.

As these and many other examples in the assessment illustrate, the broad shift of manufacturing offshore has had unintended consequences for defense production, and not only in assured access to products and production capacity. Necessary skills, ranging from production engineers to skilled trades, have also been adversely affected. Access to the necessary skilled workforce is often the top concern of domestic manufacturers, impeding current production capacity and potential future growth.

The DoD is taking steps to adjust its procurement policies to eliminate reasons for companies to avoid defense contracting, and is working with other federal agencies to address areas of economic, technological, and informational vulnerabilities. In addition to filling existing gaps, efforts are underway to ensure long-term, leading capabilities in new, critical defense technologies including hypersonics, directed energy, microelectronics, artificial intelligence, machine learning, and quantum science and computing.[37] But achieving goals in these and other defense technologies requires that commercial manufacturers have access to and effectively implement leading-edge production capabilities throughout the value chain.

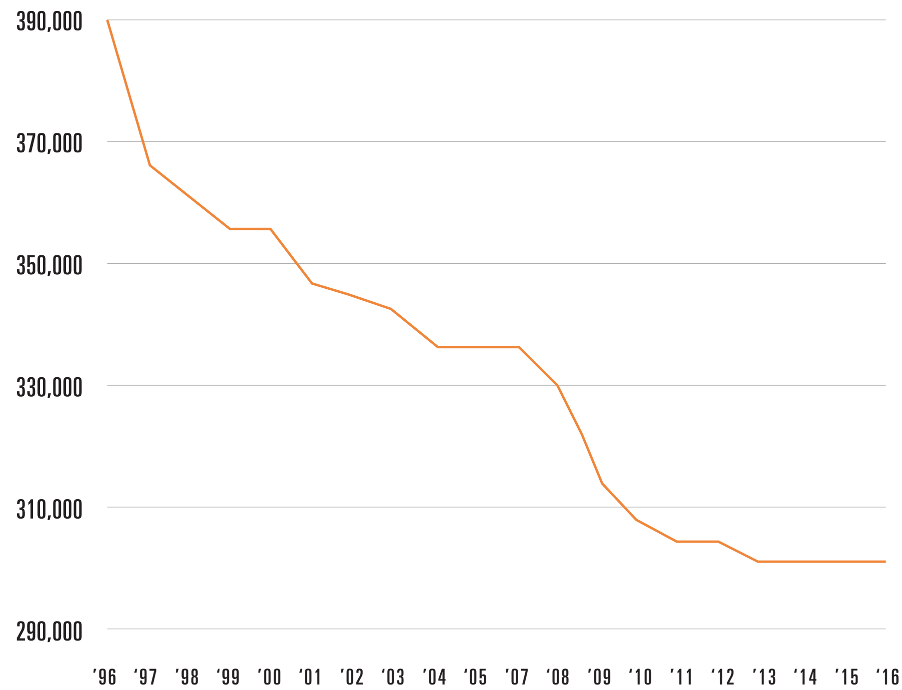
It is important to emphasize that the DoD cannot solve the nation's manufacturing problems on its own. Although multiple defense programs and initiatives exist to address critical manufacturing issues, including the Manufacturing Technology (ManTech) program, Title III, armories, Manufacturing USA institutes, and Defense Innovation Unit, these can at best address defense-specific production issues. They cannot solve the gaps and weaknesses in the total national industrial base on which defense production must rely. A coordinated, whole-of-government approach is essential to meet the grand challenges facing the future of U.S. manufacturing.[38]

Loss of the Industrial Commons

As the issues and shortcomings identified in the defense industrial base make clear, the U.S. manufacturing sector has lost not only production capacity but also the skills and supplier base needed to regain domestic production. This industrial commons, a term originally coined by Gary Pisano and Wily Shih ten years ago in the *Harvard Business Review*, is the "collective R&D, engineering and manufacturing capabilities that sustain innovation."[39] One of the serious unintended consequences of offshoring in the last decades is a severely diminished industrial commons. As large manufacturers have moved production abroad, their supply chains have followed and the image of manufacturing as a promising career choice has suffered. The result is that the number of manufacturing establishments in the United States has dropped by more than a quarter since 1993 (Figure 6).[40] Many that remain are struggling with low profit margins, an aging workforce, and diminished long-term prospects. Many manufacturers, large and small, identify skill availability as a major challenge.

33. Ibid, p. 29
34. Senate Armed Services Committee. (2012). Senate Armed Services Committee Releases Report on Counterfeit Electronic Parts. Retrieved from https://www.armed-services.senate.gov/press-releases/senate-armed-servicescommittee-releases-report-on-counterfeit-electronic-parts
35. Office of the Under Secretary of Defense for Acquisition and Sustainment, "FY2017 Annual Industrial Capabilities," Report to Congress, March 2018, p. 40.
36. Ibid, p. 42
37. U.S. Department of Defense, "Summary of the 2018 National Defense Strategy of the United States of America: Sharpening the American Military's Competitive Edge," at https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf
38. See, Kota and Mahoney, *Manufacturing Prosperity*, op.cit.
39. Pisano, Gary P. and Willy C. Shih, "Restoring American Competitiveness," *Harvard Business Review*, July-August 2009.

Figure 6: Number of U.S. Manufacturing Establishments



Source: U.S. Census Bureau

The lost industrial commons has had readily observable impacts in particular industries and regional business clusters. As one example, the Cincinnati region was once a hotbed of machine tool builders, led by Cincinnati Milacron, at one time the world's largest machine tool manufacturer. Today, although a few American machine tool manufacturers remain, such as Hurco, Hardinge, and Bourn & Koch, the global machine tool industry is led by German, Japanese, and S. Korean companies though many have U.S. production facilities. Another example is electronic displays. By locating production in Asia, U.S. companies ceded the ability to innovate in displays, a technology especially dependent on advances in manufacturing process innovation, which has been essential to larger, more vivid displays. And despite large government investments in the coming generation of flexible displays, few U.S. companies have the manufacturing knowledge to compete in the market. Other examples include semiconductor packaging, PCBs with high-density interconnects, and advanced materials including biomaterials, ceramics, and carbon fiber composites for aerospace applications.[41]

Restoring the industrial commons is an essential, albeit difficult, step, not only to restore America's ability to innovate in hardware, but also to apply new production technologies and regain manufacturing productivity growth. Necessary steps include:

- Training and education, for skilled trades, design engineering, and product/process integration;
- Rebuilding a strong network of machine shops and contract manufacturers;
- Restoring production capacity in critical intermediary goods and processes; and
- Building on strengths in industries such as medical devices and aerospace to ensure a strong, comprehensive supply base remains in this country.

40. County Business Patterns
41. See, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," September 2018, p.41.

Other gaps in essential production knowledge and capacity for defense industries must also be addressed. Although regional pockets of manufacturing knowledge remain throughout the country, the large drop in the number of manufacturing establishments and competitive pressures facing remaining small and medium-sized manufacturers (SMMs) create a time bomb in which additional expertise and capacity could be lost quickly if concerted national efforts are not mobilized to address the problem.

Educating the workforce required to grow advanced manufacturing in the United States is a national priority, and another case where the country is behind the competition. Technology is changing both the type of workers needed (i.e. from general to specialized labor) and the type of skills that are required. Advanced manufacturing requires workers with new multidisciplinary competencies, combining mechanics, electronics, and software knowledge and skills. New roles in information management are emerging across the value chain and proficiency in new computerized modeling and simulation tools and data analytics is increasingly required. Complex systems thinking and cybersecurity competencies are becoming more important as processes and machines become increasingly interdependent.[42] Generating the needed workforce requires both training and retraining, but the United States is lagging competitors: the United States spends just 0.03 percent of its GDP on labor-market training—well below the OECD average.[43]

Figure 7: Manufacturers' Response to Skills Shortage

Source: NAM Manufacturers' Outlook Survey, 2018, quarter 4

42. Cambridge University, "Emerging Trends in Global Advanced Manufacturing," 2017, at https://institute.unido.org/wp-content/uploads/2017/06/emerging_trends_global_manufacturing.pdf

43. OECD, at https://stats.oecd.org/viewhtml.aspx?datasetcode=LMPEXP&lang=en

In a tight employment market, companies have much greater incentive to upgrade the skills of their existing workforce. A recent survey by the National Association of Manufacturers provides insight into how companies are addressing their skills shortages (Figure 7). A combination of internal training programs and utilizing local educational institutions is most common, though taking steps to address skills shortages does not mean the problem is solved. Most manufacturers continue to identify skill availability as a major concern.

Especially in regions where manufacturing remains important and continues to grow, existing programs are helping to meet these shortages and can provide lessons for national efforts. For instance, as the automotive industry has expanded in South Carolina, the International Center for Automotive Research at Clemson University has developed a significant research and training capacity, including K-12 outreach programs.[44] In Oregon, the Oregon Manufacturing Innovation Center has created a partnership of industry, higher education, and government to address near-term manufacturing challenges through applied research and advanced technical training.[45] Other initiatives have integrated high school education with apprenticeships with local manufacturers.

One example is Wisconsin Fast Forward, which helps train high school students for high-demand manufacturing fields. In 2018, a presidential executive order created the Council for the American Worker, led by the Departments of Commerce and Labor, to consolidate existing federal programs and fund new training initiatives, including expanded apprenticeship programs. As part of the effort, companies and trade unions have committed funding to expand apprenticeships, retrain workers, and provide continuing education programs in the next five years.[46]

At least one longstanding issue in restoring the industrial commons may be improving: the perception of manufacturing as a desirable career choice. According to a 2016 survey, **37 percent of millennials perceive manufacturing as a high-technology career choice, notably higher than both Generation X (27 percent) and Baby Boomers (23 percent).** More millennials (49 percent) believe engineering is a needed skill in manufacturing compared with only 41 percent of Baby Boomers. Forty percent of millennials also recognize that manufacturing careers are high paying versus only 26 percent of Generation X.[47] These findings bode well for the ability to recruit young people into manufacturing careers, essential to rebuilding the nation’s industrial commons.

44. https://cuicar.com/
45. https://www.oregon4biz.com/Oregon-Business/Industries/Advanced-Manufacturing/OMIC/
46. Dana Wilkie, “The Blue-Collar Drought,” Society for Human Resource Management, Feb. 2, 2019 at https://www.shrm.org/hr-today/news/all-things-work/pages/the-blue-collar-drought.aspx
47. Protolabs’ 2016 Survey conducted by Opinion Research Corporation, at https://www.protolabs.com/resources/blog/millennials-more-upbeat-on-manufacturing-s-future/

CHAPTER 2

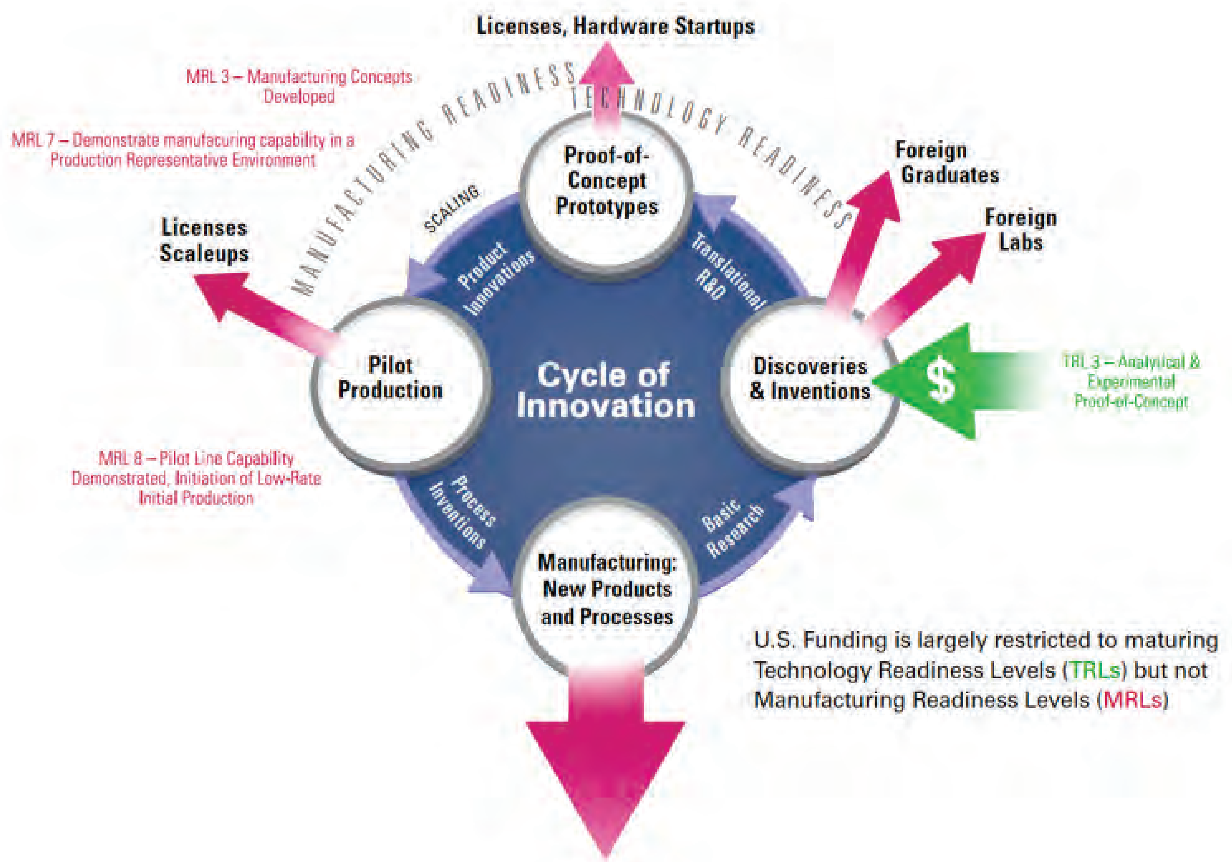
GAPS IN THE NATIONAL INNOVATION ECOSYSTEM

Issues in the U.S. industrial commons compound other gaps in the nation's innovation ecosystem, particularly in hardware. After decades of offshoring, thought leaders in both the public and private sectors are realizing that the nation cannot maintain its economic and defense security superiority based mostly on software. The integration of hardware and software—often called Operations Technology (OT) and Information Technology (IT) integration—is more essential than ever to competitive products, and weapons systems.

Therefore, gaps in the nation's innovation ecosystem are increasingly recognized with a growing imperative that they must be addressed.

As first described in *Manufacturing Prosperity*, the cycle of innovation (Figure 8) is the process that creates new products and processes from initial basic research. Historically, this cycle has served the United States well throughout the post-war period, but has evolved serious gaps in the past 20-30 years.

Figure 8: The U.S. Cycle of Innovation



First, opportunity for foreign competitors to take advantage of research outcomes is, at the moment, a fundamental part of the system. Academic research, especially in science and engineering (S&E), is dependent on foreign graduate students, predominantly from Asia. More than one-third of foreign students in U.S. universities are Chinese.

Second, U.S. universities are often encouraged to partner with foreign institutions, and foreign-based companies are frequently participants in U.S. academic research centers. The research center may have little choice because it needs access to state-of-the-art equipment made abroad, but the foreign participants can capture research results for production in their home countries.

Third, the lack of funding available to move proof-of-concept prototypes beyond the lab provides opportunities for foreign firms to license technologies directly or to invest in local start-ups directly, thereby gaining access to new technologies. Several major U.S. research universities, including Stanford University, Northwestern University, and others, have partnered with the Beijing Institute of Collaborative Innovation (BICI) to fund translational research and give BICI priority to license promising technologies.[48]

Finally, scaling new technologies to commercial-scale production is costly and often requires a comprehensive supply base that is not readily available in this country, providing another opportunity for the new technologies that emerge from federal R&D funding to be produced, and generate wealth, abroad.[49]

Funding for basic research, especially federal funds flowing to U.S. research universities, continues to be an essential foundation for the cycle. But assumptions that were reasonable in the past—that private companies would fund the needed translational research and would develop the manufacturing capabilities and capacity to create commercial products—have become less realistic.

Partly this is due to offshoring of production and the resulting loss of industrial commons. There is less domestic capability in private industry to perform the translational research needed to advance technology and manufacturing readiness levels. It is also because there are more opportunities for the inventions and discoveries resulting from basic research to be adopted by foreign companies with successful commercialization done abroad. **Because of these leakages in the cycle of innovation, the unfortunate result is that U.S. investments in basic R&D are subsidizing product development for foreign companies.** In the current environment, the federal government must invest in translational research, to complement its spending on basic science, to raise the return on the nation's total R&D investment.

National priority should be given to develop mechanisms to address these gaps in the cycle of innovation. Funding is needed across the entire cycle

1) to provide grants and scholarships to American graduate students in engineering;

2) to fund translational research to advance MRLs and TRLs for promising technologies to ensure potential products are commercialized in the United States; currently, once academic researchers prove the basic science, funding is no longer available.

3) to invest in the start-ups that license the technologies so they can reach commercial scale production in this country; and

4) to closely connect the U.S. supplier base with the needs of entrepreneurs striving to commercialize new hardware technologies, and to provide government procurement contracts to new manufacturers to accelerate their path to volume production.

48. For example, see, https://research.northwestern.edu/news/global-partnership-enhance-northwestern-innovations
49. For a more comprehensive explanation of the innovation cycle and its leakages, see M*anufacturing Prosperity,* pp. 27-30.

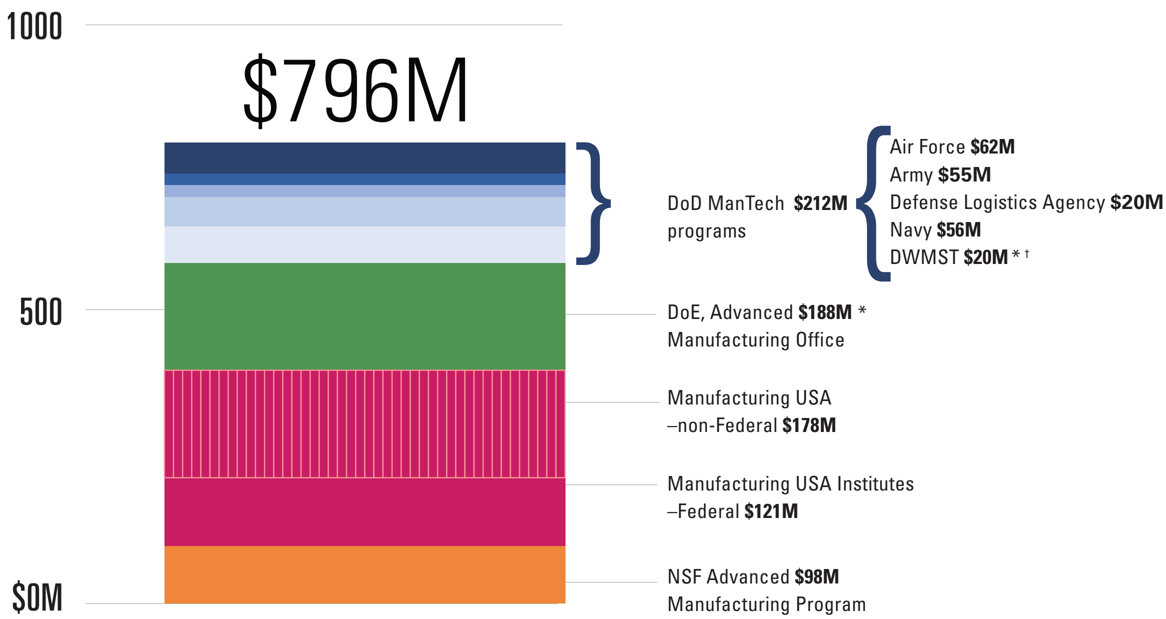
Federal Support for Manufacturing

The current Administration has recognized the need to increase the nation's return on its investment in R&D as part of the President's Management Agenda. In April 2019, NIST released a Green Paper, *Return on Investment Initiative for Unleashing American Innovation*.[50] The paper addresses multiple impediments to technology transfer, the need for technology maturation (aka translational research) funding, and preference for domestic manufacturing of IP resulting from federally funded research. With appropriate action, the initiatives identified in the Green Paper would begin to address the gaps in the innovation cycle, but it would only be a start.

There is certainly room for government to do much more to restore the nation's industrial commons, plug gaps in the manufacturing innovation ecosystem, and to lay stronger foundations for long-term global competitiveness. Calling for additional funding support to advance MRLs and TRLs, for instance, is based on recognition that the overwhelming majority of federal R&D spending goes for basic research, with very little devoted to manufacturing.

Federal spending on manufacturing-related R&D is difficult to determine due to insufficient information and inconsistent labeling. Estimates range from $773 million by the OECD[51] to $3.7 billion by the GAO.[52] A recent unpublished analysis by MForesight estimates that in 2017 $796 million of federal R&D spending could be reasonably attributed to manufacturing, primarily through three agencies: the Advanced Manufacturing Office at the Department of Energy, NSF's Advanced Manufacturing Program, and DoD's Manufacturing Technology

Figure 9: Core Federal Funding for Manufacturing-related R&D



* excludes funding for Manufacturing USA Institutes
† Defense-Wide Manufacturing Science & Technology

Source: MForesight analysis

50. Available at https://doi.org/10.6028/NIST.SP.1234
51. Organization for Economic Co-operation and Development, "industrial production and technology" in Government Budget Appropriations or Outlays for R&D (GBAORD) for 2016, at https://stats.oecd.org/Index.aspx?DataSetCode=GBAORD_NABS2007
52. The Government Accountability Office surveyed 58 Federal program offices across 11 agencies asking whether their activities helped foster (1) innovation, (2) global trade, (3) supported the workforce, or (4) offered financial or business assistance. The report found that 30 programs self-reported to be "fostering innovation through their support for basic and applied R&D" in the amount of $3.7B (table 3, pg.16). The agency breakdown suggests the survey included programs that support manufacturing R&D financially or business expertise, not just technology R&D. See, https://www.gao.gov/assets/690/683753.pdf.

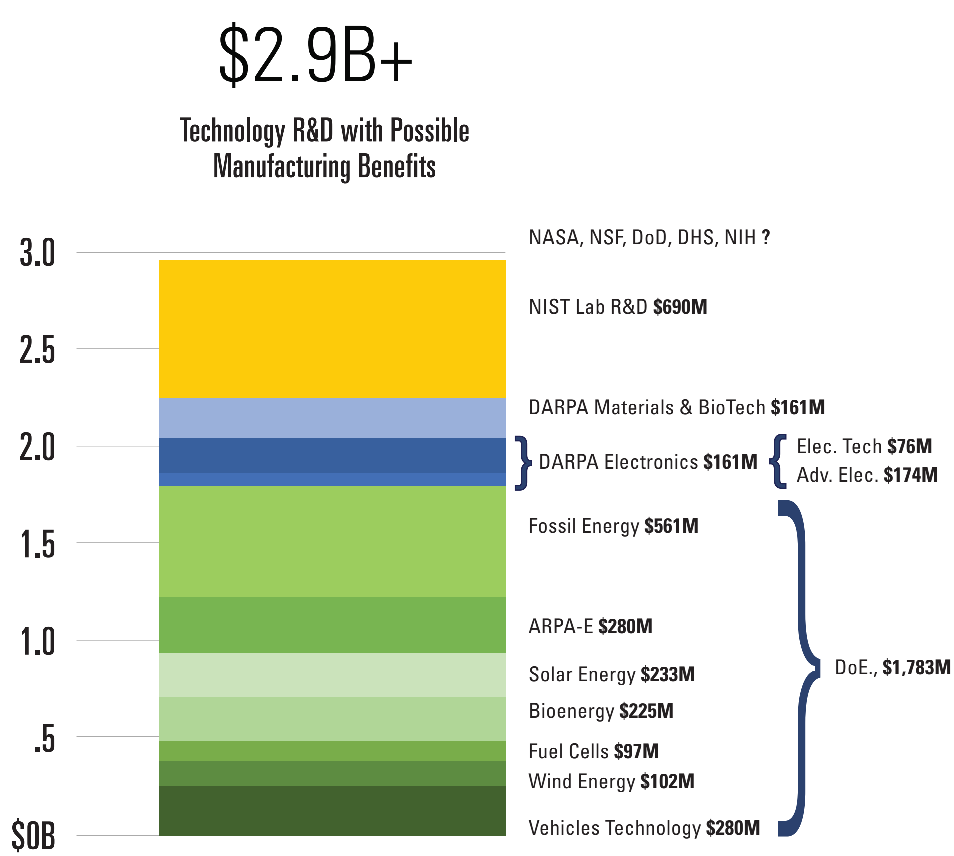
(ManTech) programs. The Manufacturing USA institutes, currently 14 institutes addressing a variety of both product and process technologies, are funded by DoD, DoE, and DoC. Including the required cost share for the institutes, which is non-federal money, boosts the total to $796 million (Figure 9).

If this $796 million is considered core funding for manufacturing R&D, other programs at these agencies and other agencies fund R&D that often has manufacturing components. For instance, the Defense Advanced Research Projects Agency (DARPA) often funds programs to address manufacturing capabilities. An example is the Electronics Resurgence Initiative, a $200 million program over 4 years intended to reinvigorate the U.S. semiconductor manufacturing base.[53] Agencies such as the National Institute for Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA) fund research that benefits manufacturing, but in the absence of detailed spending data, it is difficult to determine how much of their R&D budgets impact manufacturing technology R&D.

Still other programs, such as DoE's Bioenergy Technology Office, Fossil Energy Office, and ARPA-E, also fund manufacturing-related R&D. When these and similar programs are included, total federal R&D spending with impact on manufacturing could be as much as $2.9 billion (Figure 10).

At $796 million, U.S. R&D spending on manufacturing-related technology is far below the amount invested by other advanced economies. Even a generous estimate of $2.9 billion places the United States well below Japan, Germany, and S. Korea. Japan spent over 3 times as much, Germany nearly 6 times as much, and S. Korea more than 10 times as much as the U.S in manufacturing-related R&D. As a proportion of total R&D, the United States is last in the OECD, well below the average and behind key

Figure 10: Total Federal Manufacturing-related R&D



Source: MForesight analysis

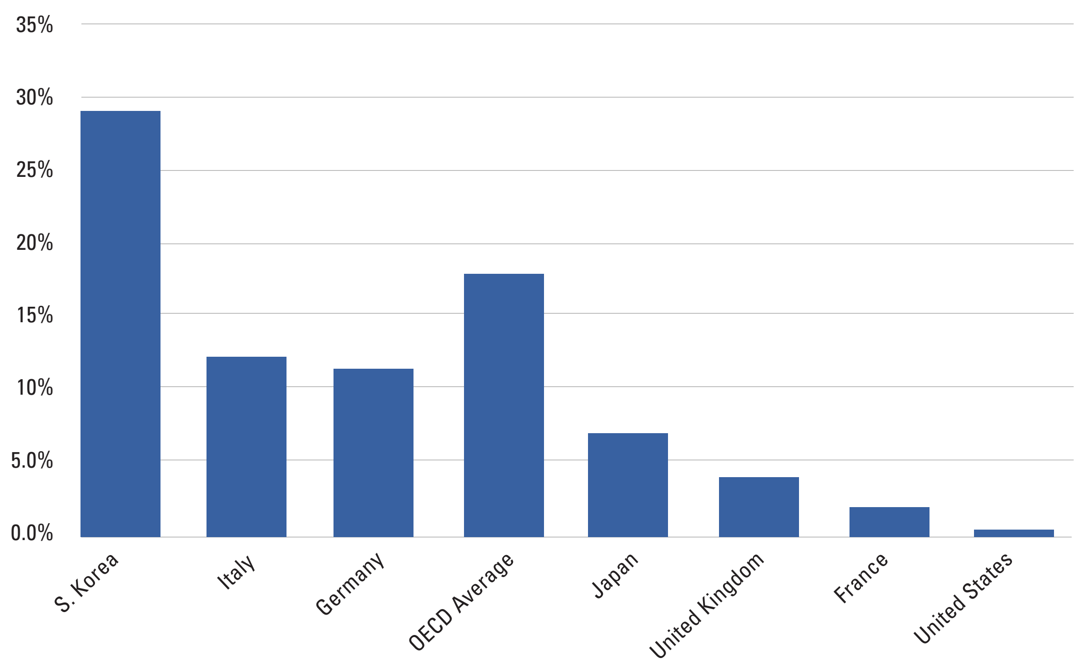
53. "DARPA Rolls Out Electronics Resurgence Initiative", 09/13/2017, https://www.darpa.mil/news-events/2017-09-13

competitor nations (Figure 11). Even when the spending category is modified to include all advanced manufacturing related R&D, the U.S. spent $2.9 billion, or 1.6 percent of the total R&D budget in 2017.

It is important to note that these three countries—Japan, Germany, and South Korea—have maintained trade surpluses in advanced manufacturing, are well ahead of the United States in their use of industrial robots, and have a greater share of high-technology production in their manufacturing sectors. Unless the United States supplements its large investments in basic research with new investments in translational R&D, at least on par with other advanced economies, U.S. scientific discoveries will continue to benefit overseas manufacturers with the resources to develop these discoveries further, scale production, and export finished products back to the United States.[54] Until U.S. private industry regains its ability to fund and perform these crucial steps in translational R&D, create finished products, and scale production, the federal government must invest more in applied engineering and manufacturing R&D.

Figure 11: Share of Total R&D Spent on Industrial Production and Technology R&D, 2015

(minimum $10 billion in total annual R&D)



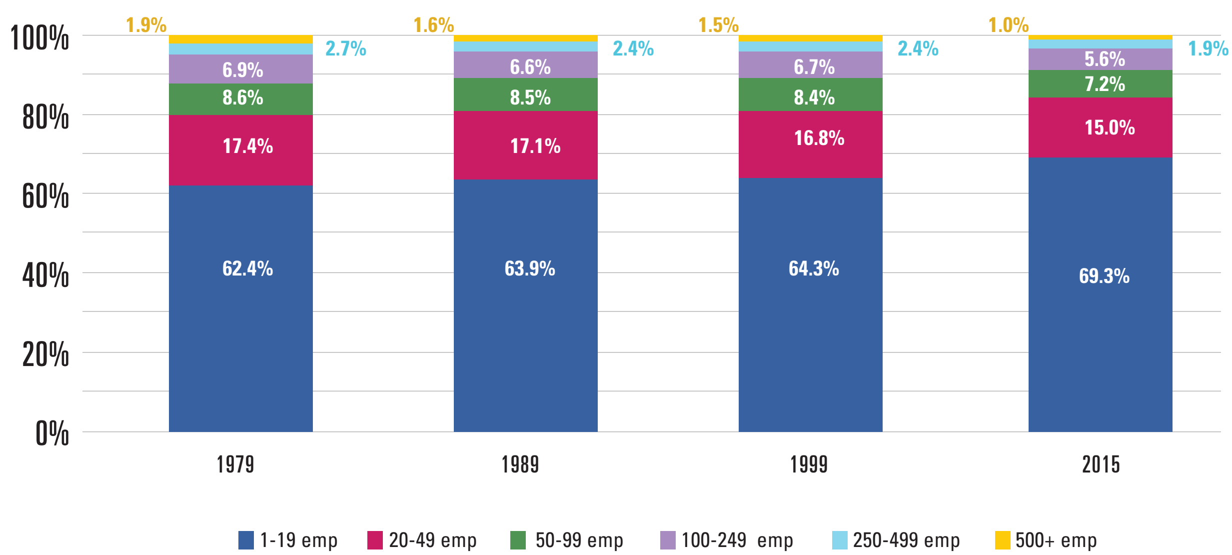
54. Jost Wubbeke, Mirjam Meissner, et. al., *Made in China 2025: The Making of a High-Tech Superpower and Consequences for Industrial Countries*, Mercator Institute for China Studies, Dec. 2016, p. 6, at https://www.merics.org/sites/default/files/2018-07/MPOC_No.2_MadeinChina2025_web.pdf

Support for Small and Medium-Sized Manufacturers

Small and medium-sized manufacturers are the foundational backbone of the U.S. industrial base. While large multinational manufacturers have global interests and often derive a majority of their revenue and profits from foreign markets, SMMs are typically rooted to their local communities. The risk they face is often most intense from import competition, which is more likely to drive them out of business than to drive them offshore. They have much greater interest in the United States as a production location, and have much more to lose from the decline in the national industrial commons, than large multinationals with diverse global production capacity and the resources to locate factories and suppliers wherever is most advantageous to them. This at least partially explains the growing importance of SMMs in U.S. manufacturing (Figure 12), and the reason to support SMMs in much-needed government efforts to rebuild the industrial commons.

MForesight has previously documented the importance of SMMs and a comprehensive, competitive supplier base to the overall future of U.S. manufacturing.[55] Yet multiple market and network failures inhibit the pace of adoption of advanced technologies by SMMs and the emergence of highly productive, integrated next-generation supply chains. Overcoming these barriers to progress requires both public and private initiatives that at least keep pace with the efforts of international competitors. Despite programs such as the Hollings Manufacturing Extension Partnership (MEP) and the Manufacturing USA institutes, other countries spend far more on programs to support SMMs and conduct translational research. Germany, for instance, spends 20 times as much as the United States on manufacturing extension services. Japan spends even more.[56] Surveys of U.S. SMMs provide insight into the challenges they face and the many opportunities government has to help.

Figure 12: Size Distribution of U.S. Manufacturers by Number of Employees



Source: U.S. Census Bureau

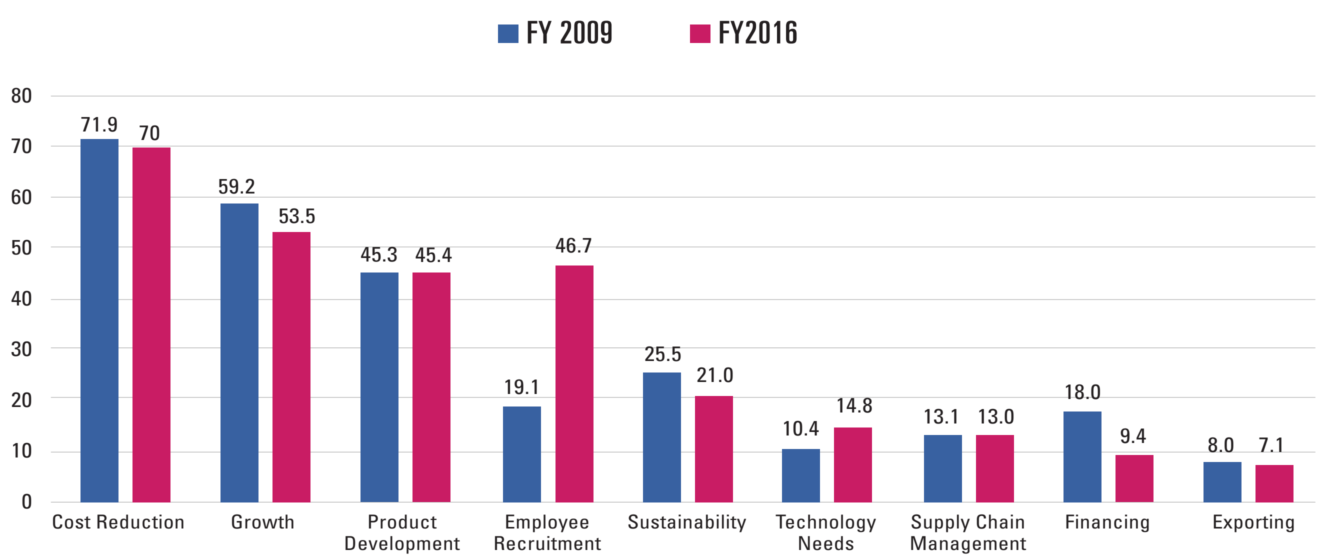
55. Tom Mahoney and Susan Helper, *Ensuring American Manufacturing Leadership Through Next-Generation Supply Chains*, MForesight, June 2017.
56. https://itif.org/publications/2011/09/14/international-benchmarking-countries%E2%80%99-policies-and-programs-supporting-sme

Figure 13 illustrates both major challenges and how they have changed over time. Cost reduction and growth are consistent priorities, driven both by consistent demands for annual cost reductions from large customers and by import competition. However, finding skilled talent has become much more challenging over time, as has the need to upgrade production technology and to develop new products.

Although some government assistance is available from MEP, SBA, and targeted state programs, much more should be done. Loan guarantees and other forms of financial assistance could help SMMs accelerate equipment upgrades and embrace smart manufacturing technology; increasing government funding of apprentice programs and technical education would rebuild the pipeline of technical talent; more programs to engage with universities in translational R&D would help with new product introductions and export opportunities; fellowship programs for retired business and technical experts to work with start-ups would provide a valuable source of expertise.

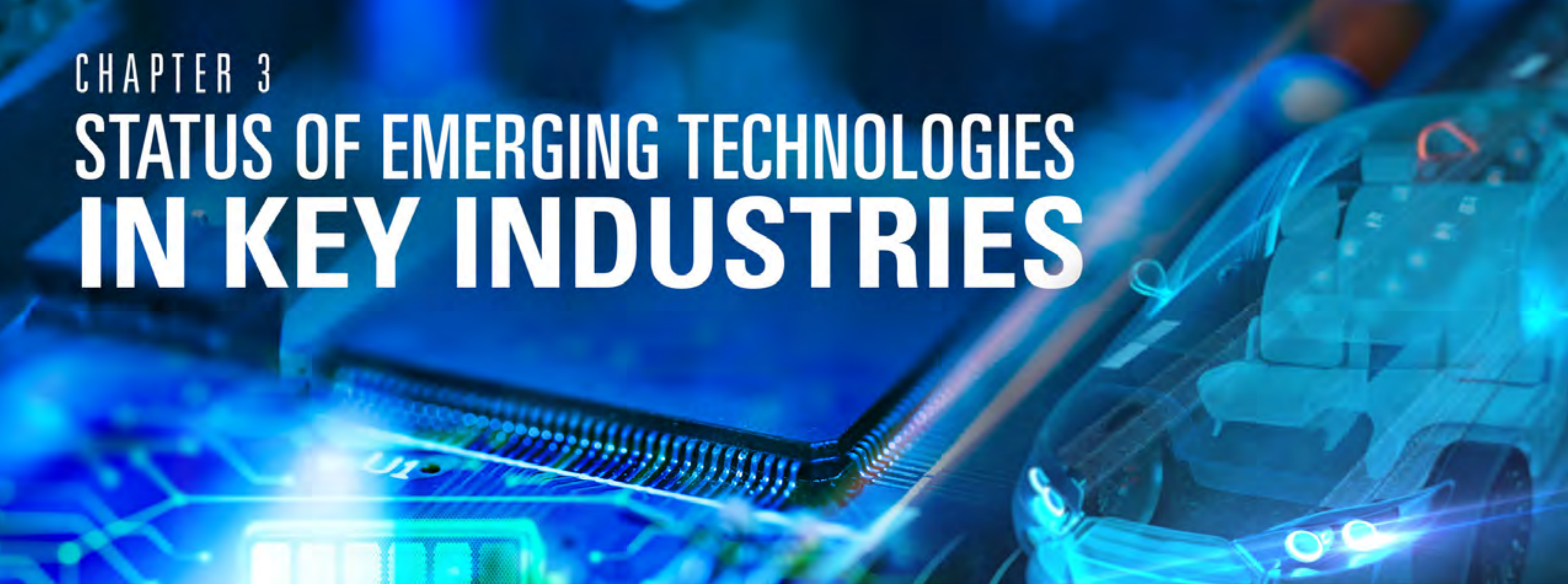
Competing nations provide support for their SMMs across all of these parameters. As a result, they have positive trade balances in manufacturing and have maintained manufacturing output and employment far better than the United States. In 2018, the United States had a trade deficit in goods of $891 billion, whereas Germany maintained a trade surplus in goods of $280 billion, Japan more than $26 billion, and S. Korea more than $95 billion.[57] These trade balances are influenced by a wide variety of factors, but generally reflect national policies to support manufacturing, especially SMMs, and a different set of business decisions that have resisted wholesale offshoring of productive capacity.

Figure 13: Challenges Facing U.S. SMMs



Source: NIST MEP Client Surveys

57. Foreign data are for 2017. See, https://comtrade.un.org/data/



CHAPTER 3
STATUS OF EMERGING TECHNOLOGIES IN KEY INDUSTRIES

Despite some positive developments in recent years—the creation of the Manufacturing USA institutes, for instance—overall, trends in U.S. manufacturing have been weak. Growth in both output and employment has accrued to just a few industries, anticipated new investments from corporate tax cuts have largely failed to materialize, and trade deficits, especially with China, have reached record highs. The DoD has recognized threats to the defense industrial base resulting from weaknesses in the commercial industrial base, but addressing the problems is complex and specific solutions, apart from tariffs, have yet to materialize.

In this context, it is useful to consider how well U.S. manufacturing is positioned to take advantage of new technologies poised to disrupt both commercial and defense industries. Given its importance to the nation's industrial base, the future of the motor vehicle industry deserves specific attention.

Case 1: Batteries for Electric Vehicles

A conservative estimate has the motor vehicle industry, including cars, trucks, and parts, comprising at least 15 percent of U.S. manufacturing output.[58] In the past decade, the motor vehicle industry has accounted for the largest share of U.S. manufacturing output growth. Clearly, the most significant and pervasive change in U.S. manufacturing will come from the shift to electric vehicles (EVs). Although the pace of change is difficult to predict—McKinsey estimates that EVs will be 17 percent of car sales by 2030[59]—major automakers are increasing their investments in both electrification and autonomy. For instance, Ford is increasing its investment in EVs to $11 billion and is planning to introduce 40 new plug-in or hybrid vehicles by 2022. General Motors plans to spend $8 billion on electric and autonomous vehicles. Much of GM's R&D on EVs is done at its Advanced Technical Center near Shanghai, China, the world's largest EV market. Volkswagen is investing $91 billion to convert much of its vehicle lineup to electricity in the coming decade.[60]

There is some debate about the impact of this massive technology shift on the volume of vehicles produced for the U.S. market, which was 17.5 million in 2017 but could decrease to no more than 12 million in the future as autonomous vehicles encourage ride sharing and pay-per-mile business models.[61] Adding even more potential disruption to the industry, by some estimates, electric vehicles require 40 percent fewer parts and assembly labor than conventional vehicles.[62] Costs will shift from mechanical components—a gasoline engine costs around $5,000—to electric motors and inverters costing $2,000 and battery packs with sufficient range that currently cost nearly $20,000.[63] As a critical input to the largest manufacturing sector, it is incumbent for the United States to control development and production of EV batteries.

58. Based on analysis of the 2016 Census of Manufactures at https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ASM_2016_31VS101&prodType=table
59. https://www.mckinsey.com/featured-insights/innovation-and-growth/globalization-in-transition-the-future-of-trade-and-value-chains?cid=other-emlnsl-mip-mck&hlkid=0c823927be10461681597b702d11f4a6&hctky=10424165&hdpid=061101a9-35af-42ab-9f48-92747f862bb6
60. https://www.reuters.com/article/us-volkswagen-electric-insight/bet-everything-on-electric-inside-volkswagens-radical-strategy-shift-idUSKCN1PV0K4
61. A study by Bain projects that U.S. car sales could fall as low as 11.5 million vehicles by 2025, the same level seen during the Great Recession when GM and Chrysler were forced to declare bankruptcy. See, https://www.ozy.com/fast-forward/can-automakers-catch-up-with-google-in-driverless-cars/92393
62. https://www.reuters.com/article/us-britain-autos-factbox/factbox-the-challenges-consequences-of-moving-to-electric-cars-idUSKBN1AB1RJ
63. https://www.reuters.com/article/us-volkswagen-electric-insight/bet-everything-on-electric-inside-volkswagens-radical-strategy-shift-idUSKCN1PV0K4

Batteries currently comprise 40 percent of the cost of electric vehicles.[64] Planned introductions of EVs in the next few years will require huge growth in battery output. The United States has long had a robust program for battery research, with federally sponsored R&D in the 1980s providing much of the basis for the emergence of lithium-ion battery technology. But the United States has not had much of a production base in advanced lithium-ion batteries.[65] It is not uncommon for breakthroughs in battery technology to be announced, followed by nothing emerging in commercial markets. Laboratory prototypes frequently do not translate well to commercial production scales, though each of these commercial failures arguably adds to collective knowledge about what is manufacturable at scale. In several cases, Boston Power for one example, battery startups with technology developed in the United States have moved to China, where they receive strong government and financial support to ramp up manufacturing.[66] Typically, manufacturing at scale is the roadblock to achieving desired breakthroughs in energy density, safety, and longevity for affordable EVs with sufficient range and recharge times needed to build market acceptance. The U.S. automotive industry is working collaboratively to address key technology needs. The United States Advanced Battery Consortium, a collaborative organization of Ford, General Motors, and Fiat Chrysler, funds R&D in advanced energy storage systems for mobile applications.

Currently in the United States, the largest EV battery producer is Tesla, in partnership with Panasonic. The Gigafactory in Nevada produces an estimated 35 gigawatt-hours with a plan to triple output by 2020,[67] largely accounting for the U.S. 22 percent share of global output.[68] Other manufacturers in the U.S. market include LG Chem, with a factory in Michigan that made batteries used in the Chevrolet Volt and a new factory planned in Georgia; Xalt Energy in Midland, Michigan; and SK Innovation, which is building a factory in Commerce, Georgia with a planned annual volume of 9.8 gigawatt-hours.[69]

A number of U.S. battery start-ups are either building factories or planning production in the near future. Many of these are focusing on solid state batteries or alternative anode materials. Most have raised capital from corporate investors, including many foreign automotive companies, rather than from venture capital firms. Examples include:

- QuantumScape—A Stanford University spinoff started in 2010 it has over 20 patents and patent applications in solid-state lithium ion batteries. The initial R&D work at Stanford was supported by ARPA-E. Volkswagen is a major investor, investing in 2014, with an additional $100 million in 2018. Production is not likely until 2025.

- Solid Power—Based on technology developed at the University of Colorado, it uses a solid electrolyte and lithium-metal anode to achieve energy density of 300 Wh/kilogram, 20 percent higher than standard lithium-ion batteries. Investors include BMW, Samsung, Hyundai Motors, and Solvay. A factory being built in Louisville, KY will be operational in 2019.

- Ionic Materials—Based in Woburn, MA, Ionic Materials is developing solid state batteries using a plastic electrolyte. Investors include Renault-Nissan, Mitsubishi, Hyundai, and Hitachi.

- 24M—This MIT spinoff in Cambridge, MA has developed a proprietary manufacturing process to make semi-solid lithium-ion batteries. 24M has raised more than $60 million from venture capital firms and corporations such as Kyocera, based in Japan. Initial production will focus on stationary applications. 24M also plans to license its production technology to other manufacturers.[70]

It is worth noting that major multinational corporations headquartered in Japan, Europe, and South Korea are major investors in these U.S. battery start-ups.

64. Research by Bloomberg New Energy Finance projects that battery costs will fall 67 percent by 2030 as production scales increase and technology improves. See, https://www.bloomberg.com/news/articles/2018-03-22/electric-car-costs-set-to-fall.
65. See, "Factors Affecting U.S. Production Decisions: Why Are There No Volume Lithium-Lithium-Ion Battery Manufacturers in the United States?" ATP Working Paper 05-01, 2005 at http://www.modtech-corp.com/pdf/
66. "Why Boston Power Went to China," *MIT Technology Review*, Dec. 6, 2011 at https://www.technologyreview.com/s/426288/why-boston-power-went-to-china/#comments
67. https://cleantechnica.com/2019/01/20/tesla-gigafactory-1-timeline-a-deep-dive/
68. Tesla's Gigafactory 2 in Buffalo, New York produces solar cells and modules, not batteries.
69. https://www.autonews.com/article/20181210/OEM01/181219977/1-7b-battery-plant-in-georgia-won-t-be-enough-to-meet-industry-s-needs
70. https://qz.com/433131/the-story-of-the-invention-that-could-revolutionize-batteries-and-maybe-american-manufacturing-as-well/

As long as production is based in the United States, the nation will benefit from first-mover advantages and generate economic returns to the federal R&D that supported the innovations. This condition—domestic production–should be a fundamental requirement for any investments, public or private, to fund necessary translational research and to support commercialization of federally funded R&D.

These and many other start-ups are developing battery technology with the potential to provide the energy density needed to eliminate range anxiety in electric cars, and to achieve the cost breakthroughs necessary to lower the cost of battery packs. A few of these new battery technologies are reaching the point of scaled production, but their ultimate success remains undetermined. Raising sufficient capital to perfect new technologies and materials, to develop effective manufacturing processes, to conduct required tests to prove reliability over countless charge-discharge cycles, and to build the required high-volume factories remains a pervasive challenge for most startups. Meanwhile, large battery manufacturers in China, such as CATL and BYD, are rapidly building production capacity.[71] The risk cannot be ignored that Chinese producers will over-invest in production capacity, then flood global markets with low-cost exports, similar to what happened with solar panels ten years ago when world prices fell 80 percent.

Case 2: Sensors and Controls for Autonomous Vehicles

Autonomous vehicles use a combination of sensors, controllers, and software to understand conditions around them. Autonomy requires complex integration of inputs from multiple sensors that must be foolproof regardless of driving conditions. This integration must happen in real-time, requiring fast controllers, relays, and actuators, as well as control algorithms that avoid false positives while adapting and learning over time. This complex integration of sensor input, communication from other vehicles, and other likely sources of information must also be secure from hackers. Manufacturers and consumers will need the utmost confidence in the entire package of hardware and software, which will be amplified by the eventual ubiquity of autonomous vehicles. This level of confidence will only be possible from a strong domestic supply base, some of which is currently lacking.

Sensors required for vehicle autonomy include cameras, radar, and lidar (light detection and ranging). Cameras typically use high-definition CMOS image sensors currently sourced from Asia, which has an extensive production base for the components of digital cameras and smartphones. The leading camera sensor producers include Sony and Toshiba in Japan, Omnivision in Taiwan, and SK Hynix in South Korea. A U.S. start-up, Light, has developed technology to combine images from ten or more lenses to create high-resolution images; the company is exploring mobile applications of the technology. So far, at least, manufacturing is in China.[72]

Radar sensors for both short range (24 gHz) and long range (77 gHz) monitor surrounding objects and traffic. Chinese producers dominate the supply of radar sensor modules.

Lidar provides perhaps the greatest opportunity to develop a domestic supply base. More than 100 start-ups, many U.S. based, have raised more than $1 billion since 2015,[73] vying to develop lidar sensors with sufficient range—at least 200 meters—and low cost, ideally below $1000 per unit. Lidar captures reflections from laser pulses to detect the vehicle's surroundings. Some companies, such as Velodyne, the industry leader, spin the lasers and receptors mechanically to achieve full field of vision. Other solid state technologies, such as optical phased arrays, avoid mechanical mechanisms and may be less expensive and more reliable for automotive applications. Velodyne announced its solid state version in 2017. Quanergy, a Silicon Valley start-up with a recent valuation over $2 billion and production based in Sunnyvale, CA, claims to have the smallest lidar sensor on the market with a range exceeding 100 meters costing under $250.[74] Luminar Technologies, based in Orlando, uses a longer wavelength laser—1550 nanometers instead of the typical 850 or 905 nanometers—to achieve a range over 200 meters, enhanced detail, and less reflectivity than competitors. It began volume production in 2018 and is working with multiple automotive companies, including Volvo, Volkswagen, and Toyota. Another Silicon Valley start-up, Cepton, claims to achieve high-resolution and

71. https://www.merics.org/en/blog/chinas-battery-industry-powering-global-competition.
72. https://light.co/
73. CBInsights data, as reported by Axios. https://www.axios.com/newsletters/axios-autonomous-vehicles
74. https://www.businesswire.com/news/home/20171220005199/en/Quanergy-Opens-Automated-Factory-Mass-Produce-Solid

200 meter range with volume production beginning in 2019. Cepton has partnered with a large Japanese headlight supplier, Koito, to integrate its lidar sensors into headlight designs.[75] Finally, Waymo has announced that it will begin selling its lidar sensors to other companies this year. Production will be at several facilities in California and a new factory planned for southeast Michigan.[76] Other startups competing for what is expected to be a multi-billion dollar automotive market are located in China, Israel, Canada, Germany, and Australia.[77]

Analyzing the data flowing from these multiple sensors in real-time and using the information to actuate vehicle controls precisely and consistently is a huge technical challenge. Although electronics continue to rise as a proportion of total vehicle cost, projected to increase from roughly one-third today to half by 2030, to date these have not required the processing power and speed that autonomy will need. One system in development processes data at a rate of 2.5 billion inputs per second. Multiple technologies will need to be implemented, ranging from an on-board communication network to sophisticated processors likely specially built for this application.

Sensor integration will require a shift from multi-layer printed circuit boards (PCBs) with complex designs and bulky form factors to high-density interconnects (HDI) like those currently used in smartphones and other portable devices. HDIs enable more functions per area using finer lines, thinner materials, and laser-cut micro-via technology. Most current uses for HDIs are products manufactured in Asia. Because 90 percent of global PCB production is in Asia and only 5 percent in this country, DoD has long expressed concern that U.S. PCB producers are aging and failing to keep up with the state of the art, including HDI. In multiple cases, domestic producers are on the verge of closing domestic production facilities and sourcing from Asia, mostly China.[78]

Although the United States remains the second largest automotive market in the world, and significant investments are being made in autonomous vehicles by both traditional industry players and new entrants such as Waymo and Uber, the jury is still out regarding the location of production of key vehicle inputs, despite some bright spots. Proactive policies are needed to continue to develop superior technology and to ensure domestic production of the entire spectrum of critical inputs. Only by manufacturing all of the technology needed for the electric autonomous vehicles of the near future can the United States a) ensure full control of the technology, b) compensate for the employment transitions resulting from the shift from traditional to electric vehicle production, and c) ensure a strong commercial production base for many of the dual-use technologies needed by the military. The industry is too important to domestic manufacturing and national security to lose control of its supply chains.

Case 3: Flexible Electronics

Flexible electronics have been the subject of extensive R&D since at least the 1990s, much of it funded by the U.S. military. Despite initiatives such as FlexTech (originally the U.S. Display Consortium, then the FlexTech Alliance); the Flexible Display Center at Arizona State University; NextFlex, the Manufacturing USA institute for flexible hybrid electronics; and numerous research achievements at U.S. universities, broad-based manufacturing of flexible electronics and displays has not emerged in the United States. Some estimates predict a market worth nearly $90 billion by 2024 with most of that growth expected to be in consumer electronics; automotive, healthcare, and industrial applications should also see significant growth.[79] Unfortunately, the United States has very little production base in many of the product lines expected to have the highest application of flexible electronics: smartphones, portable computers, and large displays.

Asian industrial groups, including Samsung, LG, and Hanwha in S. Korea, Fuji Electric in Japan, and BOE Technology in China, lead in commercializing flexible electronics products. Most of the critical intellectual property associated with many products, such as OLED displays, was acquired from Western sources.[80] However, a recent analysis of over 3,200 patents for

75. See, https://arstechnica.com/cars/2019/02/the-ars-technica-guide-to-the-lidar-industry/
76. See, https://www.forbes.com/sites/alanohnsman/2019/01/22/waymo-adding-a-michigan-factory-and--hundreds-of-jobs-to-build-self-driving-vehicles/#2d801f914e63
77. See, https://www.technavio.com/blog/top-companies-global-automotive-lidar-sensors-market
78. Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain, p. 42.
79. See, https://www.grandviewresearch.com/industry-analysis/flexible-electronics-market
80. Committee on Best Practice in National Innovation Programs for Flexible Electronics, *The Flexible Electronics Opportunity*, Washington: National Academy Press, 2014, p. 73.

thin film transistors used in flexible electronics found that the United States is well behind Japan and S. Korea in initial patent filings, which is consistent with the commercial focus of Asian producers. Only two U.S. companies, Kodak and Fuji Xerox, were found to have a significant patent portfolio in the technology.[81] Despite U.S. leadership in the initial research that created the technology, the locus of continued technology development and product commercialization has moved to Asia. Their R&D focus has been on production technologies, not basic research. Arguably, flexible electronics are a clear case of technology development following manufacturing capacity to Asia leaving the domestic production base to small niche players. Especially for display technologies, any significant U.S. production needs to come from foreign firms establishing factories here or American producers licensing foreign technology.

One area in which the United States may build a competitive advantage is the processing equipment and materials needed to manufacture flexible electronics. 3M and other domestic firms make flexible substrates and other materials. Kateeva, a Silicon Valley start-up, makes machines that use inkjet technology to print OLED screens, both hard and flexible. In 2016, Kateeva raised $88 million from a group of Chinese investors[82] and its customers all appear to be in Asia, including Samsung and LG in South Korea and BOE Display and CTL in China.

Another promising area for U.S. producers is flexible substrates. Work at universities such as Purdue, MIT, Arizona State, and Northeastern; companies such as 3M, Molex, and Brewer Science; and research institutes such as NextFlex and the Nano-Bio Manufacturing Consortium is developing an increasing number of options for flexible substrates. Examples include polymers, flexible glass, fabrics, metal foils, and flexible ceramics. Selection of substrate depends on the application, with trade-offs regarding cost, throughput, electrical, thermal, and mechanical properties, packaging, and transparency, among many considerations. Printing with conductive inks is creating new opportunities for cost-effective, high-volume manufacturing.[83]

Though R&D continues, products utilizing flexible electronics are emerging in segments such as medical devices, wearable electronics, sensors, and near-field communication tags. These are likely to be the target markets for U.S. producers, not large flexible displays or foldable smartphones for which both the production and R&D expertise has solidly moved to Asia.

Case 4: Semiconductor Packaging

Semiconductor packaging is the process by which semiconductor devices or integrated circuits are encased in metal, glass, plastic, or ceramic packages to protect them from the environment, dissipate heat, and provide the means to connect them to PCBs. Packaging moved to Asia in the 1980s because it was labor intensive, but as circuit density has increased, packaging has become more complex and is now fully automated. Automation alone creates opportunities to reshore packaging to provide greater domestic control of the full production process, but emerging responses to technical challenges in the industry are creating opportunities to build competitive advantage from packaging.

As circuit density approaches the limits of Moore's law—current state of the art is 7 nanometers, though most fabrication foundries and devices are larger[84]—new packaging technologies are emerging to achieve high performance in a small size. System-in-Package (SiP) allows firms such as Apple to mix multiple components—central processors, logic, analog, and memory—into a single package to reduce overall system size. The emergence of SiP and continued advances in the technology create an opportunity to re-establish packaging capability in the United States as existing packaging facilities become obsolete.[85]

With appropriate incentives, SiP operations could be built near U.S. existing fabs, which could then create advantages to establishing circuit board assembly plants nearby, too. By taking advantage of a discontinuous technology, SiP, much more of the semiconductor value chain could be rebuilt in this country with positive impacts on defense electronics and most other hardware sectors as digitalization becomes pervasive.[86]

81. See, https://sagaciousresearch.com/flexible-electronics-patent-landscape-report/download/Flexible_ Electronics.pdf
82. Paul Mozur and Jane Perlez, "China Bets on Sensitive U.S. Start-Ups, Worrying the Pentagon," *New York Times*, 3/22/17 at https://www.nytimes.com/2017/03/22/technology/china-defense-start-ups.html
83. See, https://semiengineering.com/non-traditional-chips-gaining-steam/
84. For example, Intel's Core i7 "Coffee Lake" processors are built on 14 nm nodes; most of AMD's Ryzen processors use 12nm.
85. Shih, W. (2018). Can an integrated semiconductor manufacturing capability be restored in the United States? Unpublished manuscript. Harvard Business School, Cambridge, MA
86. *Manufacturing Prosperity*, p. 38.

Changes in Manufacturing Technology

As these few important industries illustrate, the United States is at risk of continuing to lose control of critical technologies for commercial and defense industries, but also has the opportunity to take advantage of strong domestic innovation to rebuild essential industrial capabilities. Past patterns can be reversed. The mechanisms to secure needed growth in productivity are emerging, mostly in the form of smart manufacturing technologies but also including advances in key production processes. Ensuring the long-term, broad-based success of U.S. manufacturing will require rapid adoption of smart manufacturing technologies: first mover advantages are strong and network effects are significant. Research by McKinsey has shown that 1) the cost savings and profit increases enabled by smart manufacturing technologies—through more efficient production, higher capacity utilization, rapid design iterations, etc.—more than compensate for the necessary investments, 2) extending the technology throughout supply chains provides tighter integration of the full production network, generating efficiencies and greater profitability across the value chain, and 3) the resulting financial benefits are greater the more rapidly the technologies are implemented as costs drop, flexibility increases, and customer satisfaction rises.[87]

Developing and transitioning new manufacturing technologies, including smart manufacturing, is identified as a core component of the U.S. National Advanced Manufacturing Strategy released in October 2018.[88] Achieving this will require a combination of workforce training, investment incentives, and technical and financial assistance to ensure that manufacturers, especially SMMs, have the knowledge, wherewithal, and confidence to upgrade their operations.

Examples of smart manufacturing technologies include:

- Additive manufacturing: Also known as three-dimensional (3-D) printing, additive manufacturing (AM) uses a growing variety of methods and materials to build parts, components, and sub-assemblies directly from computer models. Until recently, AM has most commonly been used for rapid prototyping of new designs, but technical advances are enabling faster production, manufacture of metal parts, and in some cases, production of large parts and assemblies resulting in fully operational final products. Metal AM is especially important to continued penetration of the technology beyond prototyping. A few American companies, such as Desktop Metal, HP, Markforged, and Stratsys, have established leading positions in metal AM.

- Robotics: Rapid advances in robotics have created robots with better sensory perception and manipulative ability, allowing use of robots for a broader variety of tasks. Collaborative robots, or cobots, are able to work side-by-side with people, providing greater flexibility and higher utilization rates. In some cases, companies "hire" cobots, paying an hourly rate rather than incurring up-front capital expenses.[89]

- Production monitoring: A suite of sensors embedded or retrofitted to industrial equipment can monitor conditions in the factory and individual machines.[90] These sensors and the control systems that use the resulting data are becoming more affordable and easier to use and integrate into existing software systems. They enable operational improvements such as predictive maintenance to minimize or eliminate downtime, inventory tracking to minimize work-in-process, higher quality by identifying the source of flaws and initiating corrective action, and improved work flow to maximize capacity utilization.

- Data analysis and systems integration: Manufacturers are taking advantage of a growing flow of data, from production data on the shop floor to data from customers on use and satisfaction with the product. Large manufacturers and their suppliers are able to integrate their design, engineering, purchasing, and production systems to maximize efficiency while allowing greater customization and minimizing waste. Digital platforms are emerging to facilitate this data flow, and cloud computing has made storing, processing, and sharing data easier and more affordable.

- A challenge facing manufacturers is collecting the right data, assuring its integrity, and applying appropriate analytics to inform decisions.

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87. See, https://www.mckinsey.com/business-functions/operations/our-insights/lighthouse-manufacturers-lead-the-way
88. National Science and Technology Council, "Strategy for American Leadership in Advanced Manufacturing," October 2018.
89. Examples include Ready Robotics and Hirebotics. Both provide Robotics as a Service.
90. Examples of sensors include thermocouples, accelerometers, strain gages, cameras, and microphones.

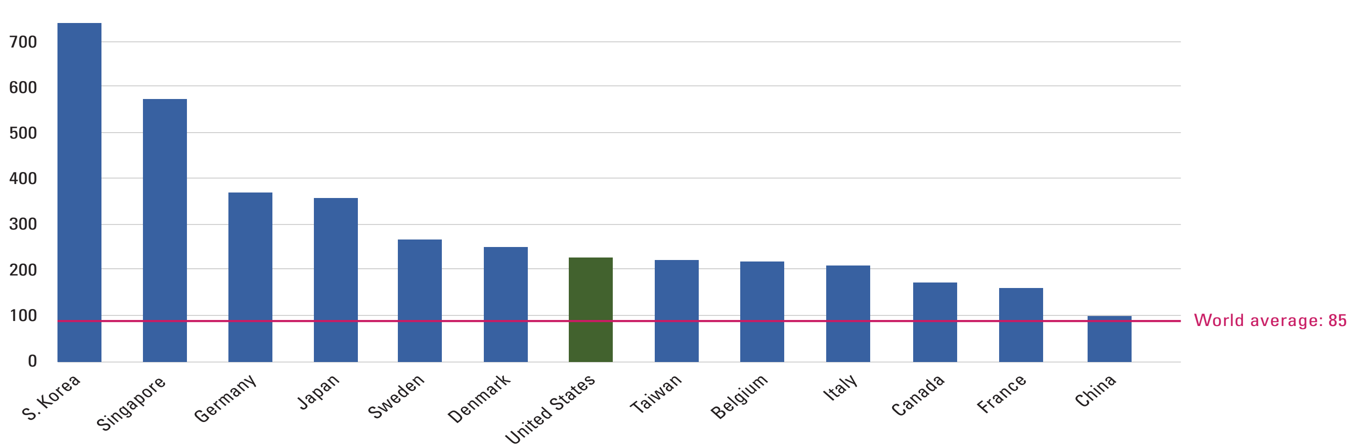
These are examples of technologies that are available now. Over time, other emerging technologies, such as machine intelligence and high-speed mesh communications to fully enable the IIoT, will become available, affordable, and essential. The promise of these technologies is a much more efficient, flexible manufacturing base. Not only will they enable greater customization of output as customer demands shift, but also allow smaller lot sizes and cost-effective production of complex parts. The more these technologies are implemented, the more likely U.S production will increase. They reduce the value of low-cost labor—labor content becomes a negligible portion of production costs—while raising the value of quick response to customer demand and, therefore, encouraging factory location decisions based on proximity to customers.

Unfortunately, the United States may already be falling behind in both development and implementation of smart manufacturing technologies. For example, in its recent report, *Fourth Industrial Revolution: Beacons of Technology and Innovation in Manufacturing*, the World Economic Forum surveyed over 1,000 manufacturing sites worldwide, identifying 16 as the most advanced. Only one is in the United States.[91] Other data indicate that technology used by U.S manufacturing industries ranges in age from 2.5 years in motor vehicles to over 6 years in chemicals, with an average of 4.6 years.[92] SMMs are even slower to invest in new technologies, frequently turning to used or refurbished machine tools for expansion or replacement.

Competing nations have already established a clear lead on the United States in implementation of robots (Figure 14).[93] China has made robotics a priority industry in China 2025. The new generation of cobots, are not caged or fenced, but work side-by-side with workers. They are safe, less expensive, and easier to deploy. Most importantly, when deployed sensibly, they increase productivity, create new business opportunities, and free workers to be more creative and innovative, key ingredients to long-term business success.

Smart manufacturing technologies, combined with other advances in production processes and materials, create the conditions to rebuild the U.S. industrial base, but success only comes if the technologies are implemented. National resources need to be mobilized to provide a combination of technical and financial assistance, especially to SMMs; updated educational programs to provide the necessary technical and analytical skills, systems integration, and market knowledge; and investment in communications infrastructure.

Figure 14: Robots per 10,000 Employees in Manufacturing, 2017, selected countries

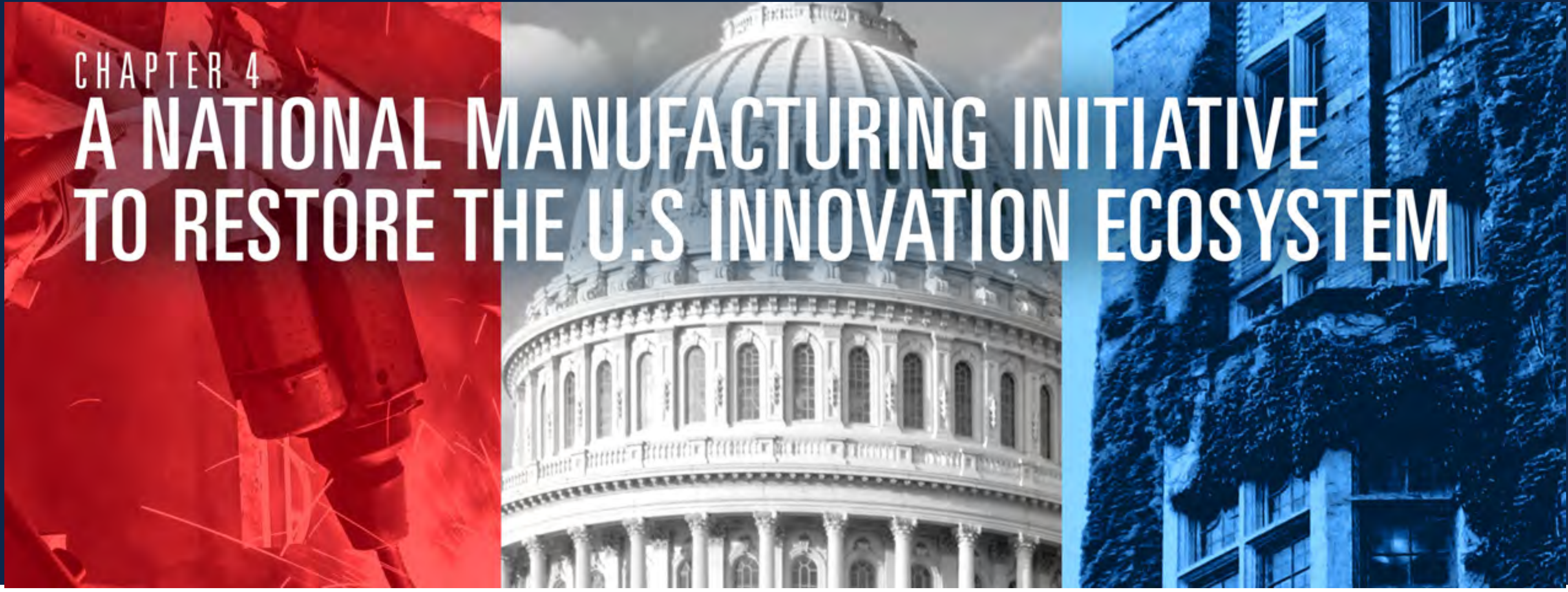


Source: International Federation of Robotics, 2018

91. See, http://www3.weforum.org/docs/WEF_4IR_Beacons_of_Technology_and_Innovation_in_ Manufacturing_report_2019.pdf
92. Mandel, p. 20.
93. International Federation of Robotics, *World Robotics Report 2018*, at www.ifr.org

Widespread implementation of smart manufacturing technologies is a necessary but insufficient condition for restoring the long-term health of U.S. manufacturing. These technologies will help to shift the business case away from offshore production, but other steps are needed to use advanced technology to build long-term manufacturing competitive advantage. First, managers and strategists must recognize that smart manufacturing technologies and the software-based tools that enable rapid design iterations and product and process simulations are also available to competitors. These tools accelerate the ability to copy process innovations, speed development cycles, lower barriers to entry, and lead to rapid commoditization of entire product categories.[94] Second, the essential inputs to important future industries must be produced in the United States. For example, the myriad technological inputs to autonomous electric vehicles—batteries, sensors, controllers, displays, etc.—should be produced here, not only to ensure a production base for a very large industrial sector but also to guarantee that innovation continues here. Other technologies and industrial sectors, such as those identified in recent DoD reports, must also maintain comprehensive domestic production capabilities. Third, the ability to produce new technologies that emerge from the nation's R&D investments is essential to creating new industries and new competitive advantages for the United States. Funding research for the sake of knowledge creation is admirable in the abstract, but **generating wealth by commercializing the results of R&D whenever possible is the best long-term justification for continued investment. If those benefits accrue to foreign manufacturers, support for continued public R&D funding could wane quickly.**

94. Willy Shih, "Why High-Tech Commoditization is Accelerating," *MIT Sloan Management Review*, Summer 2018.



CHAPTER 4
A NATIONAL MANUFACTURING INITIATIVE TO RESTORE THE U.S INNOVATION ECOSYSTEM

Given the pervasive and persistent pattern of weakness in the U.S. manufacturing sector, indicated by weak productivity growth, output increases in just a few industries, falling numbers of SMMs, shortages of skilled trades and engineering expertise, expanding trade deficits in advanced technologies, and growing risks to defense production, it is clear that major changes are needed. The relatively low level and piecemeal support for manufacturing, especially compared to major international competitors, is clearly insufficient to advance U.S. manufacturing despite the opportunities being created by smart manufacturing technologies, advanced materials, and other innovations. Continuing to rely solely on market forces to ensure a strong national manufacturing sector has proven to be fallacious. A new approach is necessary, not only to generate wealth from the nation's investment in R&D but also to restore the industrial commons and respond to the initiatives of international competitors.

Currently, no federal agency has the health of the nation's manufacturing as its primary mission. DoD has the most critical interest and has a variety of relevant programs and initiatives, but simply focusing on critical defense manufacturing capabilities will not ensure a strong commercial production base. Furthermore, justifying programs to support manufacturing solely on the basis of national defense disregards the crucial high-wage employment, innovation, and wealth building that only a strong, balanced commercial manufacturing sector can provide. Other agencies, such as DoE, NIST, and DoC, have direct interaction with manufacturers and programs to support industry, but together all of these programs and funding initiatives are piecemeal. Recent history has proven that this approach does not work.

Recent history has also proven that manufacturing matters to the wealth and security of the nation. Bold steps are needed commensurate with this importance. Strategic, significant, coordinated, and sustained government action is essential to rebuild the industrial commons, restore lost capacity to produce hardware innovations, and strengthen the ability to manufacture at scale so the nation can establish and lead the industries of the future. Although the mechanics of implementation can take many forms, the overall effort can be considered a National Manufacturing Initiative (NMI) that sets rebuilding U.S. manufacturing as a national imperative.

Similar in concept to, but more ambitious than, other federal initiatives, such as the National Robotics Initiative and the National Nanotechnology Initiative, an NMI would mobilize the entire federal government and engage the private sector to rebuild the nation's manufacturing competitiveness. Through a combination of strategic agency coordination, modification and augmentation of existing programs, and creation of new programs as needed, an NMI will provide a renewed national emphasis on manufacturing. Specific features of this proposed initiative include:

1) **Fund Translational Research:** The United States must take the necessary steps to ensure that breakthroughs in research are commercialized here. Achieving this requires additional funding for the translational research needed to advance both technology and manufacturing readiness levels (TRLs and MRLs). Too many research results languish as prototypes in academic and national laboratories, or worse, are commercialize abroad. The NMI would include the resources needed to create a series of Translational Research Centers

(TRCs), strictly focused on advancing TRLs and MRLs, that would continue development of research results to increase the flow of commercial products. As envisioned, these TRCs would be based at, though separate from, research universities; would be structured as public-private partnerships; and would be subject to clear metrics used to gage success and eligibility for continued funding. The TRCs would also have the flexibility to generate financial benefit from supported technologies that are successfully commercialized, either through equity stakes in start-up companies, sharing of licensing income, or some other mechanism.

In contrast to many of the few (14) existing Manufacturing USA institutes, TRCs would not be technology specific. They would be established initially at major research universities in states with high concentrations of manufacturers, gradually expanding to nearly all research universities with each TRC covering multiple smaller universities in a region. Their purview would not be predetermined, but would flow from local decisions about the most promising technologies, those most likely to reach successful commercialization after advancing their TRLs and MRLs. All commercial production of the resulting technologies would be located in the United States.

The TRCs would be closely networked to avoid overlap and duplication. For instance, translational research to advance the MRL of a technology using composite materials might also be applicable to ceramic or metamaterial production. Opportunities to share results, both successes and failures, would accelerate the learning process to the benefit of TRC operations and the success of emerging technologies.

2) **Fund Applied R&D**: In addition to support for translational research, the NMI would provide increased funds for applied research on technical issues common to multiple industrial applications. Examples include application of machine intelligence in varied production environments, cybersecurity, use of technology to decrease environmental impacts, and both production and implementation of multiple technologies needed to address other national priorities.

3) **Create Manufacturing Investment Funds:** Manufacturing Investment Funds created through public-private partnerships would raise the availability of capital for hardware start-ups. These funds would fill a gap in the venture capital markets and allow hardware start-ups to scale production in this country beyond pilot plants. They would complement the technical support provided by the TRCs with financial investments to rapidly increase the number and likely success of hardware start-ups. Several states already have small funds based on public-private partnerships that could serve as models. State investment banks, commonly used in Germany and other European nations, could also provide insightful lessons.

4) **Strengthen Support for SMMs:** Significantly more financial and technical support is needed for SMMs to rebuild domestic supply chains and strengthen the network of local contract manufacturers. In particular, SMMs need help to accelerate their implementation of smart manufacturing technologies and to access the skills required to utilize these technologies effectively. A combination of technical assistance and financial support, in the form of loans, grants, loan guarantees, and tax incentives, would be included in the NMI, augmenting the work of existing programs such as the MEP and technical assistance offered by DoE's national laboratories.

5) **Fund More Technical Training:** The NMI would provide resources, typically in partnership with state and local governments, to replicate successful training programs that will effectively grow the domestic supply of skilled engineers and engineering technicians.

Funding and Implementation

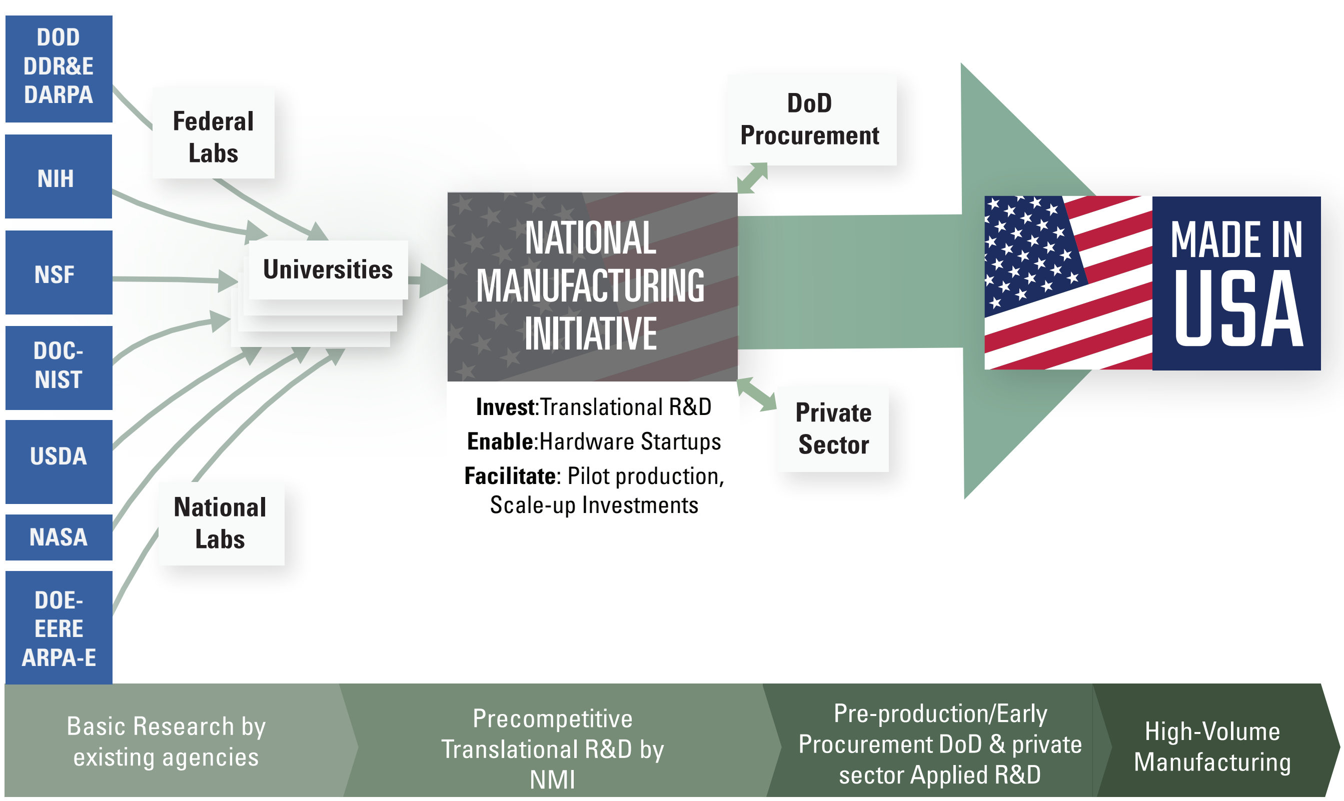
As previously documented in *Manufacturing Prosperity*, the national manufacturing community strongly supports these various elements of a National Manufacturing Initiative. The case for an NMI is not based solely on the need for greater funding for translational research and the other priority areas listed above, but also as a national rallying point for the public and private action needed to rebuild advanced manufacturing in the United States. Effective implementation will be critical. Achieving the desired outcomes will require cooperation between public, private, and academic resources; coordination across existing government agencies and programs; clear metrics to determine effective use of funds, replicate successes, and implement course corrections; and strong leadership to rally and maintain national focus. The NMI should become the touchstone for the strategic goal of restoring U.S. manufacturing, regardless of the administrative mechanisms chosen to implement it.

With its mission focused on holistic rebuilding of national manufacturing capabilities, the NMI should be funded commensurately. At least 5 percent of total federal R&D funding is appropriate, although that amount would be less than competing nations, such as Germany, Japan, and South Korea, that spend 7-30 percent of their federal S&T budgets on translational research. To put this in perspective, **the U.S. IP Commission has estimated that the cost to the U.S. economy of IP theft, counterfeit goods, and pirated software by Chinese actors could be nearly $2 billion per day![95]**

A start-up period would be needed to establish an effective operational model that includes not only administrative structures and talent, but also draws in experienced engineers and business leaders. These experts would engage with researchers to identify promising technologies, design and conduct the necessary translational research, and build the financial, legal, and technical mechanisms needed to transfer production to U.S.-based factories.

Although funds are needed for fellowships, loan guarantees, and support services, the majority of

Figure 15: Role of the National Manufacturing Initiative



95. White House Office of Trade and Manufacturing Policy, "How China's Economic Aggression Threatens the Technology and Intellectual Property of the United States and the World," June 2018, p. 5

funds should be used for funding engineering and manufacturing R&D at universities, federal laboratories, and TRCs, to bridge the gap between research and manufacturing, and to make needed advances in technology and manufacturing readiness that will reduce the risk of commercialization by domestic manufacturers. The NMI would engage multiple federal S&T agencies (DoD, NSF, ARPA-E, NASA, etc.) to maximize the impact of their funding by setting technology priorities, maturing promising product and process technologies, accessing relevant expertise, and leveraging procurement opportunities to meet defense mission requirements. The NMI would also coordinate closely with agencies that provide key services to manufacturers, such as the International Trade Administration and the Hollings Manufacturing Extension Partnership.

It is important for the NMI to have key objectives and metrics early in its existence. With the overall objective to strengthen foundational manufacturing and to advance domestic full-scale production of new hardware technologies emerging from federally funded R&D, metrics should be devised to determine progress toward meeting those objectives. Metrics to consider include the number of technologies successfully reaching commercial production; private sector job creation; new manufacturing facilities built in the United States; domestic availability of critical defense technologies; exports of advanced hardware technologies; and return on investment for both public and private stakeholders. Consistent tracking of metrics will allow for timely assessments and course corrections to ensure that the NMI remains focused on the success of the U.S. manufacturing sector and that NMI funds provide a return on investment to taxpayers who are funding over $150 billion of R&D annually through various federal agencies.

The NMI would provide a focal point for the federal government's efforts to strengthen civilian manufacturing, a necessary condition for strong defense production. The DoD would work within the framework of the NMI to support translational research in technologies important to defense. The NMI would also facilitate connections between hardware start-ups and other federal agencies, especially the DoD, to leverage federal purchasing power as a lead customer. Government purchase orders can be used by new manufacturers to get financing for plant and equipment to scale production.

The NMI would intently focus on the success of domestic manufacturing. Procedures should be implemented to limit the possibility that the technologies, products, and processes supported by the NMI leak to foreign competitors. After all, the guiding mission of an NMI is to coordinate national resources to strengthen domestic manufacturing and to build the industries of the future in the United States.

Finally, if managed appropriately in collaboration and partnership with the private sector, NMI operations should accelerate technology commercialization without the specter of "picking winners and losers." Government has played an indispensable role in American industrial development throughout history. Government mandates in areas such as emissions control and vehicle safety, government mission priorities in space and defense, and long-term technical support in agriculture and electronics are all ways that the U.S. government has supported industrial development and global leadership. In fact, two leading U.S. manufactured exports are aircraft and weapons, areas with significant government R&D investment.[96]

Creating a National Manufacturing Initiative is commensurate with the importance of manufacturing to long-term national wealth and security. By leveraging the discoveries and inventions emerging from existing R&D programs with a commitment to strategic, sustained investment in manufacturing, the NMI would help to establish the hardware industries of the future in the United States. The result will be a manufacturing sector that produces high-value defense, industrial, and consumer products with broad-based supply chains, diverse industrial clusters, and the foundational support for high-paying services that depend on strong manufacturing.

96. Between 2013 and 2017, the U.S. accounted for 34% of global arms exports.https://www.graphicnews.com/en/pages/38243/MILITARY-Sales-of-U.S.-weapons-soar

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