NATIONAL STRATEGY FOR ADVANCED MANUFACTURING

A Report by the

SUBCOMMITTEE ON ADVANCED MANUFACTURING

COMMITTEE ON TECHNOLOGY

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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Under section 102 of the America COMPETES Reauthorization Act of 2010 (42 U.S.C. §6622), as amended, the NSTC Committee on Technology is responsible for planning and coordinating Federal programs and activities in advanced manufacturing research and development and developing and updating a quadrennial national strategy for advanced manufacturing. The Subcommittee on Advanced Manufacturing (SAM) addresses these responsibilities and is the primary forum for information-sharing, coordination, and consensus-building among participating agencies regarding Federal policy, programs, and budget guidance for advanced manufacturing.

About this Document

This 2022 National Strategy for Advanced Manufacturing, developed by the SAM following extensive public outreach, is based on a vision for United States leadership in advanced manufacturing that will grow the economy, create quality jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare. This vision will be achieved by developing and implementing advanced manufacturing technologies, growing the advanced manufacturing workforce, and building resilience into manufacturing supply chains. Strategic objectives are identified for each goal, along with national technical and program priorities and recommendations for the next four years.

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Abbreviations and Acronyms

2D/3D	two-dimensional/three-dimensional
AI	artificial intelligence
AM	additive manufacturing
AR	augmented reality
BARDA	Biomedical Advanced Research and Development Authority
BEA	Bureau of Economic Analysis
CAP	cross-agency priority
CEA	Council of Economic Advisors
CMOS	Complementary Metal Oxide Semiconductor
COVID-19	Coronavirus disease 2019
CO_2	carbon dioxide
CTE	career and technical education
DEIA	Diversity, Equity, Inclusion, and Accessibility
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DOS	Department of State
ED	Department of Education
EDA	Economic Development Administration
EERE	Office of Energy Efficiency and Renewable Energy
EOP	Executive Office of the President
FDA	Food and Drug Administration
FY	fiscal year
GHG	greenhouse gas
HHS	Department of Health and Human Services
HI	heterogeneous integration
IC	integrated circuit
ICME	integrated computational materials engineering
I-Corps	Innovation Corps
IoT	internet of things
IIoT	industrial internet of things
IPCC	Intergovernmental Panel on Climate Change
ISM	in-space manufacturing
IT	information technology
K-12	kindergarten through high school
LGBTQ	lesbian, gay, bisexual, transgender, and questioning
MEP	Manufacturing Extension Partnership
MGI	Materials Genome Initiative
MIC	made in China
ML	machine learning
MSI	minority-serving institution
MRL	manufacturing readiness level
NEC	National Economic Council
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSTC	National Science and Technology Council
OEM	original equipment manufacturer
OMB	Office of Management and Budget

OSTP	Office of Science and Technology Policy
OT	operational technology
PPE	personal protective equipment
Perkins V	Perkins Career and Technical Education Act
R&D	research and development
RFID	radio frequency identification
SAM	Subcommittee on Advanced Manufacturing
SBA	Small Business Administration
SBIR	Small Business Innovation Research
SMMs	small and medium-sized manufacturers
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer
TRL	technology readiness level
R&D	research and development
U.S.	United States
USDA	United States Department of Agriculture
USPTO	U.S. Patent and Trademark Office
VR	virtual reality
WIOA	Workforce Innovation and Opportunity Act
XR	extended reality

Executive Summary

Manufacturing is an engine of America's economic strength and national security. It plays a vital role in almost every sector of the United States economy, from aerospace to biopharmaceuticals and beyond. Advances in manufacturing enable the economy to continuously grow as new technologies and innovations increase productivity, enable next-generation products, support our capability to address the climate crisis, and create new, high-quality, and higher-paying jobs.

The United States remains a leader in advanced technologies; however, production and employment in several high-technology manufacturing industries have fallen sharply in the 21st century. To address global competition, the United States has taken steps to revitalize the manufacturing sector, increase the resilience of U.S. supply chains and national security, invest in R&D, and train Americans for jobs of the future.

This Strategy presents **a vision for United States leadership in Advanced Manufacturing** that will grow the economy, create jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare.

Three interrelated goals are set to achieve the stated vision:

(1) Develop and implement advanced manufacturing technologies;

(2) Grow the advanced manufacturing workforce; and

(3) Build resilience into manufacturing supply chains.

To achieve these goals, 11 strategic objectives and 37 technical and program recommendations are identified for the next four years. The objectives are selected to:

(1) Enable clean and sustainable manufacturing to support decarbonization;
(2) Accelerate manufacturing innovation for microelectronics and semiconductors;
(3) Implement advanced manufacturing in support of the bioeconomy;
(4) Develop innovative materials and processing technologies;
(5) Lead the future of smart manufacturing;
(6) Expand and diversify the advanced manufacturing talent pool;
(7) Develop, scale, and promote advanced manufacturing education and training;
(8) Strengthen connections between employers and educational organizations;
(9) Enhance supply chain interconnections;
(10) Expand efforts to reduce supply chain vulnerabilities; and
(11) Strengthen and revitalize advanced manufacturing ecosystems

This Congressionally-mandated strategy seeks to improve U.S. Government coordination and provide long-term guidance for Federal programs and activities in support of U.S. manufacturing competitiveness, including advanced manufacturing research and development. Public input from over 700 individuals and organizations from across the country informed the strategy.

Introduction: Manufacturing and America's Future

Advanced manufacturing is defined as the innovation of improved methods for manufacturing existing products, and the production of new products enabled by advanced technologies. The United States remains a global leader in several advanced technologies.[1] Domestic and global demand has skyrocketed for the technologies and equipment needed to address the climate crisis. However, production and employment have fallen sharply in several advanced manufacturing industries. The trade balance in advanced technology products—a traditional strength of the United States—shifted from surplus to deficit starting in 2001, with a trade deficit of $197 billion in 2021.[2]

Manufacturing is one of the largest sectors of the United States economy[3,4] accounting for 11 percent of gross domestic product.[5] While relatively constant from 1960 through 1990, employment in the manufacturing sector began declining in the late 1990s; in the decade from 2000 to 2010, one-third of U.S. manufacturing workers (nearly six million people) lost their jobs.[6] Fewer than two million of those jobs have been regained. Notably, however, manufacturing employment is now above its 2020 peak, the first time since 1978 that it has exceeded its previous business cycle peak.

The COVID-19 global pandemic exposed the fragility of manufacturing supply chains, causing major shortages of key products such as medical supplies, critical minerals, and semiconductors.[7] To strengthen the manufacturing supply chain, small and medium size manufacturers (SMMs)—those who employ fewer than 500 workers, comprise 98% of the total number of manufacturers and account for 43% of the employees[8]—will require assistance from the United States Government and their larger customers and suppliers.

It is, therefore, imperative for the United States to develop and implement strategies to regain American leadership through investments in advanced manufacturing. Furthermore, the nation's manufacturing and industrial base underpins the U.S. military capabilities using advanced technologies to secure our democracy.

This Strategy updates the 2018 *Strategy for American Leadership in Advanced Manufacturing*[9] using public input.[10] It is mandated by the America COMPETES Reauthorization Act of 2010 which mandated the original advanced manufacturing strategy (of 2012) and updates every 5 years.[11] Appendix A illustrates Federal agency participation and metrics. Appendix B summarizes progress made since the publication of the *2018 Strategy.*

1 https://itif.org/publications/2022/06/08/the-hamilton-index-assessing-national-performance-in-the-competition-for-advanced-industries/

2 https://www.census.gov/foreign-trade/balance/c0007.html

3 https://www.nist.gov/el/applied-economics-office/manufacturing/manufacturing-industry-statistics

4 https://www.bls.gov/web/empsit/ceshighlights.pdf

5 https://data.worldbank.org/indicator/NV.IND.MANF.ZS

6 https://data.bls.gov/timeseries/CES3000000001 7 https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

7 https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

8 https://cdn.advocacy.sba.gov/wp-content/uploads/2021/08/30144808/2021-Small-Business-Profiles-For-The-States.pdf

9 https://www.manufacturing.gov/news/announcements/2018/10/strategy-american-leadership-advanced-manufacturing

10 https://www.Federalregister.gov/documents/2021/10/05/2021-21644/national-strategic-plan-for-advanced-manufacturing-request-for-information?utm_medium=email&utm_source=govdelivery

11 America COMPETES Reauthorization Act of 2010 (Pub L. 111-358) § 102; 42 U.S.C. § 6622.

Vision, Goals, Objectives, and Recommendations for Advanced Manufacturing

This Strategy is designed to realize a vision for U.S. leadership in Advanced Manufacturing that will grow the economy, create high-quality jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare.

Grow the Economy. Advanced manufacturing applies innovative technologies to produce new products and improve the production of existing products. Manufacturing jobs, and especially those in advanced technologies, provide better pay, more consistent hours, and stronger worker protection than the labor market as a whole and have broad impacts on jobs in other sectors[12]. These significant impacts make advances in manufacturing—and America's ability to translate those advances into products, processes, and services—an Administration priority and a key element of the nation's overall manufacturing strategy.[13]

Create High-Quality Jobs. Innovation and implementation of new technologies in advanced manufacturing requires a highly skilled and diverse workforce. The National Association of Manufacturers estimates that the United States could have more than two million unfilled manufacturing jobs by 2030.[14] Renewed investment in workers is needed, including education in foundational science ranging from elementary school through post-graduate degrees, technical training programs with industry-recognized credentials, apprenticeships and internships, and leadership development programs. The inclusion of individuals from groups historically underrepresented in advanced manufacturing and/or from underserved regions creates the opportunity to expand the manufacturing workforce and the concomitant economic benefit. The U.S. will prioritize upskilling the workforce and increasing the quantity and quality of advanced manufacturing jobs in rural areas and economically distressed regions to strengthen regional economic conditions, while recognizing the benefits of clustered economic development.[15,16] The U.S. will also invest in manufacturing processes which protect worker safety and health; such safety and human-centered processes, which protect and keep workers on the job, are essential to long-term global competitiveness.

Enhance Environmental Sustainability. Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources.[17] Incorporating sustainable material management principles and additive manufacturing into product design and development reduces the amount of material and energy required to manufacture a product and increases safety. The United States will improve environmentally favorable processes throughout the manufacturing sector, including the efficient use of clean electricity in materials processing and manufacturing, and in water processing.

Address Climate Change. The climate crisis poses an immediate and existential threat to national and global security, environmental and human health, and economic interests. The United States has committed to an ambitious and achievable goal to reduce net greenhouse gas (GHG) emissions 50-52

[12] https://www.epi.org/publication/manufacturing-still-provides-a-pay-advantage-but-outsourcing-is-eroding-it/
[13] https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/
[14] https://www.nam.org/2-1-million-manufacturing-jobs-could-go-unfilled-by-2030-13743/
[15] https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/
[16] https://eda.gov/arpa/build-back-better/
[17] https://www.epa.gov/sustainability/sustainable-manufacturing

percent below 2005 levels in 2030, create a carbon pollution-free power sector by 2035, and achieve net-zero emissions economy-wide by 2050.[18,19] Advanced manufacturing solutions can unleash new opportunities to cut pollution and reduce carbon emissions via industrial decarbonization, building a more circular economy, using sustainable biomass to replace petroleum-based products, and scaling up manufacturing of clean energy and other climate-aligned technologies, incorporating game-changing innovations to help achieve net-zero emissions across the entire economy.

Strengthen Supply Chains. The supply chains and ecosystems that support U.S.-based manufacturing have been weakened by several factors, including underinvestment in innovative technologies, insufficient investment in training, and outsourcing and offshoring for short-term gains.[20] The COVID-19 pandemic and shifting geopolitical competition have exposed these and other vulnerabilities, exacerbating economic loss while also revealing national security and health risks. The United States needs resilient, collaborative, and digitally integrated manufacturing supply chains to prevent and recover quickly from disruptions.

Ensure National Security. Advanced manufacturing technologies are critical to national security, delivering innovative capabilities to our nation's warfighters so the United States can sustain and strengthen defense against our most consequential strategic competitors.[21] Recognizing the increase in non-kinetic threats to the United States from strategic competitors, the nation must accelerate the pace of technology development and implementation as well as transformation of our manufacturing supply chains

Improve Healthcare. Advanced manufacturing can be used to produce numerous new and improved healthcare products, including small-molecule drugs, medical devices, biologics, vaccines, advanced therapies, and biocompatible materials. While biomedical manufacturing shares many cross-cutting technology needs with other sectors, it also has unique needs that dictate specifically tailored applications. Manufacturing processes and solutions must ensure safety and efficacy, promote human and animal health, and minimize drug shortages, while also securing the U.S. global leadership in pandemic response and preparedness.

Goals, Objectives, and Recommendations

This Strategy's vision will be accomplished through the pursuit of three goals. Attaining these goals requires achieving the strategic objectives and recommendations outlined under each goal. The goals, objectives, and recommendations for the next four years appear on the following pages. Appendix C contains further discussion of each recommendation.

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[18] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

[19] https://www.Federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

[20] While some offshoring and outsourcing has promoted efficiency, these strategies have sometimes also led to increased vulnerability and reduced job quality. See chapter 6 of https://www.whitehouse.gov/cea/written-materials/2022/04/14/summary-of-the-2022-economic-report-of-the-president/ and https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

[21] https://www.defense.gov/Spotlights/National-Defense-Strategy/

Goals	Objectives	Recommendations
Goal 1: Develop and Implement Advanced Manufacturing Technologies	1.1: Enable Clean and Sustainable Manufacturing to Support Decarbonization	1.1.1: Decarbonization of Manufacturing Processes
		1.1.2: Clean Energy Manufacturing Technologies
		1.1.3: Sustainable Manufacturing and Recycling
	1.2: Accelerate Manufacturing for Microelectronics and Semiconductors	1.2.1: Nanomanufacturing of Semiconductors and Electronics
		1.2.2: Semiconductor Materials, Design, and Fabrication
		1.2.3: Semiconductor Packaging and Heterogeneous Design
	1.3: Implement Advanced Manufacturing in Support of the Bioeconomy	1.3.1: Biomanufacturing
		1.3.2: Agriculture, Forest, and Food Processing
		1.3.3: Biomass Processing and Conversion
		1.3.4: Pharmaceuticals and Healthcare Products
	1.4: Develop Innovative Materials and Processing Technologies	1.4.1: High-Performance Materials Design and Processing
		1.4.2: Additive Manufacturing
		1.4.3: Critical Materials
		1.4.4: In-Space Manufacturing
	1.5: Lead the Future of Smart Manufacturing	1.5.1: Digital Manufacturing
		1.5.2: AI in Manufacturing
		1.5.3: Human-Centered Technology Adoption
		1.5.4: Cybersecurity in Manufacturing
Goal 2: Grow the Advanced Manufacturing Workforce	2.1: Expand and Diversify the Advanced Manufacturing Talent Pool	2.1.1: Promote Awareness of Advanced Manufacturing Careers
		2.1.2: Engage Underrepresented Communities
		2.1.3: Address Social and Structural Barriers for Underserved Groups
	2.2: Develop, Scale, and Promote Advanced Manufacturing Education and Training	2.2.1: Incorporate Advanced Manufacturing into Foundational STEM Education
		2.2.2: Modernize Career Technical Education for Advanced Manufacturing
		2.2.3: Expand and Disseminate New Learning Technologies and Practices
	2.3: Strengthen the Connections Between Employers and Educational Organizations	2.3.1: Expand Work-Based Learning and Apprenticeships
		2.3.2: Establish Industry-Recognized Credentials and Certifications
Goal 3: Build Resilience into Manufacturing Supply Chains	3.1: Enhance Supply Chain Interconnections	3.1.1: Foster Coordination within Supply Chains in Supply Chain Management
		3.1.2: Advance Innovation for Digital Transformation of Supply Chains
	3.2: Expand Efforts to Reduce Manufacturing Supply Chain Vulnerabilities	3.2.1: Trace Information and Products Along Supply Chains
		3.2.2: Increase Visibility into Supply Chains
		3.2.3: Improve Supply Chain Risk Management
		3.2.4: Stimulate Supply Chain Agility
	3.3: Strengthen and Revitalize Advanced Manufacturing Ecosystems	3.3.1: Promote New Business Formation and Growth
		3.3.2: Support Small and Medium-sized Manufacturers
		3.3.4: Assist Technology Transition
		3.3.4: Build and Strengthen Regional Manufacturing Networks
		3.3.5: Improve Public Private Partnerships

Goal 1. Develop and Implement Advanced Manufacturing Technologies

Recent advances in areas such as automation, data science, artificial intelligence, machine learning, biotechnology, and materials science, combined with urgent technical challenges in economy-wide decarbonization, healthcare, and national security are creating new opportunities for advanced manufacturing. In order to compete globally, the United States must leverage and protect its technology leadership through rapid development and implementation of innovative manufacturing technologies.

While typical Federal investments in advanced manufacturing-related research, development, and deployment focus on mission-specific goals within each agency, portfolio-based strategies coordinated across agencies would be more effective. Public-private partnerships to advance targeted technology sectors are key to developing and implementing new manufacturing technologies. Such public-private partnerships present the opportunity to create and share industry-relevant facilities where colocation of tools, technology, and embedded expertise can expand regional innovation ecosystems and drive economic growth both within and across regions.

Five strategic objectives have been identified under Goal 1:

1.1. Enable Clean and Sustainable Manufacturing to Support Decarbonization
1.2. Accelerate Manufacturing Innovation for Microelectronics and Semiconductors
1.3. Implement Advanced Manufacturing in Support of the Bioeconomy
1.4. Develop Innovative Materials and Processing Technologies
1.5. Lead the Future of Smart Manufacturing

For each objective, a set of recommendations is identified, with outcomes to be accomplished over the next four years.

Objective 1.1. Enable Clean and Sustainable Manufacturing to Support Decarbonization

Climate change is caused by the total amount of carbon dioxide and other greenhouse gases (GHG) added and persisting in the atmosphere. The manufacturing sector accounts for approximately one-third of the nation's primary energy usage and 30 percent of energy-related GHG emissions.[22,23] Manufacturing of industrial materials such as steel, cement, and chemicals also produces GHG emissions directly via chemical processes. Reduction of manufacturing-related energy consumption and GHG emissions is possible through the use of clean and efficient manufacturing technologies[24] and reduction of emissions over the full product life cycle.

The United States has committed to 50-52 percent reduction of net GHG emissions below 2005 levels in 2030, and net-zero by 2050.[25] The Inflation Reduction Act, signed into law in August 2022, in combination with the infrastructure modernization investments in the Bipartisan Infrastructure Law enacted in November 2021, will provide significant resources and incentives to help reach the climate and clean energy goals. These new resources, via the National Climate Task Force and the Executive Order on America's Supply Chains, will facilitate the efforts to advance clean energy and climate-aligned manufacturing across the U.S. Government. The manufacturing sector will be integral in these

[22] https://www.eia.gov/energyexplained/use-of-energy/industry.php;
[23] https://www.eia.gov/tools/faqs/faq.php?id=77&t=11
[24] https://www.whitehouse.gov/bipartisan-infrastructure-law/
[25] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

decarbonization efforts given the opportunities to decarbonize the manufacturing processes themselves, as well as the opportunities to scale up U.S. manufacturing of zero carbon equipment. Advanced manufacturing can enable lower cost, zero emission technologies in the energy, industrial, construction, and transportation sectors.

The recommendations for this objective are:

> ***1.1.1. Decarbonization of Manufacturing Processes:*** *Develop and demonstrate advanced manufacturing technologies that increase energy efficiency, electrify industrial processes, employ low-carbon feedstocks and energy sources in manufacturing, support new chemistries that avoid direct greenhouse gas emissions from industrial processes, capture and store industrial carbon dioxide, and create alternatives to GHG-intensive industrial products. Create and disseminate validation tools and processes to assist the integration of electrified and efficient technologies into manufacturing. Create transparency on advanced materials and processes with lower energy and carbon footprints.*

> ***1.1.2. Clean Energy Manufacturing Technologies:*** *Improve materials, manufacturing processes and product designs for clean electricity generation and storage; zero-emission transportation, buildings, and industry to enable a decarbonized economy. Enhance the manufacturing of devices and materials that enable more efficient power conversion and transmission with advanced conducting materials, processing technologies and machine development. Manufacture advanced batteries with high energy densities and secure novel sustainable materials for low- and high-voltage applications.*

> ***1.1.3. Sustainable Manufacturing and Recycling:*** *Develop economically viable manufacturing technologies that separate valuable materials from waste streams, as well as alternatives to energy- or pollution-intensive materials. Conduct R&D in the areas of sorting, purification, and deconstruction technologies. Scale up sustainable materials design and manufacturing, recycling and circular methods for multiple materials classes, and pilot programs and facilities. Improve data and methods to assess life cycle impacts and identify areas for improvement.*

Objective 1.2. Accelerate Manufacturing for Microelectronics and Semiconductors

Semiconductors are the foundation of microelectronics, and advances in semiconductor technology are critical for national security and for almost every sector of the economy.[26] They are the backbone of power electronic devices that control and condition the flow of electricity, enabling the charging of electric vehicles and integrating renewable energy sources into the power grid. The ubiquity of microelectronics provides opportunities to magnify sustainable manufacturing processes that account for climate, environmental, and other impacts over the product life cycle. The manufacturing industry faces fundamental performance limitations of complementary metal oxide semiconductor technology, diversification of the market beyond processors and memory, and intense global competition.

Future performance improvements require research into manufacturing and processing capabilities for new microelectronic materials, devices, and interconnect solutions that will power future computing and storage devices. The recent passage of the CHIPS and Science Act[27] into law in August of 2022, which provides investments in semiconductor infrastructure, will help achieve the objectives below.

[26] https://www.epa.gov/smm-electronics/national-strategy-electronics-stewardship-nses

[27] https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

The recommendations for this objective are:

1.2.1. Nanomanufacturing of Semiconductors and Electronics: *Invest in fabrication of integrated photonics, additive and direct printed electronics, unique sensor formats, and hybrid electronic fabrication to harness the power of nanomanufacturing. Develop physical, chemical, and biological methods to precisely place and bind atoms into desired molecules and structures.*

1.2.2. Semiconductor Materials, Design, and Fabrication: *Develop advanced manufacturing capabilities that allow the creation and testing of new devices, materials, and architectures. Provide easy access to design tools and microelectronics foundries for domestic companies and universities that provide fundamental insights and a trained workforce. Incorporate efficient and sustainable operations for microelectronics devices and components.*

1.2.3. Semiconductor Packaging and Heterogeneous Design: *Introduce new materials, tools, designs, processes, assembly, and tests for advanced packaging with higher densities, yields, and reliability. Enhance R&D and prototyping to improve manufacturing throughput and reliability. Develop national facilities for heterogeneous packaging integration R&D.*

Objective 1.3. Implement Advanced Manufacturing in Support of the Bioeconomy

The United States bioeconomy is "economic activity that is driven by innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences"[28] and includes industries, products, and services. In biomanufacturing, microbes and different organisms (bacterial cells, viruses, yeast, cyanobacteria, algae) can be programmed to make a variety of products such as food, feeds, fuels, fibers, bioplastics, natural rubbers, renewable chemicals, nutraceuticals, non-food materials, and other high value products. This process," utilizes sustainable biomass or a sugar source as the feedstock, providing an alternative to petrochemical-based production for many products like plastics, fuels, and materials.

In September 2022, an Executive Order was signed on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy.[29] This Executive Order calls for a whole-of-government approach to advance biomanufacturing to provide innovative solutions in health, climate, change, energy, food security, agriculture, supply chain resilience, and national and economic security. Priorities in the Executive Order are also outlined in this Strategy document, which include expanding domestic biomanufacturing capacity, connecting relevant infrastructure, and growing the biomanufacturing workforce.

Manufacturing is essential to next-generation medical therapies and devices that have biological interfaces with both humans and animals. By combining life science discoveries with advanced technologies such as those in smart manufacturing, the United States can make extensive leaps forward in the creation of high-quality bio-based products. Implementation of robust biosafety, biosecurity, and data privacy controls should be prioritized to ensure support of a bioeconomy that promotes and protects U.S. leadership, competitiveness, and national security.

To continue improving food safety, and food accessibility, and food supply chain resilience, advanced manufacturing processes must fully leverage new technologies and accelerate new fields such as cellular agriculture, alternative proteins, and personalized nutrition. Steps should be taken to create

[28] https://nap.nationalacademies.org/catalog/25525/safeguarding-the-bioeconomy
[29] https://www.whitehouse.gov/briefing-room/presidential-actions/2022/09/12/executive-order-on-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe-and-secure-american-bioeconomy/

more opportunities to further pursue lab-to-market biotechnologies and develop manufacturing scale-up and scale-out of emerging products. This section on manufacturing technologies addresses critical issues in health, disease, climate change, energy, food and nutrition security, economic development, and the continued development of a diverse and multi-disciplinary workforce.

The recommendations for this bjective are:

> ***1.3.1 Biomanufacturing:*** *Support research to advance biomanufacturing including genomic and protein engineering production tools, engineering of multicellular systems, biological models, and biotechnology methods for bioprocessing. Support advancement in multi-omics and bio-metrology for predictive modeling and bioprocessing analytical tools. Support enhancement of feedstock readiness, technical readiness, and manufacturing readiness level analytical tools. Prioritize implementation of safeguards to ensure that these products are not used for nefarious purposes.*

> ***1.3.2 Agriculture, Forest, and Food Processing:*** *Support research in advanced genome sequencing, bioinformatics, predictive modeling for functional phenotypes, and integration of control systems and the teaming of humans and machines in food, feed, fuel, and fiber manufacturing. Develop sustainable energy low-cost water processing technologies including nutrient recovery systems that produce fit-for-purpose water from waste streams and unconventional sources.*

> ***1.3.3 Biomass Processing and Conversion:*** *Develop methods, processes, and technologies to tap into the one billion tons of biomass that could be sustainably produced in the U.S. and converted into feedstocks for manufacturing. Advance predictive process modeling, biological process analysis and genomic and protein engineering for desirable biomass feedstock pre-processing, processing and deconstruction. Advance anaerobic treatment of bio-based waste streams to produce biogas, renewable natural gas, fertilizer, plant nutrients, soil amendments, biochar, engineered carbon, animal bedding material, surfactants, polymers, clean bioenergy, electricity, and combined heat/cooling power.*

> ***1.3.4 Pharmaceuticals and Healthcare Products:*** *Advance continuous manufacturing, in-line process monitoring and control, integrated AI-assisted systems, and novel cell culture techniques. Prioritize developments in subtractive and additive machining and biobased manufacturing to create patient-specific medical products, devices, and biologically-driven drug delivery systems.*

Objective 1.4. Develop Innovative Materials and Processing Technologies

Advanced materials are essential for the development of new products and economic and national security, with applications across multiple industrial sectors. Advanced materials may include extreme temperature structural materials used in hypersonics, materials for harsh environments, high-strength lightweight metal alloys, synthetic biologic materials, and many others. Using new materials often requires innovative manufacturing techniques. Advanced processes like additive manufacturing and nanomanufacturing create opportunities for new materials as design constraints are greatly relaxed. Processing technologies for new high-performance advanced materials can increase cost-effectiveness and competitiveness by replacing (or complementing) prevailing methods with faster, more efficient, precise, and robust methods. Advanced materials and processes can reduce life cycle greenhouse gases and other environmental consequences in manufacturing and product use.

The recommendations for this objective are:

1.4.1. High-Performance Materials Design and Processing *Advance material design and processing capabilities through the integration of physics-based computational and data-driven machine learning tools. Accelerate testing, qualification and process validation of high-performance materials to streamline entry into market. Develop predictive capabilities for materials behavior and performance under harsh service conditions.*

1.4.2. Additive Manufacturing: *Develop additive manufacturing (AM) process optimization frameworks that are accessible to all users. Create new sensors to advance process monitoring and control capabilities. Develop machine learning algorithms to analyze large, secure, interoperable data streams and realize feedback control. Produce tools to create new AM-specific materials and capabilities. Integrate additive manufacturing technologies with smart manufacturing platforms.*

1.4.3. Critical Materials: *Identify and integrate substitute materials and technologies to reduce or replace the use of critical materials in high-demand technologies. Develop advanced separation and processing methods for critical materials from primary, secondary, and unconventional sources. Develop design and manufacturing methods for critical components and products that can be reused, recycled, remanufactured, and repurposed.*

1.4.4. In-Space Manufacturing: *Develop new additive manufacturing processes in microgravity environments to create replacement parts and space infrastructure. Enable integration of robotics with in-space additive manufacturing processes for deep space exploration. Prioritize biomanufacturing investments in microgravity to enable extended space presence including sustainable food production, processing, and recycling, and the deactivation of hazardous materials.*

Objective 1.5. Lead the Future of Smart Manufacturing

Smart manufacturing via digital design and manufacturing collects and distributes the information needed by production equipment to transform designs and raw materials into products, resulting in a highly connected industrial enterprise that can span a single company or across an entire supply chain. Smart manufacturing distributes relevant information to every level of the enterprise, from the factory floor to the C-suite, thus improving product quality and traceability while reducing cost.

The Industry 4.0 paradigm describes transformational changes to technology, industry, and societal patterns and processes brought on by increased interconnectivity and smart automation. Future advances depend on the widespread adoption of a robust digital infrastructure in manufacturing, the availability of a digital-fluent workforce, and the creation of AI-powered manufacturing business models that aggregate data across manufacturers while protecting proprietary information. Such aggregation will provide manufacturing companies with better solutions than each company can develop on its own by giving them the benefit of accumulated production experience of all firms engaged in the network.[30]

The recommendations for this objective are:

1.5.1. Digital Manufacturing: *Enable the application of advanced sensing, control technologies, and machine learning across the manufacturing sector. Advance smart manufacturing by pursuing*

[30] https://doi.org/10.6028/NIST.AMS.100-47

digital twins. Develop standards for data compatibility to enable seamless integration of smart manufacturing.

1.5.2. Artificial Intelligence in Manufacturing: *Prioritize R&D in machine learning, data access, confidentiality, encryption, and risk assessment to enable the adoption of artificial intelligence in manufacturing. Develop best practices, standards, and software tools to scale new business models that monetize production data while maintaining data security and respecting intellectual property rights. Balance the interests of producers and consumers in areas such as privacy, intellectual property, and rights to repair.*[31]

1.5.3. Human-Centered Technology Adoption: *Promote the development of new technologies and standards that expand collaborative work between humans and machines by enabling safe and efficient human-machine interactions that augment human capabilities and empower production workers.*

1.5.4. Cybersecurity in Manufacturing: *Develop standards, tools, and testbeds, and disseminate guidelines for implementing cybersecurity in smart manufacturing systems. Focus efforts on updating the capital equipment of SMMs and replacing production equipment that cannot be made cybersecure. Provide purchasers a Software Bill of Materials for each product directly or by public release per President's Executive Order 14028 on Improving the Nation's Cybersecurity.*

Goal 2. Grow the Advanced Manufacturing Workforce

Transformational changes in advanced technology hold the promise of creating millions of new, sustainable, high-quality American jobs, including in advanced manufacturing.[32] Although there remains some disagreement, most evidence suggests that automation, artificial intelligence, and robotics will yield a net worldwide increase of manufacturing jobs over the coming decade.[33] These technologies should be developed and deployed in a way that complements workers' skills, rather than substituting for them.[34] To sustain and grow a robust advanced manufacturing industry with high-quality jobs, the United States must grow the manufacturing workforce with a particular emphasis on including individuals from backgrounds historically underrepresented in STEM fields, and develop the skills of its workers with agile education and training systems that keep pace with innovation. Work-based learning models such as registered apprenticeships have shown many benefits for both workers and employers.[35]

The Federal Government can provide leadership in growing the manufacturing workforce by promoting a vision of advanced manufacturing workforce development that unifies public and private stakeholders, and by increasing coordination of Federal policies and programs across agencies to maximize overall effectiveness and enable place-based initiatives.

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31 https://www.whitehouse.gov/briefing-room/presidential-actions/2021/07/09/executive-order-on-promoting-competition-in-the-american-economy/

32 https://www.nber.org/papers/w30332?utm_campaign=ntwh&utm_medium=email&utm_source=ntwg22

33 https://www.weforum.org/agenda/2020/10/dont-fear-ai-it-will-lead-to-long-term-job-growth/; see also https://mitpress.mit.edu/9780262367745/the-work-of-the-future/

34 https://workofthefuture.mit.edu/wp-content/uploads/2021/01/2021-Research-Brief-Helper-Reynolds-Traficonte-Singh4.pdf

35 https://wol.iza.org/articles/do-firms-benefit-from-apprenticeship-investments/long and https://www.aspeninstitute.org/wp-content/uploads/2019/01/1.3-Pgs-56-74-Scaling-Apprenticeship-to-Increase-Human-Capital.pdf

Three strategic objectives have been identified under Goal 2:

2.1. Expand and Diversify the Advanced Manufacturing Talent Pool
2.2. Develop, Scale, and Promote Advanced Manufacturing Education and Training
2.3. Strengthen Connections Between Employers and Educational Organizations

Objective 2.1. Expand and Diversify the Advanced Manufacturing Talent Pool

According to recent surveys, an estimated 2.1 million manufacturing jobs could be unfilled by 2030 unless the United States acts quickly.[36] Thus, increasing worker compensation is a key way to increase the attractiveness of manufacturing as a career.[37] Strategies to meet the anticipated demand for workers include broadening and diversifying the demographic base of the manufacturing workforce. To meet the coming workforce challenge, people from backgrounds historically underrepresented in STEM and women from all backgrounds, including returning citizens, will need to participate at much higher rates. Further, expanding and diversifying the advanced manufacturing workforce will also enhance innovation, resilience, and performance.

The United States has launched several initiatives to grow the manufacturing workforce. The Good Jobs Initiative will provide information to workers, employers, and government entities as they seek to improve job quality and create access to good union jobs.[38] The Talent Pipeline program helps employers build sector partnerships to connect workers to good jobs.[39] Further, the Administration made efforts to expand registered apprenticeships,[40] and provided funding for industry-led, worker-centered partnerships.[41] The National Biotechnology and Biomanufacturing Initiative aims to expand the biomanufacturing workforce with an emphasis on promoting equity and supporting underserved communities.[42] These efforts will deliver significant manufacturing-related benefits.

The recommendations for this objective are:

***2.1.1. Promote Awareness of Advanced Manufacturing Careers**: Promote awareness of advanced manufacturing careers with coordinated campaigns and events tailored to inspire students, with particular focus on people from backgrounds historically underrepresented in advanced manufacturing. Work with institutions and community leaders, and provide touchpoints with industry, particularly through hands-on experiences.*

***2.1.2. Engage Underrepresented Communities**: Institutionalize industry-led capacity-building partnerships that work with community colleges and area high schools to engage students and families from backgrounds underrepresented in advanced manufacturing and in underserved communities, particularly those transitioning from fossil-fuel based industries. Actively engage*

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[36] https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-diversity.html

[37] https://hrexecutive.com/cappelli-no-hr-we-dont-have-a-labor-shortage-crisis/

[38] https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/02/president-biden-to-announce-21-winners-of-1-billion-american-rescue-plan-regional-challenge/

[39] https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/17/fact-sheet-the-biden-harris-administration-launches-the-talent-pipeline-challenge-supporting-employer-investments-in-equitable-workforce-development-for-infrastructure-jobs/

[40] https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/01/fact-sheet-biden-harris-administration-launches-the-apprenticeship-ambassador-initiative-to-create-equitable-debt-free-pathways-to-high-paying-jobs/

[41] https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/02/president-biden-to-announce-21-winners-of-1-billion-american-rescue-plan-regional-challenge/

[42] https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/12/fact-sheet-president-biden-to-launch-a-national-biotechnology-and-biomanufacturing-initiative/

colleges and universities, with a focus on minority-serving institutions. Clearly define shared goals, strategies, and resources among partners, including unions and community representatives. Implement industry-wide technical assistance, support services, and mentorship for people from underserved communities.

2.1.3. Address Social and Structural Barriers for Underserved Groups: *Ensure that Federal programs drive towards diversity, equity, inclusion and accessibility by establishing standards, policies, related metrics, evaluations, and accountability. Require inclusion plans for Federally-sponsored grants to ensure opportunities for veterans and people from backgrounds historically underrepresented and underserved communities in advanced manufacturing.*

Objective 2.2. Develop, Scale, and Promote Advanced Manufacturing Education and Training

Education and workforce development systems must be capable of responding with agility to the changing mix of skills and competencies needed for advanced manufacturing. To reach more students and to promote advanced manufacturing education, pedagogy must continue to explore new techniques and delivery systems. This means developing and making more widely-available sector partnership training programs[43] as well as a greater number of dynamic and engaging distance learning and hybrid courses (that combine virtual and in-person instruction). It also means scaling up more real-world, hands-on, work-based learning opportunities for students in advanced manufacturing programs.

Changes in education and training begin with advanced manufacturing awareness in the early foundations of STEM education and continue through postsecondary career and technology education programs, employer-based training, and apprenticeship and other work-based programs.

The recommendations for this objective are:

2.2.1. Incorporate Advanced Manufacturing into Foundational STEM Education: *Extend the elementary and secondary STEM improvement agenda to incorporate key concepts, foundational knowledge, and skills for advanced manufacturing technologies. Raise awareness for multiple career pathways and enhance industry engagement to provide students with hands-on training opportunities. Support technical education and STEM programs with a stronger focus on engineering and technology. Prepare teachers to lead exciting, learning-intensive student projects that integrate advanced manufacturing concepts and careers*

2.2.2. Modernize Career and Technical Education (CTE) for Advanced Manufacturing: *Modernize and scale CTE through grants and industry-based efforts that strengthen teaching and learning to improve student engagement and outcomes and inspire student interest in manufacturing careers. Prepare teachers and postsecondary faculty to teach courses that deliver both academic knowledge and skills for advanced manufacturing using updated instructional methods. Support student competition opportunities that provide skills needed for advanced manufacturing, such as digital skills and systems thinking.*

[43] Sector partnerships bring together key actors in the workforce system, including employers, training institutions, unions, and community organizations, to design jobs and training to address issues of recruitment, retention, career path – not just short-term placement; they are an evidence-based strategy that is a growing workforce investment priority across Administrations. https://www.aspeninstitute.org/programs/workforce-strategies-initiative/sector-strategies/

2.2.3. Expand and Disseminate New Learning Technologies and Practices: *At the secondary and postsecondary levels, implement hybrid courses that include advanced simulations, along with the use of cutting-edge equipment and methods used in advanced manufacturing. Expand upskilling and reskilling pathways for adults through learning technologies that reach more students and increase exposure and access to advanced manufacturing occupations. Support efforts to improve student access to high-speed internet.*

Objective 2.3. Strengthen the Connections Between Employers and Educational Organizations

The imbalance between supply and demand for manufacturing workers can be addressed by building stronger relationships between employers and providers of training and education. Industry must clearly define its skill needs and support for solutions, while educational institutions must lead in developing the needed educational materials for quality credentialing and certification. On-the-job training and apprenticeships are important for skill development in manufacturing that require collaboration among industry, worker representatives, education providers, and government agencies.

The recommendations for this objective are:

2.3.1. Expand Work-Based Learning and Apprenticeships: *Expand high-quality, paid work-based learning and apprenticeships including internships, pre-apprenticeships, and registered apprenticeship. Promote platforms for workers to attain advanced manufacturing skills through ascending levels of earn-and-learn experiences. Connect advanced manufacturing employers to existing apprenticeship sponsors and apprenticeship partners.*

2.3.2. Promote Industry-Recognized Credentials and Certifications: *Encourage investment in modularized industry-recognized credentials and certifications for emerging manufacturing technologies. Encourage industry partnerships with educators to develop and update assessment methods. Track changing occupational requirements and define credentials for new advanced manufacturing occupations.*

Goal 3. Build Resilience into Manufacturing Supply Chains

The United States manufacturing supply chain is a complex ecosystem that connects raw material and component producers, logistics firms, integrators, and business support services. These interdependent entities design, produce, and assemble components and final products and the ecosystems they are part of create and benefit from product and process innovation. A key area for improvement is in supply chain and ecosystem resilience.

Resilience is the ability to recover from an unexpected shock and requires visibility, agility, and redundancy[44], which can be improved through better management and advanced digital modeling. Lack of digital infrastructure and transparency makes our supply chains vulnerable and unable to adapt when faced with shocks and stressors. Supply chain resilience will mitigate such risks through interdependent systems that can withstand a wide range of external shocks including geopolitical conflicts, cyberattacks, energy disruptions, financial crises, natural disasters, and pandemics.[45]

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[44] https://www.whitehouse.gov/wp-content/uploads/2022/04/Chapter-6-new.pdf

[45] https://www.nist.gov/news-events/news/2022/04/nist-releases-study-blockchain-and-related-technologies-manufacturing

The *Executive Order on America's Supply Chains: A Year of Action and Progress*[46] directed Federal agencies to take concrete steps to increase supply chain resilience. Initial steps include mapping, monitoring, and analyzing supply chains to prepare for and respond to disruptions. However, additional mapping and modeling of supply chain weaknesses is needed to support collective action across diverse public and private stakeholders and guarantee supply chain integrity.

Small- and medium-sized manufacturers (SMMs) comprise 98 percent of U.S. manufacturing firms and account for about half of the nation's manufacturing services and products.[47] They should be supported to increase resilience of manufacturing supply chains and ecosystems.

Three strategic objectives have been identified under Goal 3:

3.1. Enhance Supply Chain Interconnections
3.2. Expand Efforts to Reduce Manufacturing Supply Chain Vulnerabilities
3.3. Strengthen and Revitalize the Advanced Manufacturing Ecosystem

Objective 3.1. Enhance Supply Chain Interconnections

Strong collaborations between manufacturing firms can provide such benefits as reduced costs, increased innovation, and adaptability to supply chain disruptions[48]. However, extensive offshoring and outsourcing have resulted in weak collaborations and isolated industries. As a result, U.S. small manufacturers have fallen behind larger firms in terms of their technology investments, in part because of lead firms' singular focus on reduction of easily measured costs such as unit prices.[49] When SMMs lag in technology, their larger customers suffer as well. For example, slowness of suppliers in adopting additive manufacturing (AM) has created bottlenecks for aerospace and defense manufacturers in forging and casting supply chains; in some cases, parts have been delivered nearly a year after they were ordered.[50] Overall, labor productivity of the largest manufacturers is 58 percent higher than their middle-sized counterparts; a significant part of this gap is explained by lack of technology adoption among smaller firms.

The recommendations for this objective are:

3.1.1. Foster Collaboration within Supply Chains: *Promote public-private partnerships to improve technology adoption and environmental emissions reduction in manufacturing supply chains. Build trust and transparency between participants in supply chains.*

3.1.2. Advance Innovation for Digital Transformation of Supply Chains: *Work toward a vision of a digital supply chain highway (digital thread/digital twin) for critical sectors, from raw material to end-of-life and then recycling for reuse, to allow private and public sectors to use and analyze vertical and horizontal supply chains.*

Objective 3.2. Expand Efforts to Reduce Manufacturing Supply Chain Vulnerabilities

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[46] https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/
[47] http://docs.house.gov/meetings/AP/AP02/20211026/114154/HHRG-117-AP02-Wstate-BonvillianW-20211026.pdf
[48] Chapter 6 of https://www.whitehouse.gov/cea/written-materials/2022/04/14/summary-of-the-2022-economic-report-of-the-president/
[49] https://obamawhitehouse.archives.gov/sites/default/files/docs/supply_chain_innovation_report_final.pdf
[50] https://www.whitehouse.gov/cea/written-materials/2022/05/09/using-additive-manufacturing-to-improve-supply-chain-resilience-and-bolster-small-and-mid-size-firms/

Supply chain resilience is a critical United States priority[51] with Federal and state agencies beginning to map, monitor, and analyze supply chains in critical sectors. These efforts include examining all aspects of a product's lifecycle, from the raw materials for manufacturing and distribution, through maintenance and repair, to final disposition. The resilience of America's supply chain is dependent on innovative manufacturing processes and advanced technologies. The global pandemic exposed the vulnerabilities across supply chains in multiple industries and underscored the urgent need to evaluate and adopt new technologies, continuously improve efficiency and effectiveness of logistics processes, reduce risk, and maintain a highly skilled supply chain workforce. Research must objectively evaluate existing frameworks and processes that define life-cycle cost and value, and develop and monitor supply chain metrics such as the value of resilience and cost of lead time.[52] Research in logistics and supply chain management that integrates government and private sector knowledge will result in stronger insights, trend analysis, and decision-management tools.

The recommendations for this objective are:

3.2.1. Trace Information and Products Along Supply Chains: *Develop universal awareness, common data sharing, improved reporting, and standardized cybersecurity integrations to help identify and quickly mitigate risks. Develop tools and practices to help larger supply chain partners, including the Federal government, flag vulnerabilities and improve cybersecurity measures.*

3.2.2. Increase Visibility into Supply Chains: *Develop and implement supply chain mapping strategies, digital tools, and standards that preserve privacy while improving supply chain visibility, particularly for firms and industries that provide inputs into many individual supply chains with large spillover effects Such firms and industries include energy production, semiconductors, or transportation, as well as those important for national security, including climate and health security. Prioritize monitoring critical nodes using AI systems and economic analyses to provide advance notice of supply chain shocks and stressors.*

3.2.3. Improve Supply Chain Risk Management: *Improve risk management of external factors in supply chains through improved prediction of consequences of decisions made in uncertain environments. Ensure agility in the presence of pandemics and other low probability, high consequence events. Consider stress-testing supply chains against these events. Develop and diffuse techniques that help firms measure, value, and improve the resilience of their supply chains.*

3.2.4. Stimulate Supply Chain Agility: *Develop technology that supports manufacturing surge capacity and lead-time reduction during supply chain shocks and stressors. Establish and implement best practices in advanced processes and workforce training to promote collaboration among lead firms and suppliers.*

Objective 3.3. Strengthen and Revitalize Advanced Manufacturing Ecosystems

Advanced manufacturing ecosystems comprise a rich tapestry of manufacturing enterprises of all types and sizes. All play important roles in the process of innovation that leads to new products, new processes, new business models, and the creation of new markets. The U.S. Government's plans to advance the technological leadership of both small and large manufacturers[53] will promote disruptive

[51] https://www.whitehouse.gov/wp-content/uploads/2022/02/Capstone-Report-Biden.pdf
[52] See for example https://acetool.commerce.gov/; https://onlinelibrary.wiley.com/doi/full/10.1002/joom.1113
[53] https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/

innovations, leading to the creation and development of new markets. Young or small companies frequently face challenges in scaling from prototype to commercial practice. Government agencies at the state and Federal levels must be attuned to these challenges and support them through efforts that incorporate "Made in America by All of America's Workers."[54] Services such as the DOC-sponsored Hollings Manufacturing Extension Partnership technology-driven market intelligence[55] can help companies identify customers and markets for products and services based on their technology assets.

Public-private collaboration across the full spectrum of technology, workforce, and economic development is essential to strengthening and safeguarding America's advanced manufacturing supply chains and contributes to the power of regional innovation ecosystems to drive economic development. Economic development programs should help cluster initiatives to form around assets in a particular sector and successfully establish a manufacturing ecosystem. Collaboratives for advanced manufacturing innovation should focus on dissemination, adoption, and commercialization of advanced manufacturing technologies. These various partnerships must be interconnected and further strengthened through evaluation tools and methods to counter supply chain fragility. The United States needs to build and enhance these types of consortia to maintain global leadership in advanced manufacturing.

The recommendations for this objective are:

3.3.1. Promote New Business Formation and Growth: *Prioritize programs that provide key support for new manufacturing business formation and growth, including entrepreneurial training, mentoring for scientists and engineers, and long-term tracking of business growth and impact.*

3.3.2. Support Small and Medium-Sized Manufacturers: *Assist and incentivize SMMs to adopt advanced manufacturing technologies and contribute to the development of upskilling training. Ensure that SMMs are supported broadly by Federal programs and institutions to foster understanding and commitment to advanced manufacturing.*

3.3.3. Assist Technology Transition: *Coordinate across agencies and between Federal technology transfer-related policy groups to identify technologies across all communities and institutions suitable for transition from laboratory to market. Prioritize funding for research into measurement science and standards development to increase the sustainable transition of R&D to manufacturing.*

3.3.4. Build and Strengthen Regional Manufacturing Networks: *Create regional collaboratives that strengthen links between technology and workforce development for regional economic advancement. Strategically assist in developing multi-sector and multi-jurisdictional planning, leadership, technical, and professional expertise to sustain and grow regional manufacturing networks.*

3.3.5. Improve Public-Private Partnerships: *Support existing and new public private partnerships for development of advanced manufacturing technologies in tandem with workforce education. Continue to use Federal convening powers to ensure that relevant parties, particularly SMMs and underserved communities, are fully engaged. Seek greater alignment and accessibility of Federal grant programs for such collaborations.*

[54] https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/25/executive-order-on-ensuring-the-future-is-made-in-all-of-america-by-all-of-americas-workers/

[55] https://www.nist.gov/mep/grow

Additional Interagency Contributors

Department of Agriculture
Sujata Emani
Kourtney Hollingsworth*
Michael Sussman

Department of Commerce
Nell Abernathy
Dwendolyn Chester
Alaa Elwany*
Lisa Fronczek
Nancy Gilbert
Joann Hill
Rob Ivester*
Al Jones
Mary Ann Pacelli
Clifton Ray*
Kelley Rogers
John Schiel
Dave Seiler
Don Ufford*
Zachary Valdez*
Jim Warren
Samm Webb

Department of Defense
Senthil Arul
Keith DeVries
Michael Parkyn*
John Yochelson*

Department of Energy
Ann Hampson
Pete Langlois
Jeremy Mehta*
Andrew Schwartz
Steve Shooter
Nebiat Solomon
Kelly Visconti

Department of Health and Human Services
Jay Kadakia
Anne Talley

Department of Labor
Jenn Smith

Environmental Protection Agency
Raymond Smith

Federal Aviation Administration
Cindy Ashforth
Robert Bouza

National Aeronautics and Space Administration
Vince Cappello
Susan Poland
Stephanie Yeldell

National Science Foundation
V. Celeste Carter
Georgia-Ann Klutke
Thomas Kuech
Elizabeth Mirowski
Andrew Wells

Small Business Administration
Amber Chaudhry

*Report Leadership

Appendix A. Agency Participation and Metrics

Potential contribution of Federal departments and agencies to the goals and objectives is listed in the Table below. All Federal activities listed in this Strategy are subject to budgetary constraints and other approvals, including the weighing of priorities and available resources by the Federal government in formulating its annual budget and by Congress in legislating appropriations.

Goals	Objectives	DOC	DOD	DOE	DOL	DOT	ED	EPA	HHS	NASA	NSF	USDA
Goal 1: Develop and Implement Advanced Manufacturing Technologies	1.1: Enable Clean and Sustainable Manufacturing to Support Decarbonization	●	●	●		●		●	●		●	●
	1.2: Accelerate Manufacturing for Microelectronics and Semiconductors	●	●	●							●	
	1.3: Leverage Advanced Manufacturing in Support of the Bioeconomy	●	●						●	●	●	●
	1.4: Develop Innovative Materials and Processing Technologies	●	●	●		●		●	●	●	●	●
	1.5: Lead the Future of Smart Manufacturing	●	●	●						●	●	●
Goal 2: Grow the Advanced Manufacturing Workforce	2.1: Expand and Diversify the Advanced Manufacturing Talent Pool	●	●	●	●		●		●	●	●	●
	2.2: Develop, Scale, and Promote Advanced Manufacturing Education and Training	●	●	●	●	●	●		●	●	●	●
	2.3: Strengthen the Connections Between Employers and Educational Organizations	●	●		●	●	●		●		●	●
Goal 3: Build Resiliency into Manufacturing Supply Chains	3.1: Enhance Supply Chain Interconnections	●	●	●					●	●	●	●
	3.2: Expand Efforts to Reduce Manufacturing Supply Chain Vulnerabilities	●	●	●		●		●	●	●	●	●
	3.3: Strengthen and Revitalize Advanced Manufacturing Ecosystems	●	●	●		●	●		●	●	●	●

Federal departments and agencies play key roles in fostering U.S. advanced manufacturing innovation. The goals, objectives, and recommendations outlined in this Plan were developed by the Federal departments and agencies with direct responsibility for or interest in advancing manufacturing innovations. State and local governments also provide key support for advanced manufacturing through partnerships and collective actions that bolster investments in research and development, education and workforce development, and resilient manufacturing supply chains and ecosystems.

To evaluate progress towards the proposed goals, objectives, and priorities, the suggested metrics are level of participation of departments and agencies and the development of new programs and projects based on the stated priorities.

Appendix B. Progress Made in Achieving the Objectives from the 2018 Strategic Plan

The National Science and Technology Council published a National Strategic Plan for Advanced Manufacturing in October 2018.[56] This section summarizes the progress made in the major goals and objectives defined in that plan. The 2018 strategic plan presented a vision for American global leadership in advanced manufacturing across industrial sectors to ensure national security and economic prosperity. This vision was to be achieved by pursuing three goals:

- Develop and transition new manufacturing technologies;
- Educate, train, and connect the manufacturing workforce; and
- Expand the capabilities of the domestic manufacturing supply chain.

Strategic objectives were identified for each goal, along with technical and program priorities with outcomes to be accomplished over four to five years. The suggested metrics for evaluating progress towards the 2018 goals and objectives were the level of participation of agencies and development of new programs and projects based on the stated priorities.

The table identifies Federal agencies that have contributed to the goals and objectives.

Goals	Objectives	DoD	DOE	DOC	HHS	NSF	NASA	DOL	USDA	ED
Manufacturing Technologies	Intelligent Manufacturing Systems	✓	✓	✓	✓	✓	✓			
	Materials and Processing Technologies	✓	✓	✓		✓	✓		✓	
	Medical Products Manufacturing	✓	✓	✓	✓	✓	✓			
	Electronics Design and Fabrication	✓	✓	✓		✓	✓			
	Food and Agricultural Manufacturing	✓	✓	✓	✓	✓			✓	
Manufacturing Workforce	Tomorrow's Manufacturing Workforce	✓	✓	✓		✓	✓	✓	✓	✓
	Career and Technical Education	✓	✓	✓		✓	✓	✓	✓	✓
	Industry-Recognized Credentials	✓		✓		✓	✓	✓	✓	✓
	Match Skilled Workers with Industries	✓	✓	✓			✓	✓	✓	
Domestic Supply Chain	Small and Medium-Sized Manufacturers	✓	✓	✓		✓	✓			
	Ecosystems for Manufacturing Innovation	✓	✓	✓		✓	✓			
	Defense Manufacturing Base	✓	✓	✓		✓	✓	✓		
	Advanced Manufacturing for Rural Communities			✓		✓		✓		

<u>Goal 1: Develop and transition new manufacturing technologies</u>.

The following strategic objectives were identified under this Goal:

1. Capture the future of intelligent manufacturing systems
2. Develop world-leading materials and processing technologies
3. Assure access to medical products through domestic manufacturing,
4. Maintain leadership in electronics design and fabrication
5. Strengthen opportunities for food and agricultural manufacturing

The Federal Government invests in a portfolio of manufacturing R&D activities within many agencies. The agencies coordinate efforts to avoid duplication, while ensuring that their investments meet mission needs and complement one another, where appropriate. The agencies participating in the

[56] https://www.manufacturing.gov/sites/default/files/2021-06/Advanced-Manufacturing-Strategic-Plan-2018.pdf

NSTC Subcommittee on Advanced Manufacturing have worked across administrations to coordinate and optimize Federal investments in advanced manufacturing R&D.

Federal Government programs have been successful in promoting technology development and transfer to manufacturing enterprises, especially those that are small- and medium-sized. These programs include Manufacturing USA institutes, NIST MEP, DOE's Manufacturing Demonstration Facilities and Embedded Entrepreneurship program, and NSF's Future Manufacturing Program. In addition, the SBIR/STTR programs in DOC, DoD, DOE, HHS, NASA, NSF, and EPA have provided entrepreneurial assistance for manufacturing R&D.

Examples of agency programs that have contributed to the progress in advanced manufacturing R&D are listed in the table below.

Agency	Technology Development Programs	
DOC	Manufacturing USA Manufacturing Extension Partnership Additive Manufacturing Robotics for Smart Manufacturing Advanced Materials Measurements Standard Reference Materials	AI in Manufacturing Biopharmaceutical Manufacturing Smart Manufacturing Systems Advanced Manufactung Roadmaps Regional Innovation Hubs) Manufacturing USA National Emergency Assistance Program Rapid Assistance for Coronavirus Economic Response
DoD	Manufacturing Technology Programs Manufacturing USA institutes Defense Industrial Base Modernization	
DOE	Manufacturing USA Institutes Manufacturing Demonstration Facility Critical Materials Institute BOTTLE Consortium High Performance Computing for Manufacturing Lab-Embedded Entrepreneurship	Education and Workforce Roadmap (NREL) Robotics, High Performance Computing, and Energy Storage Internships Small Business Innovation Research and Small Business Technology Transfer programs American Made Challenges
HHS	Biomedical Advanced Research and Development Authority Centers for Innovation in Advanced Development and Manufacturing Division of Research, Innovation, and Ventures programs TechWatch Advancing Regulatory Science for Continuous Manufacturing	Regulatory Science and Innovation Grants Centers for Excellence in Regulatory Science Innovation Emerging Technology Team Advanced Technology Team
NASA	Game Changing Development Program Advanced Exploration Systems Program Technology Demonstration Missions Program	Space Technology Research Grants Programs Transformative Aeronautics Concepts Program

NSF	Cyber-Physical Systems Engineering Research Centers Future Manufacturing Program Industry/University Cooperative Research Centers	Advanced Manufacturing Program Foundational Research in Robotics Future of Work at the Human-Technology Frontier National Robotics Initiative 3.0
USDA	Science Theme Teams Small Business Innovation Research Forest Products Lab Pilot Plant Facilities	Bioeconomy, Bioenergy, and Bioproducts Program Intramural and Extramural Research Programs

Goal 2: Educate, train, and connect the manufacturing workforce.

The following strategic objectives were identified under this Goal:

1. Attract and grow tomorrow's manufacturing workforce
2. Update and expand career and technical education pathways
3. Promote apprenticeship and access to industry-recognized credentials
4. Match skilled workers with the industries that need them

Federal investments in education and workforce development are integral to building a diverse and skilled workforce of the future. While ED focuses on K-12 education and DOL on workforce development and certifications, other agencies, such as DoD, NASA, and NSF support STEM education and related workforce training and development programs that specifically benefit the manufacturing sector.

The Manufacturing USA institutes, in cooperation with MEP Centers, have also been active in education and workforce development. In FY2021, educational and workforce programs across Manufacturing USA trained more than 90,000 people across the nation, helping to convince many to pursue careers in manufacturing. The DOL, under the Workforce Innovation and Opportunity Act (WIOA), has helped train displaced manufacturing workers and those who desired to enter the workforce. Many of the programs at the Manufacturing USA Institutes and DOL focused on training assistance to veterans. ED, under the Carl D. Perkins Career and Technical Education Act (Perkins V) has helped attract high school and community college students to manufacturing.

Examples of programs across agencies that have contributed to the progress in manufacturing education, training, and workforce development are listed in the table below.

Agency	Education and Workforce Development Programs	
DOC	Manufacturing USA Institutes, Education and Workforce Programs NIST Internship Program	MEP Workforce Development Programs NIST Summer Undergraduate Fellowship
DoD	Army Educational Outreach Program STARBASE Manufacturing USA Institutes, Education & Workforce Programs	Veterans To Energy Careers Manufacturing Engineering Education Program
ED	Carl D. Perkins Career and Technical Education Act	WIOA Title II, Adult Education and Family Literacy Act

Agency	Education and Workforce Development Programs	
DOE	Manufacturing USA institutes, Education and Workforce Programs Lab-Embedded Entrepreneurship Programs Better Plants Online Learning for Industrial Partners 500001 Ready Navigator Advanced Manufacturing Education and Workforce Roadmap Nuclear Relevant Scholarships and Fellowships	EERE High Performance Computing for Manufacturing Internship Program EERE Energy Storage Internship Program EERE Robotics Internships Program Nuclear Energy University Nuclear Leadership Program Office of Science Undergraduate Laboratory Internships Office of Science Community College Internships Office of Science Visiting Faculty Program Office of Science Graduate Student Research Program
DOE	Manufacturing USA Institutes, Education Workforce Programs Lab-Embedded Entrepreneurship Programs Better Plants Online Learning for Industrial Partners Ready Navigator	High Performance Computing for Manufacturing Internship Program Energy Storage Internship Program Robotics Internships Program
DOL	Apprenticeship Programs Trade Adjustment Assistance America's Promise Job Training Grants Strengthening Community Colleges Grants Growing Apprenticeships in Nanotechnology and Semiconductors	One Workforce Grants Scaling Apprenticeships Through Sector-Based Strategies Grants Apprenticeship: Closing the Skills Gap Grants
NASA	Faculty Fellowship Program STEM Engagement Programs	Established Program to Stimulate Competitive Research (EPSCoR) Minority University Research and Education Projects
NSF	Advanced Technological Education Program Training-Based Workforce Development for Advanced Cyberinfrastructure Engineering Research Centers Program Future Manufacturing Program Revolutionizing Engineering Departments Program	Broadening Participation in Computing and Engineering Programs Non-Academic Research Internships for Graduate Students (INTERN) Training-Based Workforce Development for Advanced Cyberinfrastructure
USDA	Academic Scholarships and Aides 4-H Science Program Partnerships with Universities Including MSIs and Community Colleges Cooperative Extension Network	Agriculture and Food Research Initiative (AFRI) Education and Workforce Development Grants

Goal 3: Expand the capabilities of the domestic manufacturing supply chain.

The following strategic objectives were identified under this Goal:

1. Increase the role of small and medium-sized manufacturers in advanced manufacturing
2. Encourage ecosystems of manufacturing innovation
3. Strengthen the defense manufacturing base
4. Strengthen advanced manufacturing for rural communities

The United States manufacturing supply chain is a complex system of large and small manufacturers, integrators, raw materials producers, logistics firms, and companies providing other support services (accounting, finance, legal counsel, etc.). These companies, many of them outside the United States, form interdependent networks that provide a wide variety of finished goods to the United States and global customers.

Examples of agency programs that have contributed to the domestic manufacturing supply chain and ecosystem are listed in the table below.

Agency	Supply Chain Programs	
DOC	Manufacturing USA Institutes MEP Centers Cybersecurity Supply Chain Risk Management Program Review of Semiconductor Manufacturing and Advanced Packaging	Advisory Committee on Supply Chain Competitiveness Office of Supply Chain, Professional and Business Services
DoD	Manufacturing USA institutes Industrial Base Programs	
DOE	Manufacturing USA Institutes Critical Materials Institute BOTTLE Consortium Manufacturing and Energy Supply Chain Office	
DOE	Manufacturing USA institutes Manufacturing Supply Chain Program	
NASA	Supply Chain Risk Management (SCRM) Program	
NSF	America's Seed Fund Convergence Accelerator Program Innovation Corps Operations Engineering Program	Partnerships for Innovation Pathways to Enable Open-Source Ecosystems Regional Innovation Engines
USDA	Storage Facility Loans Local Food Promotion Program Farmers Market Value-Added Producer Grants Regional Food System Partnership Dairy Business Innovation Initiatives Business & Industry Guaranteed Loan Program	Food Supply Chain Guaranteed Loan Program Meat and Poultry Inspection Readiness Grants Cooperative Extension Network

Agency	Supply Chain Programs	
EPA	Sustainable Materials Management Program	

Appendix C. Recommendations in Detail

Goal 1. Develop and Implement Advanced Manufacturing Technologies

Objective 1.1. Enable Clean and Sustainable Manufacturing to Support Decarbonization

Recommendation 1.1.1. Decarbonization of Manufacturing Processes: *Develop and demonstrate advanced manufacturing technologies that increase energy efficiency, electrify industrial processes, employ low-carbon feedstocks and energy sources in manufacturing, support new chemistries that avoid direct greenhouse gas emissions from industrial processes, capture and store industrial carbon dioxide, and create alternatives to GHG-intensive industrial products. Create and disseminate validation tools and processes to assist the integration of electrified and efficient technologies into manufacturing. Create transparency on advanced materials and processes with lower energy and carbon footprints.*

The availability of abundant, low-cost, clean electricity would enable drastic reductions in carbon dioxide and other emissions in manufacturing industries. Nearly 43 percent of all U.S. manufacturing emissions are from industrial process heating.[57] Many manufacturing processes require moderate to high process temperatures that are currently achieved by using fossil-derived fuels with high emissions. For some products, like cement and iron, carbon dioxide (CO_2) is released from chemical transformations that occur in standard processing, which is particularly difficult to abate. U.S. manufacturing plants can affordably reduce emissions by employing novel, electrified, and efficient advanced manufacturing processes that reduce energy consumption, have lower temperature requirements, and circumvent chemical transformations that release CO_2. For the CO_2 sources that are the most challenging to abate, carbon capture with either storage or utilization must be considered.

Replacing fossil-based thermal processes with innovative electrified heating technologies can cut emissions and provide productivity and competitiveness advantages. Novel electrochemical processes that enable chemical transformations to occur at much lower temperatures provide another opportunity to electrify industrial processes. Chemical reactions can be made more efficient through catalyst design, use of electrochemistry, or intensified process techniques. Significant energy improvements can also be gained by applying process intensification principles to mixing and separations, including combining multiple processes in a single unit. To abate CO_2 production inherent in iron and cement production, innovative approaches such as direct iron reduction and material replacement should be further developed. Reductions in the cost of hydrogen production and its integration into manufacturing processes as a fuel source are needed. Furthermore, advancements in carbon capture integration, efficiency, cost, and CO_2 storage and utilization can be employed to abate emissions from the manufacturing sector.

Recommendation 1.1.2. Clean Energy Manufacturing Technologies: *Improve materials, manufacturing processes and product designs for clean electricity generation and storage; zero-emission transportation, buildings, and industry to enable a decarbonized economy. Enhance the manufacturing of devices and materials that enable more efficient power conversion and transmission with advanced conducting materials, processing technologies and machine development. Manufacture advanced batteries with high energy densities and secure novel sustainable materials for low- and high-voltage applications.*

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[57] https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf

In pursuit of net-zero emissions by 2050, the United States is aiming to reach 100 percent carbon pollution-free electricity by 2035. The significant cost reduction of low-carbon, or "clean," electricity has accelerated expanded use and accessibility of clean electricity worldwide, with 72 percent of new capacity coming from renewables.[58] Enabling highly emissive sectors such as transportation, construction, energy, and manufacturing to use low-cost clean electricity as an alternative to fossil fuel-based power and energy sources will require changes and upgrades to power generation and management.

Manufacturing advances that produce cost-competitive technologies for clean energy production, storage, and utilization domestically position the United States to lead the global energy transition. Innovations such as advanced composite materials for wind turbine blades and efficient power electronics for charging and grid integration are needed to meet growing demands driven by the electrification of multiple sectors. A major enabling technology needed to achieve this is economical battery production for grid-scale energy storage. Manufacturing process improvements are needed for increased energy densities enabled by next generation design and chemistries. A domestic supply chain that includes recycling should enable high-performance low-cost energy storage devices to power the nation's electrified energy and transportation sectors. Smart grids, comprised of advanced power electronics, high-speed connectivity, and phasor measurement units, balance power distribution based on energy production, storage, and consumption parameters. A reliable clean power supply depends upon technologies delivered through advanced manufacturing such as advanced battery production, efficient power storage and management, and grid utilization.

Recommendation 1.1.3. Sustainable Manufacturing and Recycling: *Develop economically viable manufacturing technologies that separate valuable materials from waste streams, as well as alternatives to energy- or pollution-intensive materials. Conduct R&D in the areas of sorting, purification, and deconstruction technologies. Scale up sustainable materials design and manufacturing, recycling and circular methods for multiple materials classes, and pilot programs and facilities. Improve data and methods to assess life cycle impacts and identify areas for improvement.*

Incorporating sustainable material management principles into product design and development reduces the amount of material and energy required to manufacture a product, which contributes to decarbonization. This includes the design and use of new materials that remain in use for longer durations, or that replace those with detrimental energy, health, and environmental impacts. Rather than exporting high-value waste streams, the development of a reuse and recycling infrastructure in the United States would simultaneously create domestically sourced raw materials and new jobs.

Circular manufacturing[59] minimizes the use of feedstocks and maximizes the reuse of processed materials and components. Advanced separation technologies are needed to efficiently process complex feedstocks and waste streams for co-production and recycling. Automated sorting and material detection technologies must be deployed at distributed collection and processing sites to address the existing bottlenecks for current recycling and reuse strategies. Following separation, advanced processing technologies must be leveraged to enable secondary and recycled materials to replace virgin materials with equivalent or better cost and performance. Designing products for

[58] https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019

[59] Circular manufacturing is a model of production which preserves resources, reduces waste, and involves sharing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible while creating value and new business opportunity.

material recovery, recycling, and reuse enables efficient use of materials and energy within the value chain, reducing the need to extract materials from the environment, and enabling a circular economy.

As the second largest chemical-producing nation, the United States is an important enabler of the food, pharmaceutical, cleaning, and hygiene sectors. The chemical industry is also the largest energy consumer of the industrial sectors[60] with up to 85 percent of total production costs attributed to energy utilization.[61] Sustainable chemistry technologies that reduce or eliminate the use or generation of hazardous substances and increase energy efficiency will have the greatest impact in the industrial sector. Technology is needed to reduce water consumption and fouling in manufacturing processes and to efficiently process non-traditional water and wastewater resources to remove contaminants and obtain clean fit-for-purpose water.

Objective 1.2. Accelerate Manufacturing for Microelectronics and Semiconductors

Recommendation 1.2.1 Nanomanufacturing of Semiconductors and Electronics: *Invest in fabrication of integrated photonics, additive and direct printed electronics, unique sensor formats, and hybrid electronic fabrication to harness the power of nanomanufacturing. Develop physical, chemical, and biological methods to precisely place and bind atoms into desired molecules and structures.*

Microelectronics are dependent on a diverse global supply chain that has recently suffered resiliency challenges. Advanced microelectronic systems and components have seen many innovations over the past three decades, driven by the rapid advance of manufacturing technologies for new materials, design, and nanomanufacturing. As the design space moves towards three-dimensional circuits, manufacturing processes are moving to sub-nanometer resolutions enabled by the expansion of heterogeneous integration techniques. Microelectronics hardware design tools and atomically precise manufacturing and metrology processes are required to meet the increasing complexity and resolution of integrated circuits (ICs) and systems.

Advancing innovative microelectronics requires integration of novel pilot production and manufacturing scale-up capabilities. Innovations include photonic integrated circuits that offer rapid access to and transport of massive quantities of data, but the inflection point for this technology will only occur with foundry level production of full system solutions that include integrated lasers and detectors. Another example of innovation is atomically-precise manufacturing techniques that can enable processes that are sensitive to single atom dimensions, like quantum tunneling

Recommendation 1.2.2. Semiconductor Materials, Design, and Fabrication: *Develop advanced manufacturing capabilities that allow the creation and testing of new devices, materials, and architectures. Provide easy access to design tools and microelectronics foundries for domestic companies and universities that provide fundamental insights and a trained workforce. Incorporate efficient and sustainable operations for microelectronics devices and components.*

While silicon will remain the primary platform for most microelectronic systems, other types of materials are needed for such applications as power, sensing, photonic, and quantum. Quantum sheets, wires, and dots are being considered to increase system performance via incorporation into digital frameworks that provide enhanced local functionality, such as optical communication. The integration of these materials requires new fabrication and process capabilities with improved means

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[60] https://www.eia.gov/energyexplained/use-of-energy/industry.php#:~:text=In percent202020 percent2C percent20the percent20industrial percent20sector,of percent20total percent20U.S. percent20energy percent20consumption

[61] https://www.energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf

to transfer, locate with sub-micron precision, and interface with alternative and low-dimensional materials. To renovate the power grid, power electronics require new materials that complement the wide and ultra-wide bandgap materials that are in use today, such as silicon carbide and gallium nitride. Manufacturing components and devices from those materials will be driven by advances in processing and defect control that can be easily integrated into manufacturing infrastructure.

Long-term investments in the design and fabrication of quantum computing hardware are needed to maintain global leadership in the future of computing. Rapid developments and the technological promise of new quantum-based devices and systems require research and development of new manufacturing approaches appropriate for quantum devices, including economical and sustainable approaches to cool them to ultralow temperatures for optimal performance. Quantum computing, networking, and sensing rely on non-traditional devices made from materials as varied as superconductors and 2D topological insulators. These systems need extreme precision, reproducible processing, and defect control to realize their technical and commercial potentials.

Broad access to facilities for fabricating semiconductor systems from exotic materials, insulators, and biological cells is also needed to research, develop, and efficiently implement new computer architectures that will be used in future neural computers.

Recommendation 1.2.3. Semiconductor Packaging and Heterogeneous Design: *Introduce new materials, tools, designs, processes, assembly, and tests for advanced packaging with higher densities, yields, and reliability. Enhance R&D and prototyping to improve manufacturing throughput and reliability. Develop national facilities for heterogeneous packaging integration R&D.*

As data grows exponentially and downscaling of transistor density slows due to atomic limitations, chip designers are finding it more difficult to address the needs of high-performance computing, machine learning, and artificial intelligence. Similarly, the decreasing form-factor (or size) of mobile computing devices has elevated the importance of system and chip packaging. To meet the needs of increasingly complex and demanding computations, chip designers have identified heterogeneous integration, which places separately manufactured dies that perform different functions, such as logic, memory, and power management, into a single package that in aggregate provides higher performance, lower energy consumption, and lower cost.

Microelectronics manufacturing is increasingly reliant on advances in substrates, interconnects, chiplets[62], and interposers. Substrates protect and support the integrated circuit chip while providing thermal dissipation. The device, substrates, interconnects, dies, chiplets, and interposers must be co-designed and manufactured to provide optimal electronic, mechanical, thermal, and photonic functionalities. Finally, packaging quantum computing devices to integrate with more traditional computing devices must be considered in future semiconductors designs to achieve optimal performance and value.

Objective 1.3. Implement Advanced Manufacturing in Support of the Bioeconomy

Recommendation 1.3.1. Biomanufacturing: *Support research to advance biomanufacturing including genomic and protein engineering production tools, engineering of multicellular systems, biological models, and biotechnology methods for bioprocessing. Support advancement in multi-omics and bio-metrology for predictive modeling and bioprocessing analytical tools. Support enhancement of*

[62] A chiplet is a tiny integrated circuit (IC) that contains a well-defined subset of functionality

feedstock readiness, technical readiness, and manufacturing readiness level analytical tools. Prioritize implementation of safeguards to ensure that these products are not used for nefarious purposes.

The confluence of advances in biological and material sciences accelerated by developments in computing, data analytics, artificial intelligence, machine learning, genomic engineering, and synthetic biology has given rise to a wave of innovation in biomanufacturing. Biomanufacturing applications span many sectors including defense, space, agriculture and food, health and medicine, consumer products, and advanced materials and energy production. They offer potential solutions for such challenges as climate change, water scarcity, food and nutrition security, and infectious diseases in humans, animals, and plants. To ensure biosafety and biosecurity, these materials and technologies can be developed and deployed in ways that align with United States principles and values and international best practices, and not in ways that lead to accidental or deliberate harm to people, animals, or the environment, as outlined in the Executive Order on Biotechnology and Biomanufacturing.[63]

Biomanufacturing offers solutions including sustainable, on-demand, and concentrated production of critical and novel molecules and products, and hybrid mechanical/biological systems that combine the regenerative properties of biology with the structural strength and precision of traditional structures. Integration of biomanufacturing into a broader product portfolio would benefit from additional biological and genetic engineering, bioprocess design, and standardization of methods in biomanufacturing.

Recommendation 1.3.2. Agriculture, Forest, and Food Processing *Support research in advanced genome sequencing, bioinformatics, predictive modeling for functional phenotypes, and integration of control systems and the teaming of humans and machines in food, feed, fuel, and fiber manufacturing. Develop sustainable energy, low-cost water processing technologies including nutrient recovery systems that produce fit-for-purpose water from waste streams and unconventional sources.*

Incorporating advanced manufacturing technologies in agriculture, forest, food, and fiber industries can improve productivity, supply chain resiliency, and sustainability. New technologies are necessary to engineer greater production and resiliency for agriculture and food processing, aquatic production of food, and manufacturing of alternative protein products. Adoption of technologies that support distributed production and processing of food will enable not only development of new types of food and other related products but also enable equitable food distribution.

The application of digital thread technologies in food processing will support food traceability and safety in global food production from creation through consumption. Adoption of manufacturing techniques such as bio-fermentation to produce alternative proteins from single-cells, micro-algae production, cultivated and farmed feedstock, altered protein profiles in crops, and cultured tissue, meat, and seafood alternatives will promote diversified sources and improved food security.

Recommendation 1.3.3. Biomass Processing and Conversion: *Develop methods, processes, and technologies to tap into the one billion tons of biomass that could be sustainably produced in the U.S. and converted into feedstocks for manufacturing. Advance predictive process modeling, biological process analysis and genomic and protein engineering for desirable biomass feedstock pre-processing, processing and deconstruction. Advance anaerobic treatment of bio-based waste streams to produce biogas, renewable natural gas, fertilizer, plant nutrients, soil amendments, biochar, engineered carbon,*

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63 https://www.whitehouse.gov/briefing-room/presidential-actions/2022/09/12/executive-order-on-advancing-biotechnology-and-biomanufacturing-innovation-for-a-sustainable-safe-and-secure-american-bioeconomy/

animal bedding material, surfactants, polymers, clean bioenergy, electricity, and combined heat/cooling power.

Conversion of biomass is critical to the development of bioproducts including fuel and high value-consumer products. Continuous development of biobased processes and products for fuel, fiber, materials, and energy is dependent on developing new technologies that expedite the breakdown of biomass, such as lignin, for use in advanced materials. Processing and capturing the aromatic monomers that comprise lignin will enable more efficient biofuel and bioproduct production.

Advanced processing techniques can be enabled by using biomass that can be easily broken down as feedstock and by improving the effectiveness of deconstruction methods with new solvents. Technologies in genomic engineering, microbial processes, and chemical processes, such as recoverable ionic solvents, will be key to increasing the economic viability of commercial biomass conversion. These technologies will also enable newer products, such as cellulose nanomaterials as functional additives, nontoxic binders, packaging materials, and the development of new functional characteristics in bio-products needed to expand their use in unexplored chemical and additive markets.

Recommendation 1.3.4. Pharmaceuticals and Healthcare Products: *Advance continuous manufacturing, in-line process monitoring and control, integrated AI-assisted systems, and novel cell culture techniques. Prioritize developments in subtractive and additive machining and biobased manufacturing to create patient-specific medical products, devices, and biologically-driven drug delivery systems.*

Advanced manufacturing can be used to produce numerous new and improved healthcare products, including small molecule drugs, medical devices, biologics, vaccines, advanced therapies, and biocompatible materials. Biomedical manufacturing shares many cross-cutting technology challenges with other industry sectors, but there are unique challenges for specific medical applications. Manufacturing processes for each must ensure safety and efficacy, promote human and animal health, and minimize drug shortages, while also securing the United States global leadership in pandemic response and preparedness.

Technologies that will modernize production, intensify processes, and improve process control include smart manufacturing, continuous manufacturing, inline process monitoring and control, automated closed-loop systems, integrated AI-assisted systems, novel cell culture techniques, and higher yield alternative systems. Advances in machining, additive manufacturing, and biobased manufacturing can accelerate or augment capabilities for creating patient-specific medical products and devices, biologically-driven drug delivery systems, and implants that closely mimic natural properties. As the industry adopts these advanced manufacturing methods and produces novel products, simultaneous innovation will be required in the development of measurement tools to increase manufacturing efficiency and product performance. The continued evolution of medical products and device manufacturing will reduce operating costs and help rebuild a resilient domestic supply chain of biologic medicines, tissue products, machines, and biocompatible materials manufactured in the United States and by trusted allies and partners.

Objective 1.4. Develop Innovative Materials and Processing Technologies

Recommendation 1.4.1. High-Performance Materials Design and Processing: *Advance material design and processing capabilities through the integration of physics-based computational and data-driven machine learning tools. Accelerate testing, qualification and process validation of high-*

performance materials to streamline entry into market. Develop predictive capabilities for materials behavior and performance under harsh service conditions.

Systems that impact personal and public safety or have profound national security or economic impact, such as nuclear reactors or hypersonic defense systems, typically involve operation under harsh service conditions such as extreme temperatures, pressures, chemicals and corrosive media, particulate loads, or radiation.[64] The development and adoption of lightweight, high strength, high conductivity, corrosion-resistant metals, composites, and other classes of advanced materials are important enablers for emerging manufacturing capabilities.

To develop sophisticated materials that meet the requirements of harsh service conditions, the United States must develop entirely new paradigms for alloys and other materials that leverage and, more importantly, integrate well-established physics-driven tools, integrated computational materials engineering, and data-driven machine learning. Computational methods development for high-performance material engineering and performance prediction are critical factors to reducing the cost and time to market for new applications. The United States Materials Genome Initiative[65] is developing the materials innovation infrastructure that will deliver new materials quickly at a fraction of existing costs and should be leveraged to develop the required high-performance materials.

Recommendation 1.4.2. Additive Manufacturing: *Develop additive manufacturing (AM) process optimization frameworks that are accessible to all users. Create new sensors to advance process monitoring and control capabilities. Develop machine learning algorithms to analyze large, secure, interoperable data streams and realize feedback control. Produce tools to create new AM-specific materials and capabilities. Integrate additive manufacturing technologies with smart manufacturing platforms.*

Advances in AM technologies have incorporated unique metallic alloys, integrated composite structures, and ceramic materials into complex high-performance goods that meet evolving demands. Expanding the role of additive and hybrid capabilities through dedicated R&D to address persisting challenges (such as lack of repeatability and predictability), as well as increasing their manufacturing/technology readiness level is crucial to enable their integration with established manufacturing technologies.

Although AM has already revolutionized prototype and low-volume production, further advances are needed to unlock the potential of parts fabricated with high-performance materials through improving performance modeling and analysis, in-process monitoring and control, and tailored post-process non-destructive evaluation, especially for high-consequence applications.[66] Several iconic U.S. manufacturers have come together to with the support of the Federal government to launch the AM Forward Initiative, which aims to improve the competitiveness of America's small-and-medium-sized manufacturers by helping them adopt AM.[67] The United States must continue to invest in and support advanced R&D to overcome key technological barriers that hinder the adoption of additive manufacturing.

[64] https://www.energy.gov/sites/default/files/2021-04/Materials for Harsh Environments_ 2020 Virtual Workshop Summary Report.pdf

[65] https://www.mgi.gov/sites/default/files/documents/MGI-2021-Strategic-Plan.pdf

[66] https://doi.org/10.6028/NIST.AMS.600-10

[67] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/06/fact-sheet-biden-administration-celebrates-launch-of-am-forward-and-calls-on-congress-to-pass-bipartisan-innovation-act/

***Recommendation 1.4.3. Critical Materials**: Identify and integrate substitute materials and technologies to reduce or replace the use of critical materials in high-demand technologies. Develop advanced separation and processing methods for critical materials from primary, secondary, and unconventional sources. Establish new design and manufacturing methods for components and products for reuse, recycling, remanufacturing, and repurposing of critical materials.*

Critical materials[68] are the building blocks of technologies essential to energy, transportation, health, and defense industrial bases. Global demand for critical materials such as rare earth elements, lithium, cobalt, nickel and platinum group metals is expected to increase fourfold by 2040 to meet global decarbonization goals.[69]

Manufacturing innovation to expand midstream processing capabilities[70] and improved material and manufacturing efficiency will build resilient, diverse, and secure critical materials supply chains. Employing advanced manufacturing techniques can improve utilization of materials and reduce life-cycle impacts by minimizing or even eliminating waste streams.[71] Novel substitute materials and technologies should be identified and validated to reduce dependence on critical materials; and efficient separation processes can enable diversified supply of critical materials. Furthermore, efficient recycling and reuse can mitigate supply chain risk by establishing a circular economy and enabling a domestic supply of critical materials.

***Recommendation 1.4.4. In-Space Manufacturing:** Develop new additive manufacturing processes in microgravity environments to create replacement parts and space infrastructure. Enable integration of robotics with in-space additive manufacturing processes for deep space exploration. Prioritize biomanufacturing investments in microgravity to enable extended space presence including sustainable food production, processing, and recycling and the deactivation of hazardous materials.*

Since the beginning of the space age, all the resources or equipment needed for space missions have been manufactured on earth and shipped to space. Envisioning the need for future larger space infrastructure, in-space manufacturing (ISM) can provide technological superiority for improved capabilities to build space infrastructure, such as communications antennas, earth observations platforms, and solar power arrays. As articulated in the National Strategy for In-Space Servicing, Assembly, and Manufacturing,[72] ISM offers opportunities to enhance and accelerate United States leadership in space, by expanding the space-based economy and inspiring the next generation of students, innovators, and leaders. ISM can also enable the development of new and improved products for terrestrial applications using the unique microgravity environment of space, which can result in high-value products that are beneficial for life sciences, industrial materials, and sustainable development.

Efforts to further space mission capabilities include demonstrating AM technologies in microgravity for printing electronics and sensors, metal components for replacement and repair, and lunar regolith 3D-printing technologies for infrastructure. Other critical areas include developing biomanufacturing technologies for deep space exploration, which can advance the practicality of an integrated, multi-

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[68] https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals
[69] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
[70] The domestic midstream supply chain generally covers material processing and refinement, up to component manufacturing.
[71] https://www.gao.gov/products/gao-16-699
[72] https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf

function, multi-organism biomanufacturing system to support extended missions in Mars-like conditions.

Objective 1.5. Lead the Future of Smart Manufacturing

Recommendation 1.5.1. Digital Manufacturing: *Enable the application of advanced sensing, control technologies, and machine learning across the manufacturing sector. Advance smart manufacturing by pursuing digital twins. Develop standards for data compatibility to enable seamless integration of smart manufacturing.*

Digital manufacturing involves the use of an integrated, computer-based system incorporating simulation, 3D visualization, analytics, and collaboration tools to create product and manufacturing process definitions simultaneously. Technology-based productivity improvements have consistently driven job growth by providing new tools that increase the productivity of factory floor workers. New scientific understanding and widespread high-speed computing and communications technologies now enable tremendous new productivity gains, but only if information technology can be integrated with operational technology.

The promise of digital manufacturing is guaranteeing high uptime and high-quality parts by monitoring and controlling every stage of the production process. While existing methods can be used to bring almost any manufacturing process under control, implementations are often expensive and time-consuming, lack generality, and are not fully dependable, limiting their application to the most expensive or highest volume products. New methods are needed to transition smart manufacturing from a collection of heroic demonstrations to routine and widespread use. The ultimate realization of smart manufacturing will result from the implementation of a digital twin, a computational model that reflects reality so precisely that it can accurately anticipate and avoid faults before they occur. Implementation of digital twins requires ubiquitous sensing of critical process parameters that will be facilitated by the production of low-cost, miniature, and accurate sensors, and process models that account for uncertainty.

Recommendaton 1.5.2. Artificial Intelligence in Manufacturing: *Prioritize R&D in machine learning, data access, confidentiality, encryption, and risk assessment to enable the adoption of artificial intelligence in manufacturing. Develop best practices, standards, and software tools to scale new business models that monetize production data while maintaining data security and respecting intellectual property rights. Balance the interests of producers and consumers in areas such as privacy, intellectual property, and rights to repair.*[73]

Machine learning (ML) as a subset of artificial intelligence requires large datasets to deliver transformative capabilities. Provisioning such large-scale datasets for manufacturing applications may require access to production data across companies that critically depends on ensuring proprietary information is not compromised. With such assurances, machine learning has the potential to categorize the collective production experience of manufacturers across companies and provide individual manufacturers with low-cost solutions customized for their applications. That potential promises huge gains, as compared to the prevailing practice of developing local solutions on individual factory floors and protecting them as trade secrets. Such siloed development inevitably results in

[73] https://www.whitehouse.gov/briefing-room/presidential-actions/2021/07/09/executive-order-on-promoting-competition-in-the-american-economy/

massive, economy-wide inefficiencies due to the costly reinvention of solutions that are routinely applied elsewhere.

The definition of key manufacturing problems and provision of datasets associated with those problems is foundational to enable the use of ML methods in manufacturing.[74]

Recommendation 1.5.3. Human-Centered Technology Adoption: *Promote the development of new technologies and standards that expand collaborative work between humans and machines by enabling safe and efficient human-machine interactions that augment human capabilities and empower production workers.*

The integration of process sensing and analytics with augmented/virtual/extended reality (AR/VR/XR), robotics, and human interaction improves manufacturing productivity by providing workers with continuous, real-time information to adapt activities to the parts they process and assemble.

Widespread adoption of AR/VR/XR in manufacturing requires a workforce trained to employ digital tools and improved software that reduces implementation cost. Human/machine collaborative tools and systems must provide safe human-machine interactions to enable cooperative work between humans and robots in close proximity. Because human co-workers are inherently unpredictable, new breakthroughs in artificial intelligence are needed to enable robots to anticipate human actions in all operations and ensure occupational safety and improved production efficiency. Use of such tools can enhance front-line worker skills rather than substitute for them.

Recommendation 1.5.4 Cybersecurity in Manufacturing: *Develop standards, tools, and testbeds, and disseminate guidelines for implementing cybersecurity in smart manufacturing systems. Focus efforts on updating the capital equipment of SMMs and replacing production equipment that cannot be made cybersecure. Provide purchasers a Software Bill of Materials for each product directly or by public release per President's Executive Order 14028 on Improving the Nation's Cybersecurity.*

Manufacturing companies typically maintain digital production and logistical plans which can become vulnerable to cyber-tampering or espionage. Stolen data can reveal intellectual property or be surreptitiously modified to introduce product defects, making cybersecurity a top priority for advanced manufacturing.[75] Cybersecurity in manufacturing organizations is complicated by the need to protect against vulnerabilities in both information technology (IT) and operational technology (OT) systems.

IT/OT concerns can often be addressed by conventional risk management techniques, such as data encryption, updating security patches, mapping data flows to identify vulnerabilities, restricting the access of personal devices to sensitive data, augmenting the security protocols of cloud providers, and using multifactor authentication. However, many manufacturers use legacy systems with well-known vulnerabilities that cannot be protected through simple software updates. New research efforts are needed to develop and/or update standards and guidelines[76] to implement emerging manufacturing cybersecurity technologies, including AI for threat detection and handling and distributed ledger technology to ensure the validity of sensitive manufacturing information and verification across supply chain networks.

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[74] https://doi.org/10.6028/NIST.AMS.100-47

[75] https://www.whitehouse.gov/briefing-room/presidential-actions/2021/05/12/executive-order-on-improving-the-nations-cybersecurity/

[76] https://www.nist.gov/cyberframework

Goal 2. Grow the Advanced Manufacturing Workforce

Objective 2.1. Expand and Diversify the Advanced Manufacturing Talent Pool

Recommendation 2.1.1. Promote Awareness of Advanced Manufacturing Careers: *Promote awareness of advanced manufacturing careers with coordinated campaigns and events tailored to inspire students, with particular focus on people from backgrounds historically underrepresented in advanced manufacturing. Work with institutions and community leaders, and provide touchpoints with industry, particularly through hands-on experiences.*

Public perceptions often do not reflect the emerging career opportunities of the growing, technology-driven advanced manufacturing sector. Awareness is growing, but manufacturing is still widely assumed to be physically intense, dull and repetitive, and sometimes dangerous. Further, manufacturing jobs have developed a persistent and largely outdated reputation as low-skilled, poorly paid, and at-risk; however, these perceptions do not reflect the reality of career opportunities and benefits of the growing, technology-driven advanced manufacturing sector.

Coordinated messaging around the promise of advanced manufacturing can change the narrative from one of decline to opportunity. This effort is needed to capture interest, showcase clear pathways into the industry, and inspire a new generation to pursue rewarding careers

To establish a narrative of opportunity, key messaging must dispel stigmas and reinforce pride and the social value of manufacturing careers. Effective campaigns will highlight relatable role models, illustrate the value proposition of career and technical education, and underscore the pivotal role of advanced manufacturing in meeting national challenges such as climate change, global economic competition, and national security.

Messaging campaigns should work together with existing events, including Manufacturing Day, and bring together industry and academic institutions to inform students through real-world experiences, media campaigns, and other STEM exposure opportunities.

In cases where the negative image fits the reality, the United States should seek to improve the reality. Implementation of the recommendations in this report, especially around training, will greatly help. In addition, while advanced manufacturing will require skill enhancements, in many cases, unfilled jobs reflect a "wage shortage" rather than a "skill shortage."[77]

Recommendation 2.1.2. Engage Underrepresented Communities: *Institutionalize industry-led capacity-building partnerships that work with community colleges and area high schools to engage students and families from backgrounds underrepresented in advanced manufacturing and in underserved communities, particularly those transitioning from fossil-fuel based industries. Actively engage colleges and universities, with a focus on minority-serving institutions. Clearly define shared goals, strategies, and resources among partners, including unions and community representatives Implement industry-wide technical assistance, support services, and mentorship for people from underserved communities.*

Messaging will translate into action only if job quality improves and underserved communities and the organizations that represent them are proactively and consistently engaged.

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[77] https://www.forbes.com/sites/ethankarp/2021/03/02/the-case-for-raising-wages-in-manufacturing/?sh=76ed781b5480

Federal agencies can accelerate change by forging relationships between industry and two- and four-year colleges, with special focus on minority serving institutions, community-based organizations, professional societies, industry associations, labor union and joint labor-management organizations, and economic/social development agencies at local, regional, and state levels.

To engage underserved communities effectively, multiple avenues must be explored and pursued. These include increasing the flow of information about advanced manufacturing opportunities; improving the cultural relevance of curricula; increasing the use of near-peer role models and mentorship; and leveraging the influence of respected community institutions and thought leaders.

Recommendation 2.1.3. Address Social and Structural Barriers for Underserved Groups: *Ensure that Federal programs drive towards diversity, equity, inclusion and accessibility by establishing standards, policies, related metrics, evaluations, and accountability. Require inclusion plans for Federally-sponsored grants to ensure opportunities for veterans and people from backgrounds historically underrepresented and underserved communities in advanced manufacturing.*

The United States has a long history of social and structural barriers to entry and advancement in STEM occupations, such as advanced manufacturing. These barriers affect many communities, including women, racial and ethnic minorities, the disabled, and veterans. A 2021 Federal interagency report describes a wide range of barriers that have resulted in underrepresentation by these groups in technical careers.[78] These barriers include policies, workplace climate, cost of education, biases, inadequate support, stereotypes, institutional cultural resistance to change, experience requirements, language and cultural challenges, and lack of human capital resources.

Overcoming these barriers requires an honest and thorough review of the challenges faced by affected communities, followed by comprehensive and resolute action. Sustained efforts will not only expand the talent pool for entry-level workers but will help incumbent and dislocated workers with adjacent skills move into the advanced manufacturing workforce. Essential steps include the reassessment of selection/advancement metrics; the development of more diverse manufacturing workforce leadership teams; targeted work-based learning initiatives; the provision of support services including transportation and childcare assistance; and recognizing, empowering, and effectively utilizing the diversity already present within the advanced manufacturing workforce.

Lasting change requires sustained resources as well as a commitment to monitor progress. Federal agencies can accelerate progress by making diversity, equity, inclusion, and accessibility planning an integral part of funding proposals and evaluation criteria for awards.

Objective 2.2. Develop, Scale, and Promote Advanced Manufacturing Education and Training

Recommendation 2.2.1. Incorporate Advanced Manufacturing into Foundational STEM Education: *Extend the elementary and secondary STEM improvement agenda to incorporate key concepts, foundational knowledge, and skills for advanced manufacturing technologies. Raise awareness for multiple career pathways and enhance industry engagement to provide students with hands-on training opportunities. Support technical education and STEM programs with a stronger focus on engineering and technology. Prepare teachers to lead exciting, learning-intensive student projects that integrate advanced manufacturing concepts and careers*

[78] https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf

Like other STEM-intensive industries, advanced manufacturing depends on a robust STEM workforce and education system. The CO-STEM Federal Education Strategic Plan outlines priority approaches for improving the STEM education pipeline.[79] However, advanced manufacturing technology and career awareness do not figure prominently as objectives, nor are they featured in popular STEM programs and competitions. Thus, there is an enormous opportunity to enhance these programs by incorporating advanced manufacturing technology and career awareness. Furthermore, this addition has the potential to expand the STEM workforce by inspiring and attracting students into new and diverse educational pathways.

Students should be exposed to the interdisciplinary nature of advanced manufacturing through touchpoints with industry and project-based learning. Competitions in robotics and other disciplines motivate students and provide first-hand experience of the interdisciplinary nature of practical technology and engineering applications. Maker education fosters creativity and contextualizes learning of mechanical, electrical, and computer science skills through multidisciplinary experiences.[80]

Professional development can teach educators how to better integrate manufacturing skills development with adjacent STEM subjects. The ASM International Materials Camps for teachers, which show teachers how to demonstrate engineering concepts in the classroom, provides one of several promising models.[81]

Recommendation 2.2.2. Modernize Career Technical Education (CTE) for Advanced Manufacturing: *Modernize and scale CTE through grants and industry-based efforts that strengthen teaching and learning to improve student engagement and outcomes and inspire student interest in manufacturing careers. Prepare teachers and postsecondary faculty to teach courses that deliver both academic knowledge and skills for advanced manufacturing using updated instructional methods. Support student competition opportunities that provide skills needed for advanced manufacturing such as digital skills and systems thinking.*

CTE courses and pathways need updating to inform and inspire students to consider careers in advanced manufacturing. CTE educators often face challenges, such as a shortage of up-to-date equipment to support their programs or insufficient resources to stay abreast of the latest manufacturing technologies. Successful approaches include integrating leading technologies and effective strategies for engaging students, engaging business and industry as partners in co-designing CTE programs of study and offering work-based learning opportunities to ensure the knowledge, skills, and credentials students earn will prepare them to succeed in the workforce. Overall, secondary and post-secondary CTE programs remain widely undervalued and under-resourced relative to their importance to the future of the United States economy.

Greater investments to address this gap should begin in middle school, where showcasing cutting-edge technologies and careers can introduce students to a range of technical career pathways. Building on this foundation, essential investments in high school CTE career pathways include concurrent or dual enrollment opportunities between colleges/universities and secondary schools, work-based learning opportunities, and the opportunity to earn industry-recognized credentials alongside academic coursework. At the postsecondary level, two-year colleges provide the institutional gateways to a

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[79] https://www.whitehouse.gov/wp-content/uploads/2022/01/2021-CoSTEM-Progress-Report-OSTP.pdf

[80] Novel approaches such as entrepreneurship-based learning give students relevant context as they work on projects in cross-functional teams.

[81] https://www.asmfoundation.org/teachers/materials-camps/

variety of advanced manufacturing careers, as well as opportunities to develop stackable credential and connected degree models that help people to enter and advance in the field. Digital skills warrant particular emphasis as smart and digital manufacturing systems become more prevalent.

Teachers and postsecondary faculty need preparation to deliver curricula using leading-edge pedagogies and learning technologies. Competitions, such as those in robotics, deliver value by engaging students and providing academic and skill-oriented experiences.

Recommendation 2.2.3. Expand and Disseminate New Learning Technologies and Practices: *At the secondary and postsecondary levels, implement hybrid courses that include advanced simulations, along with the use of cutting-edge equipment and methods used in advanced manufacturing. Expand upskilling and reskilling pathways for adults through learning technologies that reach more students and increase exposure and access to advanced manufacturing occupations. Support efforts to improve student access to high-speed internet.*

The disruption of in-person education and training caused by the COVID-19 pandemic accelerated the development, proliferation, and acceptance of transformative learning tools and distribution systems. The blended learning model—mixing online and in-person instruction—has proven to be particularly effective and scalable in the context of technical learning.[82] Hybrid learning uses asynchronous learning modules for students to develop conceptual knowledge and baseline skills specific to manufacturing equipment. Game-based-learning and virtual reality simulations have immense potential to enhance these distance and blended learning models. Enriched distance and blended learning models expand the reach of an instructor to a larger student body while offering support specialization and time-sharing models for scarce and costly equipment and instructors.

The modularization of coursework and competency-based assessment can help workers transition to new occupations through reskilling and continuous learning throughout their careers. Initiatives such as "Internet For All" also enable the delivery of educational content to underserved communities.[83]

Objective 2.3. Strengthen the Connections Between Employers and Educational Organizations

Recommendation 2.3.1. Expand Work-Based Learning and Registered Apprenticeships: *Encourage investment in modularized industry-recognized credentials and certifications for emerging manufacturing technologies. Encourage industry partnerships with educators to develop and update assessment methods. Track changing occupational requirements and define credentials for new advanced manufacturing occupations.*

Skills in the advanced manufacturing sector can be best attained via conceptual learning coupled with practical workplace experiences. Apprenticeship programs provide a widely recognized framework for combining earning and learning, while benefiting all students, especially those from low-income communities.

The gold standard for work-based learning is the Registered Apprenticeship, an industry-driven pathway in which individuals obtain work experience, mentorship, classroom instruction, progressive wage increases, and a portable, nationally recognized credential.

[82] https://olj.onlinelearningconsortium.org/index.php/olj/article/viewFile/1726/558

[83] https://www.commerce.gov/news/press-releases/2022/05/biden-harris-administration-launches-45-billion-internet-all-initiative

Many employers, however, find it challenging to meet all of the requirements of a fully recognized Registered Apprenticeship. Small and mid-sized enterprises are particularly challenged to provide the resources to support work-based learning models. As a result, insufficient apprenticeship and work-based learning opportunities exist in advanced manufacturing relative to the need.

This supply-side bottleneck must be cleared. One remedy is the expansion and integration of work-based learning programs within secondary and postsecondary CTE programs. Work-based learning can also be offered through internships and cooperative learning programs that provide academic credit at post-secondary institutions, and through high school pre-apprenticeship programs.

Recommendation 2.3.2. Establish Industry-Recognized Credentials and Certifications: *Expand high-quality paid work-based learning and apprenticeships including internships, pre-apprenticeships, and registered apprenticeship. Promote platforms for workers to attain advanced manufacturing skills through ascending levels of earn-and-learn experiences. Connect advanced manufacturing employers to existing apprenticeship sponsors and apprenticeship partners.*

Educational programs cannot effectively interact with emerging technologies without a continuously evolving system of credentials. Such credentials give earning power to workers, planning indicators to employers, and clear investment signals to the education and training community. While legacy manufacturing skills are already defined by the Manufacturing Skills Standards Council[84], definition of additional competencies is needed in advanced manufacturing.

The current array of credentials is too numerous, overlapping, and not universally grounded in competencies. Future credentials must be industry-led, competency-based, and nationally portable. Well-designed credentials can create substantial economic value by allowing industry to identify the latest knowledge, skills, and abilities of value in the labor market. Such credentials allow education and training providers to tailor their programs of study and enable graduates to effectively convey their competency to employers.

To realize the potential of improved credentials, college, and K-12 programs must upgrade student assessments, grant credit for prior training, and design competency-based evaluations. Employers and the training community can add additional value by rigorously developing and disseminating micro-credentials and digital badging[85] to supplement basic credentials. As new production technologies develop, educators and industry experts must efficiently work together to establish new occupational requirements.[86]

Goal 3. Build Resilience Into Manufacturing Supply Chains

Objective 3.1. Enhance Supply Chain Interconnections

Recommendation 3.1.1. Foster Coordination within Supply Chains: *Promote public-private partnerships to improve technology adoption and environmental emissions reduction in manufacturing supply chains. Build trust and transparency among participants in supply chains.*

Major innovations in decentralized supply chains can suffer from a dilemma: upstream firms will not supply something until they see a demand for it, but downstream firms will not invest in products

[84] https://www.msscusa.org/

[85] Digital Badging is a digital representation of a skill, learning achievement or experience.

[86] The Department of Labor has established the site https://www.apprenticeship.gov/ to provide resources and technical assistance to jobseekers, employers, and educators.

requiring that input unless there is a ready supply (as in the cases of additive manufacturing or the electric vehicle supply chain). Similarly, improved coordination could help with greening the supply chain, by identifying common opportunities to reduce emissions and use of hazardous materials. Excess waste is created when a supplier does not adequately understand what the customer is doing with the product or cannot effectively distinguish between activities that add value versus those that result in waste.

The SEMATECH[87] partnership is one example of a public-private partnership that addressed these issues by coordinating demand and supply of semiconductor equipment. The EPA's E3: Economy - Energy – Environment program[88], is a second example of a public-private partnership that brought together suppliers and customers to identify ways to reduce emissions. The new AM Forward initiative[89] for additive manufacturing is a third success story illustrating how public-private partnerships address these issues.

Recommendation 3.1.2. Advance Innovation for Digital Transformation of Supply Chains: *Work toward a vision of a digital supply chain highway (digital thread/digital twin) for critical sectors, from raw material to end-of-life and then recycling for reuse, to allow private and public sectors to use and analyze vertical and horizontal supply chains.*

By replicating physical operations in virtual space, firms in supply chains can share information to rapidly convert designs and raw materials into products. Digitizing the supply chain will improve efficiency, increase return on investment, and enable clean and sustainable manufacturing.

Achieving the digital transformation requires technical innovation in several key areas: robust industrial internet of things; artificial intelligence and machine learning algorithms; robotics that can be applied across a broad range of manufacturing processes; radio frequency identification; and machine tools and controllers that can plug-and-play in an integrated, information-centric system. The United States must expand ongoing R&D efforts to represent, structure, communicate, store, standardize, and secure product, process, and logistical information in a digital manufacturing environment.

Objective 3.2. Expand Efforts to Reduce Manufacturing Supply Chain Vulnerabilities

Recommendation 3.2.1. Trace Information and Products Along Supply Chains: *Develop universal awareness, common data sharing, improved reporting, and standardized cybersecurity integrations to help identify and quickly mitigate risks. Develop tools and practices to help larger supply chain partners, including the Federal government, flag vulnerabilities and improve cybersecurity measures.*

Visibility into supply chain relationships is necessary to identify vulnerabilities for firms to adequately plan and manage risks for disruptive events.[90] Gaining this knowledge requires both improved technology and improved trust between buyer and supplier.[91] Most major manufacturers lack insight into the supply chains on which they depend, particularly for relationships more than two layers deep. They also lack insight into interdependencies among products that rely on the same, or similar, components that may have limited domestic or global production capacity. Proprietary interests of

[87] https://www.darpa.mil/about-us/timeline/sematech

[88] https://www.epa.gov/e3

[89] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/06/fact-sheet-biden-administration-celebrates-launch-of-am-forward-and-calls-on-congress-to-pass-bipartisan-innovation-act/

[90] https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains

[91] https://mackinstitute.wharton.upenn.edu/2021/building-supply-chain-continuity-capabilities-for-a-post-pandemic-world/

suppliers' limit access to information that manufacturers need to effectively manage supply and for the suppliers to effectively manage production planning. Lack of information is frequently due to lack of trust between original equipment manufacturers (OEMs) and suppliers; addressing this issue is necessary before a digital transformation can occur.

Improved traceability of information and products will enable better decision-making, limit supply chain risks for key products, and strengthen adaptability in the event of shocks and stressors. Transparency in supply chains promotes awareness of risks, identifies bottlenecks, and helps organizations determine whether alternative sources of critical inputs are needed. Transparency also empowers consumers to make informed purchasing decisions and businesses to better manage their suppliers and serve their customers.

Recommendation 3.2.2. Increase Visibility into Supply Chains. *Develop and implement supply chain mapping strategies, digital tools, and standards that preserve privacy while improving supply chain visibility, particularly for firms and industries that provide inputs into many individual supply chains with large spillover effects. Targeted industries should include energy production, semiconductors, and transportation, as well as other important for national security, including climate and health security. Prioritize monitoring critical nodes using AI systems and economic analyses to provide advance notice of supply chain shocks and stressors.*

The complex and vast ecosystem of global manufacturing supply chains has not been fully mapped and shared among stakeholders domestically or abroad. The numerous suppliers, data systems, and hidden interdependencies involved make it very difficult to accurately depict a manufacturing company's entire supply network. As a result, major supply chain disruptions often lead to widespread loss of revenue and failure to produce critical goods. Visibility into supply chains via supply chain mapping and analysis would address this weakness by enabling detection of supply chain threats and vulnerabilities, mitigating risks, and creating opportunities for performance growth.

To ensure resilience and market security for public good, the Federal government should collaborate with industry partners and like-minded allies to identify firm-to-firm network structures and create maps of supply chains for critical industries. Sector-to-sector connections (but not firm-to-firm connections) can be illustrated using disaggregated, publicly available data from the Bureau of Economic Analysis's Input-Output Accounts Data.[92,93] Supply chain mapping can be enhanced with monitoring of critical nodes. For example, the HHS Supply Chain Control Tower[94] has provided demand signals for personal protective equipment (PPE) that was critical during the COVID-19 pandemic. The daily-updated platform delivered visibility on PPE inventory levels, manufacturer capacity, distribution flows, and point-of-care consumption to inform decision-making preparedness and response. Federal economic and market tools can also be used to strengthen manufacturing capability to meet demand and respond to supply chain challenges.[95,96] Using these tools can enable daily or regular decisions about each manufacturing unit operation, sustainable production rates, short- and long-term strategic investments, and forward-looking plans to introduce new high-tech products into the marketplace. The benefit of increased visibility into sector-to-sector and cross-border connections in supply chains must be balanced against the benefit of privacy for individual firms and firm-to-firm connections.

[92] https://www.bea.gov/industry/input-output-accounts-data
[93] https://www.whitehouse.gov/cea/written-materials/2022/04/14/summary-of-the-2022-economic-report-of-the-president/Chapter-6
[94] https://aspr.hhs.gov/AboutASPR/ProgramOffices/ICC/Pages/IM-Division.aspx
[95] https://www.usda.gov/oce
[96] https://www.ams.usda.gov/

Recommendation 3.2.3. Improve Supply Chain Risk Management: *Improve risk management of external factors in supply chains through improved prediction of consequences of decisions made in uncertain environments. Ensure agility in the presence of pandemics and other low probability, high consequence events. Consider stress-testing supply chains against these events. Develop and diffuse techniques that help firms measure, value, and improve the resilience of their supply chains.*

Lack of information today limits the ability of entities across the supply chain to make informed decisions on topics such as reliably sourcing raw materials and parts, effectively utilizing and expanding production capacity, determining costs and prices, and preparing for and responding to unanticipated disruptions. Short-term and long-term dislocation of supply and demand results in shortages and significant price increases for critical products. Moreover, lack of information and transparency can result in substandard, counterfeit, and illicitly sourced products, materials, and equipment entering the supply chain undetected, with serious consequences. To better manage risk and increase resilience, firms need better information along with better systems and tools to use information so they can best manage risk of disturbances and complex global relationships.

To address these vulnerabilities and improve supply chain decision-making at all levels, technology hubs and industrial clusters should be expanded and better connected so that they can effectively utilize common information platforms and market intelligence. Federal agencies are uniquely positioned to organize, mobilize, and communicate strategic intelligence to provide early warning to the nation's supply chain about prospective cyberthreats, supply chain shocks, and geopolitical risks. Manufacturing entities must also use shared knowledge to improve resilience to the effects of climate change and understand the effects of increasing weather disturbances, coastal and inland flooding, wildfires, and more on their suppliers, customers, and distribution networks. Manufacturers must ensure economic flexibility in the presence of pandemics and other low probability, high consequence events and should consider stress-testing their supply chains against these events. Adoption of agile practices like these often enhances cost competitiveness and resilience of firms, because investing in problem-solving capabilities that reduce downtime will improve performance in steady times as well as in emergencies.

Recommendation 3.2.4. Stimulate Supply Chain Agility: *Develop technology that supports manufacturing surge capacity and lead-time reduction during supply chain shocks and stressors. Establish and implement best practices in advanced processes and workforce training to promote collaboration among lead firms and suppliers.*

Digital transformation can render supply chains far more responsive and resilient. The challenge in achieving the vision is not just technical, but also organizational and economic: suppliers and their workers must have incentives and capabilities to adopt such technically demanding processes.

If firms invest in their workers' ability to solve problems, they will be able to pivot quickly to alternative products or processes or react to unusual situations. Resilient and flexible companies and workers will identify an alternative raw material to replace one that is unavailable, incorporate a process very different from what has traditionally been standard, or increase the flexibility of the production process so that the firm can use a less-specialized input.

Agility may require upfront investment by firms in a supply chain, but over time can reduce costs and enhance efficiency. Investing in problem-solving capability that reduces lead time can improve performance in normal times as well as in emergencies. These agile manufacturing processes, and the associated workforce training, must be effectively distributed throughout the supply chain to promote more effective collaboration and connectivity among firms. If successfully implemented, these processes can significantly improve the competitiveness of the United States manufacturing sector.

Objective 3.3. Strengthen and Revitalize Advanced Manufacturing Ecosystems

Recommendation 3.3.1. Promote New Business Formation and Growth: *Prioritize programs that provide key support for new manufacturing business formation and growth, including entrepreneurial training, mentoring for scientists and engineers, and long-term tracking of business growth and impact.*

Breakthrough technologies typically take a long time to find their way to market. Federal programs aimed to assist small businesses navigate these periods of uncertainty. Such programs are particularly important in manufacturing, where private capital finds risk-reward tradeoffs unattractive. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide capital to small companies with new ideas. SBIR and STTR and other complementary programs are intrinsic to many government agencies.[97]

The NSF Innovation Corps (I-Corps™) Program provides intensive training in the market discovery required to move new discoveries toward commercialization.[98] Many other agencies have adopted the I-Corps model to establish similar programs focused on translational research, so that agency-supported research can be commercialized as products or services to benefit the public. The DoD Rapid Innovation Fund finances small businesses' mature technology ideas to transition into defense programs. The Mentor-Protégé Program partners small businesses with larger companies to receive business development support in several areas.[99] The SBA Small Business Development Centers provides business and technology assistance for start-ups and existing small businesses.[100]

Recommendation 3.3.2. Support Small and Medium-Sized Manufacturers: *Assist and incentivize SMMs to adopt advanced manufacturing technologies and contribute to the development of upskilling training. Ensure that SMMs are supported broadly by Federal programs and institutions to foster understanding and commitment to advanced manufacturing.*

Small and medium-sized manufacturers (SMMs) comprise 98 percent of U.S. manufacturing firms and account for about half of industrial output.[101] Individually, many SMMs face challenges in adopting advanced technologies and providing adequate training and compensation to their workers.[102] SMMs need Federal assistance to continue their significant contributions to the manufacturing ecosystem and participate in advanced manufacturing.

Government has a critical role to play in addressing the vulnerability of SMMs. Networks such as the Manufacturing USA Institutes—with members that include both industry and educational institutions convene education and training providers to meet the technology and training needs of SMMs. The DOC-sponsored Hollings Manufacturing Extension Partnership (MEP) provides more examples of how Federal programs can support SMMs. It is imperative to connect SMMs to sources of new technologies, technical infrastructure, and specialized knowledge through other companies, institutes of higher learning, Federal laboratories, Manufacturing USA institutes, and more. Education and training systems

[97] https://www.sbir.gov/sites/default/files/SBA_Final_FY19_SBIR_STTR_Annual_Report.pdf
[98] https://www.nsf.gov/news/special_reports/i-corps/
[99] https://www.sba.gov/federal-contracting/contracting-assistance-programs/sba-mentor-protege-program
[100] https://www.sba.gov/local-assistance/resource-partners/small-business-development-centers-sbdc
[101] http://docs.house.gov/meetings/AP/AP02/20211026/114154/HHRG-117-AP02-Wstate-BonvillianW-20211026.pdf
[102] https://mitpress.mit.edu/books/creating-good-jobs

are essential in delivering the programs necessary to upskill the workforce for advanced manufacturing.[103] SMMs also seek trusted advisors from local, state, and regional organizations for appropriate advice on possibilities of new technologies. Expanding SMM access to technologists from the Federal and state levels will further production and engineering functions critical to these firms.[104]

Recommendation 3.33. Assist Technology Transition: *Coordinate across agencies and among Federal technology transfer-related policy groups to identify technologies across all communities and institutions suitable for transition from laboratory to market. Prioritize funding for research into measurement science and standards development to increase the sustainable transition of R&D to manufacturing.*

The manufacturing sector must be able to rapidly adapt manufacturing capabilities that leverage R&D advances. Not unique to advanced manufacturing, this priority crosses all R&D areas supported by the Federal government. The critical role of technology transfer and the importance of facilitating the transition of technologies from the laboratory to the market is recognized in the President's Management Agenda as a Cross-Agency Priority (CAP) Goal.[105] Federal agencies are directed to ramp up coordination efforts through the Lab-to-Market CAP Goal to improve technology transfer via five strategies: (1) identify regulatory impediments and administrative improvements in Federal technology-transfer policies and practices; (2) increase engagement with private sector technology development experts and investors; (3) build a more entrepreneurial R&D workforce; (4) support innovative tools and services for technology transfer; and (5) improve understanding of global science and technology trends and benchmarks.[106]

To facilitate effective paths forward, Federal efforts should not only focus on the companies that are most likely to further develop and implement advanced manufacturing technologies, but also capitalize on capabilities in underrepresented communities and rural America. At the same time, advances in measurement science and standards cannot be overlooked since these are essential to support repeatability and widespread adoption of advanced manufacturing technology.

Recommendation 3.34. Build and Strengthen Regional Manufacturing Networks: *Support existing and new public private partnerships for development of advanced manufacturing technologies in tandem with workforce education. Continue to use Federal convening powers to ensure that relevant parties, particularly SMMs and underserved communities, are fully engaged. Seek greater alignment and accessibility of Federal grant programs for such collaborations.*

The U.S. manufacturing capacity is regionally clustered in both urban and rural settings across the country, providing ready access to suppliers, essential services, and workers to enhanced productivity and innovation[107]. The needs, assets, and opportunities within regions are different and should be addressed by businesses and government organizations active in those regions. This is the reason that the stakeholders in the Manufacturing USA institutes work closely with the economic, industrial, educational and community-based leadership of the regional ecosystems in which they are based and invest. Well-designed and operated public-private partnerships have pivotal contributions to make in strengthening advanced manufacturing ecosystems. Only public-private partnerships can attract and focus resources while providing frameworks to connect essential stakeholders including industry,

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[103] https://www.commerce.senate.gov/services/files/0DAF8AC6-8382-4E85-BEBA1F8B5F577922
[104] https://docs.house.gov/meetings/AP/AP02/20211026/114154/HHRG-117-AP02-Wstate-BonvillianW-20211026.pdf
[105] https://www.performance.gov/pma/
[106] https://www.nist.gov/news-events/news/2020/11/taking-innovation-lab-market
[107] https://www.sciencedirect.com/science/article/abs/pii/S0048733314001048

educational institutions, workforce investment boards, local and community-based organizations, and Federal and state agencies.

Federal agencies should leverage public-private networks to make their funding opportunities more easily accessible, particularly to SMMs and underrepresented communities. Federal agencies can strengthen regional advanced manufacturing supply chains by tightening linkages between technology and workforce development and making funding opportunities more easily accessible, particularly to SMMs and underrepresented communities Synergies between programs should be described, enabling networks to weave funding streams together in pursuit of larger goals. Federal agencies should make greater efforts to coordinate grant announcements with evaluation criteria that drive complementarity into program execution, post-award grant administration, regulation, and oversight. Such coordination of Federal funding strategies will empower regional networks to find the support they need to thrive. Agency partnerships with programs such as the EDA Build Back Better Regional Challenge[108], Good Jobs Challenge[109], and Build to Scale Program[110] will help foster recovery of all U.S. communities, create good-paying jobs, and maintain the United States' global leadership in advanced manufacturing.

Recommendation 3.3.5 Improve Public-Private Partnerships: *Support existing and new public private partnerships for development of advanced manufacturing technologies in tandem with workforce education. Continue to use Federal convening powers to ensure that relevant parties, particularly SMMs and underserved communities, are fully engaged. Seek greater alignment and accessibility of Federal grant programs for such collaborations.*

Well-designed and operated public-private partnerships have pivotal contributions to make in strengthening advanced manufacturing ecosystems. Public-private partnerships can attract and focus resources while providing frameworks to connect essential stakeholders including industry, Federal laboratories, educational institutions, workforce investment boards, and labor and community organizations as well as Federal and state agencies. Manufacturing USA Institutes, the NSF Engineering Research Centers and Industry-University Research Partnerships, and the MEP Centers, serve as excellent examples of collaborations and partnerships that de-risk new technologies, push these technologies to higher MRL/TRL levels, and provide great educational opportunities. The recently announced AM Forward compact to encourage SMM adoption of additive technologies could be extended to other technologies and industries.[111] Community colleges and feeder high schools must also be integrated into local and regional partnerships to establish new educational programs and support partnership initiatives.

Greater efforts must also be made to select and strategically align Federal grant programs. The strength of relationships within public-private partnerships determines their survival and growth. Thus, ongoing facilitation is needed by an intermediary group or individual to ensure that each partnership's return on investment is widely understood and remains positive.

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108 https://eda.gov/arpa/build-back-better/

109 https://eda.gov/arpa/good-jobs-challenge/

110 https://eda.gov/oie/buildtoscale/

111 https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/06/fact-sheet-biden-administration-celebrates-launch-of-am-forward-and-calls-on-congress-to-pass-bipartisan-innovation-act/