CYMANII

CYBERSECURITY MANUFACTURING ROADMAP 2022

PUBLIC VERSION

...SECURING THE JOBS AND INDUSTRIES OF THE FUTURE

Contents

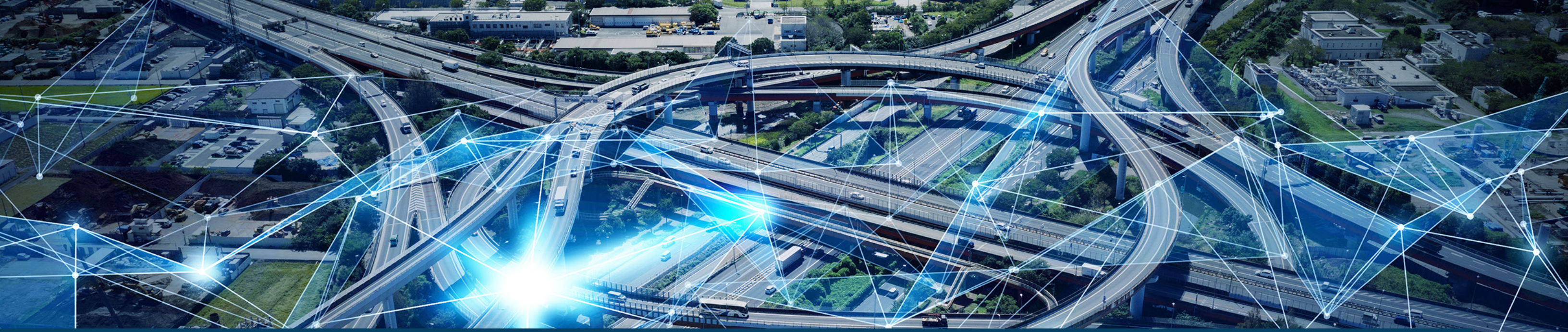
ABOUT CYMANII

The Cybersecurity Manufacturing Innovation Institute (CyManII – Cī-man-ē) was launched by the Department of Energy to advance cybersecurity in energy efficient manufacturing. CyManII is focused on pursuing targeted research and development that **advances our understanding of and acts upon the evolving cybersecurity threats** to greater energy efficiency in manufacturing industries, by developing **new cybersecurity technologies and innovations**, and **sharing information and knowledge** to the broader community of U.S. manufacturers.

CyManII has several unique attributes to meet its national objectives with both a sense of urgency and a robustness that drives an holistic technical approach.

1. CyManII is the only institute focused exclusively on cybersecurity of U.S. manufacturing.
2. CyManII's leadership team and lead developers hold sufficient security clearances to fully access and understand the threat vectors and future challenges that require focused innovation today.
3. The CyManII team assembles first-in-class expertise from manufacturing and cybersecurity from industry, academia, and National Laboratories.
4. CyManII is committed to upskilling and reskilling 1 million workers in order to transform the industry and usher in a new era of cybersecurity for U.S. manufacturers.
5. CyManII's approach to cybersecurity is integrated, holistic, and verifiable.
6. CyManII creates a "cyber security revolution" that increases operational resiliency, productivity, and profits.

This is an abbreviated version of the CyManII 2022 Roadmap for the general public. CyManII members have access to the full Roadmap version.



ABOUT THIS ROADMAP

Roadmap Purpose

The **CyManII Roadmap** outlines a broad vision for cybersecurity in U.S. manufacturing for the next five years and is aimed squarely at SMM, large manufacturers as well as OEMs that supply large production industries. The purpose of this Roadmap is to present a robust and aggressive pathway to transform the industry by making U.S. manufacturers the most cybersecure in the world. Attacks will be increasingly focused at the advanced persistent threat or sabotage levels, in addition to IP theft and ransomware. The aim of these attacks is simple: disrupt our critical manufacturing ecosystem and undermine our economy. **The stakes are very high.**

This Roadmap is specifically intended to speak to an informed audience in **industry** who are generally aware of the cyber risks associated with manufacturing processes. It is not intended to be an educational document about these risks. Our work force development programs address this gap for SMMs, and technicians operating equipment on a factory floor. This Roadmap is also not intended for the myriad of cyber research centers existing today.

With this dynamic in mind, this Roadmap offers manufacturers insight into the national benefits of a dedicated effort to secure U.S. manufacturing industry from cyber threats. The research path described in this Roadmap is essential as U.S. manufacturers of all sizes drive toward processes that are data intensive, digitized, and utilize emergent applications of Artificial Intelligence (AI) and Machine Learning (ML) to drive productivity gains in the face of growing complexity. Some industry insights that have influenced CyManII's efforts in developing this Roadmap:

- The manufacturing sector continues to introduce technical and digital innovations creating a digital thread that crosscuts industries and interdependent supply chains of all sizes.
- While manufacturers may not be focused on the details of how to secure digitization and digital threads from cyber threats, they are highly focused on the cyber benefits that CyManII offers as they pursue their fundamental goals of productivity, quality, and profit.
- As several CyManII industry members have clearly articulated: Manufacturers want to purchase products to digitize their operations but are concerned about the cyber risks that are introduced.

Thus, the cyber security innovations offered by CyManII provide the opportunity to sell more devices while interweaving cybersecurity into U.S. manufacturing operations. Ensuring that manufacturers' IP, vital data, and system operation are cybersecure across the digital threads within critical manufacturing is essential for the competitiveness of U.S. manufacturers in the global market, as well as our national and economic security.

Roadmap Audience

The primary stakeholders for this Roadmap are the U.S. Department of Energy (DOE) and members of CyManII. **The key audience for this Roadmap are the representatives from the manufacturing industry whose partnership will be vital to ensuring that CyManII's work is as relevant and impactful as possible**. In addition, the awareness of this document among a broader stakeholder community (e.g., other U.S. Government agencies and research institutions) will be important to the success of CyManII's efforts to enable constructive dialogue and unveil opportunities for collaboration and knowledge sharing.

The DOE will use this Roadmap to understand CyManII's planned efforts and to provide guidance as the key U.S. government sponsor. The Roadmap will inform DOE in its portfolio of work and describe how CyManII is positioned to achieve its goals.

For this Roadmap version, CyManII needs **its members'** feedback on the areas of proposed R&D in cybersecure energy and emissions-efficient innovation. It will be critical for CyManII to partner with and learn from members to enable the innovation represented by the tenets of **ε-PURE: cybersecure energy and emissions-efficient solutions that are Pervasive, Unobtrusive, Resilient, and Economical**. Members can also assess how their organization's internal cybersecurity plans align with CyManII's Roadmap to identify high-priority areas for direct project engagement. *Note: a vital subset of the U.S. manufacturing industry includes SMM, who represent the backbone of U.S. manufacturing but may have more limited cybersecurity skills and resources*.

CyManII leadership will use the Roadmap as a guide for its areas of research and foundational activities. CyManII will leverage the Roadmap to focus its own organizing principles, and as a means to engage with, and receive feedback from, key stakeholders. The Roadmap will inform and shape future Requests for Proposals managed by the Institute.

Other stakeholders—who may include the broader R&D community, non-members and other government agencies—should use this Roadmap to help them engage with CyManII, provide feedback on CyManII's work, shape and inform R&D, and guide the transition of investments and priorities.

The CyManII Roadmap is the foundational roadmap for this new Institute. It represents an agile, living planning process and will be updated regularly, based on CyManII research theme progress and as new needs and insights emerge over the course of ongoing work. ***This roadmap was developed with extensive input from experts from the manufacturing***

industry, academia, and government to add insights that ensure the Roadmap addresses manufacturers' needs and concerns*. As CyManII progresses through its initial five-year period, the Roadmap will be updated with a focus on work to be done within, and beyond the initial five years.*

Key Terms for this Roadmap

TERM	DEFINITION
Attack Surface	The set of points on the boundary of a system, a system component, or an environment where an attacker can try to enter, cause an effect on, or extract data from, that system, component, or environment.[1]
Baselining	The process of establishing the starting point of any process/metric, from which the improvement or impact of any change measure is calculated. It is used to gauge how effective an improvement or change initiative is.[2]
Cybersecurity	Prevention of damage to, protection of, and restoration of computers, electronic systems, electronic communications services, wire communication, and electronic communication, including information contained therein, to ensure its availability, integrity, authentication, confidentiality, and nonrepudiation–OR–the process of protecting information by preventing, detecting, and responding to attacks.[3]
Cyber Physical	Interacting digital, analog, physical, and human components engineered for function through integrated physics and logic.[4]
Decarbonization	Decarbonization can be expressed as a product of [the reduction of] two factors: (1) specific carbon emissions per unit energy; and (2) energy requirements per unit value added, often called energy intensity.[5]
Digital Supply Chain	The consistent and sustainable connectivity between the manufacturer and the lowest-level suppliers to the delivery of the product to the customers.[6]
Digital Thread	A data-driven architecture that links together information generated from across the product lifecycle.[7]
Emissions (Carbon) Efficiency	The extent to which a given level of output is produced with minimum feasible emissions relative to direct sector peers.[8]
Energy Efficiency	When a given level of service is provided with reduced amounts of energy inputs or services are enhanced for a given amount of energy input.[9]
Energy Productivity	A measure of the economic benefit we receive from each unit of energy we use — calculated by dividing total economic output by the amount of energy consumed.[10]

TERM	DEFINITION
Exploit	A program, or piece of code, designed to find and take advantage of a security flaw or vulnerability in an application or computer system, typically for malicious purposes such as installing malware. An exploit is not malware itself, but rather it is a method used by cybercriminals to deliver malware.[11]
Manufacturing Competitiveness	The extent to which key drivers (such as energy productivity, resiliency/agility, talent, emissions control, and cost competitiveness) propel a segment of industry to a leading position in revenue, secure innovation, and quality of product.
Measurement and Verification	Measurement and Verification, or M&V, is a process of planning, measuring, collecting, and analyzing data to verify and report energy savings within a facility or facilities resulting from the implementation of energy-efficiency measures.[12]
Quantification	The application of consistent criteria to assign a numerical value to a measurement of something. Quantification produces a standardized form of measurement by intelligent aggregation of sources that allows statistical procedures and mathematical calculations.
Resilience	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.[13]
Vulnerability	Weakness in an information system, system security procedures, internal controls, or implementation that could be exploited or triggered by a threat source.[14]

1 https://doi.org/10.6028/NIST.SP.800-53r5
2 https://www.whatissixsigma.net/baseline-measurement/
3 https://csrc.nist.gov/glossary/term/cybersecurity
4 https://doi.org/10.6028/NIST.SP.800-171r2
5 Nakicenovic, N., 1996. Decarbonization: doing more with less. Technological Forecasting and Social Change 51 (1), 1–17.
6 https://www.nist.gov/blogs/manufacturing-innovation-blog/digital-supply-chain-assessment-sets-stage-optimizing
7 https://arc.aiaa.org/doi/10.2514/1.J057255
8 https://www.sciencedirect.com/science/article/pii/S0921800919310675
9 https://www.energy.gov/eere/analysis/energy-efficiency-vs-energy-intensity
10 https://www.ase.org/sites/ase.org/files/gaep_playbook-energy-productivity_alliance-to-save-energy.pdf
11 https://www.cisco.com/c/en/us/products/security/advanced-malware-protection/what-is-exploit.html
12 https://www.bpa.gov/EE/Utility/measurementandverification/Pages/default.aspx
13 https://doi.org/10.6028/NIST.SP.800-160v2
14 https://doi.org/10.6028/NIST.FIPS.200

A. EXECUTIVE SUMMARY

> *I don't buy for one second that the vitality of American manufacturing is a thing of the past. American manufacturing was the arsenal of democracy in World War Two and it must be part of the engine of American prosperity now… America can't sit on the sidelines in the race to the future. Our competitors aren't waiting. To ensure the future is made in America, we need to win not just the jobs of today, but the jobs and industries of tomorrow.*[17]
>
> *– President Joe Biden*

The jobs of tomorrow are **secure**, **safe**, and **smart**, and the industries of tomorrow are **digital**, **democratized**, and **decarbonized**. This future is built by manufacturers that optimize and innovate across the combination of physical, cyber, and energy layers in legacy systems and new technologies. This combination allows for dramatic increases in overall equipment efficiency, which decrease costs, increase productivity, and encourage innovation—all elements that feed U.S. manufacturing competitiveness. However, this digital transformation **(see Section B for more details)** also creates new and larger "attack surfaces" that are difficult and expensive to secure and can result in costly and far-reaching damage. In this new manufacturing environment, it is more difficult than ever to instill confidence in manufacturing industry partners, owners, operators, and consumers that their products and intellectual property (IP) are secure and protected.

In recognition of this environment and the urgency of these challenges, the Department of Energy (DOE) identified the critical need for an organization—the **Cybersecurity Manufacturing Innovation Institute (CyManII)**—to work across the manufacturing industry, research and academic institutions, and federal government agencies to develop technologies to enable U.S. manufacturing to thrive and grow **(see Section C for more details)**. This joint, collaborative mission must harden U.S. manufacturers to current cyber-exploits while providing the training needed for companies to protect themselves against evolving threats. Simultaneously, we must begin designing and implementing next-generation architectures that are cyber-inspired and secure by design.

The Future State of U.S. Manufacturing

CyManII's innovative approach to secure manufacturing and deep knowledge of the threats is a combination which uniquely positions CyManII to drive U.S. manufacturing towards the future state of secure, digital manufacturing.

Manufacturers are deploying advanced manufacturing and digital technologies to improve efficiency at a rapid pace, with variable levels of insight into the associated cyber risks. At the manufacturing process level, cyber risks can be reasonably managed. However, as advanced manufacturing evolves to digital threads that integrate processes, enterprises, supply chains, and ecosystems, the nature and complexity of cyber risk grows dramatically. **Figure 1** conveys the current state, the future state, and CyManII research theme enablers of the pathway between the two for cybersecure, efficient digital manufacturing.

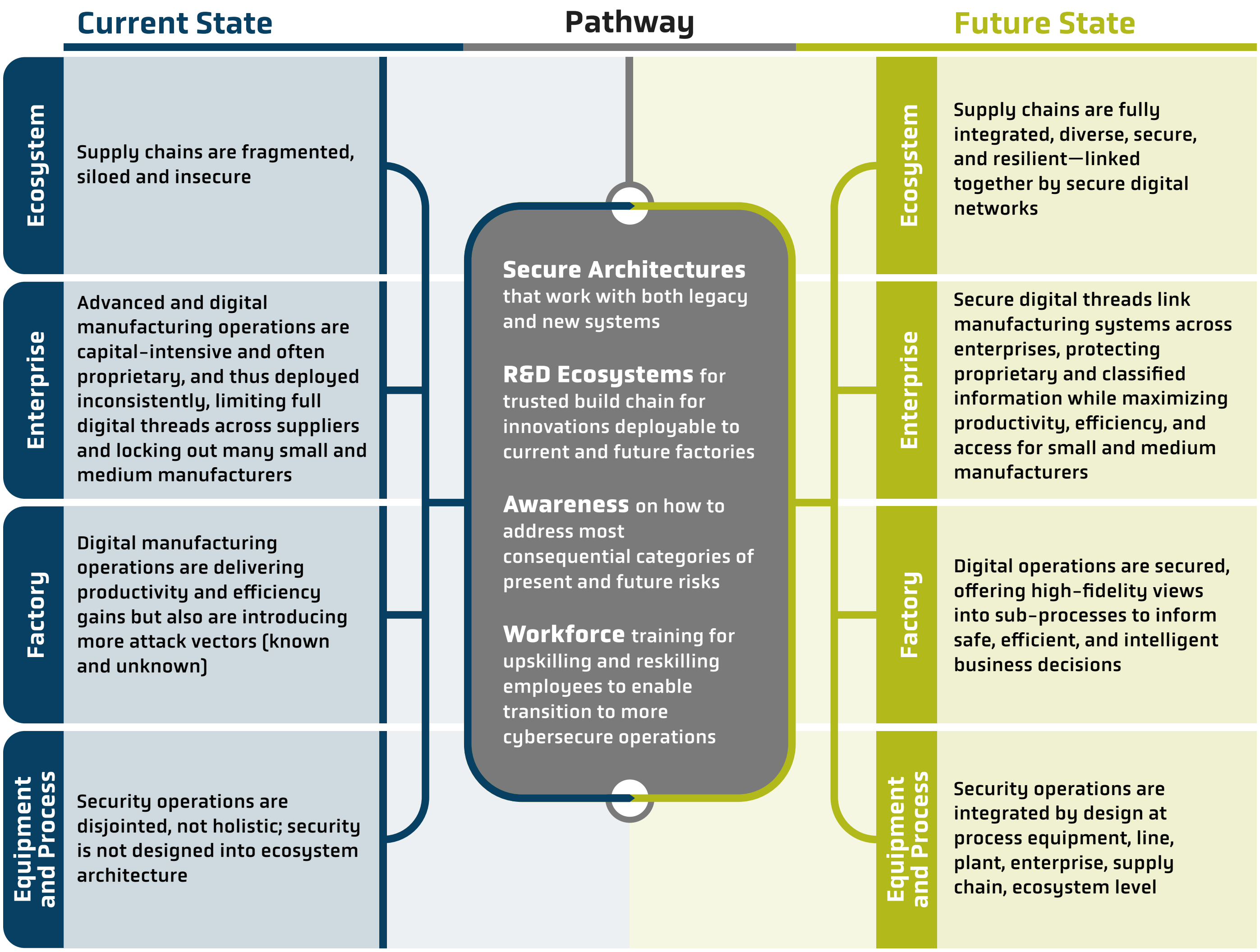


Figure 1—The pathway to a Future State

The transition pathway from current state to future state will require that CyManII and manufacturing partners work closely together to build secure architectures specifically designed to work with legacy and new systems, recognizing the essential role that legacy equipment plays in most manufacturing operations. Similar to how computers are periodically updated to ensure they are compatible with state-of-the-art technologies and protected against new cyber threats, manufacturing systems must be continuously upgraded to ensure maximal effectiveness, efficiency, and cybersecurity. This process helps protect a system from becoming outdated, outmoded, and a portal for a cyber attack or breach. Similarly, the secure digital thread can be used to ensure that aging or legacy systems remain compatible with digital and cybersecurity requirements while also continuing to meet manufacturing enterprise, supply chain, and ecosystem capabilities. This transition pathway also requires increased awareness among manufacturers on approaches for addressing present and future cyber risks and a workforce that is upskilled and reskilled through CyManII's training programs to help their employers transition to more cybersecure operations.

Operations and Security

In most manufacturing enterprises, operations are generally well integrated, which provides a foundation for integrating security throughout the enterprise. However, security may be designed into specific machines or systems but not designed into system architectures. The holistic approach of CyManII is to integrate security and operations not just at the individual machines/processes level, but also through line and plant operations, and eventually enterprise, supply chain, and ecosystems using CyManII's secure manufacturing architecture (SMA). CyManII's approach to security is reminiscent of earlier industry-wide efforts to prioritize quality by integrating quality into products and processes, including designing products, production systems and overall supply chains.

Digital manufacturing and Industrial Internet of Things (IIoT) technologies are being deployed across manufacturing, delivering productivity and other gains while also creating known and unknown attack vectors and growing cyber risk due to the increased connectivity and access such systems provide. CyManII is not developing digital manufacturing technologies, but rather the architecture needed to instill security into digital manufacturing at the process level – and when processes are connected in plants, throughout enterprises, and along supply chains to build full digital threads. CyManII's future state allows manufacturers to make intelligent decisions to optimize efficiency and productivity at the plant level, increasingly with the aid of artificial intelligence (AI) and machine learning (ML) approaches that rely on massive data gathered without introducing new attack vectors.

The Digital Thread

The digital thread is "the communication framework that enables connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed and functional perspectives."[15] The digital thread makes it possible to verify products, ensure that the latest technologies are deployed throughout the ecosystem, and strengthen the workforce.[16] Digitization, including digital threads, also introduces the prospect for dramatic gains in energy efficiency, but securing these operations from cyber threats are essential for these energy efficiency gains to be realized.

Importantly, the digital thread (and other manufacturing innovations) also leads to metrics that matter for manufacturers which include a) decreasing the amount of waste, b) decreasing the time to the first high-quality part, c) increasing overall equipment efficiency, and d) increasing the overall resiliency of operations. These four elements increase productivity and maximize profits. The digital thread is how we connect designs and interconnected manufacturing operations – and this thread must be secure. One of the key elements of that security is the proprietary information and critical data that companies – and their adversaries – value. Securing these operations is necessary at the final assembly stage but also throughout all tiers of the supply chain (Tier 1, 2, 3, 4, 5, ...).

Securing these digital threads requires new cyber-informed, secure-by-design architectures to be placed into/onto legacy and new systems. Ensuring that these secure manufacturing architectures are **energy- and emissions-efficient and Pervasive, Unobtrusive, Resilient, and Economical (ε-PURE)** is essential if the U.S. is to lead manufacturing innovation and productivity globally. Coincident with this, it is essential that the incumbent work force be widely trained in basic cyber hygiene, avoidance of advanced persistent threat vectors, and the potential of cyber sabotage. This will require a change in workforce development approaches and a focus on performing this training at a very high volume to reach millions of U.S. manufacturing employees.

As manufacturing supply chains and digital threads are built, manufacturers must also protect proprietary information that competitors and adversaries value. While the digital thread allows for quick deployment of new capabilities (e.g., models, analytics), doing so must preserve security of proprietary and classified information. Greater integration among OEMs, "primes" and their tiered supply chains can allow for access to the latest process data, the latest equipment functionality (e.g., all of a machine tool's functionality), and the capabilities of a diverse manufacturing ecosystem (including SMMs).

CyManII's future state enables the promise of digital manufacturing to be realized securely. Doing so supports point of assembly (e.g., local) manufacturing and enables distribution of the supply chain to multiple smaller entities, providing greater resiliency (e.g., back-up capacity in the event of a single plant going down) and greater opportunities to SMMs. This distributed approach also has the potential to maximize production efficiency across the entire ecosystem and enable metrics trade-offs between efficiency and resilience. For example, an ecosystem that is 100% utilized might be efficient, but if one element is interrupted, there is no excess capacity and supply chains are disrupted, as was observed during the COVID-19 pandemic or the Fukushima disaster in Japan. Furthermore, the approach provides insight into ecosystem weaknesses such as lack of support for legacy systems. This insight will form the foundation for ecosystem element sun-setting and upgrading opportunities, ensuring a strong U.S. manufacturing base.

Progression towards this future state--and towards the democratization of manufacturing—are dependent on digital threads as the communication framework that enables a connected data flow and integrated view of an asset's data throughout its life cycle. The jobs and industries of tomorrow depend on the successful implementation of digital threads across broad manufacturing sectors ranging from clean energy to iron/steel manufacturers. *If these digital threads are not cybersecure, U.S. manufacturers will be compromised in multiple cyber-exploit scenarios*.

Engaging with U.S. Manufacturing Industry

One of CyManII's most critical functions is its engagement with the manufacturing industry to understand challenges **(see Section D for more details)** and partner to identify solutions. CyManII is purpose-built to ensure that U.S. manufacturers are protected from the modern cyber-physical threats that they face now and will encounter in the future.

CyManII is a research institute that addresses the fundamental challenges of cybersecurity with a manufacturing context. Because levels of cybersecurity maturity vary greatly, CyManII is meeting manufacturers where they operate today and placing them on a pathway towards a vastly improved cyber future state that is founded on both manufacturing industry and national priorities. This future state is defined by its **robust**, **resilient**, and **decarbonized** nature.

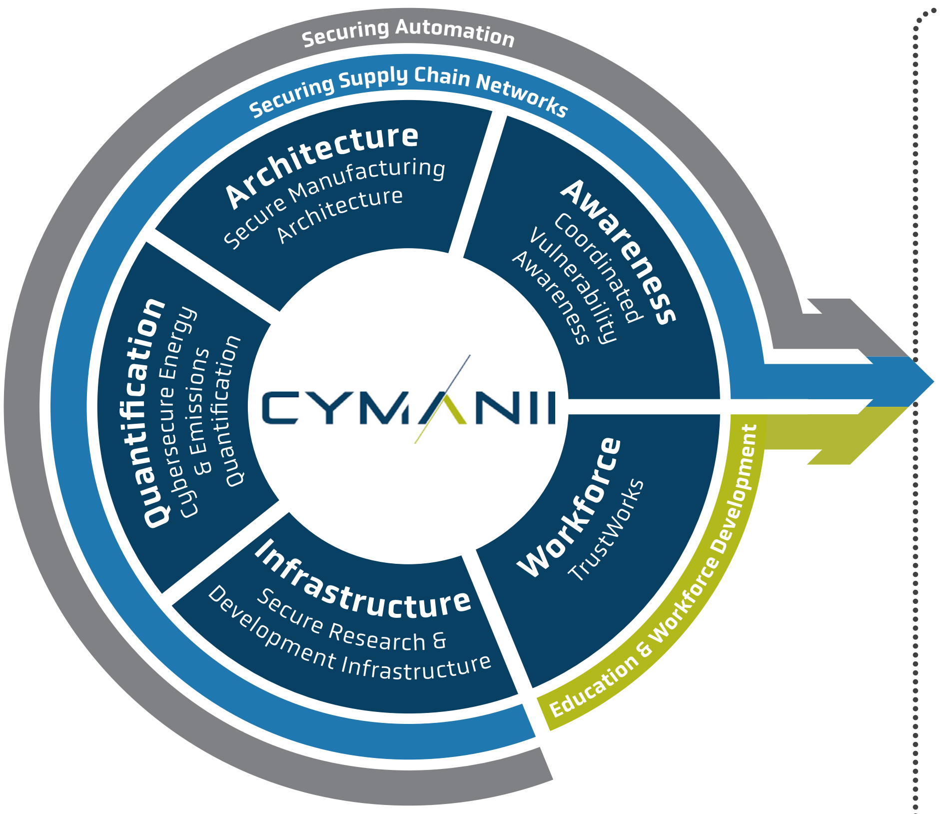
TRAITS OF THE FUTURE STATE	U.S. GOVERNMENT	MANUFACTURING INDUSTRY
ROBUST Robust systems withstand cyber-exploits, resulting in minimum downtime	Robust systems minimize the disruption of key economic sectors and protect important domestic technologies	Robust systems increase competitiveness, and keep employees safe from cyber-physical threats
RESILIENT Resilient systems recover quickly from any successful cyber-exploits	Resilient systems increase the reliability of critical infrastructure and decrease the energy wasted during "black starts"	Resilient systems maximize productivity, agility, margins, and opportunity
DECARBONIZED Decarbonized systems are both clean and efficient	Decarbonized systems increase U.S. competitiveness and energy productivity while limiting the effects of climate change	Decarbonized systems reduce waste and emissions, allowing manufacturers to increase margins and hit environmental targets

Research Themes

Consistent with these guiding principles, CyManII is assembling a consortium of partners with an integrated manufacturing industry approach to developing and deploying broad sets of new innovations while upskilling and reskilling manufacturing floors and the people that operate them. The core research themes needed to address fundamental technical challenges in a cooperative, systematic, and agile fashion are **Quantification**, **Architecture**, **Infrastructure**, **Awareness**, and **Workforce**.

RESEARCH THEME	CYMANII FOUNDATIONAL TASK
Quantification	CyManII's innovations will enable the *industries of tomorrow* to measure decarbonization impacts at the process and supply chain network levels and validate the degree of cyber hardening that results from the implementation of specific cybersecurity solutions.
Architecture	CyManII is dedicated to a future state of secure manufacturing industry that is built on next-generation architectures that are cyber-informed and secure-by-design.
Infrastructure	CyManII will introduce a trusted ecosystem that will allow the innovations of tomorrow's manufacturing industry to be validated in today's environment.
Awareness	CyManII will define the categories of tomorrow's cyber vulnerabilities and establish a network to distribute vulnerability information to manufacturers on a daily, weekly, and monthly basis.
Workforce	CyManII will launch a new cyber training approach to prepare the manufacturing workforce for the jobs of tomorrow and equip manufacturers with the skills needed to protect physical and cyber assets including emergent digital threads.

Within these core research themes, and to drive the R&D necessary for the jobs and industries of tomorrow, CyManII has identified 18 key Research Routes **(see Section E for more details)**. These Research Routes were developed through a highly integrated technical approach, incorporating insights from within and across each of the five research themes. The Research Routes will be essential to pursuing the path towards the bold targets that CyManII has set in recognition of the transformation that is needed to ensure the current and future competitiveness of U.S. manufacturing **(see Section F for more details)**.



Key Outcomes:

- **Securely quantified energy productivity**, costs, and emissions to design more securely efficient products, automated process, and supply chain networks
- **Usable and effective cyber-secured architectures** for product-process automation and product supply chain networks to reduce downtime and accelerate adoption of innovations
- **Federated manufacturing research ecosystem** that allows secure development and evaluation of CyManII innovations and attracts new industry participants from "digital threads" of key sector supply chains
- **Focused industry risk management** on mitigating/preventing categories of vulnerabilities in manufacturing automation and supply chain networks
- Virtual/mixed-mode experiential competency-based cybersecurity **education and workforce development**

Figure 2—The CyManII research themes and key outcomes

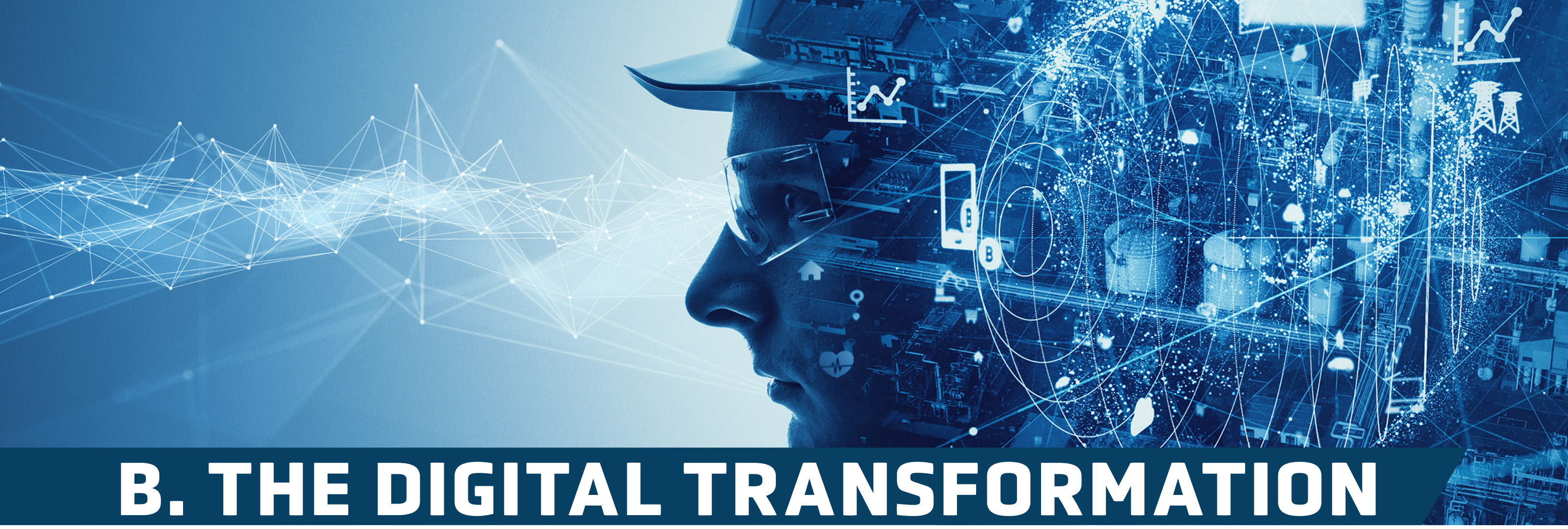
Current Opportunities

Beyond CyManII's immediate mandate to secure American manufacturing lies critical opportunities to secure our critical infrastructure. There are several distinct opportunities where CyManII can assist in elevating the national security of our nation, including three examples outlined below.

1. CyManII's technical approach of building **Secure Manufacturing Architectures (SMA)** will implement, and potentially expand, the principles of cyber informed engineering (CIE), an emerging approach to "engineer out" cyber risk early in the lifecycle of Industrial Control Systems (ICS) by integrating cyber considerations as a foundational element of engineering risk management. As such, CyManII will produce architectures that are cyber inspired and secure by design. ***CyManII,** as a national Institute with national impact, is ideally suited to assist the DOE with the development and deployment of a National CIE Strategy.*

2. Executive Order 14017 (*EO on America's Supply Chains*) requires the submission of a "report on supply chains for the energy sector industrial base."[18] The responses represent the first comprehensive U.S. government plan to build an Energy Sector Industrial Base (ESIB). The DOE defines the ESIB as the energy sector and associated supply chains that include all industries/companies and stakeholders directly and indirectly involved in the energy sector. These energy sector industries and their supply chain networks are extremely diverse. As a significant DOE investment, CyManII is a critical partner on the pathway to a national ESIB which enables the secure re-shoring of U.S. manufacturing. *It is **CyManII**'s technical work on **Cybersecure Energy and Emissions Quantification (CEEQ)** that supports the secure development of the ESIB, which comprises multiple asset owners and manufacturers.*

3. Section 5726 of the National Defense Authorization Act for Fiscal Year 2020 (Pub. L. 116-92) directed DOE to establish a two-year pilot program within the National Laboratories—in partnership with relevant federal agencies, academic partners, energy sector asset owners and operators, and critical component manufacturers—to identify new classes of energy sector security vulnerabilities and evaluate technology and standards that isolate and defend ICS from security vulnerabilities and exploits in the most critical energy sector systems. CyManII played a major role in this process by leading the identification of 20 categories of cyber vulnerabilities present in U.S. critical infrastructure. Based on this work, DOE has selected CyManII to provide national leadership for the identification and mitigation of cyber vulnerabilities in the nation's critical energy infrastructure. ***CyManII**'s work focuses on identifying categories of security vulnerabilities specific to ICS, creating a shared baseline of enumerated common weaknesses.*



B. THE DIGITAL TRANSFORMATION

> *Technology companies are under intense market pressure to prioritize "first to market" over security, thereby passing on risk to companies and individuals. The aggregated vulnerability assumed by these companies and individuals has created a significant national concern: rampant insecurity that passes costs of billions of dollars to downstream consumers and that has the potential both to disrupt our day-to-day life and to undermine public confidence in and the effectiveness of key institutions.*[19]
>
> *– Cyberspace Solarium Commission*

Digital designs, advanced manufacturing, and product innovations are creating a new "digital thread" between consumers, SMMs, large manufacturers, and OEMs that produce digital technologies for other manufacturers. These digital thread ecosystems create unlimited opportunities to increase our global competitiveness, democratize manufacturing, and revitalize American innovation. Currently, these digital threads are a patchwork of architectures, protocols, and information sharing with incomplete or unenforceable security that creates additional complexity and expenses for many SMMs. **Building a cybersecure digital thread is key to ensuring U.S. manufacturers and supply chains are secure and efficient**.

B.1. Securing The Digital Thread

Manufacturing is consistently among the most often targeted industries for nation-state cyber-exploits.[20] Each year, these exploits put coveted IP at risk, cause untold damage to systems and their operators, and cost manufacturers millions in lost productivity due to downtime. Beyond that, these cyber-exploits prevent many manufacturers from adopting new technologies and data management systems that would allow them to reduce waste, increase productivity, and improve their overall competitiveness in the marketplace. **A recent survey showed that 91% of manufacturers are invested in these digital technologies, but 35% say that the accompanying cybersecurity challenges and vulnerabilities inhibit them from doing so fully.[21]**

U.S. manufacturing faces global economic, national security, and environmental threats that require *robust cyber and physical security, supply chain resilience, and the fusion of information technology/operational technology (IT/OT) operations with energy and emissions efficiency*. More importantly, current industrial control architectures are fundamentally unfixable since most manufacturing protocols are insecure by design and existing cybersecurity practices rely on "border controls" that are too easily breached. Threat actors are rapidly leaping ahead of these perimeter defenses by developing and automating exploitable vulnerabilities embedded in our digital supply chain (e.g., SolarWinds attack) to impact manufacturers of all sizes.

SMMs—the backbone of the U.S. manufacturing industry—typically have limited cybersecurity skills and resources. This prevents them from taking advantage of the new technologies that drive information sharing and materials exchange across digitally controlled supply chain networks. Many SMMs face an existential threat from their larger competitors who can afford to embrace the new era of digital manufacturing. Unfortunately, many of these same SMMs were only able to survive the globalization of the last few decades by carefully managing their margins, so they are hesitant to fully commit to technologies and processes that may present new costs, challenges, and avenues for disruption.

To mitigate this dynamic, and to aid domestic manufacturers in increasing competitiveness and capturing the value of the digital thread, **CyManII is developing future-state, secure manufacturing architectures that are secure by design and informed by deep knowledge of the evolving threat vectors**. These architectures enable manufacturers to maximize security, resiliency, and overall market competitiveness in the face of current and evolving threat vectors.

B.2 CyManII Benefits and Opportunities

CyManII's work will generate opportunities to increase U.S. manufacturing competitiveness by focusing on securing the digital thread from start to finish for new and legacy systems. Simultaneously, CyManII will address the fundamental challenges in securing automation and its supply chain networks. CyManII works with manufacturers to embrace the opportunities for improved competitiveness within a domestic ecosystem that enables both SMMs and OEMs to participate and pivot to new, secure markets in an agile fashion. CyManII's secure manufacturing architectures reduce the time and uncertainty involved in making quality parts. CyManII links these new architectures to productivity increases from overall operational efficiency (i.e., labor, materials, energy, emissions)––and enables manufacturers to be more productive and more profitable while helping to decarbonize their operations and supply chains.

This future-focused approach makes a company more secure (i.e., protecting systems from exploit and accelerating recovery following an exploit) and more efficient (i.e., producing less scrap, creating fewer emissions, using less energy, and requiring shorter lead times). CyManII offers four key areas of opportunity for manufacturers to bridge the gap between the *current and future state*: **Automation**, **Supply Chain Networks**, V**ulnerability Management**, and **Workforce Development**.

FOR AUTOMATION, CYMANII...

... is developing the secure protocols, methods, and infrastructure required to integrate new innovations and maximize the value of the digital thread.

... is leading research that will allow manufacturers to securely integrate systems that vary in age and sophistication by developing security architectures for legacy environments.

... will drive results that inform business strategy and decision making by quantifying the energy productivity of specific innovations and processes.

FOR SUPPLY CHAIN NETWORKS, CYMANII...

... will allow SMMs to ensure the security and authenticity of their components throughout the entire supply chain by integrating multiple levels of security screening.

... will enable manufacturers to decarbonize by monitoring and evaluating the environmental impacts of their supply chains.

... will provide secure and efficient communication channels and ensure synchronized pedigree and provenance tracking throughout the supply chain.

FOR VULNERABILITY MANAGEMENT, CYMANII...

... will empower manufacturers to quickly evaluate cybersecurity risks and make informed business decisions.

... will coordinate security practices across numerous departments, buildings, work centers, and production shifts.

... will establish secure and coordinated processes for disclosing vulnerabilities and will allow manufacturers to plan and prioritize their responses to cyber-exploits.

FOR WORKFORCE DEVELOPMENT, CYMANII...

... in cooperation with manufacturers, will attract a workforce that is prepared for the next generation of secure, open Industrial Control Systems (ICS) and interfaces.

... will help SMMs integrate Institute results and create specialized technical training programs to educate and upskill employees.

... will enable manufacturers to stay up to date and train their workforce on rapidly evolving and effective cybersecurity best practices.

B.3 CyManII's Partnership with the U.S. Manufacturing Industry

CyManII's integrated approach is built specifically to help manufacturers realize CyManII's benefits and pursue these opportunities. It provides a framework to connect the research themes with both technical and non-technical workstreams. These workstreams are rooted in the needs of the manufacturing industry, and they are designed to help manufacturers overcome the challenges that they will face whilst realizing the potential of the digital thread. The foundational elements of these research themes, and the manufacturing industry's interface roles, are:

RESEARCH THEME	CYMANII RESEARCH	MANUFACTURING INDUSTRY ROLE
Quantification	**Cybersecure Energy & Emissions Quantification** (CEEQ) CEEQ applies baselining techniques for securely quantifying energy productivity, costs, and emissions to guide the design of products, processes, and supply chain networks	Industry provides measurement and process innovations and operational efficiency objectives that are addressed by CEEQ
Architecture	**Secure Manufacturing Architecture** (SMA) SMA will design and develop effective cybersecure architectures for product-process automation and product supply chain networks to reduce downtime and accelerate innovations	Industry develops new advanced manufacturing processes that rely on digital transformation and are secured by SMA
Infrastructure	**Shared Research & Development Infrastructure** (SRDI) SRDI is building a federated manufacturing infrastructure that allows secure development and evaluation of CyManII innovations and establishes the CyManII member ecosystem	Industry provides advanced manufacturing assets and supplier networks whose digital threads need to be secured for their competitiveness
Awareness	**Coordinated Vulnerability Awareness** (CVA) CVA will reshape industry risk management practices around mitigating/preventing categories of vulnerabilities in manufacturing automation and supply chain networks	Industry provides context for high-consequence vulnerabilities and actionability gaps to be addressed by the community
Workforce	**TrustWorks** TrustWorks will lead the development of virtual/mixed-mode experiential competency-based cybersecurity	Industry seeks a pipeline of talent and continuous learning refresh for their workforce

CyManII will interface on each research theme with the manufacturing industry in a unique way that will allow manufacturers to take full advantage of the benefits that CyManII has to offer. Due to CyManII's integrated approach, each of these interactions with manufacturers will inform the work done across all research themes.

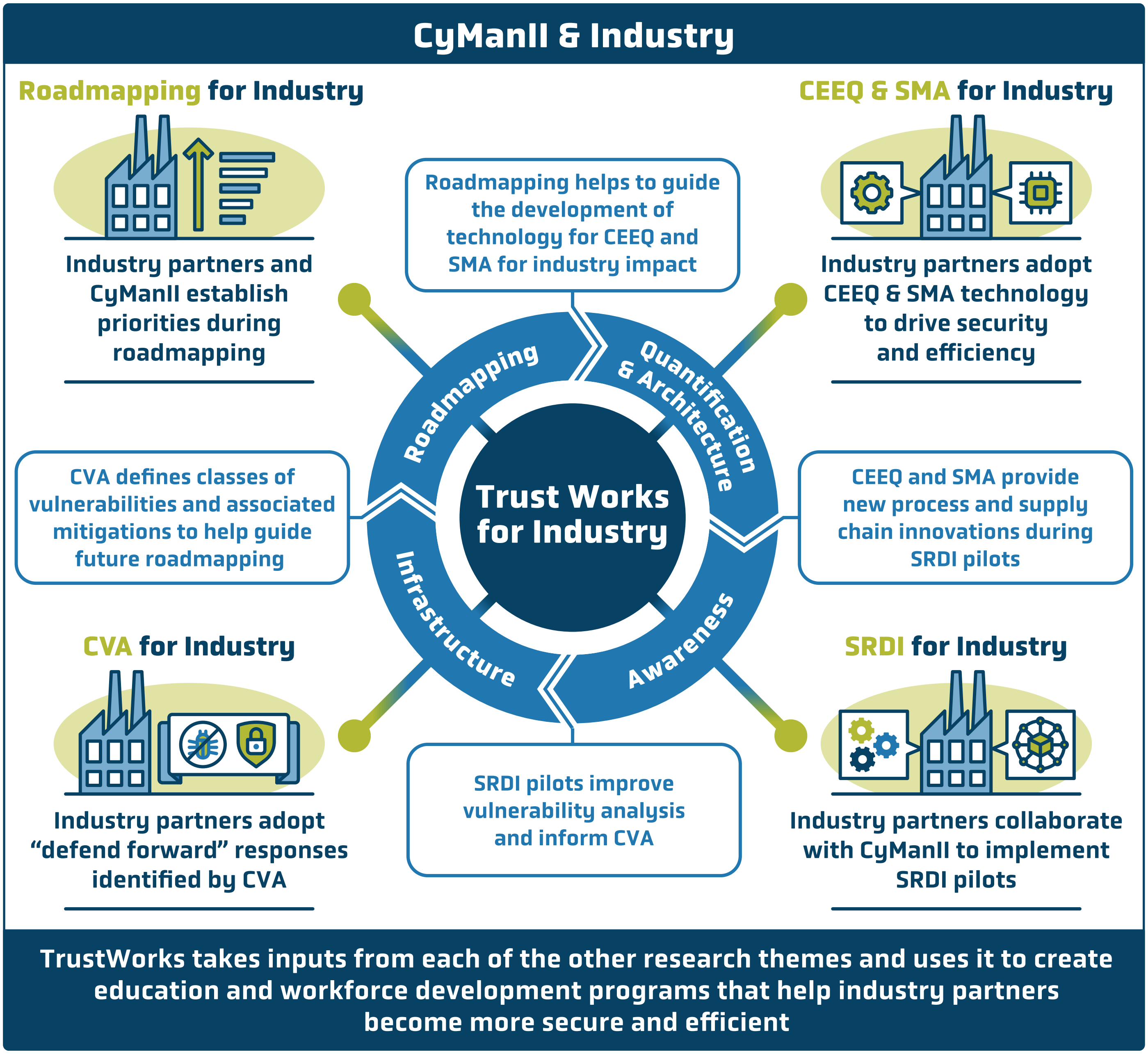


Figure 3—The CyManII research themes and ecosystem

C. ADVANCED MANUFACTURING INDUSTRY OVERVIEW

C.1 The State of U.S. Manufacturing

Manufacturing accounts for approximately 25% of the total energy consumed annually in the U.S.; this share also holds globally (see Figure 4). The associated U.S. energy cost, $130B, represents approximately 11% of the GDP and nearly 15 million direct jobs.[22, 23, 24] Numerous reports state that each $1 spent in the U.S. manufacturing sector generates between $1.3 and $1.8 in other economic activity, a multiplier that exceeds the value for any other sector.[25] There are approximately 300,000 manufacturing establishments in the U.S., the vast majority of which are categorized as SMMs.

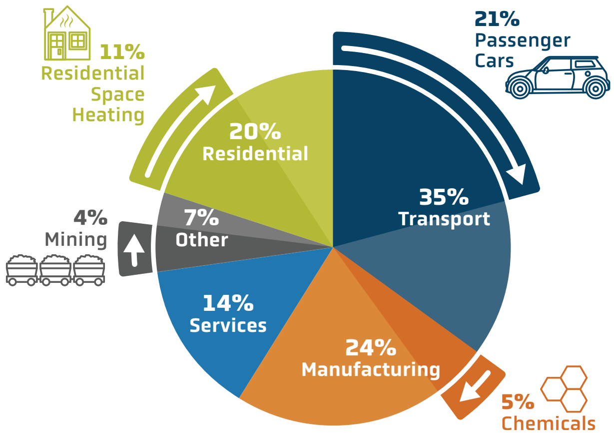


Figure 4—Energy use by category for all IEA countries[26]

C.2 Summary of Manufacturing Trends

Manufacturing sectors vary significantly based on their differing processes, priorities, and labor forces, but there are cross-cutting trends and considerations that are recognizable across manufacturing. Understanding these trends is key to incorporating the digital thread into the design-build-deliver life cycle in manufacturing, a process that includes the following steps:

- Incorporating digital tools and digitization throughout an entire manufacturing facility
- Connecting multiple manufacturing enterprises to one another
- Achieving the full digital orchestration of the manufacturing supply chain

The digital thread goes by many names––smart manufacturing, Industry 4.0/5.0, IIoT—but they all describe elements of connected digital networks that expand from the factory floor. Manufacturers face challenges when implementing digital threads—such as system integration issues and data/communication inconsistencies across acquired businesses—that CyManII is poised to address.

Modern manufacturing facilities face concerns with improving production efficiency, supply chain transparency, workforce retention and energy intensity. The CyManII team was conscious of these considerations when outlining the value proposition of digitization and CyManII's support to secure digital threads in both legacy and new systems. CyManII also factored in manufacturers' ability to manage the vulnerabilities of factory software and the smart factories using that software. CyManII is poised to assist its diverse membership by protecting digital threads from the factory floor to the manufacturing enterprise and ultimately across the ecosystems that feed and consume members' products, while recognizing the different needs and skill sets from SMMs to OEMs. Manufacturers' motivations for engaging with digital threads are detailed in the ensuing table.

ENERGY CONSUMPTION

The industrial sector (including mining, construction, agriculture, and manufacturing) is the most energy-intensive sector, accounting for one third of all U.S. energy consumption.[27] **Manufacturing accounts for 77% of the entire sector's energy consumption**. While energy improvements are not a primary concern for manufacturers, the sector's energy intensity and energy consumption have dropped significantly since 2000, as manufacturers have turned to lean manufacturing and digitization to operate more efficiently and maximize production.[28]

Since 2005, DOE has conducted several bandwidth studies of current energy consumption and potential savings opportunities by U.S. manufacturing. CyManII has built on these studies and created **Baseline of Knowledge (BLoK)** papers that evaluate potential savings opportunities for energy, emissions and cybersecurity.

An improvement area for manufacturing identified by CyManII is the reduction of carbon emissions within the supply chain, as industrial supply chains currently account for 40% of annual global greenhouse gas (GHG) emissions.[29] Carbon reduction is another area of improvement, as natural gas accounted for 37% of energy inputs for industry in 2018, an increase from previous years when coal and petroleum were more prevalent.[30]

These changes, however, require capital and personnel to initiate, creating a **gap between multinational manufacturers that can implement such changes and their SMM counterparts that cannot**, regardless of the interdependencies between them. As connected digitization grows, SMMs should be mindful of opportunities to improve energy efficiency and integrate digital threads concurrently, as many of these tools can be modified to monitor and improve energy consumption, emissions efficiency, and product effectiveness.

INDUSTRY/AUTOMATION

There is a wide spectrum of automation and cybersecurity adoption, with natural differences among industries—**process variations, operational concerns, market and regulatory influences, and industry stability**—impacting how companies approach the implementation of digital threads. On the advanced end of cybersecurity adoption are automotive, aerospace, defense, and electronics manufacturing, due to their focus on consumer safety, their large average headcount per company, and their overarching cultures that promote forward-thinking initiatives. Certain operations are better positioned to integrate smart manufacturing and cybersecurity:

- **Continuous flow operations** cannot afford production interruptions for any reason (including cyber-exploits), compared to their discrete or batch manufacturing counterparts.
- Companies producing standard products may find value in automated process controls for consistency, compared to **customized product fabrication** which may require more advanced technology to self-adjust and modulate based on product requirements.
- The U.S. government's shift towards Cybersecurity Maturity Model Certification (CMMC) policies is a signal that **customers can apply external pressure** on high-tech manufacturers to integrate cybersecurity into their products and processes.
- **Newer industries can move more nimbly** when adopting automation without the burden of having to integrate legacy equipment compared to "proven out" industries with long-standing operations.

The largest motivations for manufacturers to implement digital threads all relate to **efficiency optimization (labor, inventory, process/waste, energy/emissions)**. Digitization has also begun expanding beyond facility use to operate on an enterprise level. This is reflected in the types of automation that manufacturers adopt, which have shifted from discrete monitoring technology to connected IIoT systems that act as a unifying factor across facilities.

Unifying facilities with legacy systems pose a challenge, especially as company acquisitions increase the difficulty inherent in streamlining diverse operations, standardizing operations, and maintaining legacy equipment. SMMs, in turn, will need to stay competitive while adopting flexible and modular digital threads to improve their efficiency and resiliency of manufacturing supply chain and retain their share in the market.

SUPPLY CHAIN

The rapid globalization of the last 20 years has transformed manufacturing supply chains into fragmented networks of design, production, and distribution. The rapid digitization of the next 20 years will transform manufacturing supply chains into intricately interconnected collaborations across the globe. **The response of manufacturers to COVID-19's supply shortages has highlighted glaring issues with supplier response times, communication between suppliers, and global connectivity**. The disruption of supply chains due to COVID-19 has encouraged manufacturers to improve traceability, diversify their suppliers, and increase the resiliency of their supply chains.

Before the COVID-19 pandemic, manufacturers struggled to manage visibility of their national and global supply chains. Customers in different markets have also begun demanding "make to stock" products, requiring manufacturers and suppliers to operate with less premade materials. As the complexity of material sourcing, logistics channels, and lead times increase, some manufacturers have employed enterprise-level technologies to track shipments and provide customers with additional information.

Manufacturers, however, have **struggled to escalate existing digital threads from the factory floor to the entire supply chain**. Only companies with leverage over their suppliers can enforce the upgrades necessary to redesign supplier processes and maintain cybersecurity protocols across hundreds of vendors. CyManII's approach to supply chain automation and digitization has evolved to accommodate supplier variability and manufacturer resources.

WORKFORCE

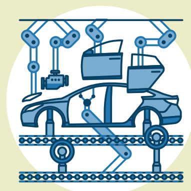
As of 2021, 12.4 million employees work in manufacturing, a slight increase from 2020 but a 5% decrease from 2019's peak (largely resulting from COVID-19).[31] Manufacturing is one of the largest employers in the country and the workforce has grown in the last decade. However, according to the Bureau of Labor Statistics, manufacturing sub-sectors account for 12 of the 20 fastest-shrinking fields of employment.

Several factors have contributed to this decline: international competition, a shift from low-skilled to high-skilled work, baby boomer retirement and an absence of manufacturing information in higher education. In addition, **manufacturing's institutional knowledge—the expertise and experience gained over decades—is being lost**, as there are fewer early-career employees to whom this information may be passed. These factors have reduced the number of new employees entering the field and have increased the competition for skilled labor. Digital threads offer an opportunity to augment and mitigate workforce gaps by leveraging automation, smart analytics, and improved training tools.

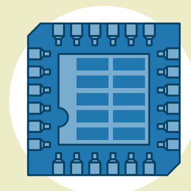
C.3 Manufacturing Sector Profiles

CyManII's primary focus is on eight manufacturing sectors, identified due to their highly energy-intensive nature, their share of all U.S. manufacturing, their alignment with DOE and Office of Energy Efficiency and Renewable Energy (EERE) priorities, and their prevalence in White House investment priorities over the next decade:

Clean Energy Technologies
(electrical vehicles, solar panels, wind turbines)

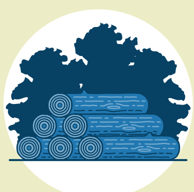


Transportation



Semiconductors

Chemical Conversion



Forest Products

Cement

Iron and Steel

Food and Agriculture

Other energy-intensive sectors are not featured in this profile because they are not a current DOE funding focus. The sectors listed above, however, cover a wide range of automation and process types, and other sectors could benefit from CyManII's work in these areas. CyManII is now exploring future work in the chemical, defense industrial base (DIB), and biomedical manufacturing sectors.

Each of the eight identified sectors is illustrated and defined in a two-page **Sector Profile** (see Appendix A). These Sector Profiles provide an opportunity to engage with manufacturing industry, with sector specific detail, on examples of trends and opportunities in the areas listed above, and in support of the digitization necessary to make progress in these areas. This engagement will help CyManII update and refine its approach to working across the 8 sectors in Year 2 and beyond. The profiles include trends related to productivity, resiliency, and the following:

Automation:

Key trends including the level of automation, growth, and automation tools

Energy consumption:

Total annual energy used, percent of energy consumption by the sector within the manufacturing industry

Manufacturing resiliency:

Average downtime costs, causes of downtime

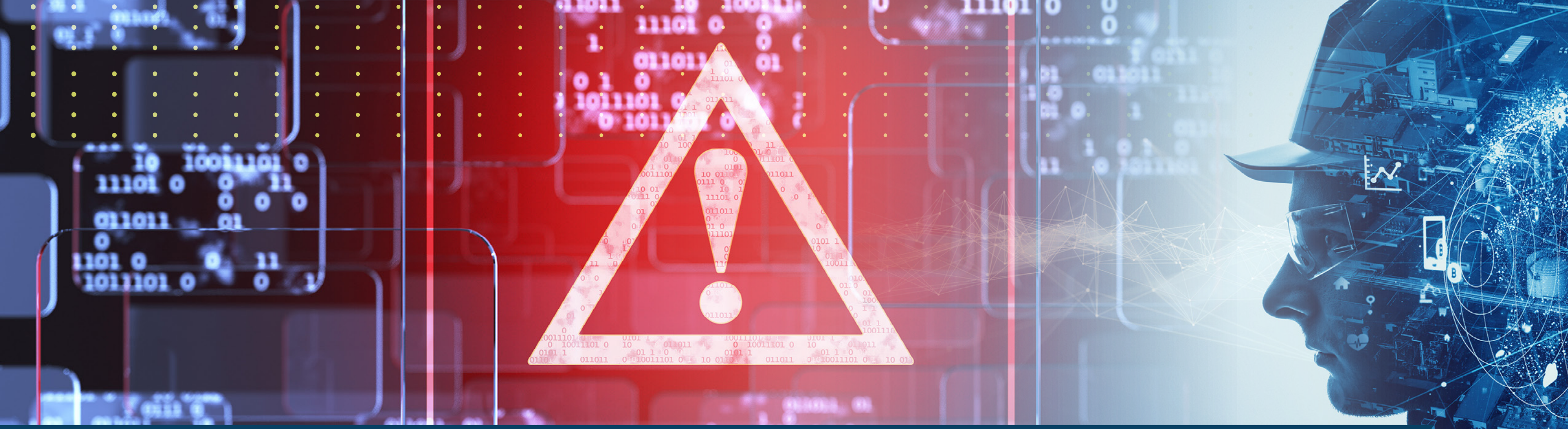
Energy intensity:

Potential energy savings per process, total sector savings potential

Some terms related to connected digitization, such as Industry 4.0 and 5.0, have marketing value but overlap in their focus on strengthening a factory's ecosystem of connectivity (e.g., the Cloud, smart sensors and factories, predictive maintenance). **The benefit of digital threads is that they democratize the access of factories from siloed operations to enterprise-wide visibility**.

As CyManII evaluated the digital backbone of each manufacturing sector, they outlined their services to increase digital connectivity and strengthen the resiliency of these connected networks. Looking at energy efficiency, manufacturers can transition to more electrified technologies to improve energy efficiency in their facilities. Electrified technologies can reduce process heating energy requirements through the use of alternative designs and sensor-based detection approaches.

The Sector Profiles also highlight differences between sectors, from workforce distribution to energy consumed per unit of product. In each profile, recommendations and opportunities for improvement are detailed for manufacturing industry and cybersecurity experts to better tailor their efforts.



D. ADVANCED MANUFACTURING CHALLENGES

In pursuing Industry 4.0 and beyond, the manufacturing industry is developing and integrating new technologies, from AI and ML to machine-to-machine (M2M) communication and IIoT. In concert, these resources will provide manufacturers with the agility and efficiency required to thrive in the new era, but incorporating them will force manufacturers to address a variety of new challenges. The challenges listed below enumerate their primary concerns, and they fall cleanly into two main categories. **Technology Challenges** that arise within newly adopted Industry 4.0 systems, and **Ecosystem Challenges** that arise within the complex networks and processes that manufacturers leverage to get the most out of their technology. The transformational solutions for both challenge areas will need to address both key legacy systems and advanced systems in development for the future.

D.1 Technology Challenges

LEGACY SYSTEMS

Securing legacy systems and mitigating risks in a dynamic environment present many hurdles to the adoption of Industry 4.0 technology and the convergence of IT and OT systems.

Vulnerabilities from Industry 3.0 Systems	There are many potential exploits that remain in OT systems through legacy Industry 3.0 developments and equipment[32]
Updating Legacy Systems	Some older manufacturing systems were not designed for, nor are resilient to, modern communications environments, making them difficult to integrate or upgrade[33]

ADVANCING INDUSTRY 4.0

There are a variety of new and evolving challenges that will grow with the adoption and advancement of industry digital manufacturing technologies.

Increasing Access Points and Attack Surfaces	A system's interconnections will grow as manufacturing processes are integrated into the digital thread, increasing the system's attack surface (i.e., a system's number of exposed vulnerabilities)[34]
Lack of Interoperability Standards	Companies face the challenge of installing hardware and verifying communication interoperability, and this challenge is exacerbated by the diversity of data formats and communication protocols, making the selection of a secure method more difficult
Evolving Cybersecurity Threats	As with any other sector, threats vary and change over time, evolving to be more capable in exploiting newer and more numerous intersections of devices and software[35]

IT/OT CONVERGENCE

The convergence of IT and OT systems will create new challenges and amplify challenges native to each system due to their distinct needs and capabilities.

Lack of Necessary Cybersecurity Capabilities in OT	OT systems are more vulnerable to attacks due to inherent limitations in the cybersecurity and processing capabilities of many types of OT equipment[36]
Data-Centric vs. Physical Output-Centric Security	IT-based security measures are not easily adaptable to all elements of the OT environment, which requires precise standards and specifications (e.g., minimal lag time in control communications or controlled physical state transitions) to ensure safe, correct, and efficient operations[37,38]
Event Detection in Complex OT Environments	Event detection is difficult due to the complexity of the manufacturing equipment, systems, and controls, and many manufacturers lack the monitoring and analysis techniques required to properly secure systems throughout the digital thread[39]

D.2 Ecosystem Challenges

COMPLEX PROCESSES

As technologies grow and the digital thread is implemented more broadly, manufacturing systems, control processes, and supply chains are becoming more complex, leading to many new challenges requiring solutions that can bridge the most key legacy systems and new innovations under development.

Security by Design	Systems, processes, and culture are engineered to maximize efficiency, so security is rarely a priority during design or decision making[40]
Supply Chain Vulnerabilities	Supply chains create vulnerabilities for manufacturers, either due to breaches to their own networks or via embedded vulnerabilities in their products[41]
Inaccurate and Incomplete Security Assessments	The OT sector does not generally engage in periodic security assessments or assess its security posture or maturity, and due to the limited visibility into the cybersecurity of workforce and business processes, assessments are difficult to perform and often incomplete[42]
Complex Compliance and Regulatory Requirements	The complexity of compliance and regulatory requirements only increases with greater connectivity between business divisions, companies, and supply chains

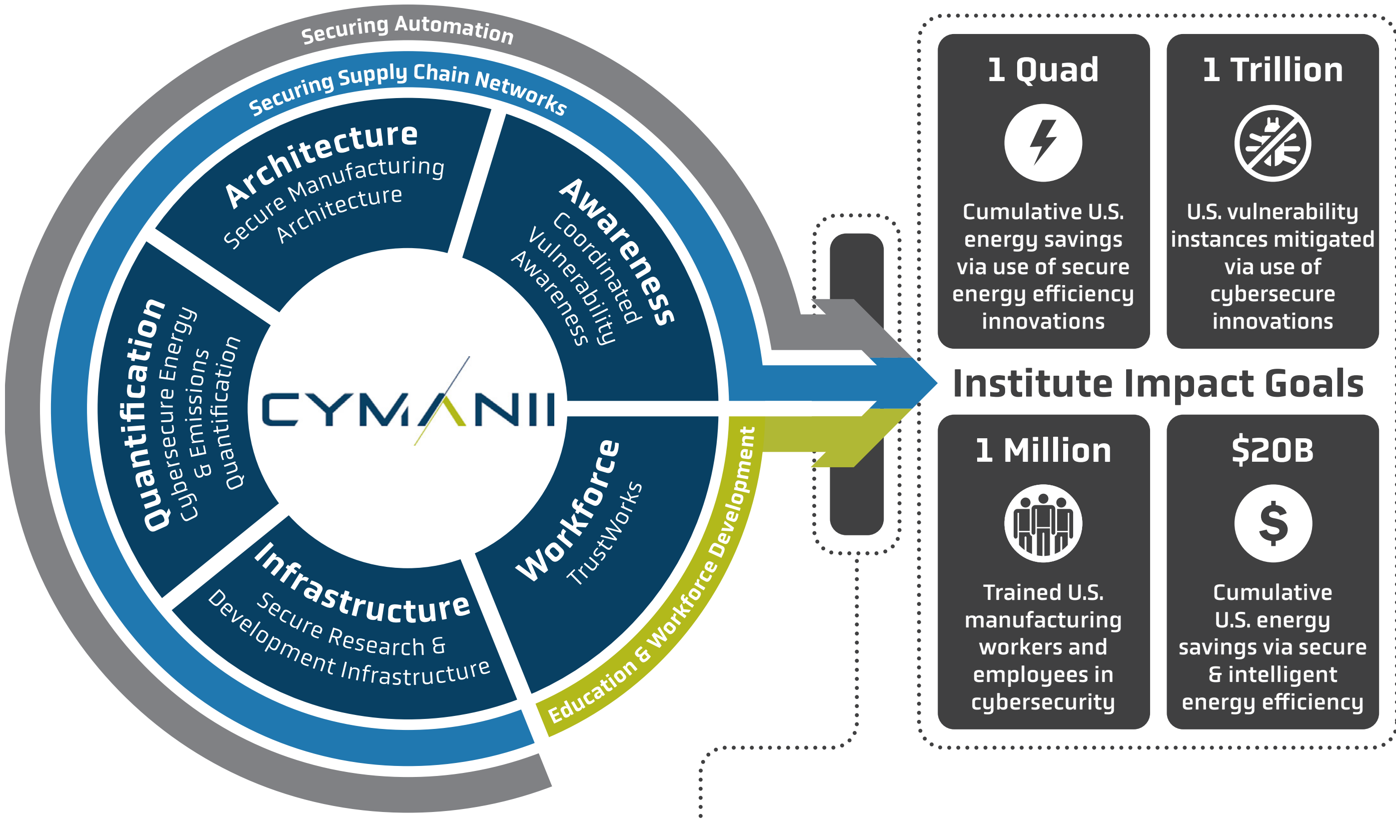
CORPORATE CULTURE

New skills requirements, evolving training needs, and shifts in automation and labor requirements all represent new challenges for a secure manufacturing environment.

Safety-Security Disconnect	The significant overlap between the cybersecurity and safety related risks of manufacturing systems is rarely acknowledged during assessments by both security and safety professionals[43]
Risk Quantification & Decisions	Modern cybersecurity risks are not presently quantifiable and responsive mitigations are dynamic; this ever-changing landscape requires the management of consequences and prioritization of key functions, both of which are difficult to achieve in heavily outsourced and multidisciplinary environments[44]
Conflicting Priorities in IT and OT Integration	The conflicting priorities of IT (i.e., confidentiality, integrity, and availability of data) and OT (i.e., mitigating cyber-physical risks) security will present a challenge to implementing Industry 4.0 technologies[45,46]
Workforce Development and Education	The digitization of the manufacturing industry and its supply chain will have significant impacts on labor and skills needs and on workforce behaviors, processes, and best practices[47,48,49]
Corporate Silo Mentality	Manufacturing leadership often treats IT and OT departments as unrelated entities, and many operators have yet to develop effective data sharing and communications strategies to enable the adoption of new technologies in the face of converging IT and OT systems[50,51]

E. RESEARCH TOPICS (RESEARCH ROUTES)

CyManII's integrated technical approach takes advantage of the aforementioned challenges and opportunities––through the pursuit of the Research Routes captured in this section––to drive towards the Impact Goals that CyManII has set as the bold targets for the next five years.



Key Outcomes

Securely quantified energy productivity, costs, and emissions to design more securely efficient products, automated process, and supply chain networks	**Usable and effective cyber-secured architectures** for product-process automation and product supply chain networks to reduce downtime and accelerate adoption of innovations	**Federated manufacturing research ecosystem** that allows secure development and evaluation of CyManII innovations and attracts new industry participants from "digital threads" of key sector supply chains	**Focused industry risk management** on mitigating/preventing categories of vulnerabilities in manufacturing automation and supply chain networks	Virtual/mixed-mode experiential competency-based cybersecurity **education and workforce development**

Figure 5—Integrated Technical Approach for impact

Vulnerability instance: Discovered or undiscovered manifestation of a vulnerability in a concrete location or locations in a specific component, system, or system of systems. May exist due to flaws in system design, flaws in implementation of a system design, flaws in operational process, or errors in system configuration.

Deriving the Impact Goals

- The **4 metrics** selected for the Impact Goals capture the essence of industry's feedback on their needs, DOE's priorities for this MII, and the implications of working to develop ε-PURE cybersecure energy and carbon innovations for and with industry.
- The **4 quantities** were derived from an understanding of industry's needs for substantial improvements, CyManII's understanding of what is realistically possible with DOE's investment in Technology Readiness Levels (TRL) 2–6 R&D, and what would challenge the industry and academia to spur innovation.

Baselining the Impact Goals

The purpose of the CEEQ framework is to advance baselining and support roadmapping. The conceptual scheme of CEEQ is proposed as a CyManII innovation to enable secure energy-efficient, low emissions, smart manufacturing.

Research Routes for the Impact Goals

Quantification	CEEQ enables the tracking and optimizing of energy and carbon innovations to save energy and money.
Architecture	SMA enables the mitigation and nullification of vulnerability instances.
Infrastructure	SRDI enables the practical integrations, experiments, and demonstrations to show that CEEQ and SMA are progressing towards their Impact Goals.
Awareness	CVA enables awareness of the threat from vulnerabilities and the need to mitigate them with ever increasing effectiveness and efficiency.
Workforce	TrustWorks enables training the workforce that is needed to apply the innovations and improve overall competitiveness of U.S. manufacturing.

Integrated Technical Approach

CyManII has both an innovative approach to secure manufacturing and a deep knowledge of the threats. This combination uniquely positions CyManII to drive U.S. manufacturing towards a future state of cybersecurity by enabling the development of a next generation of secure architectures. These architectures improve resilience for entire categories of vulnerabilities, and possibly eliminate entire categories.

Given the rapid evolution of the threat landscape, it is necessary to pursue an approach that reduces the opportunity for exploits *and* the volume of successful exploits. The integrated approach described in this Roadmap points to those solutions.

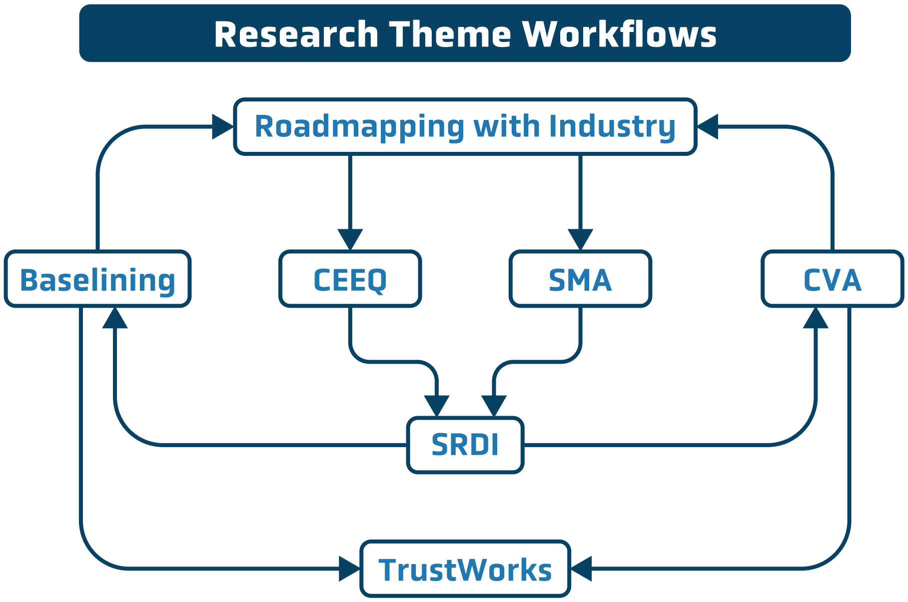


Figure 6—Integrated Technical Approach

CyManII Research Route Development

Given CyManII's focus on TRL 2–6, the Research Routes establish the capability for manufacturers to continuously integrate improvements for cybersecurity, resilience, and energy efficiency. This roadmap focuses on building these capabilities.

- **Near term (1–3 years)**: Initial, modest development and instantiations of innovations and improvements for cybersecurity, resilience, and energy efficiency with end-to-end continuous improvement and development DevSecOps demonstrations on SRDI for a small set of tangible scenarios (equipment and use cases).
- **Mid term (4–6 years)**: Development of properties and capabilities accelerates along with increased demonstrations of the broad applicability of CyManII's integrated technical approach to improve the cybersecurity, energy-efficiency, and carbon reduction varied manufacturing contexts/use-cases.

- **Long term (7+ years)**: The volume of continuous/incremental innovations and improvements stabilizes, has a sense of completeness, and is driven by emerging challenges and opportunities in cybersecurity, resilience, and energy efficiency for manufacturers.

An important question is when U.S. manufacturing will realize the benefits from the "potentialities" in these capabilities. Of course, that depends on when and how adoption proceeds for specific contexts, manufacturers and equipment suppliers (see section F for more on adoption pathways).

Within the 5 key research themes, CyManII has identified 18 essential **Research Routes** to a) address key gaps and challenges identified during the stakeholder engagement phase of this roadmapping effort, and b) realize the desired future state of the manufacturing industry. This is CyManII's program of research, which forms the foundation for the deployment of systems and tools to accelerate and integrate breakthrough energy-efficient, advanced manufacturing science and technology.

The term *Research Route* represents a straightforward planning framework with two key elements:

1. an objective––an outcome that the Research Route is intended to achieve––and
2. a set of supporting activities that must be conducted to accomplish the objective.

Each of the research theme sections below captures the list of Research Routes that have been developed through the roadmapping process in CyManII's first year. Sections E.1. through E.5. describe the Research Route objectives (summarized in the table below) and supporting activities.

CyManII Research Routes

Content available for CyManII members

CyManII Research Routes

Content available for CyManII members

CyManII Research Routes

Content available for CyManII members

Future Roadmap Updates

The continuous innovation/improvement and integrated approach, for the eighteen Research Routes and many of their activities, has—by definition—feedback and cross-feed interactions that make all of the routes and activities interdependent (at least indirectly). This means that most activities will be occurring continuously, and in parallel. The Year 2 CyManII Roadmap will delve into interdependencies through detailed conversations with industry to identify critical/constraining dependencies that may affect priorities, transitions, and impact.

The Year 2 CyManII Roadmap will include timing of major milestones of the Research Routes and will articulate how they contribute to the overall Impact Goals, and interim goals/milestones.

Additional details on Research Routes are available to CyManII members

F. CYMANII IN IMPLEMENTATION

This Roadmap is but one part of CyManII's long-term research vision for developing the science, technology, and demonstrated implementations to transform U.S. manufacturers with secure automation and supply chain networks that implement decarbonization innovations. The pathway to the future state of cybersecurity is guided in specifics by the Research Routes and activities in this Roadmap.

F.1 Institute Approach

The CyManII process of designing and implementing research themes in stages across each of five one-year budget periods (BP) allows CyManII to practice agile engineering and integration techniques, which remove serial process barriers (typically found in waterfall design) and enable the key stakeholders, developers, and members to collaborate more closely on accelerating delivery. During each BP, teams are required to apply continuous improvement and development processes, and refine research themes based on ongoing roadmapping, baselining, and manufacturing industry transition efforts.

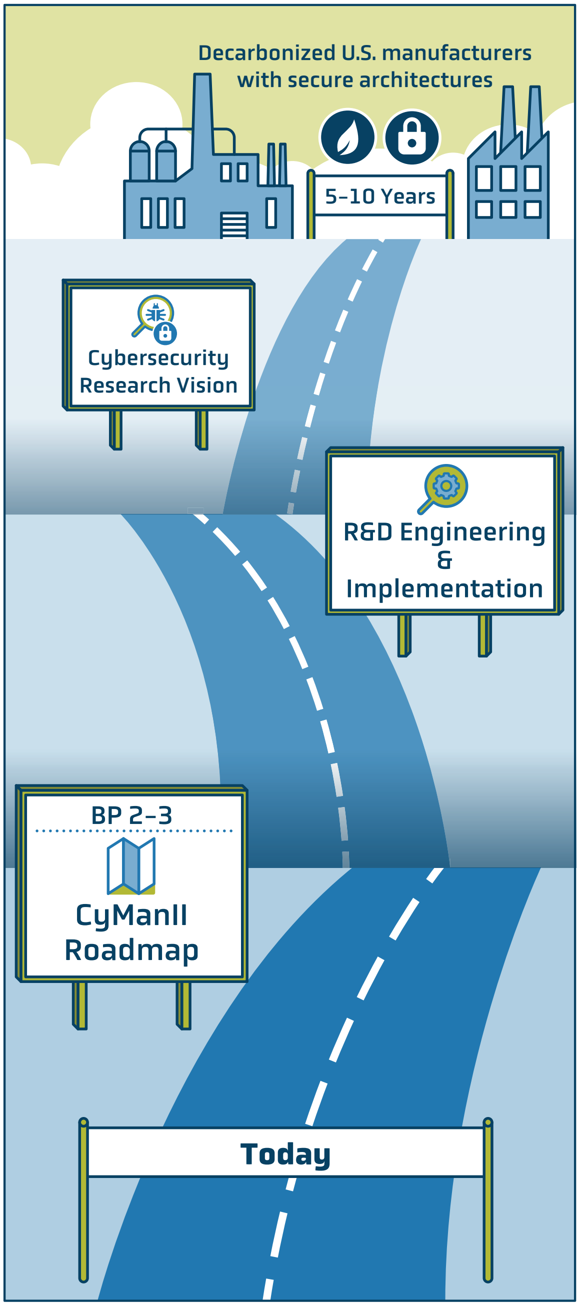


Figure 7—CyManII's Research Vision

F2. Research Landscape

The CyManII team is comprised of leading manufacturing and cybersecurity researchers and experts – extremely well connected throughout their respective professional networks and acutely aware of a broad range of research activities and professional advances. CyManII's work is influenced and informed by a variety of relevant guiding documents, e.g., the *Federal Cybersecurity Research and Development Strategic Plan* (Dec 2019).

This Roadmap acknowledges the reality that the current state of cybersecurity is not sustainable. There are simply not enough resources to secure software, hardware, networks, and systems that were never designed to be secure. Hardening systems, which is the current approach, is necessary but not sufficient. To secure our Nation, we must develop and implement cyber-informed, secure-by-design architectures to secure our supply chains and automated processes, including the digitization and democratization of manufacturing.

CyManII's vision is not anchored to the current world of insecure systems of software and hardware. Rather, CyManII will pursue ambitious and aggressive pathways to new systems of architectures that will exponentially increase our Nation's ability to withstand the fiercest cyber-attacks. The core research vision is to focus on ensuring architectures, systems, and processes have security properties that are backed with uncontradicted evidence for those properties. The technologies to define and ensure such properties have been emerging from research labs and have been successfully applied in varied and complex systems (of systems) by large technology companies over the last decade. CyManII will amplify and accelerate these new design concepts and implement them with our industrial partners to assure U.S. manufacturing competitiveness and security.

CyManII's research vision is to incrementally build (1) an ever-expanding library of relevant security properties and situations (models of systems) which can be applied and ensured with non-contradictory evidence, and (2) continually demonstrate/pilot with U.S. manufacturers and OEMs how to apply these methods and tools to securely incorporate decarbonization innovations in thousands of diverse systems. The value of these results is that the resulting systems will be (1) more resilient, (2) have used fewer scarce technical resources (experts) to provide that resilience (i.e., will be more efficient and economical), and (3) be more sustainable (from both the technology and financial perspective) and agile in response to changing threats and risks from cyber adversaries.

Additional details on the following topics are available to CyManII members

- Innovation
- Standards and Frameworks
- Partnerships and Collaboration
- Transformation Routes
- CyManII in 2022

ENDNOTES

15 "What is the Digital Thread in Manufacturing? Definition & Benefits (ibaset.com), December 2016, https://www.ibaset.com/what-is-the-digital-thread.

16 Kurfess and Grimes, "The Role of the Digital Thread for Security, Resilience, and Adaptability in Manufacturing," National Center for Manufacturing Science (NCMS), Spring 2021, https://www.ncms.org/wp-content/uploads/Kurfess-Grimes_Bridge511.pdf.

17 Joseph Biden, "Remarks by President Biden at Signing of Executive Order on Strengthening American Manufacturing," transcript of speech delivered at South Court Auditorium, White House, Washington DC, January 25, 2021, https://www.whitehouse.gov/briefing-room/speeches-remarks/2021/01/25/remarks-by-president-biden-at-signing-of-executive-order-on-strengthening-american-manufacturing/.

18 "Cybersecurity and Digital Components: Supply Chain Deep Dive Assessment," U.S. Department of Energy, 2022, https://www.energy.gov/sites/default/files/2022-02/Cybersecurity Supply Chain Report - Final.pdf.

19 Cyberspace Solarium Commission, "*CSC Final Report*," Cyberspace Solarium Commission, March, 2020 https://drive.google.com/file/d/1ryMCIL_dZ30QyjFqFkkf10MxIXJGT4yv/view.

20 "Cybersecurity for smart factories," Deloitte and MAPI, 2019, https://www2.deloitte.com/us/en/pages/energy-and-resources/articles/smart-factory-cybersecurity-manufacturing-industry.html?nc=1.

21 "The Rise of Smart Factories…and the cybersecurity risk they pose," Swivelsecure, 2018, https://swivelsecure.com/solutions/manufacturing/the-rise-of-smart-factories.)

22 "Manufacturing Energy Consumption Survey (MECS)," U.S. Energy Information Administration, 2014, https://www.eia.gov/consumption/manufacturing/data/2014/.

23 "United States GDP Annual Growth Rate," Trading Economics, accessed September 24, 2021, https://tradingeconomics.com/united-states/gdp-growth-annual.

24 "Number of private sector manufacturing employees in the United States from 1985 to 2020 (in 1,000s)," *Statista*, May 17, 2021, https://www.statista.com/statistics/664993/private-sector-manufacturing-employment-in-the-us/.

25 "Advanced Manufacturing Office Multi-Year Program Plan for Fiscal Years 2017 through 2021," U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE), 2017, https://www.energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf.

26 "Energy Efficiency Indicators: Overview," IEA, December 2020, https://www.iea.org/reports/energy-efficiency-indicators-overview.

27 "Use of energy explained: Energy use in industry," U.S. Energy Information Administration (EIA), last updated August 2, 2021, https://www.eia.gov/energyexplained/use-of-energy/industry.php.

28 "EIA Survey of Energy Use by U.S. Manufacturers Shows Increased Use of Natural Gas, HGLs," U.S. Energy Information Administration (EIA), September 17, 2020. https://www.eia.gov/todayinenergy/detail.php?id=45156.

29 Charles Cannon, et al,"The Next Frontier of Carbon Accounting: A Unified Approach for Unlocking Systemic Change,"Rocky Mountain Institute (RMI), 2020, https://rmi.org/insight/the-next-frontier-of-carbon-accounting/.

30 "EIA Survey of Energy Use by U.S. Manufacturers Shows Increased Use of Natural Gas, HGLs." U.S. Energy

Information Administration (EIA), September 17, 2020. https://www.eia.gov/todayinenergy/detail.php?id=45156.

31 "Graphics for Economics News Releases: Employment by Industry," U.S. Bureau of Labor Statistics, accessed September 2021, https://www.bls.gov/charts/employment-situation/employment-levels-by-industry.htm.

32 "Industry 4.0 and cybersecurity—Managing risk in an age of connected production," *Deloitte*, 2017, https://www2.deloitte.com/content/dam/insights/us/articles/3749_Industry4-0_cybersecurity/DUP_Industry4-0_cybersecurity.pdf.

33 Ibid.

34 Ibid.

35 Ibid.

36 "IT/OT Convergence: A fruitful integration of information systems and operational systems," Cigref, December 2019, https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf.

37 Ibid.

38 "Safety, Security & Privacy in the Interconnected World of IT, OT & IIoT," Ponemon Institute, February 2019, https://www.tuvopensky.com/wp-content/uploads/2019/02/TUV-Rheinland-OpenSky-2019-Research-Report-on-Safety-Security-and-Privacy-in-the-Interconnected-World-of-IT-OT-_-IIoT.pdf.

39 "IT/OT Convergence: A fruitful integration of information systems and operational systems," Cigref, December 2019, https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf.

40 "Industry 4.0 and cybersecurity—Managing risk in an age of connected production," *Deloitte*, 2017, https://www2.deloitte.com/content/dam/insights/us/articles/3749_Industry4-0_cybersecurity/DUP_Industry4-0_cybersecurity.pdf.

41 Ibid.

42 "IT/OT Convergence: A fruitful integration of information systems and operational systems," Cigref, December 2019, https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf.

43 "Industry 4.0 and cybersecurity—Managing risk in an age of connected production," *Deloitte*, 2017, https://www2.deloitte.com/content/dam/insights/us/articles/3749_Industry4-0_cybersecurity/DUP_Industry4-0_cybersecurity.pdf.

44 "IT/OT Convergence: A fruitful integration of information systems and operational systems," Cigref, December 2019, https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf.

45 "Industry 4.0 and cybersecurity—Managing risk in an age of connected production," *Deloitte*, 2017, https://www2.deloitte.com/content/dam/insights/us/articles/3749_Industry4-0_cybersecurity/DUP_Industry4-0_cybersecurity.pdf.

46 "Safety, Security & Privacy in the Interconnected World of IT, OT & IIoT," Ponemon Institute, February 2019, https://www.tuvopensky.com/wp-content/uploads/2019/02/TUV-Rheinland-OpenSky-2019-Research-Report-on-Safety-Security-and-Privacy-in-the-Interconnected-World-of-IT-OT-_-IIoT.pdf.

47 "Industry 4.0 and ICS Sector Report: Cyber security for the industry 4.0 and ICS sector," European Cyber

Security Organization, March 2018, https://www.ecs-org.eu/documents/uploads/industry-40-and-ics-sector-report-032018.pdf.

48 "Safety, Security & Privacy in the Interconnected World of IT, OT & IIoT," Ponemon Institute, February 2019, https://www.tuvopensky.com/wp-content/uploads/2019/02/TUV-Rheinland-OpenSky-2019-Research-Report-on-Safety-Security-and-Privacy-in-the-Interconnected-World-of-IT-OT-_-IIoT.pdf.

49 "Industry 4.0 and cybersecurity—Managing risk in an age of connected production," *Deloitte*, 2017, https://www2.deloitte.com/content/dam/insights/us/articles/3749_Industry4-0_cybersecurity/DUP_Industry4-0_cybersecurity.pdf.

50 "IT/OT Convergence: A fruitful integration of information systems and operational systems," Cigref, December 2019, https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf.

51 "Safety, Security & Privacy in the Interconnected World of IT, OT & IIoT," Ponemon Institute, February 2019, https://www.tuvopensky.com/wp-content/uploads/2019/02/TUV-Rheinland-OpenSky-2019-Research-Report-on-Safety-Security-and-Privacy-in-the-Interconnected-World-of-IT-OT-_-IIoT.pdf.

APPENDICES

Contents

Appendix A: Manufacturing Sector Profiles

Sector Profiles: General

	DESCRIPTION	ANNUAL REVENUE ($, 2019)	INDUSTRY TRENDS	SUPPLY CHAIN TRENDS	WORKFORCE INFORMATION (2019)
Cement	Producing hydraulic and non-hydraulic cement for concrete and masonry	$12.7 billion	Cement manufacturing generates large amounts of CO_2 and other greenhouse gases (GHGs), so facilities are regulated by state/federal agencies.	The largest cement companies have consolidated the industry. High shipping costs discourage long-distance distribution, so U.S. cement is regionally sourced.	12,807
Food & Agriculture	Meat and dairy processing, grain and oilseed milling, produce preserving, and confectionary production	$780 billion	The rise in 'clean eating' is pushing manufacturers to be more transparent about their supply chains and maintain quality for their products.	Consumer preferences and COVID-19 disruptions have driven supply chains to become more secure, locally sourced, and innovative.	1.70 million
Forest Products	Processing raw lumber for finished raw materials (construction materials), paper products, cardboard, prefabricated homes, and furniture	$304 billion	Industry success is dependent on residential construction activity and global economic conditions in developed nations.	During COVID-19, manufacturers anticipated lulls in wood products, but the increase demand for housing, towels, and tissues created shortages and delays across the supply chain.	955,400[1]
Iron & Steel	Smelting and metallurgy to refine ore, scrap, and crude iron to create iron, steel, and alloy materials	$92 billion	Electric Arc Furnaces (EAF) have grown in use, and their ability to recycle steel scrap has helped reduce waste in the industry.	Globally, there has been an increase in joint ventures, mergers and acquisitions, and steel recycling initiatives	146,000
Chemical Conversion	Transforming organic and inorganic raw materials through chemical processes into products	$797 billion	Because chemicals are intermediary commodities, companies often shift to support growing end markets in economic slowdowns.	Intensifying global competition has pushed companies to remain competitive by tailoring products and services to each client.	851,000
Semiconductors	Refining silica to create crystal-based wafers and attaching transistors to generate metal oxide semiconductors	$194 billion	In an effort to grow U.S. manufacturing and reduce global dependence, 10 new high-volume fabs will start construction in 2022.	Global geopolitical instability can disrupt the semiconductor supply chain since many raw materials and components are sourced from around the globe.	241,134
Transportation	Producing machinery for transporting people and goods, much as motor vehicles, ships and boats, aerospace products, railroad rolling stock and parts	$968 billion	70% of the sector's revenue is generated by the top 50 companies	Military budgets, employment, interest rates, and consumer income all impact the industry's success.	1.73 million
Clean Energy	Manufacturing clean energy devices for clean energy generation sources, such as biomass, wind, hydroelectric, and solar	—	As of 2021, there are over 900 facilities in the United States that are specialized in at least one form of clean energy generation.	Biomass, hydroelectric, geothermal, and nuclear energy have had modest energy generation growth in the last decade (2-4% per source). while solar and wind energy generation has more than doubled	n/a

[1] as of 2018

Sector Profiles: Energy

	ANNUAL PRIMARY ENERGY CONSUMPTION (QBTU)[2]	ANNUAL EMISSIONS (MILLION METRIC TONS [MMT] CO_2)	MOST ENERGY-INTENSIVE PROCESS	TOTAL POTENTIAL SAVINGS (QBTU)
Cement	0.25	41 MMT	Pyroprocessing: raw meal passes through cement kiln to produce clinker	0.07
Food & Agriculture	1.28	117 MMT	Grain and Oil Seed Milling	0.48
Forest Products	2.70	140 MMT	Process heating, onsite steam generation, and paper drying	0.62
Iron & Steel	1.05	81 MMT	Hot rolling	0.39
Chemical Conversion	7.14	n/a	Plastics Materials and Resins, Petrochemicals, and Other Basic Organic Chemicals	0.77
Semiconductors	0.05	0.2 MMT	Process tooling during the fabrication process	n/a
Transportation	0.35	53 MMT	Aerospace product manufacturing	n/a
Clean Energy	+11.8 (generated)	n/a	Highly specialized components and devices: parts that require communication systems	n/a

[2] QBtu = Quadrillion British Thermal Units

Sector Profiles: Automation

	LEVEL OF AUTOMATION	GROWTH OF AUTOMATION	BENEFITS OF SECURE AUTOMATION
Cement	Low	Predictive process models, IoT and increased sensors are being deployed to tweak process parameters and use less energy.	Implementing digitalization and sustainability initiatives can increase margins by $4–$9/ton of cement.
Food & Agriculture	Medium	Automation is expected to grow by 7.5% annually through 2025.	Automated data collection tools and preventative maintenance can reduce downtime by 50%.
Forest Products	Low	64% of the industry has made investments in digitalization over the past 3 years.	For a single sawmill, productivity can increase 30% in five years through integrated process control and real-time process adjustments.
Iron & Steel	Medium	Industry is shifting towards more agile and streamlined processes.	Secure automation can reduce the number of security breaches, equipment failures and user error faults, which are the main causes of downtime.
Chemical Conversion	Medium	Manufacturers are adding integrated IoT systems with predictive monitoring capabilities to their existing automated control systems.	Secure data infrastructure can track and optimize production in real time, optimize production, and gain additional revenue.
Semiconductors	High	Innovation is being leveraged for increasingly complex manufacturing techniques like assembling small, densely packed transistors.	Increased domestic manufacturing and integrating security protocols will prevent $7.5 billion lost annually from counterfeit parts.
Transportation	High	The use of robots and additive manufacturing tools has skyrocketed in the last decade, making this industry a manufacturing leader in advanced technology tools.	Ensuring cybersecurity may be a requirement for secure customers (defense, critical infrastructure).
Clean Energy	Varies	Clean energy equipment requires specialized materials and digital components to be manufactured and assembled into finished products (turbines, blades, advanced drivetrains).	Secure asset management can assist manufacturers with managing complex builds and assembly of clean energy generation tools. Automation can also support the infrastructure and logistics required to deliver, install, and maintain clean energy tools in remote locations.

CEMENT MANUFACTURING

DEFINING THE SECTOR

The cement manufacturing industry encompasses the production of hydraulic cement (which binds with water to set) and non-hydraulic cement (which sets upon exposure to carbon dioxide in the air). Hydraulic cement is the main ingredient and chief binding agent for concrete and masonry.

Over 95% of the nation's cement production is portland cement, the most common hydraulic variety.

The remainder largely consists of masonry cement, used to produce stucco and mortar.

Cement is produced in 96 plants across 34 states and Puerto Rico.

The seven leading producers of cement, in descending order, are Texas, California, Missouri, Florida, Alabama, Michigan, and Pennsylvania, which constitute **60% of all cement production** in the country.

59% of U.S. portland cement production comes from the top five companies.

79% of production comes from the top 10 companies.

Overall, about 79% of U.S. cement capacity was foreign-owned in 2017.

Industry Growth Trends

Both new and old facilities are heavily regulated by state and federal environmental boards, as cement production emits NO_x, SO_2, CO_2, and CO, and is considered to be the third-largest industrial polluter.

Annual Market Growth

2017:	2018:	2019:
$12.4B	$12.7B	$12.5B

Workforce Information

2017:	2018:	2019:
14,164	13,016	12,807

Size and Revenue

Estimated revenue of the US cement manufacturing industry in 2020: **$12.7B**

Supply Chain Trends

In recent years, several mergers and acquisitions have taken place among the largest companies in the cement industry. Regional manufacturers have maintained competitiveness because shipping costs for heavy weighted products significantly increase transportation and logistics costs.

Cement has many applications, for construction, residential, and industrial uses, and even for constructing renewable structures like wind turbines.

CEMENT MANUFACTURING

Key Innovation Trends

Level of Automation: Low

Regulations, legacy investments, and the consolidation of the market have impacted the industry's ability to drastically change their operations.

Growth of Automation

Predictive process models, **IoT** and **increased sensors** are being deployed to tweak process parameters and use less energy.

Important Technology

Automated control systems, typically at the local network level

Data collection tools for regulatory reporting

Material analysis and quality control devices to reduce product variability

Manufacturing Resiliency

Implementing digitalization and sustainability initiatives can increase margins by

$4 – $9/ton of cement.

Opportunities by technology type include:

Process digitalization:
10–15% productivity savings

Automation and robotics:
10–15% productivity savings

Advanced analytics:
6–12% increased yield, energy efficiency, and throughput

For a cement plant, these savings translate into real-world benefits:

Meeting customer demand by using real-time data to adjust production.

Automating manual tasks and upskilling the workforce.

Minimizing the industry's environmental footprint and securing licenses to operate across jurisdictions.

Energy Consumption

The sector consumes approximately:

245 trillion Btu (TBtu)

of primary energy each year.

Percent of sector energy consumption:

1.3% of all U.S. manufacturing energy consumption each year.

Cement production accounts for **3% of U.S. industrial CO2 emissions**.

Cement production also has a steep carbon footprint, contributing to **8%** of all global CO2 emissions.

Energy Intensity

Highest potential energy savings per process:

Pyroprocessing is the most energy-intensive step in cement processing, as raw meal passes through a cement kiln to produce clinker.

The sector could save 50 TBtu annually by making improvements to this step, like adding cooling machinery or improving electrical and thermal efficiency.

Total industry savings potential:

The entire sector **can save up to 68.3 TBtu per year** by upgrading technologies and monitoring the process for preventative equipment maintenance.

CHEMICAL CONVERSION MANUFACTURING

DEFINING THE SECTOR

The Chemical Conversion Manufacturing sector is based on the transformation of organic and inorganic raw materials by a chemical process and the formulation of products. This sector distinguishes the production of basic chemicals that comprise the first industry group from the production of intermediate and end products produced by further processing of basic chemicals that make up the remaining industry groups.

What subsectors are included?

- Basic Chemical Manufacturing
- Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing
- Resin, Synthetic Rubber, and Artificial Synthetic Fibers and Filaments Manufacturing
- Pharmaceutical and Medicine Manufacturing
- Soap, Cleaning Compound, and Toilet Preparation Manufacturing
- Paint, Coating, and Adhesive Manufacturing

Major Processes

Chemical products result from chemical processes, which are a complex combination of reaction, distillation, absorption, filtration, extraction, drying, and screening operations.

Industry Trends

Chemical manufacturing is often referred to as the industry of industries, as its products flow into many industries. Chemical companies are impacted by economic slowdowns (i.e., COVID-19 shutdowns), and the industry may shift to support growing end markets (healthcare, electronics).

Supply Chain

The chemicals market has faced ongoing pressure as a result of intensifying global competition, saturated markets reducing opportunities for organic growth, and increasing customer demand for tailored products and services.

Size and Revenue

2017: **$765B**

2019: **$797B**

Workforce Information

Total Employed in the Sector (last three years):

2019:	2020:	2021:
851K	842K	852K

Key Innovation Trends

Automation Level: Med

Manufacturers **already utilize many automated control technologies**, but the sector hasn't adopted new digital and analytics technologies as quickly.

Growth of Automation

Manufacturers expect the digital transformation of the chemical industry to focus on **autonomous operations, advanced analytics**, and **artificial intelligence (AI)**.

Important Technology

Integral parts of manufacturing processes in this industry.

DCS
Distributed Control Systems

SIS
Safety Instrumented Systems

SCADA
Supervisory Control and Data Acquisition (SCADA)

Manufacturing Resiliency

One measure of manufacturing resiliency is **reducing unplanned interruptions and their resulting costs**.

Success Story

A chemical manufacturer in France suffered a disruption costing them **2,000 tons of product.** By integrating a web-based data infrastructure to track and optimize production in real time, the plant regained the lost product (**valued at $4.7 million in revenue**).

The chemical sector can take advantage of real-time key performance indicators (KPIs) and AI pattern recognition to reduce response times and increase productivity

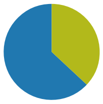
Energy & Emissions

Energy Consumption

Primary energy consumed annually by the U.S. Chemical manufacturing industry:

7.14 quadrillion Btu (QBtu)

Percent of sector energy consumption



In 2018, the chemical manufacturing sector accounted for **37% of all U.S. manufacturing energy consumption**.

In 2019, GHG emissions totaled **185.6 million metric tons (MMT)** of **CO2 equivalent (CO2e)**.

Of all emissions, non-fluorinated chemicals (**ammonia, hydrogen, petrochemicals**) accounted for **177 MMT of CO2e**.

Energy Intensity

Highest potential energy savings per process:

Plastics Materials and Resins (23%), **Petrochemicals (20%)** and **Other Basic Organic Chemicals (19%)**. These subsectors account for two-thirds of the sector's energy consumption. This is due to extreme reaction conditions (high temperature and pressure) and required cooling systems to maintain reaction conditions.

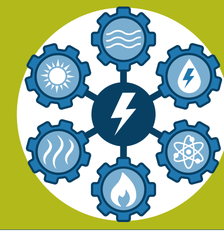
Total industry savings potential:

Annual savings if manufacturers incorporate **next-generation automation technologies** across the chemical sector's processes:

0.77 QBtu

Heat recovery strategies, smart analytics and future research and development (R&D) will enable **significant energy savings**.

CLEAN ENERGY EQUIPMENT MANUFACTURING



DEFINING THE SECTOR

This sector is focused on the manufacturing of clean energy devices for clean energy generation sources including biomass, solar, hydro-electric, wind, geothermal, and nuclear. Each of these distinct subsectors has a complex manufacturing supply chain that enables clean energy generation in the United States and across the globe.

Biomass Energy

Biomass processing plants generated 4.7 QBtu in 2020

Biomass energy generation utilizes components like deconstruction chambers, pelletizers, furnaces, and fractionation machines.

Compared to the national average emissions for all energy generation methods, biomass energy saves **0.7 to 1.2 pounds of CO2E/kilowatt-hour (kWh)** on a lifecycle basis.

The U.S. has 82 manufacturing facilities that specialize in densified biomass fuel.

Energy generated from biomass has grown **4% over the last 10 years**.

The biofuel supply chain consists of producing or harvesting biomass feedstock, treating feedstock in specialized depots, and distributing byproducts like biofuels, bioproducts, and biochar to customers.

Solar Energy

Solar arrays generated 1.3 QBtu in 2020

Solar energy utilizes solar arrays made from polysilicon wafers, thin films, cells, and modules in addition to various array and storage machinery.

Compared to the national average emissions for all energy generation methods, solar energy saves **1.36 to 1.49 pounds of CO2E/kWh** on a lifecycle basis.

The U.S. has 26 manufacturing facilities that specialize in some aspect of solar cell manufacturing.

Energy generated from solar arrays has grown **1,269% over the last 10 years**.

A significant portion of the solar manufacturing supply chain resides overseas, but many different organizations are working to reshore portions of the supply chain by increasing the competitiveness of domestic manufacturing through innovation and automation.

Hydroelectric Energy

Hydroelectric power plants generated 2.6 QBtu in 2020

Hydroelectric energy generation utilizes components like gates, valves, generators, penstocks, transformers, and turbines.

Compared to the national average emissions for all energy generation methods, hydroelectric energy saves **1.06 to 1.46 pounds of CO2E/kWh** on a lifecycle basis.

The U.S. has nearly 200 manufacturing facilities that specialize in hydropower components.

Energy generated from hydroelectric sources has grown **2% over the last 10 years**.

The hydropower supply chain supports existing plant owners and new developers by manufacturing the highly specialized components required to build and maintain hydropower facilities. Suppliers also support hydropower facilities with asset management strategies.

Wind Energy

Wind farms generated 3.0 QBtu in 2020

Wind energy generation utilizes components like blades, towers, generators, and turbines. Composite blades and parts can be recycled into cement production, which can reduce the cement industry's greenhouse gases (GHG) emissions by as much as 27%.

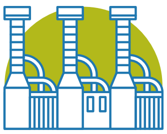
Compared to the national average emissions for all energy generation fuels, wind energy saves **1.52 to 1.54 pounds of CO2E/kWh** on a lifecycle basis.

The U.S. has more than 500 manufacturing facilities that specialize in wind components.

Energy generated from wind farms has grown **226% over the last 10 years**.

The wind energy supply chain encompasses the manufacturing of turbine blades and advanced drivetrains as well as the infrastructure and logistics required to deliver, install, and maintain wind turbines in remote locations.

Geothermal Energy



Geothermal power facilities generated 0.2 QBtu in 2020

Geothermal energy utilizes highly specialized turboexpanders and steam turbines to generate electricity.

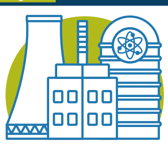
Compared to the national average emissions for all energy generation methods, geothermal energy saves **1.36 to 1.46 pounds of CO2E/kWh** on a lifecycle basis.

In 2015, the U.S. accounted for roughly 18% of global binary cycle geothermal turbine manufacturing and **9% of geothermal steam turbine manufacturing**.

Energy generated from geothermal facilities has grown **3% over the last 10 years**.

The geothermal turbine supply chain is composed of the production of specialized materials, the manufacture of these materials into different components, and the assembly of these components into finished turbines.

Nuclear Energy



Nuclear electric power facilities generated 8.3 QBtu in 2020

Nuclear reactors utilize uranium oxide (UO2) fuel rods and steam generators by submerging the fuel rods in water, channeling the fuel rod reactions to heat the water, and collecting the resulting steam.

Compared to the national average emissions for all energy generation methods, nuclear energy produces more emissions than other renewables but still saves **1.2 – 1.56 pounds of CO2E/kWh** on a lifecycle basis.

As of 2021, there are **93 reactors** operating across **28 states**.

Nuclear power is the largest source of clean energy in the U.S. (52%), and production is expected to grow as new facilities are approved and constructed.

The nuclear fuel supply cycle includes several stages—Mining, Enrichment, Milling, Manufacture, and Reprocessing.

Today, reactor fuel needs are met from direct mine output (85% of all fuel in 2017). New reactors, however, will require expansions in capacity for manufacturing, fuel enrichment and reprocessing facilities.

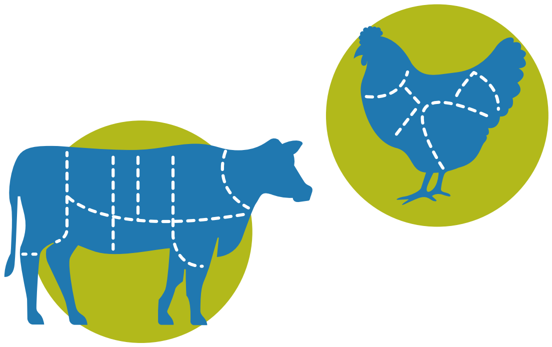
FOOD AND AGRICUTURE MANUFACTURING

DEFINING THE SECTOR

Food manufacturing involves the transformation of raw agricultural materials into food, beverage, and tobacco products for intermediate or final consumption, which are typically sold to wholesalers or retailers for distribution to consumers.

Food manufacturing includes the following divisions:

- Animal Food Manufacturing
- Grain and Oilseed Milling
- Sugar and Confectionery Products
- Fruit and Vegetable Preserving and Specialty Food Manufacturing
- Dairy Products
- Animal Slaughtering and Processing
- Seafood Product Preparation and Packaging
- Bakeries and Tortillas
- Other Food Manufacturing



The largest subset of this industry is meat processing, which includes the slaughter, processing, and rendering of livestock and poultry.

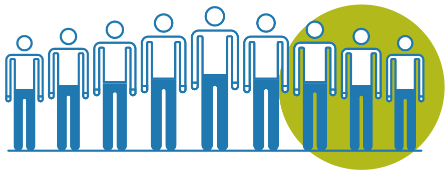
Workforce Information

In 2010, food production made up

12.6% of jobs

in the manufacturing industry, constituting the largest individual manufacturing industry in the country.

US food and beverage manufacturing sector employment in 2018:



1.7 million+ people

(nearly **30%** employed in meat and poultry manufacturing)

Expected industry growth annually through 2022: **2.9%**

Size and Revenue

Estimated revenue of the U.S. food manufacturing industry in 2021: **$780 billion**

Industry Trends

With changes in consumer preferences, as well as disruptions from COVID-19, supply chains are shifting to include more secure, locally sourced, and innovative organizations.

Annual Market Growth:

2017:	2018:	2019:
$775B	$790B	$790B

FOOD AND AGRICUTURE MANUFACTURING

Key Innovation Trends

Level of Automation: Medium

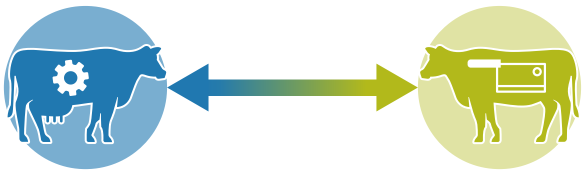
The food and agriculture sector employs **3.1 robots** for every 1 million hours of labor.

The use of SCADA and Programmable Logic Controls (PLCs) in the industry has also led to increased plant-level controls.

Growth of Automation

Automation in this sector is expected to grow 7.5% each year between **2019** and **2025.**

Important Technology



There is a wide spectrum of automation use, from fully integrated dairy plants to less-automated meat processing.

Technologies **like foreign object detection sensors and co-bots** don't require full process integration, so they have grown in use.

Manufacturing Resiliency

Annual cost to manufacturers for 500 downtime hours: Up to $20,000 – $30,000 per hour

Leading causes of downtime:

Aging equipment	Operator error	Lack of time to perform maintenance
42%	19%	13%

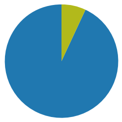
Manufacturers can use **automated data collection tools to predict maintenance needs** before equipment fails. This can reduce machine downtime by **50%** and increase machine life up to **40%**.

Energy & Emissions

Total energy used by sector

1.3 QBtu of primary energy each year.

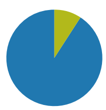
Percent of sector energy consumption



The sector accounts for 7% of the total energy consumed by U.S. manufacturing each year. The most energy-intensive products require drying, evaporation and pasteurization steps, like dairy, bread, and instant coffee.

Sector Emissions

In 2012, food and beverage manufacturers produced **117 MMT of CO2 emissions.**



Food manufacturing accounted for **~9.3% of U.S. manufacturing CO2 emissions** that year.

Energy Intensity

Highest potential energy savings per process: The subsectors with the highest possible energy savings:

Grain and Oil Seed Milling	Sugar Manufacturing	Fruit and Vegetable Processing
70 TBtu/yr	47 TBtu/yr	47 TBtu/yr

Wet corn milling is an energy-intensive process (under Grain and Oil Seed Milling) that is used to break down corn kernels. The industry can save **27 TBtu annually** by adding energy efficient controls and technologies to this one process.

Total industry savings potential:

The industry can save 0.48 QBtu per year by leveraging current technologies across all food and beverage manufacturing subsectors, in addition to CyManII's proposed security R&D infrastructure savings.

FOREST PRODUCTS MANUFACTURING

DEFINING THE SECTOR

The forest products manufacturing industry encompasses the manufacturing of wood and paper products from raw lumber all the way through into finished products.

Wood Product Processes

Sawing, shaping, planning, and laminating to create construction materials

Assembling of finished products like flooring, trusses, and prefabricated homes

Paper Product Processes

Separating and matting cellulose fibers

Cutting, shaping, coating, and laminating to create finished paper products

Industry Trends

The industry's success is tied to residential construction activity, primarily in developed nations.

Expected U.S. industry growth through 2024: **1%** per year

Annual Market Growth:

2017: **$293B**

2018: **$283B**

2019: **$304B**

Supply Chain

As e-commerce grows, packaging materials (cardboard, shipping labels) have become a commodity. Modern-day forestry has become highly integrated, as sawmills collect wood chips, forest residuals, and sawdust to be repurposed for other paper products.

Workforce Information

People employed in the U.S. wood manufacturing subsector in 2020:

388,500

People employed in the U.S. paper manufacturing subsector in 2020:

355,000

Size and Revenue

Estimated revenue of the U.S. forest products manufacturing industry in 2019:

$304 billion

FOREST PRODUCTS MANUFACTURING

Key Innovation Trends

Automation Level: Low

The forest products manufacturing sector employs

0.7 robots

for every **1 million hours** of labor.

Growth of Automation

64% **of industry has made investments in digitalization over the past 3 years.** The most common applications are:

- **Designing products**
- **Machining**
- **Visually communicating product features**

Important Technology

Digital models that provide information about the state of a particular forest in real time.

Automated sawmills with 3D imaging to inspect and optimize log cutting.

Manufacturing Resiliency

The **cost of lost productivity** if a single saw is down in a sawmill is **$1,100** per hour. By **increasing their resilience through tools and improved processes**, facilities can anticipate downtime and recover faster.

Success Story

One sawmill in Denmark processes >300,000 m3 of raw timber annually, and after upgrading to an enhanced integration system connecting inverters to PLCs, they saved **$330k each year**.

This change has also increased production by **30% over 5 years**.

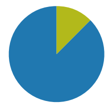
Energy & Emissions

Total energy used by sector:

2.43 QBtu

consumed by the sector. Of this, **2.0 QBtu** is used just for pulp and paper products. The sector primarily relies on steam generation over electricity for power.

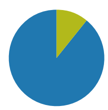
Percent of sector energy consumption



Forest products manufacturing accounts for 12.5% of the total energy consumed by U.S. manufacturing annually.

Sector Emissions

In 2018, forest products manufacturing produced 140 MMT of CO2 emissions.



Forest products accounted for 11% of U.S. manufacturing emissions that year.

Energy Intensity

Highest potential energy savings per process:

Process heating and onsite steam generation account for the most onsite energy consumption at wood and paper processing facilities.

The paper drying process consumes high levels of energy for heating and extracting water from paper. Updating this process across the entire sector can save **111 TBtu/year.**

Total industry savings potential:

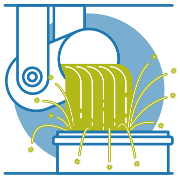
The Pulp and Paper subsector could save as much as

620 TBtu/year

CyManII's future research will also examine additional savings opportunities across the entire forest products sector.

IRON AND STEEL MANUFACTURING

DEFINING THE SECTOR



Manufacturers in this sector smelt and refine ferrous metals from ore, pig (crude iron), or scrap, using electrometallurgical and other metallurgical techniques. This sector also includes the manufacturing of alloys (such as various grades of stainless steel) by introducing other chemical elements to pure iron.

- The metal output of smelting and refining is then used in rolling, drawing, and extruding operations to make sheet, strip, bar, rod, or wire, and in molten form to make castings and other basic metal products.

Iron and steel facilities include:

Integrated mills, which produce steel by combining pig iron with steel scrap to produce refined steel. These facilities may use coal, natural gas, or other fuels and raw materials, in combination with iron, to produce steel.

Electric Arc Furnaces (EAFs), which melt steel scrap, and in some cases limited amounts of other iron-bearing materials, to produce new steel. Due to the large percentages of recycled steel used in EAFs, they may require additional refining to produce various grades of steel.

Industry Trends

Annual Market Growth:

- 2017: **$84 billion**
- 9% Increase
- 2018: **$103 billion**
- 11% Decrease
- 2019: **$92 billion**

Size and Revenue

Estimated value of raw steel produced by the U.S. iron and steel industry in 2019:

$92 billion

Supply Chain

Supply chains are shifting within the industry on a global scale, including an increase in joint ventures and mergers and acquisitions. Steel recycling is also becoming a larger part of the industry's supply chain.

Workforce Information

Number of employees in 2019:

Blast furnace and steel mill employees: **83,000**

Iron and steel foundry employees: **63,000**

Between 2015 and 2020, the iron and steel workforce has declined by about **1.2% a year**

IRON AND STEEL MANUFACTURING

Key Innovation Trends

Level of Automation: Medium

Density of industrial robots in industry:

2003: 2.4 robots/ million hours of work

2017: 4.7 robots/ million hours of work

The value added from these robots was **$2.2 trillion**.

Important Technology

Roughly 70% of U.S. steel is produced in highly automated EAFs, and their share of the market is expected to grow. It is estimated that by 2023, U.S. EAF capacity will have increased by **15%**.

Growth of Automation

The level of automation within EAF facilities is expected to increase as the industry shifts towards a more agile and streamlined production process.

Manufacturing Resiliency

Metal products facilities experience **450 hours** of unplanned downtime on average per year. The cost for each hour of downtime depends on the equipment that failed. **One facility reported** that their failed infeed screw cost them **$100,000 per hour down**.

The top 3 main causes of unplanned downtime are:

Security breaches | **Equipment failure** | **User error**

Security breaches can halt production for days or even weeks. With automation and a sound security architecture, facilities can collect trustworthy data, anticipate failures, and become more resilient.

The facility mentioned above prevented 16 hours of downtime and **saved $1.6 million** by anticipating failure and leveraging technology to expedite maintenance.

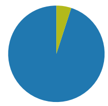
Energy & Emissions

Total energy used by sector

1 QBtu

of primary energy consumed each year.

Percent of sector energy consumption



5.1% of all energy for U.S. manufacturing is used by the iron and steel sector.

In 2020, the iron and steel sector accounts for **6% of U.S. industrial CO2 emissions**. Due to the contributions from other countries, the sector accounts for **8% of all global CO2 emissions**.

Since 1990, the industry has reduced its energy intensity by 35% and greenhouse gas emissions intensity by 37%. The growing shift from the use of basic oxygen furnaces to less energy-intensive EAFs has contributed to a substantial reduction in energy usage in the industry.

Energy Intensity

Highest potential energy savings per process:

The hot rolling process is the most energy-intensive step in iron and steel production. Some improvements that can significantly reduce energy consumption include:

- **Automating hot blast stoves and improving furnace control systems: 80 TBtu**
- **Automating combustion fans and updating hot strip mills: 65 TBtu**

Total industry savings potential:

Iron and steel manufacturing can obtain **0.24QBtu** in industry-wide savings by installing existing state-of-the-art technology. Total savings of **0.39QBtu** are possible if the industry continues to incorporate emerging R&D technologies.

SEMICONDUCTOR MANUFACTURING

DEFINING THE SECTOR

In advanced manufacturing facilities called fabs, silica is melted, mixed, purified, and cooled to create 300mm-diameter solid single crystals. These crystals are then sliced into thin wafers upon which trillions of transistors are printed to create a metal oxide semiconductor (MOS). The MOS then undergoes further processing in which the transistors are connected in intricate arrays to create hundreds of die. These printing processes take roughly 2 months, and they involve complex sequences of various techniques:

- Chemical vapor deposition
- Photolithography
- Ion implantation
- Etching
- Atomic layer deposition
- Electroplating
- Chemical-mechanical polishing

The die then undergo quality testing, and those that pass are sliced and packaged into cutting-edge microprocessors for sale to both retail and electronic device manufacturers.

What subsectors are included?

Microprocessors | Application-specific Integrated Circuits (ASICS) | Microcontrollers | Analog or Linear | Memory | Fabless Design

Industry Trends

From 1990 to 2020, the U.S. share of global semiconductor production dropped from 37% to 12% as companies built factories overseas. The largest producers are Taiwan, South Korea, and China.

Via the **Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act** and the **American Foundries Act**, the U.S. government has responded by incentivizing manufacturers to build independent capabilities in the semiconductor supply chain. There are 10 new high-volume fabs that start construction in 2022.

Annual Market Growth:

2017: **$188B**

2018: **$220B**

2019: **$194B**

Supply Chain

"Global geopolitical instability...is forcing the U.S. industry to consider how to remain competitive in a world of unforeseen uncertainty and policy constraints."

Workforce Information

People employed in the U.S. semiconductor manufacturing sector in 2019:

241,134

Size and Revenue

Estimated revenue of the U.S. semiconductor manufacturing sector in 2020:

$207 billion

SEMICONDUCTOR MANUFACTURING

Key Innovation Trends

Level of Automation: High

Semiconductor production requires a **high level of automation**, with increasingly complex manufacturing techniques required as semiconductors are made smaller and more densely packed with transistors.

Growth of Automation

Manufacturers list **AI, big data, and robotic vision** as the three most important technological innovations for the next generation of semiconductor manufacturing technology.

Important Technology

MES	APC	AMHS
Manufacturing execution systems	Advanced process controls	Automated material handling systems

Manufacturing Resiliency

Semiconductors are the backbone of electronic devices, so the security of both product and manufacturing process must be ensured.

$7.5 billion is lost annually from counterfeit parts circling the market, and foreign imports can cause international cybersecurity concerns.

Increasing domestic manufacturing, and integrating security protocols in these devices, will only further instill customer trust while saving money.

Energy & Emissions

Total annual energy used by sector:

54 TBtu

is consumed for semiconductors and related devices.

Percent of sector energy consumption:

The industry consumes 0.3% of all energy used for U.S. manufacturing.

The electricity consumption of the microchips themselves is also a **concern for the industry.**

In 2017, the semiconductor industry only produced 0.2 MMT CO_2, but it contributed larger quantities of other GHGs, like N_2O, Hydrofluorocarbons (HFCs), Perfluorinated compounds (PFCs), SF_6 and NF_3.

Energy Intensity

Highest potential energy savings per process:

The largest consumer of energy at a fab lab is the process tools **(40% – 55%).**

A significant portion of energy is diverted to environmental controls **(water chillers and HVAC for clean dry air)**.

Total industry savings potential:

HVAC and plant management (process) improvements can reduce energy consumption by **20–30%** for fabrication labs.

Savings opportunities can vary by the facility's operating conditions, so a comprehensive assessment is needed to calculate **total TBtu savings** across the industry nationally.

TRANSPORTATION EQUIPMENT MANUFACTURING

DEFINING THE SECTOR

Transportation equipment manufacturing includes a variety of industries involved in producing machinery for transporting people and goods. Production processes in this sector include bending, forming, welding, machining, and assembling metal or plastic parts into components and finished products.

Despite this industry supporting

10,000+ companies

70% of the revenue is generated by the **top 50 companies.**

Large producers benefit from economies of scale in manufacturing, marketing, and distribution, while smaller companies compete by specializing in niche markets.

What subsectors are included?

- Motor Vehicle Manufacturing
- Motor Vehicle Body and Trailer Manufacturing
- Motor Vehicle Parts Manufacturing
- Ship and Boat Building
- Aerospace Product and Parts Manufacturing
- Railroad Rolling Stock Manufacturing
- Other Transportation Equipment Manufacturing

Industry Trends

The success of the transportation equipment manufacturing industry is correlated to **employment, interest rates, consumer income, and military budgets,** so it is highly dependent upon global economic conditions in developed nations.

Electric vehicle sales share has more than doubled since 2015; by 2030, electric vehicles are expected to account for 27% of annual car sales.

Annual Market Growth

2017: **$962B** | 2018: **$964B** | 2019: **$968B**

Workforce Information

2017: **1.64M** | 2018: **1.70M** | 2019: **1.73M**

Size and Revenue

2020 U.S. transportation equipment manufacturing industry estimates:

Revenue: **$859B** | Employment: **1.58M**

Supply Chain

The transportation equipment manufacturing supply chain is complex; multiple suppliers produce parts for various stages of the manufacturing process, with a robust and varied maintenance, repair, and overhaul support sector.

Key Innovation Trends

Automation Level: High

The transportation equipment manufacturing sector employs **29.3 robots** for every 1 million hours of labor.

Growth of Automation

Between 2003 and 2017 **robot density in this sector more than doubled** from **14.2 to 29.3 robots** per million hours of labor, nearly **5 times** that of other advanced processes like chemical manufacturing.

Important Technology

Advanced additive manufacturing technology allows manufacturers in this sector to have more agile operations with complex, integrated components, and it is used to produce cheaper, lighter, and more eco-friendly parts.

Manufacturing Resiliency

Auto industry average downtime costs, indicated by surveys:

$1.3M per hour

As we have seen with the recent microchip shortage, **any interruptions in this process can drastically increase prices for consumers. Auto manufacturers must minimize unplanned downtime by securing their advanced manufacturing systems.**

Ensuring cybersecurity and minimizing unplanned downtime is even more important for other subsects of the transportation equipment industry, like aerospace products manufacturing, where operators support critical infrastructure and military needs.

Energy & Emissions

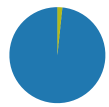
Total energy used by sector

The U.S. transportation equipment manufacturing sector consumes approximately

348 TBtu

of primary energy each year.

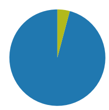
Percent of sector energy consumption



Transportation equipment manufacturing accounts for **1.8% of all energy consumed** by U.S. manufacturing each year.

Sector Emissions

In 2012, transportation equipment manufacturing produced **53 MMT of CO2 emissions.**



Transportation equipment manufacturing accounted for **~4.2% of U.S. manufacturing emissions** that year.

Energy Intensity

Highest potential energy savings per process:

Aerospace product manufacturing is one of the most energy-intensive subsectors of this industry, but it is also one of the **most promising areas to apply energy saving** innovations. If this subsector rapidly adopts additive manufacturing technology, this could lower annual energy consumption by as much as **46 TBtu** in 2030.

Total industry savings potential:

HVAC and a variety of plant management improvements in auto manufacturing facilities can reduce energy consumption by **15%**. Savings vary by the facility's operating conditions, so a comprehensive analysis is needed to calculate total TBtu savings across the industry nationwide.

Citations

CEMENT MANUFACTURING

U.S. Geological Survey, National Minerals Information Center, "*Cement Statistics and Information*," accessed September 2021, https://www.usgs.gov/centers/nmic/cement-statistics-and-information.

U.S. Geological Survey, *Mineral Commodity Summaries: Cement*, January 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf.

U.S. Geological Survey, *Mineral Commodity Summaries: Cement*, January 2018, https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2018-cemen.pdf.

"Cement Manufacturing in the US – Employment Statistics 2002-2027," IBISWorld, updated August 16, 2021, https://www.ibisworld.com/industry-statistics/employment/cement-manufacturing-united-states/.

Eleftherios Charalambous et al, *"The 21st-century cement plant: Greener and more connected,"* McKinsey & Company, 2017, https://www.mckinsey.com/industries/chemicals/our-insights/the-21st-century-cement-plantgreener-and-more-connected.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO), *Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing*, September 2017, https://www.energy.gov/sites/prod/files/2017/12/f46/Cement_bandwidth_study_2017.pdf.

Daniel Costa Reis et al, *"Potential CO2 reduction and update due to industrialization and efficient cement use in Brazil by 2050,"* Journal of Industrial Ecology 25, no. 2 (2021 April): 344-358, https://onlinelibrary.wiley.com/doi/10.1111/jiec.13130.

U.S. Environmental Protection Agency (EPA), *"Cement Manufacturing Enforcement Initiative,"* accessed September 2021, https://www.epa.gov/enforcement/cement-manufacturing-enforcement-initiative.

Portland Cement Association, *Carbon Footprint: Integrated Paving Solutions*, accessed September 2021, https://www.cement.org/docs/default-source/th-paving-pdfs/sustainability/carbon-foot-print.pdf.

Ian Tiseo, *"Greenhouse gas emissions from cement production in the United States from 1990 to 2019,"* Statista, April 23, 2021, https://www.statista.com/statistics/451804/green-house-gas-emissions-in-united-states-fromcement-production/.

CHEMICAL CONVERSION MANUFACTURING

U.S. Bureau of Labor Statistics, "Chemical Manufacturing: NAICS 325," accessed September 2021, https://www.bls.gov/IAG/TGS/iag325.htm.

National Academy of Engineering (NAP) and National Research Council, Industrial Environmental Performance Metrics: Challenges and Opportunities, (Washington, DC: The National Academies Press, 1999), *Chapter 5: The Chemical Industry*, https://www.nap.edu/read/9458/chapter/7.

Lucía Fernández, *"U.S. Chemical industry – statistics & facts,"* Statista, July 6, 2021, https://www.statista.com/topics/1526/chemical-industry-in-the-us/.

Obi Ezekoye et al, *Beating the cycle: Building resilience in chemicals*, McKinsey & Company, September 2019, https://www.mckinsey.com/~/media/McKinsey/Industries/Chemicals/Our%20Insights/Beating%20the%20cycle%20Building%20resilience%20in%20chemicals/Beating-the-cycle-building-resilience-in-chemicals-final.

Deloitte, *Supply chain management in the chemicals industry*, October 2017, https://www2.deloitte.com/content/dam/Deloitte/fi/Documents/manufacturing/Deloitte_Supply-Chain-Management_chemicals.pdf.

"The state of the chemical industry—it is getting more complex," McKinsey & Company, November 10, 2020, https://www.mckinsey.com/industries/chemicals/our-insights/the-state-of-the-chemical-industry-it-isgetting-more-complex.

OSIsoft, Aveva Group, *Implementing a digital transformation in chemical operations to maximize profitability*, May 2021, https://explore.osisoft.com/chemicals/wp-digital-transformation-chemical-industry.

U.S. Energy Information Administration (EIA), *"Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data,"* accessed September 2021, https://www.eia.gov/consumption/manufacturing/data/2018/.

Ian Tiseo, *"Greenhouse gas emissions released by chemical facilities in the U.S. from 2011 to 2019, by chemical type,"* Statista, December 4, 2020, https://www.statista.com/statistics/616006/ghg-emissions-emitted-by-chemicalfacilities-in-the-us-by-chemical-type/.

U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE), *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing*, June 2015, https://www.energy.gov/sites/default/files/2015/08/f26/chemical_bandwidth_report.pdf.

U.S. Environmental Protection Agency, *"Greenhouse Gas Inventory Data Explorer: U.S. Greenhouse Gas Emissions from Chemical Production and Use, by Subcategory 2019 – Excluding fluorinated gases,"* accessed September 2021, https://cfpub.epa.gov/ghgdata/inventoryexplorer/#industrialprocesses/chemicalproductionanduse/allgas/subcategory/current.

U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE) Advanced Manufacturing Office (AMO), *"Bandwidth Study U.S. Chemical Manufacturing,"* August 24, 2015, https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing.

CLEAN ENERGY EQUIPMENT MANUFACTURING

U.S. Energy Information Administration (EIA), Monthly Energy Review September 2021, September 2021, https://www.eia.gov/totalenergy/data/monthly/pdf/sec1.pdf.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Bioenergy Technologies Office, "Bioenergy," accessed September 2021, https://www.energy.gov/eere/bioenergy/bioenergy.

U.S. Energy Information Administration, "Monthly Densified Biomass Fuel Report: Manufacturing facilities with capacity and status, June 2021," September 15, 2021, https://www.eia.gov/biofuels/biomass/.

David Clark, Information Paper – 4: CO2e Emissions from Biomass and Biofuels, Cundall Johnston & Partners LLP, July 29, 2013, https://cundall.com/Cundall/fckeditor/editor/images/UserFilesUpload/file/WCIYB/IP-4%20-%20CO2e%20emissions%20from%20biomass%20and%20biofuels.pdf.

U.S. Environmental Protection Agency, "Greenhouse Gases Emissions Calculator – Calculations and References," accessed September 2021, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculatorcalculations-and-references.

Chris Noon, "Concrete Benefits: Recycling Old Wind Turbine Blades Could Help Cement Industry Cut CO2 Emissions," General Electric News Reports, December 9, 2020, https://www.ge.com/news/reports/concrete-benefits-recyclingold-wind-turbine-blades-could-help-cement-industry-cut-co2.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Wind Energy Technologies Office, *"Wind Manufacturing and Supply Chain,"* accessed September 2021, https://www.energy.gov/eere/wind/wind-manufacturing-and-supply-chain.

Union of Concerned Scientists (USCUSA), *"Benefits of Renewable Energy Use: Improved Public Health,"* updated December 20, 2017, https://www.ucsusa.org/resources/benefits-renewable-energy-use#:~:text=Wind%2C%20solar%2C%20and%20hydroelectric%20systems,natural%20gas%2Dfired%20power%20plants.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Water Power Technologies Office, *2017 Hydropower Market Report*, April 2018, https://hydrosource.ornl.gov/sites/default/files/2020-10/2017HydropowerMarketReport.pdf.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office, *"Solar Manufacturing,"* accessed September 2021, https://www.energy.gov/eere/solar/solar-manufacturing.

Sertac Akar et al, *Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines, National Renewable Energy Laboratory (NREL) and the Clean Energy Manufacturing Analysis Center (CEMAC)*, 2018, https://www.nrel.gov/docs/fy19osti/72150.pdf.

World Nuclear Association, *"Nuclear Power Reactors,"* July 2021, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of Nuclear Energy, "*Infographic: Five Fast Facts about Nuclear Energy (2020)*," March 22, 2021, https://www.energy.gov/ne/articles/infographic-five-fast-facts-about-nuclear-energy-2020.

World Nuclear Association, *"Nuclear Power in the USA,"* Updated September 2021, https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

Carbon Fund, *"Calculation Methods,"* accessed September 2021, https://carbonfund.org/calculation-methods/.

Thomas Graham, Jr. and Richard Mies, "As the United States develops advanced reactors, a new fuel supply chain is critical to national security," Atlantic Council, February 12, 2021, https://www.atlanticcouncil.org/blogs/energysource/as-the-united-states-develops-advanced-reactors-a-new-fuel-supply-chain-is-critical-tonational-security/.

John Wood, "Growth in Nuclear Energy: Supply Chain Challenges," Faith+Gould, March 6, 2014, https://www.fgould.com/americas/articles/growth-nuclear-energy-supply-chain-challenges/.

FOOD & AGRICULTURE MANUFACTURING

Belden: Lumberg Automation, Maintaining Reliability and Uptime of Critical Connected Systems in Industrial Settings White Paper, 2014, https://info.belden.com/hubfs/EMEA/DocumentDownloads/WP__Maintaining_Reliability_and_Uptime_of_Critical_Connected_Systems_in_Industrial_Settings.pdf.

Advanced Technology Services, Inc., "Solving the Skilled Labor Shortage in Food and Beverage Manufacturing," July 2020, https://www.advancedtech.com/wp-content/uploads/2020/07/Solving-the-Skilled-Labor-Shortage-in-Food-and-Beverage-Manufacturing.pdf.

Valerio Dilda et al, "Manufacturing: Analytics unleashes productivity and profitability," McKinsey & Company, August 14, 2017, https://www.mckinsey.com/business-functions/operations/our-insights/manufacturinganalytics-unleashes-productivity-and-profitability.

J. I. Mustafa, "Energy Consumption Along U.S. Food Supply Chain," 2016.

Alia Ladha-Sabur et al, "Mapping energy consumption in food manufacturing," Trends in Food Science Technology 86, (2019 February): 270-280, https://www.sciencedirect.com/science/article/pii/S0924224417303394?via%3Dihub.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO), Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Food and Beverage Manufacturing, September 2017, https://www.energy.gov/sites/prod/files/2019/05/f62/Food_and_beverage_bandwidth_study_2017.pdf.

FOREST PRODUCTS MANUFACTURING

Freedonia Focus Report, "Forestry: United States," February 1, 2020, https://www.freedoniafocusreports.com/Forestry-United-States-FF95076/?progid=91541.

M. Shahbandeh, "Value of industry shipments of the wood and paper manufacturing industry in the United States as of 2018 (in 1,000 U.S. Dollars)," Statista, September 6, 2019, https://www.statista.com/statistics/252844/usindustry-shipments-value-of-the-forest-products-industry-2012/.

United Nations Economic Commission for Europe (UNECE), United States Forest Products Annual Market Review and Prospects, 2015-2021, 2020, https://unece.org/fileadmin/DAM/timber/country-info/statements/usa2020.pdf.

SelectUSA, Robots and the Economy: The Role of Automation in Driving Productivity Growth, 2020, https://www.selectusa.gov/servlet/servlet.FileDownload?file=015t0000000kyXN.

Rajesh Singh et al, "Forest 4.0: Digitalization of forest using the Internet of Things (IoT)," Journal of King Saud University – Computer and Information Sciences (2021 February), https://www.sciencedirect.com/science/article/pii/S1319157821000483.

John Lewis, "Machine vision optimizes wood processing," Vision Systems Design, February 14, 2018, https://www.vision-systems.com/cameras-accessories/article/16739363/machine-vision-optimizes-woodprocessing.

Urs Buehlmann, Matt Bumgardner, and Karl D. Forth, "Lack of a plan limits Industry 4.0 development for many companies," FDMC Magazine (May 2020): 28-30, https://www.nrs.fs.fed.us/pubs/59973.

Jan Wiedenbeck and Kyle Blackwell, "Hardwood Sawmill Downtime Costs," Southern Lumberman, May 2003, https://www.nrs.fs.fed.us/pubs/jrnl/2003/ne_2003_wiedenbeck_003.pdf.

Jeanne Scweder, "Wood Packaging Producer Achieves Productivity Gains with Gigabit Ethernet," Automation World, December 7, 2019, https://www.automationworld.com/home/article/21104379/wood-packaging-producerachieves-productivity-gains-with-gigabit-ethernet.

U.S. Environmental Protection Agency, Energy Trends in Selected Manufacturing Sectors: Opportunities and Challenges for Environmentally Preferable Energy Outcomes, March 2007, https://archive.epa.gov/sectors/web/pdf/ch3-5.pdf.

U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE), Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing, June 2015, https://www.energy.gov/sites/default/files/2015/08/f26/pulp_and_paper_bandwidth_report.pdf.

U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO), "Forest Products Industry Profile," accessed September 2021, https://www.energy.gov/eere/amo/forest-products-industry-profile.

"Global Food Automation Market Analysis, Trends, and Forecast 2019-2025 – ResearchAndMarkets.com," BusinessWire, February 26, 2020, https://www.businesswire.com/news/home/20200226005409/en/Global-Food-Automation-Market-Analysis-Trends-and-Forecasts-2019-2025---ResearchAndMarkets.com.

U.S. Department of Energy, U.S. Manufacturing Energy U se and Greenhouse Gas Emissions Analysis, November 20212, https://www.energy.gov/sites/default/files/2013/11/f4/energy_use_and_loss_and_emissions.pdf.

IRON & STEEL MANUFACTURING

U.S. Geological Survey, "Iron and Steel Data Sheet—Mineral Commodity Summaries 2020," 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-iron-steel.pdf.

"Supply Chain Transformation in the Steel Industry," GEP Blog, 2019, https://www.gep.com/blog/mind/supply-chain-transformation-in-the-steel-industry.

"Iron & Steel Manufacturing in the US - Employment Statistics 2005–2027," IbisWorld, accessed November 28, 2020, https://www.ibisworld.com/industry-statistics/employment/iron-steel-manufacturing-united-states.

Michael Cowden, "US flat-rolled EAFs fuel new-capacity tsunami," Fastmarkets (Blog), August 21, 2020, https://www.fastmarkets.com/article/3947510/us-flat-rolled-eafs-fuel-new-capacity-tsunami.

SelectUSA, Robots and the Economy: The Role of Automation in Driving Productivity Growth, 2020, https://www.selectusa.gov/servlet/servlet.FileDownload?file=015t0000000kyXN.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Iron and Steel Manufacturing, August 24, 2015, https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing.

U.S. Department of Energy, U.S. Energy Information Administration, 2018 Manufacturing Energy Consumption Survey, March 2021, https://www.eia.gov/consumption/manufacturing/pdf/MECS%202018%20Results%20Flipbook.pdf.

American Iron and Steel Institute, American Iron and Steel Institute Profile 2019–2020, December 2020, https://www.steel.org/wp-content/uploads/2020/12/2020-AISI-Profile-Book.pdf.

U.S. Energy Information Administration (EIA), "Changes in steel production reduce energy intensity," July 29, 2016, https://www.eia.gov/todayinenergy/detail.php?id=27292.

"KWS Saves Steel Mill $1,600,000 in Potential Downtime with Quick Delivery," KWS, accessed September 2021, https://www.kwsmfg.com/resources/made-to-order-solutions/kws-saves-steel-mill-1600000-in-potentialdowntime-with-quick-delivery-2/.

"Unplanned Downtime – The Causes, Costs and How You Can Reduce It," Everlasting Valve Company, January 19, 2021, https://www.everlastingvalveusa.com/unplanned-downtime/.

Ali Hasanbeigi and Cecilia Springer, How Clean is the U.S. Steel Industry?, Global Efficiency Intelligence, November 2019, https://www.globalefficiencyintel.com/us-steel-industry-benchmarking-energy-co2-intensities.

SEMICONDUCTOR MANUFACTURING

SelectUSA, "Semiconductors Spotlight Overview," accessed September 2021, https://www.selectusa.gov/semiconductors-industry-united-states.

Semiconductor Industry Association, 2020 State of the U.S. Semiconductor Industry, June 2020,

https://www.semiconductors.org/wp-content/uploads/2020/06/2020-SIA-State-of-the-Industry-Report.pdf.

Congressional Research Service, Semiconductors: U.S. Industry, Global Competition, and Federal Policy, October 26, 2020, https://fas.org/sgp/crs/misc/R46581.pdf.

"Highlights of the March 2021/Q1 Edition of the Fab Databases," SEMI, March 3, 2021, https://www.semi.org/en/news-resources/market-data/world-fab-forecast-report-highlights-q1-2021.

World Semiconductors Trade Statistics (WSTS), WSTS Forecast Summary (Corrected Version), March 17, 2021, https://www.wsts.org/esraCMS/extension/media/f/WST/4987/WSTS_nr-2021_03-CORRECTED.pdf.

"Trends Impacting the Semiconductor Industry in the Next Three Years," Advanced Energy, March 2019, https://www.advancedenergy.com/globalassets/resources-root/articles/en-semi-semiconductor-industryimpacting-trends-survey.pdf.

John Adams, "America's Semiconductors Supply Chain Faces Big Cybersecurity Risks," Alliance for American Manufacturing (Blog), March 23, 2017, https://www.americanmanufacturing.org/blog/americas-semiconductorssupply-chain-faces-big-cybersecurity-risks/.

Brett Daniel, "Counterfeit Electronic Parts: A Multibillion-Dollar Black Market," Trenton Systems, July 27, 2020, https://www.trentonsystems.com/blog/counterfeit-electronic-parts.

U.S. Energy Information Administration, "First Use of Energy for All Purposes (Fuel and Nonfuel), 2018," February 2018, https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table1_1.pdf.

Katherine Derbyshire, "Saving Energy in the Fab," Semiconductor Engineering, November 9, 2016, https://semiengineering.com/saving-energy-in-the-fab/.

Jeanne Whalen, Jeff Stein, and Reed Albergotti, "Growing computer-chip shortage alarms Biden and Congress," The Washington Post, February 23, 2021, https://www.washingtonpost.com/technology/2021/02/23/biden-semiconductor-shortage-meeting/.

"Trends in Greenhouse Gas Emissions," in Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2017 (U.S. Environmental Protection Agency, April 2019), https://www.epa.gov/sites/default/files/2019-04/documents/us-ghg-inventory-2019-chapter-2-trends.pdf.

David Isaacs, “Semiconductor Industry to Continue Action on Climate Change,” Semiconductor Industry Association, June 7, 2017, https://www.semiconductors.org/semiconductor-industry-to-continue-action-on-climate-change/.

TRANSPORTATION EQUIPMENT MANUFACTURING

Dun & Bradstreet, Transportation Equipment Manufacturing Industry Profile, updated September 27, 2021, https://www.firstresearch.com/Industry-Research/Transportation-Equipment-Manufacturing.html.

U.S. Bureau of Labor Statistics, “Transportation Equipment Manufacturing: NAICS 336,” accessed September 2021, https://www.bls.gov/iag/tgs/iag336.htm.

U.S. Bureau of Labor Statistics, “May 2020 National Industry-Specific Occupational Employment and Wage Estimates: NAICS 336000 – Transportation Equipment Manufacturing,” accessed September 2021, https://www.bls.gov/oes/current/naics3_336000.htm.

Oliver Silveti Sánchez García, “Industry revenue of ‘transportation equipment manufacturing’ in the U.S. from 2012, to 2024,” Statista, September 30, 2021, https://www.statista.com/forecasts/885162/transportation-equipment-manufacturing-revenue-in-the-us.

U.S. Bureau of Labor Statistics, “Databases, Tables & Calculators by Subject,” accessed September 2021, https://data.bls.gov/timeseries/CES3133600001?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true.

SelectUSA, Robots and the Economy: The Role of Automation in Driving Productivity Growth, 2020, https://www.selectusa.gov/servlet/servlet.FileDownload?file=015t0000000kyXN.

“Downtime Costs Auto Industry $22k/Minute – Survey,” ThomasNet, March 29, 2006, https://news.thomasnet.com/companystory/downtime-costs-auto-industry-22k-minute-survey-481017.

U.S. Energy Information Administration, “First Use of Energy for All Purposes (Fuel and Nonfuel), 2018, February 2021, https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table1_1.pdf.

General Aviation Manufacturers Association, 2018 Annual Report, 2018, https://gama.aero/wp-content/uploads/GAMA-2018-Annual-Report-FINAL.pdf.

Fernando Enzo Kenta Sato and Toshihiko Nakata, “Energy Consumption Analysis for Vehicle Production through a Material Flow Approach,” Energies, Special Issue: Energy Use Efficiency 13, no. 9 (2020 May): 1996-1073, https://www.mdpi.com/1996-1073/13/9/2396.

U.S. Department of Energy, Quadrennial Technology Review 2015; Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing, November 2015, https://www.energy.gov/sites/default/files/2015/11/f27/QTR2015-6A-Additive%20Manufacturing.pdf.

Kanet Katchasuwanmanee, Richard Bateman, and Kai Cheng, “An Integrated approach to energy efficiency in automotive manufacturing systems: quantitative analysis and optimisation,” Production & Manufacturing Research 5, no. 1 (2016 January): 90-98, https://www.tandfonline.com/doi/full/10.1080/21693277.2017.1322539.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office Award Number DE-EE0009046.

The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

CYMANII

CYBERSECURITY MANUFACTURING ROADMAP 2022

PUBLIC VERSION