U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

TRANSSFORM Workshop

Empowering the U.S. Manufacturing Industry

Proceedings Report

September 8-10, 2021

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Disclaimer

Acknowledgments

Edited by Dr. Sudarsan Rachuri and Dr. Emmanuel Taylor

Executive Summary

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, and Advanced Manufacturing Office (AMO) hosted the TRANSSFORM (Transformative, Resilient, Adaptive, Nimble, Sustainable, Smart, Flexible, Optimal, Robust, and Model-based[1] – A Bold Vision for the Future of U.S. Manufacturing) Workshop on September 8–10, 2021. The objective of the workshop was to hear from stakeholders about how manufacturing digitalization can improve manufacturing competitiveness and reduce energy consumption and emissions production from U.S. manufacturing, and what research, development, and demonstrations are needed to have the desired impact. This workshop was held virtually and was attended by over 140 people.

During the TRANSSFORM workshop, representatives from the research community and industry discussed the latest advances in digitalized manufacturing innovations. The input gathered from the workshop will inform the research focus areas considered by AMO in fulfilling its mission to improve energy efficiency, decarbonize manufacturing industries, and enhance manufacturing competitiveness in the United States. In hosting this workshop, AMO sought advice from industry stakeholders (including stakeholders from AMO's current research ecosystem) with expertise in manufacturing digitalization, decarbonization, IoT, cybersecurity, supply chain flexibility, and resource efficiency. The workshop's primary objective was to bring together experts and a broad set of stakeholders to identify and discuss challenges and opportunities for improving U.S. leadership in manufacturing and manufacturing competitiveness through manufacturing digitalization. The participants examined purposely broad, open-ended questions to create a dialogue and discussion among various stakeholders.

Over the past few decades, the manufacturing sector has seen a variety of paradigms enabled by the digital revolution, including resiliency, sustainability, agility, and adaptivity, to name a few. Although each objective is unique, they are interconnected with each impacting and often enabling each other. One of the goals of this workshop is to explore these manufacturing paradigms and initiatives that have evolved over the years and how to leverage and derive cumulative impacts from them (Transformative, Resilient, Adaptive, Nimble, Sustainable, Smart, Flexible, Optimal, Robust, and Model-based). The result is a conceptual map of each of the TRANSSFORM manufacturing concepts that illustrates their benefits to the manufacturing sector The "mapping" for each of these concepts includes:

- why: the main motivation or manufacturing problem solved,
- what: the information requirements to implement the solution,
- how: the process of implementation,
- who: the expertise and people involved in implementation,
- where: the step in the supply network impacted by this concept, and

[1] For a detailed definition of these terms, please refer to Appendix A.

- when: the timeframe for implementation.

TRANSSFORM paradigms, enabled by manufacturing digitalization, will be imperative to decarbonizing the industrial sector and manufacturing the technologies needed to meet the Biden administration's goal of establishing a decarbonized economy by 2050. These manufacturing concepts enable the utilization of new and evolving technologies (process technologies, automation, autonomous systems, information and operational technologies, advanced materials, smart sensors, advanced computing, technologies for emission reductions, and AI/ML and related technologies) needed for massive decarbonization efforts, including the hard-to-abate sectors such as heavy industry and transportation for supply chain logistics.

The Industrial sector is responsible for ~25% of national carbon emissions[2]. AMO is developing an industrial decarbonization roadmap to guide investment in Research, Development, Demonstration, and Deployment (RDD&D) opportunities to address energy efficiency, electrification, Carbon Capture Utilization and Storage (CCUS), and switching to low-carbon fuels, feedstocks, and energy sources, to reduce carbon emissions in the manufacturing sector. This will help the U.S. manufacturing sector meet the Biden administration's goal of establishing a net-zero emissions economy by 2050[3]. To address climate change, we will also need to develop new and improved clean energy technologies to enable the U.S. to reach net-zero emissions economy-wide, known as "deep decarbonization." Digitalizing manufacturing and using smart manufacturing technologies could introduce potential security, reliability, and supply chain risks through cyber-attacks. Therefore, the necessary cybersecurity technologies and platforms will have to be developed concurrently to ensure a safe, competitive, and secure supply chain. To implement these innovations effectively, the workforce of the future must be trained in these concepts and training must be done equitably to tap into the full diversity of talent in the United States and ensure the impacts are felt equitably.

The foundation for resource efficiency and decarbonization is the fundamental and applied research and development in material science. Decarbonization is the process of reducing carbon intensity and lowering the amount of greenhouse gas (GHG) emissions produced from process chemistry (direct emissions) and indirect emissions from heating processes that utilize fossil fuels. Materials discovery and materials substitution, greatly aided by advances in Artificial Intelligence/Machine Learning (AI/ML), simulation, modeling, and theory-driven materials exploration will be critical for reducing direct emissions. Major challenges are hindering the integration of new materials into manufacturing processes. New materials may require process changes, which drive cost. A clear and worthwhile value proposition and return on investment (ROI) must precede these changes. Improvements in modeling and analytics are expected to bring the following advances to manufacturing:

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

- The integration of manufacturing processes with sensing, feedback, multi-physics modeling, and materials properties prediction and tuning, all in real-time.
- The ability to predict advanced materials' impacts on the life cycle assessment (LCA) of products, their footprint, and larger ecosystems

Though many technologies exist for enhancing resource efficiency, effective metrics, data, and tools are needed to fully analyze the technologies' potential and impacts within manufacturing and throughout the supply chain.

Here, we briefly summarize the major conclusions of the workshop in key areas of the workshop:

- Digitalization and Cybersecurity for Competitive Manufacturing Supply Networks
- Decarbonization
- Material Science, and Resource Efficiency
- Workforce Development and Training.

The participants discussed the research, technology, and development push and more importantly how the manufacturing end-users will adopt and implement these technologies for manufacturing competitiveness, workforce development, and industrial decarbonization. This aligns well with AMO's mission, vision, and strategic goals:

- Improve the productivity and energy efficiency of U.S. manufacturing
- Reduce lifecycle energy and resource impacts of manufactured goods
- Leverage diverse domestic energy resources in U.S. manufacturing, while strengthening environmental stewardship
- Transition DOE-supported innovative technologies and practices into U.S. manufacturing capabilities
- Strengthen and advance the U.S. manufacturing workforce

Detailed descriptions are provided in Sections 4–11 of the full report. We are summarizing the sessions that have a common set of discussions and outcomes from the sessions.

Digitalization and Cybersecurity for Competitive Manufacturing Supply Networks

Digitalization of the manufacturing system has the potential to fundamentally change how products are designed, manufactured, supplied, used, remanufactured, and eventually retired. Built upon advanced cyber-physical systems and data analytics, the digitalization of the manufacturing system will enable rapid realization of products, dynamic response to changing demand, real-time performance optimization, and decarbonization of production and supply chain networks, collectively enhancing US manufacturing competitiveness. The composition of advanced manufacturing operational technologies and IT services using newly defined cyber-physical architecture, cybersecurity, and solutions forms the basis for the open and transformative digitalization of manufacturing. The challenge for cyber-physical architecture is to develop functional decomposition models of large, evolving, and heterogeneous domains of factories and production networks. The data analytics challenge is both in the organization and extrapolation of data and in the definition of analytical methods. The heterogeneous and proprietary solutions for data capturing, preprocessing, fusion, streaming, dimension reduction, and filtering need a standard-based approach to address traceability, uncertainty quantification, security, and data provenance challenges.

It is important to understand business outcomes for collecting manufacturing-related data. Converting data into actionable insights requires hybrid modeling, including AI/ML models (data-driven models) and science-based models (causal models). Understanding both correlations and causation requires new statistical models with uncertainty quantification. The real challenge is to reduce information overload for manufacturing by order of magnitude and filter useful information to get the same level of insights with less data. In addition to this, the model-based methodology should help manufacturing engineers apply machine learning techniques and advanced analytics for manufacturing problems. This requires a repository of manufacturing models and data analytics models to enable the semi-automatic generation of analytical models using a given science-based manufacturing model. The foundational technology for enabling digitalization is human system interfaces (Augmented Reality, Virtual Reality, and Mixed-Reality) cybersecurity, extending traditional IT cybersecurity to operational technology.

The major points related to digitalization and cybersecurity for a competitive manufacturing supply network from the workshop are as follows:

- **Technology needs and opportunities:**
  - Technologies and practices are needed to enable and promote data sharing and improve cyber security and shared data governance;
  - The digitalization of manufacturing should also ensure the reuse of solutions, backward compatibility, and interoperability with legacy hardware and software systems.
  - AI and ML are expected to enhance manufacturing competitiveness in several ways, including by guiding experiments and product design, and optimizing processes;
  - Digital twins can be used to operate and optimize individual machines and whole manufacturing operations; and
  - Computer vision augmented reality, and mixed reality applied to productivity (including energy) will enhance product personalization and enable remote manufacturing
- **Model Credibility:** The credibility of manufacturing models (both science-based and data-driven) is critical for industry deployment and potential model reuse and repurposing. Verification and validation are needed to support model credibility.
- **Cybersecurity:** Several aspects of cybersecurity, which is an enabler to a secure and competitive supply chain, should be considered:
  - Increasingly, ransomware attacks are being targeted at manufacturing facilities, which are complex, and often lacking in capital and human resources;
  - Traditional approaches to cybersecurity have involved keeping OT devices offline, an approach that can no longer be applied with the proliferation of edge devices in manufacturing.
  - Innovations in software, firmware, AI, business processes, protocols, and data management are all needed to enhance the cybersecurity of the manufacturing sector;

- Data formats and standards are very critical to enable data accessibility and availability while ensuring data privacy and cybersecurity.

Digital supply networks: The following aspects of digital supply networks should be accounted for when planning work:

- Digital supply networks are a critical aspect of the manufacturing value chain. A conceptual framework is needed to do a trade-off analysis among efficiency, robustness, resiliency, and cost over the long term for digital supply chain systems;
- Supply networks are complex dynamic networks involving people, processes, equipment, policies, and incentives. The network structure is a critical factor in operational success, as the structure determines the operational efficiency and resilience of the supply chain; a
- A resilient supply network is defined by its capacity for resistance to and recovery from disruption, while an adaptive supply network responds quickly to sudden changes in demand. Resiliency in the supply network can be modeled through network topology optimization or redundancy, while better predictions can increase the adaptivity of the supply network.

Decarbonization

In the 2015 Paris Climate Agreement, as many as 200 nations committed to limiting this century's average temperature to well below 2°C and to "*pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*." Transitioning to net-zero emissions to meet the international community's goal of limiting global warming provides both challenges and opportunities for the industrial system and the associated energy system. The participants discussed the various aspects of science and technology of full decarbonization (full decarbonization means zero unabated, not captured by carbon sequestration or storage, CO_2 emissions from energy generation and industrial processes).

The major points related to decarbonization, materials science, and resource efficiency from the workshop are as follows:

- **Design Focus:** The design stage of products and processes plays a critical role in impacting the manufacturing downstream operations. The design decisions and choices have significant impacts on the total life cycle of the products and processes, including their carbon intensity. To reduce carbon footprints through design, the following recommendations were made:
  - Earlier research on Design for X (for example, design for manufacturing, design for life cycle impacts, design for material efficiency, design for reliability, design for quality) could be enhanced with current advances in sensors, controls, and advanced computing, AI/ML, human-machine interface (HMI) for complete round-trip engineering for industrial decarbonization. Smart manufacturing technologies through manufacturing digitalization are the foundational technologies for industrial decarbonization. :
  - Considering the entire value chain is important.
  - More research is needed to understand where circular economy approaches have the highest value to inform design and manufacturing decisions; and

  - To meet net-zero goals, industrial decarbonization is imperative even if it is difficult to design, develop and deploy. The U.S. should be a technology leader in this space and assist emerging economies.
- **Decarbonization Pathways:** There are many challenges preventing manufacturing decarbonization at scale, including:
  - Lack of real-time measurement of carbon emissions.
  - Lack of visibility into supply chain carbon footprint.
  - Modular, low-cost, point capture equipment is needed.
  - Better protocols and processes are needed for verifying the performance of carbon reduction technologies.

Materials Science, and Resource Efficiency

- **Advanced Materials and Manufacturing:** It is anticipated that material discovery and materials substitution will be greatly aided by advances in AI/ML, simulation, modeling, knowledge graphs, and theory-driven materials exploration. Advances are expected in smart materials, advanced composites, metamaterials, and semiconductors. Major challenges hindering the integration of new materials into manufacturing processes include changes to manufacturing and production processes, lifecycle impacts, digital twins for materials for characterization, manufacturing data sharing, and availability. A clear and worthwhile value proposition and ROI must precede these changes.

  Factors that impact the ROI include:
  1. Complete LCAs; prove improved sustainability and equivalent performance.
  2. Full materials characterization and integration into digital twin systems.
  3. Open sharing of materials data; a national database of materials information.
  4. Real-world performance validation.

- **Resource Efficiency:** The greatest hindrance to implementing resource efficiency efforts appears to be an ability to find economic justification and resources to support efforts. The widely accepted definition of resource efficiency is about using the Earth's limited natural resources sustainably and optimizing benefits derived from them while minimizing impacts on the environment. This also relates to resource productivity which is to create more with less and to deliver greater value with less input. The fewer materials are used for the resulting benefit, the better the resource efficiency. Resource productivity is defined as the ratio between gross domestic product (GDP) and domestic material consumption.

  Internal organizational resources compete against other efforts, which often have clearer connections to profitability, competitiveness, or organizational Key Performance Indicators (KPIs). Though modeling, direct measurement, and life-cycle assessment (LCA) analyses have been performed by some organizations, the value proposition for doing so can be unclear, and the equipment needed to support these efforts can be complex. Though many technologies exist for enhancing resource efficiency, effective metrics, data, and tools are needed to fully analyze their potential and impact within manufacturing, and throughout the supply chain.

Workforce Development and Training

Finding appropriately skilled workers is a challenge for U.S. manufacturers. To serve the emerging digitalized manufacturing sector, students must be proficient in the application of new technologies. Continual changes in the industry necessitate continuous training for the workforce. Training should include providing students and the existing workforce with a systems-level view when they enter the industry, allowing workers to have greater impacts.

Specifically, manufacturers need skilled technicians that are proficient in mathematics, computational approaches, and digital technology. University programs should balance classroom- and lab-based training, as manufacturing is hands-on work. Industry needs must inform the development of curricula and training. The industry should invest more in this area.

Education and curriculum development is crucial to ensuring that the leading world clusters of skill and technology are located in the United States.

The major points related to workforce development and training from the workshop are as follows:

- The workforce requires improved education on data analytics, AI/ML, digitization, IoT, robotics, and data interpretation. Interdisciplinary training must be developed in collaboration with the industry,
- Training should be available to students for upskilling the present workforce. Implementation should include community colleges and affordability options for families,
- Hands-on, problem-based, learning curricula are needed to give students practical experience,
- Workforce development is regional, an example being areas that have seen the decline in the manufacturing industry, the potential role of local educational institutions, and
- Increased education is needed on key topics, such as life cycle analysis, cyber manufacturing, systems thinking, accounting principles, Greenhouse Gas (GHG) protocols, standards data-driven decision making, energy, and water auditing, Integrated Computational Materials Engineering (ICME) tools, and materials tracking.

The recommendations and conclusions from this workshop will help in strengthening the RDD&D portfolio for AMO. Major innovation happens at the interaction of these disciplines and AMO will consider this workshop's findings in the development of AMO RDD&D strategy that sets the priorities and goals.

A broader effort to roadmap the advances needed in the U.S. manufacturing sector is being driven by the National Science and Technology Council (NSTC), Subcommittee on Advanced Manufacturing. During the TRANSSFORM workshop, the NSTC held a special roundtable discussion to inform the 2022 National Strategic Plan for Advanced Manufacturing, which is an update of a 2018 report. More details concerning the discussion held and its outcomes can be found in Appendix C of this report.

List of Acronyms

ACM	Association for Computing Machinery
AI	Artificial Intelligence
AMO	Advanced Manufacturing Office
AR	Augmented Reality
ASME	American Society for Mechanical Engineers
CCUS	Carbon Capture Utilization and Storage
CERT	Computer Emergency Readiness Team
CH_4	Methane
CHIPS	Creating Helpful Incentives to Produce Semiconductors for America Act
CNC	Computerized Numerical Control
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COVID	Coronavirus Disease
CPHS	Cyber-Physical–Human System
CPS	Cyber-Physical Systems
CSF	Cyber Security Framework
CTO	Chief Technology Officer
DAQ	Data Acquisition System
DHS	Department of Homeland Security
DNA	Deoxyribonucleic acid
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
EERE	(Office of) Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
FDA	Food and Drug Administration
FECM	Office of Fossil Energy and Carbon Management
FOA	Funding Opportunity Announcement

FY	Fiscal Year
GHG	Greenhouse Gas
HPC	High-Performance Computing
HPE	Hewlett Packard Enterprise
ICME	Integrated Computational Materials Engineering
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IT	Information Technology
KPIs	Key Performance Indicators
LCA	Life Cycle Analysis
LEEP	Lab-Embedded Entrepreneurship Program
MBSE	Model-Based Systems Engineering
MDF	Manufacturing Demonstration Facility
ML	Machine Learning
MS&A	Modeling, Simulation, and Analysis
MxD	Manufacturing x Digital (x denotes times)
NDAA	National Defense Authorization Act
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSTC	National Science and Technology Council
ORNL	Oak Ridge National Laboratory
OS	Operating System
OSTP	Office of Science and Technology Policy
OT	Operational Technology

PLCs	Programmable Logic Controllers
Q&A	Question and Answer
R&D	Research and Development
RDD&D	Research, Development, Demonstration, and Deployment
RFI	Request for Information
ROI	Return On Investment
SASE	Secure Access Service Edge
SC	Office of Science
SCADA	Supervisory Control and Data Acquisition
SMEs	Small and Mid-Size Enterprises
SMMs	Small and Medium-Sized Manufacturers
STEM	Science, Technology, Engineering, and Mathematics
TRANSSFORM	Transformative, Resilient, Adaptive, Nimble, Sustainable, Smart, Flexible, Optimal, Robust, and Model-based
USDA	United States Department of Agriculture
VR	Virtual Reality

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Workshop Overview and Purpose

Introduction

It is generally hypothesized that manufacturing is on the cusp of a fourth industrial revolution (Industry 4.0). This revolution represents the move toward manufacturing digitalization, i.e., the use of digital technologies and digitized data to enable new business models that provide new revenue and value streams. These advances allow manufacturers to take advantage of smart manufacturing concepts, leverage data across all aspects of manufacturing and the supply chain and network, make optimal use of the Industrial Internet of Things (IIoT), and implement resulting changes to manufacturing approaches.

Digitalization is one advancement that has provided the manufacturing sector with a significant opportunity to contribute to decarbonization measures and increase energy productivity. Decarbonization is the process of reducing carbon intensity, lowering the amount of greenhouse gas (GHG) emissions produced from process chemistry and indirect emissions from heating processes that utilize fossil fuels. "Deep carbonization," or net-zero emissions, is necessary to address climate change and requires developing new and improved clean energy technologies. Full decarbonization must also involve the supply chain, as the U.S manufacturing industry has to buy or make artifacts (products, parts or components, and raw materials) from a network of suppliers. It is imperative to employ these new technologies to lead massive decarbonization efforts, including the hard-to-abate sectors such as heavy industry and transportation (for supply chains).

To these ends, AMO is envisioning TRANSSFORM (Transformative, Resilient, Adaptive, Nimble, Sustainable, Smart, Flexible, Optimal, Robust, and Model-based – A Bold Vision for the Future U.S. Manufacturing).[4] TRANSSFORM will aim to enable the U.S manufacturing industry to strategically make or buy more artifacts domestically and make U.S manufacturing more competitive and innovative.

For this effort to succeed and to enable U.S. industry leadership for Industry 4.0 and beyond, AMO is gathering inputs, viewpoints, and requirements from different stakeholders through workshops, business roundtables, requests for information, and webinars. The Office hosted the TRANSSFORM Initiative Workshop on September 8–10, 2021. This event was held virtually and was attended by over 140 people.

Error! Reference source not found. provides a high-level overview of the focus of the workshop and the potential workshop topics for discussion and prioritization. The main focus is on the cyber-physical manufacturing system. Different stakeholders interact with this system to exchange information through standards and protocols, and in some cases, there may be some legal and regulatory requirements (the blue arrows and thin red arrows in the figure). This cyber-physical–human system (CPHS) for manufacturing should be built based on design principles to

[4] For a detailed definition of these terms, please refer to Appendix A.

ensure interoperability, reliability, resilience, and cybersecurity, among other factors. The system is also enabled through different technologies, such as sensors, computing and storage, controls, and communications. These enabling technologies provide the infrastructure for digitalization. Digitalization technologies include digital thread, digital twin, artificial intelligence (AI) and machine learning (ML), advanced human-system interfaces, automation, and eventually autonomy. The enabling technologies and design principles for digitalization will support an ecosystem for providing capabilities and functionalities, as shown in the figure. These interfaces with the CPHS system are shown in the thick red arrows.

Section 2 explains the main theme of TRANSSFORM: to connect conceptually with various other manufacturing programs.

Workshop Objective

During the TRANSSFORM workshop, representatives from the research community and industry discussed the latest advances in manufacturing innovations. The input gathered from the workshop will be used to inform AMO to research focus areas the Office should consider in fulfilling its mission to improve energy efficiency and decarbonize manufacturing industries. AMO hosted the workshop to seek advice from industry stakeholders (including stakeholders from AMO's current research ecosystem) with expertise in manufacturing digitalization, decarbonization, the Internet of Things (IoT), cybersecurity, supply chain flexibility, and resource efficiency.

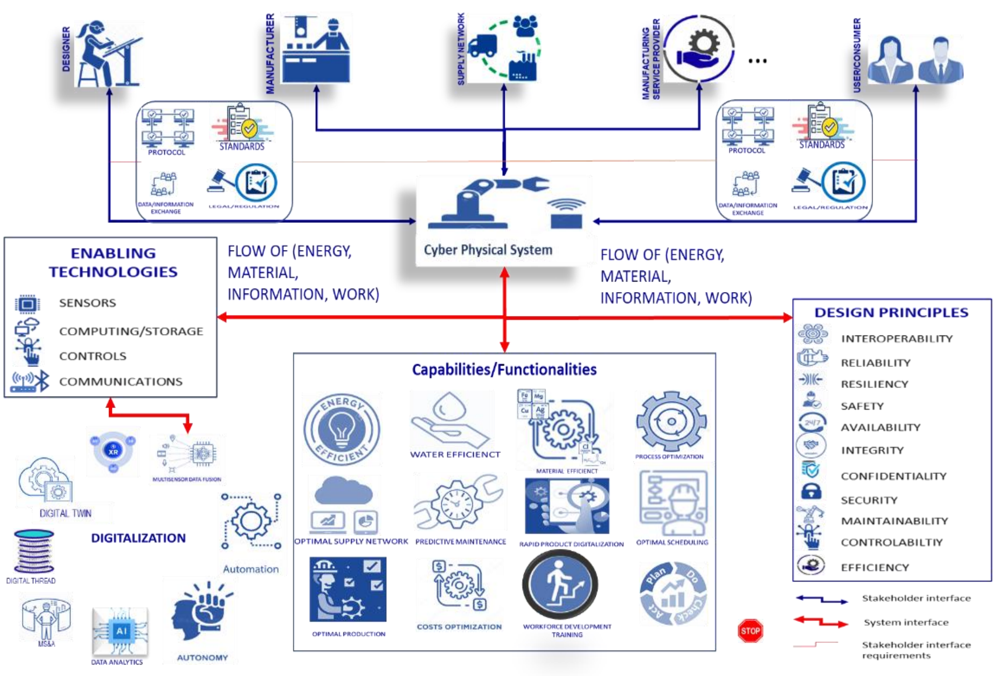

Figure 1. Cyber–physical system to realize the TRANSSFORM initiative

The workshop's **primary objective** was to bring together experts and various stakeholders to identify and discuss challenges and opportunities for U.S. leadership in manufacturing and manufacturing competitiveness. The participants examined purposely broad and open-ended questions to create a dialogue and discussion among various stakeholders. To encourage the discussions and prioritize a set of topics for the workshop, the following questions were provided:

- What research and technology advancements will allow the U.S. manufacturing enterprise to capitalize on the growing ability and capability to collect and utilize data to build upon the integration of existing stand-alone and emerging technologies and increase future efficiency (energy, material, water) for enabling decarbonization and addressing climate change, and competitiveness?
- What research and technology advancements can allow U.S. manufacturing and supply chains to become adaptable and flexible for resilience and the ability to respond to disruptions? What are your organization's or industry's greatest vulnerabilities to supply chain disruptions?
- What research and technology focus can increase the availability and access to new manufacturing technologies, materials, designs, and approaches to include advanced modeling and analytical approaches? How can new technology solutions help with the rapid transition from design to manufacturing for materials, processes, and components in priority areas?
- What strategies can help the United States implement new business models, structural changes, and cultural shifts toward energy and resource efficiency realized through design and manufacturing approaches? What challenges does your organization experience in the integration of new technologies together with existing technologies? What additional tools, definitions, or standards are needed to assist you in developing and implementing such strategies?
- What challenges or opportunities are specific to your geographic region, rather than an industry sector? Are there possible regional collaborations or ecosystems that would allow your organization to become more efficient (in energy, material, and water use) or allow for supply chain flexibility?
- What training and education are needed to prepare the workforce to implement the above? What skill gaps currently exist?

While these overarching questions guided the workshop as a whole, more specific questions were used to guide technical discussions. More specific questions and participant responses are detailed in the subsequent sections of this report.

Workshop Structure

The TRANSSFORM workshop was organized around several key technical topics related to advanced manufacturing. The topics that were discussed are provided below. The full agenda for the event can be found in Appendix B.

- Government Initiatives Addressing Advanced Manufacturing
- Digitalization of Manufacturing
- Cybersecurity Considerations for Advanced Manufacturing
- Enhancing Resource Efficiency in Manufacturing
- Decarbonization of the Manufacturing Industry
- Advanced Materials and Modeling for Energy Optimization
- Adaptable and Flexible Supply Networks for Energy Productivity

During the workshop, each topical area was explored through a combination of keynote presentations from invited speakers, moderated question-and-answer (Q&A) sessions, and facilitated discussions that included all workshop attendees.

Leading experts from industry, government, and academia were invited to provide high-level overviews concerning the current state of the art, to aid in identifying technology advancement needs, and to assist in mapping out a strategy for achieving technical objectives. Keynote presenters were given approximately 15 minutes to provide remarks, accompanied by slide presentations. Presentation slides for all presenters have been published in addition to this report.

Q&A sessions were moderated and included questions from the workshop organizers, attendees, and the moderators themselves. The facilitated discussions provided an opportunity for workshop participants to engage in dialogue in each topical area, guided by a set of focus questions. An expert facilitator guided the conversation, and workshop participants' responses were collected in real-time, using digital tools. All conversations during the workshop were documented, and the results from each discussion are presented in the subsequent sections of this report.

Introductory Remarks

During the TRANSSFORM workshop, two introductory presentations were given. The first set of remarks was delivered by Diana Bauer, the acting deputy director at AMO. Her remarks are summarized below.

<table>
<tr><th>Presenter Name</th><th>Institution</th><th>Role</th></tr>
<tr><td>Diana Bauer</td><td>U.S. Department of Energy</td><td>Acting Deputy Director, AMO</td></tr>
<tr><td colspan="3">Presentation Title:
Advanced Manufacturing Office Overview</td></tr>
<tr><td colspan="3">Key Presentation Points:
Manufacturing is central to DOE concerns.
AMO invests in research to support clean energy technology.
The industrial sector is responsible for ~25% of national carbon emissions.
AMO is developing an industrial decarbonization roadmap to guide investment in RDD&D opportunities to address energy efficiency; electrification; fuel switching; and carbon capture, utilization, and storage to reduce carbon emissions in the manufacturing sector.
The actions in the roadmap will help the U.S. manufacturing sector meet the Biden administration’s goal of establishing a clean energy economy by 2050.
Cybersecurity will be a critical concern as digitization increases in manufacturing.</td></tr>
</table>

The second set of introductory remarks was provided by Dr. Sudarsan Rachuri, the federal program manager for smart manufacturing. His presentation is summarized below.

<table>
<tr><th>Presenter Name</th><th>Institution</th><th>Role</th></tr>
<tr><td>Sudarsan Rachuri</td><td>U.S. Department of Energy</td><td>Federal Program Manager</td></tr>
<tr><td colspan="3">Presentation Title:
Future Manufacturing TRANSSFORM Workshop</td></tr>
<tr><td colspan="3">Key Presentation Points:
TRANSSFORM is a way to conceptually connect various manufacturing programs.</td></tr>
</table>

The mapping of various manufacturing programs can be explained using the Zachman Framework (Zachman 1999), which was designed to describe any complex idea (Zachman and Sowa 1992). The framework is widely used for enterprise architecture modeling. DOE is adopting this framework, as shown in the table below, with cognitive primitives as columns and manufacturing programs as rows.

For example, the rows corresponding to “Sustainable” and “Smart” (rows 5 and 6) in column 1 (“Motivation”) indicate that the motivations for sustainable manufacturing and smart manufacturing are highly interconnected. Similarly, in the Data column, the data focus for sustainable and smart manufacturing clearly shows a strong overlap in the type of data collected. One can do a similar analysis between any two or more rows, across each of the columns. This framework allows DOE to conceptually map each of the manufacturing programs, and the synergies and interconnections indicate that TRANSSFORM can help the manufacturing industry leverage the benefits of these manufacturing programs. The real power lies in reusing and replicating the methodologies, solutions, and best practices.

Similarly, the Data (What) column, when viewed across all manufacturing programs, shows that many data collected are very similar, based on canonical sets of data that are common across these manufacturing programs. Hence, it will be somewhat easy for manufacturers to consider the reuse of the data collected for implementation in different manufacturing programs. This step can be mapped and analyzed with the Motivation (Why) column to understand the real reasons for different manufacturing programs and harmonize them before they are implemented. In this way, the manufacturer can save time and effort in adopting different manufacturing programs. Similar analyses can be done for other columns across all the rows.

Conceptually Mapping Different Manufacturing Programs

		Motivation: Why	Data: What	Function: How	People: Who	Network: Where	Time: When
1	Transformative	• The Whole system thinking • Energy system modeling • Multi- and cross-disciplinary • Leapfrogging and disruptive	• CPHS • Computing • Communications • Standards • Protocols • Best practices	• Enabling technologies • Interoperability • Digitalization • Automation • Autonomy	• Industry • Academia • Government • Labs • Small and medium-sized manufacturers • Small and mid-size enterprises (SMEs)	• Machine • Shop floor • Plant • Supply network level • Innovation ecosystem	• On time • Just in time • Real-time
2	Resilient	• System's ability to avoid, withstand, and recover from adversity	• Unexpected, extreme, and rare events • Cyberattacks	• Cybersecurity • Safety • Maintainability • Reliability • Integrity • Confidentiality • Resilience modeling	• IT and OT system integrators • Suppliers • Security and safety experts	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time
3	Adaptive	• Self-optimized manufacturing performance • Intelligent and adaptive behaviors	• Data related to energy, material, water, and other resources • Process data	• Controllability • Availability • Sensor networks • Information fusion, the data acquisition system • Modeling, simulation, and analysis (MS&A)	• Control system and sensor providers • Software and hardware system providers	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time

		Motivation: Why	Data: What	Function: How	People: Who	Network: Where	Time: When
4	Nimble	• Faster, cheaper, better, and greener products, processes, and services	• Data related to cost, quality, throughput, and resources (energy, water, materials)	• Product design connected to manufacturing • Mathematical models	• Industry • Academia • Government • Labs • Small and medium-sized manufacturers • SMEs	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time
5	Sustainable	• Minimal negative environmental impacts in parallel with energy and natural resource conservation	• Data related to cost, quality, throughput, and resources (energy, water, materials) • Life cycle analysis	• Integrated product design and manufacturing • Mathematical models • Decarbonization	• Environmental scientists • Climate change experts • Materials scientists • Energy experts	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time

		Motivation: Why	Data: What	Function: How	People: Who	Network: Where	Time: When
6	Smart	• Integrated operational technology and information technology (OT/IT) for developing effective and secure CPHS platforms for better decision-making and improving the overall productivity and efficiency of manufacturing across the networked enterprise	• Data related to energy, material, water, and other resources • Process data • Digital Thread • Digital Twin • Process data • Production data	• AI/ML • Hybrid models • Sensor networks • Information fusion • Data acquisition system • IT and OT • Cloud/Edge Computing • Cyber-physical system platform, augmented/ virtual/mixed reality, MS&A	• Process engineers • System optimization experts • Plant and shop floor engineers/ managers • Programmable logic controllers/ experts in supervisory control and data acquisition (SCADA)	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time
7	Flexible	• Ability to deal with variability and variations	• Process, production variability, and variations • Product Variety • Supply–demand	• Flexible manufacturing facilities • Material, part, and component substitutions • Flexible supply networks	• Production managers • Shop floor, plant engineers • Technicians • Managers	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time

		Motivation: Why	Data: What	Function: How	People: Who	Network: Where	Time: When
8	Optimal	• Optimized system-level performance	• Data related to energy, material, and water • Process, production, and supplier data	• Optimization model • Optimal control • Forward and inverse problem modeling • Supply network integration • Optimal scheduling • MS&A	• Production managers • Shop floor, plant engineers • Technicians • Managers	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time
9	Robust	• Ability to deal with perturbations or disturbances	• Production and supply perturbation and disturbance data	• Robust optimization and control • Supply–demand modeling • Statistical modeling • MS&A	• Production managers • Shop floor • Plant engineers • Technicians • Managers	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time
1	Model-based	• System models for real-time digital continuity between product and manufacturing engineering, and operations	• Digital Thread • Digital Twin • Domain-specific data • Knowledge semantics	• Model-based systems engineering • Domain-specific modeling • Model integration • Containerization • Semantic modeling • Ontology	• System designers and modelers • Domain experts • Information • Knowledge of enterprise modelers	• Machine • Shop floor • Plant • Supply network level	• On time • Just in time • Real-time

Government Initiatives

During the government initiatives portion of the workshop, representatives from various government offices provided presentations describing the work of their departments relative to advanced manufacturing. Representatives from the following government initiatives were present:

- AMO
- National Science Foundation (NSF)
- National Institute of Standards and Technology (NIST), Office of Advanced Manufacturing

Each of the presenting organizations has a legacy of supporting innovation in the U.S. manufacturing sector. Each presentation provided insights into the relevant programs supported by each government entity and discussed ways in which manufacturers can partner with the U.S. government to adopt innovations, better inform research initiatives, and implement advancements in their manufacturing enterprises.

Summary of the Presentations

Summaries from each presentation are provided below. Each presentation is summarized in its respective table.

Presenter Name	Institution	Role
Chad Schell	U.S. Department of Energy, Advanced Manufacturing Office	Acting Program Manager for R&D Consortia
Presentation Title: Advanced Manufacturing Office Overview		
Key Presentation Points: • Mr. Schell provided an overview of AMO, including its vision, mission, guiding principles, and core areas of activity. • He discussed the Biden administration's goal related to industrial decarbonization and the supporting role of AMO. • The AMO FY 2021 budget included $218 million for R&D Projects, $133 million for R&D Consortia, and $45 million for Technical Assistance programs. • AMO works to increase energy and material efficiency in manufacturing to drive energy productivity and economic growth. • An AMO FY 2020 funding opportunity announcement led to a total of $123.6 million in AMO R&D project awards, with a commensurate $44.7 million of cost share from the awardees, covering 46 projects across 23 states.		

- The Lab-Embedded Entrepreneurship Program (LEEP) brings together innovators and entrepreneurs and partners them with mentorship programs at national labs to further develop technologies and position them for the market.
- AMO supports R&D consortia, including six Manufacturing USA® Institutes, advanced manufacturing hubs, and the Manufacturing Demonstration Facility at Oak Ridge National Laboratory (ORNL).
- AMO technical partnerships help manufacturers set and achieve energy efficiency goals, support workforce development, and provide tools to assess manufacturing competitiveness.

The role of NSF within the advanced manufacturing research ecosystem is described below.

Presenter Name	Institution	Role
Bruce Kramer	National Science Foundation	Senior Advisor

Presentation Title:

Overview of NSF Manufacturing Programs

Key Presentation Points:

- Mr. Kramer provided background information on NSF as an organization, including its mission and role within the U.S. research economy.
    - NSF supports basic research and education across science and engineering, mainly through funding projects at colleges and universities.
    - NSF accounts for 4% of federal R&D and 44% of non-medical R&D at U.S. universities, has 11,000 active projects, and supports 40,000 graduate students.
- Relevant NSF programs include Future Manufacturing, the National Robotics Initiative, Cyber-Physical Systems, and the Advanced Manufacturing Program.
- Manufacturers tend to solve problems at the machine level on the factory floor, unaware of other manufacturers' similar efforts. The result is massive duplication, which can be addressed through ML and data sharing.
- The future manufacturing program has developed an AI common in which data can be securely stored, and through which solutions can be developed.
- Another project focused on remote factory operations, assisted by machine learning, wherein remote ML systems were used to control robotic operations, and were designed to ask for human assistance when faced with uncertainty.
- The Secure Smart Machining project builds sophistication into CNC machinery through modern programming.

The role of NIST within the advanced manufacturing research ecosystem is described in the table below.

Presenter Name	Institution	Role
Mike Molnar	National Institute of Standards and Technology	Founding Director, Office of Advanced Manufacturing
Presentation Title: Overview of DOC [U.S. Department of Commerce]/NIST Manufacturing Programs		

Key Presentation Points:
• NIST sits within DOC and serves as the nation's standards and metrology body.
• NIST's work in advanced manufacturing is focused on three areas:
    o NIST lab programs
    o Manufacturing USA, a national network established in 2014 with DOE and others
    o Hollings Manufacturing Extension Partnerships, a 33-year-old national network focused on workforce development, with centers in every state
• NIST lab programs focus on transformational technology R&D and have been supported through the American Rescue Plan and efforts related to pandemic response.
• The Manufacturing USA network serves as a bridge across the valley of death for manufacturing technologies in mid-range technology readiness levels.
• The Manufacturing Extension Partnership national network supports small and medium-sized manufacturers, which account for 90% of U.S. manufacturers.
• 2021 Creating Helpful Incentives to Produce Semiconductors for America Act (CHIPS) of the National Defense Authorization Act has created opportunities related to the advanced manufacture of semiconductor devices. NIST is expected to play a significant role in the execution of forthcoming programs.
• The White House has issued an executive order mandating the reduction of manufacturing energy and carbon footprints while improving racial equity and support for underserved communities.
• Congress requires a quadrennial report on advanced manufacturing in the United States, and NIST is assisting the White House with issuing a request for information to collect information in support of the 2022–2026 report.
• DOC's Economic Development Administration has a program aimed at creating regional technology hubs to spur innovation by providing strategy and implementation grants.		

Summary of the Q&A Session

Following the government initiatives presentations, the presenters participated in a Q&A session. Workshop participants submitted questions, which were presented to the speakers. The following represents a summary of the themes discussed during the Q&A session. Full documentation of the Q&A session can be found in the TRANSSFORM Workshop Data Collection Report (Data Collection Report), published as a separate document, along with this proceedings report.

- **Societal needs:** Economic considerations and GHG emissions are important aspects of societal needs, as are environmental and social justice. A challenge is figuring out how far into the manufacturing design phase societal issues should be considered explicitly.

Increasing the efficiency of manufactured products can improve the lives of those who use them.

- **Balancing domestic manufacturing development with international collaboration:** Although manufacturing is a globally connected industry, it is important to ensure that U.S. taxpayer dollars are not being used to develop technology whose economic impacts are only in other countries. Education and curriculum development are crucial to ensure that the leading world clusters of skill and technology are located in the United States.
- **Standards and protocols:** International coordination is required to ensure standards are both common and beneficial.
- **Workforce involvement:** Finding appropriately skilled workers is a challenge for U.S. manufacturers. To serve the emerging digitalized manufacturing sector, students must be proficient in the application of new technologies. Specifically, manufacturers need skilled technicians that are proficient in mathematics, computational approaches, and digital technology. University programs should balance classroom- vs. lab-based training, as manufacturing is hands-on work. Understanding industry needs is very important.
- **Research challenges in smart manufacturing in the United States:** Smart manufacturing is a process. The advances in IT need to be duplicated for OT. Digitalization presents growth opportunities—but also potential threats that necessitate advanced cybersecurity measures. Data accessibility will become increasingly important, and new tools are needed to allow for secure data sharing.

Key Takeaways from the Government Initiatives Session

The following represent key takeaways, summarized from all aspects of the government initiatives session:

- AMO has programs and resources to support U.S. efforts toward industrial decarbonization.
- NSF has several key programs relevant to advanced manufacturing and has supported projects that have had measurable impacts on U.S. manufacturing.
- The U.S. federal government has several initiatives to support advanced manufacturing, and NIST is at the forefront of implementation for many of these.
- Economics, emissions, environmental justice, and social justice are all concerns that must be considered within the manufacturing ecosystem.
- It is important to prioritize domestic efforts in advanced manufacturing, given the inherently global nature of manufacturing supply chains.
- Workforce development needs to evolve to meet the growing demands of the advanced manufacturing sector.

- Enabling smart manufacturing requires new tools for data management and cybersecurity.

Digitalization of Manufacturing

The discussion on manufacturing digitalization was motivated by the stark contrast between the state of the art and the state of common practice within the U.S. manufacturing sector. Digitalization has the potential to improve decision-making, productivity, and efficiency in manufacturing. The digitalization workshop discussion was designed to highlight technological advances, uncover challenges, and discuss future opportunities.

The digitalization session consisted of a keynote presentation, a moderated Q&A session, and a facilitated discussion. The outcomes from each portion of the digitalization session are described below.

Summary of the Presentation

Presenter Name	Institution	Role
Sujeet Chand	Rockwell Automation	Senior Vice President

Presentation Title:

TRANSSFORM Manufacturing: An Industry Perspective

Presentation Abstract:

The disruption of global manufacturing and supply chains due to the COVID-19 pandemic has resulted in product shortages and cost increases. Companies that are further along in their digitalization journeys did better during the pandemic by meeting production schedules and managing labor shortages. The three most important post-pandemic accelerants for digital manufacturing are agility, resilience, and sustainability:

- Agility will allow manufacturing companies to dynamically address future customer needs, such as customized products and personalized medicine.
- Resilience will help companies effectively manage disruptions in the supply chain and operations due to unplanned events such as cyberattacks.
- Sustainable manufacturing has become a business imperative, and most manufacturing companies have identified aggressive goals for carbon neutrality, emissions, energy, and waste.

This talk discussed six new R&D initiatives to rapidly accelerate agility, resilience, and sustainability and help U.S. companies differentiate production through TRANSSFORM manufacturing.

Key Presentation Points:

- Key drivers for smart manufacturing include:
    - Swift approvals from the U.S. Food and Drug Administration and quicker time to market
    - Enterprise-wide risk management and business continuity

- Solutions (including automation) to today's great shortage in terms of a skilled workforce (in part due to an aging workforce)
  - Improved operational efficiencies
  - Strategies for a major shift in medical manufacturing: personalized medicine (a batch size of one) and more bio-based medicines
- Strategic imperatives for advanced manufacturing include:
  - Flexible solutions
  - Faster time to market
  - End-to-end optimization
  - Intelligent systems
  - Sustainable production
- Six R&D imperatives include:
  - Bridge chasm by scale and respect for the legacy
  - Software-defined, secure manufacturing: making legacy hardware more software-based
  - Pervasive AI and simulation: embedding AI throughout; edge, IT layer
  - Enterprise data models and connectivity: how to share and allow access to data kept in silos
  - Highly flexible machines and how to build them
  - Workforce development
- In summary, frameworks, and solutions for sustainable manufacturing should be industry-specific; otherwise, high-level platforms will not generate interest.

Summary of the Q&A Session

Following the keynote presentation, Dr. Chand participated in a moderated Q&A session. The following themes were discussed during the Q&A session. Documentation of the full conversation can be found in the Data Collection Report.

- **Data access:** It is important to think about why data are needed and what business case is being supported. Once the business outcome is identified, specific data can be collected.
- **Building solutions to scale:** Industry verticals created a context for building effective and necessary solutions that can be applied later within other contexts.
- **Role of humans:** As more technologies are integrated, humans are no longer needed for manual and repetitive tasks and can focus on higher-level tasks. Continual changes in the manufacturing industry necessitate ongoing training in AI models.
- **Decarbonization:** Developing a framework (currently missing in the manufacturing industry) is critical for applying specific processes to the bigger picture of decarbonization. For example, the World Economic Forum created a 21-point framework.

Summary of the Facilitated Discussion

The facilitated discussion on digitalization in manufacturing centered on a series of focus questions. Workshop participants were presented with a series of questions, and responses were collected from participants using a set of digital tools. The following section summarizes the questions asked and the responses volunteered by workshop participants.

Impacts of Digitalization

To open the discussion, participants were asked to comment on the impact of digitalization on their organization. Digitalization has already had significant impacts on participant organizations, according to 65% of respondents, while 30% of participants indicated that they expect digitalization to have significant impacts on their organizations in the future. Only two of the participants questioned indicated that they do not expect their organizations to experience such impacts.

Participants were then asked about the areas in which digitalization was likely to produce the greatest impacts. Participants were provided with the following choices: product design, fabrication and production, predictive and preventive maintenance, supply chain management, inventories and logistics, and "other." Participants indicated that digitalization is likely to have impacts on all but one aspect of the manufacturing industry; the exception was inventories and logistics.

Technologies for Digitalization

Participants were asked to describe the emerging technologies for digitalization that are most likely to have impacts on manufacturing in the next 10 years. The chart below summarizes the top five responses. A full listing of responses can be found in the Data Collection Report.

The use of AI to guide measurements, collaborate with human experts, and serve other purposes
ML development linked to advanced simulation, with applications in materials discovery and other applications
Technologies and practices to enable and promote data sharing, including improved cybersecurity and shared data governance
Digital twins can be used to operate and optimize individual machines and whole manufacturing operations
Computer vision, augmented reality, and mixed reality applied to productivity (including energy), new product personalization, and remote manufacturing

Most of the technologies described by participants require extensive data. Participants were asked about the research and technology advancements needed to allow U.S. manufacturing to capitalize on the growing ability to collect and utilize data. The most common responses are summarized below.

Standards for data models and policies for data sharing; frameworks and protocols that enable more open collaboration among all the stakeholders
Domain-specific AI applications to drive data requirements; deeper and sustained engagement of manufacturing (domain experts) and AI researchers

Workforce education at all levels, emphasizing SMEs, to enable the use of new tools and data interpretation; foundational research on the learnability of human-engineered systems from data
Automated data collection and data analytics with computer preprocessing; data cleaning techniques that enable easy removal of incorrect, obsolete, untrustworthy, or biased data
Trustworthiness (cybersecurity, privacy, safety, reliability, resilience)

Participants were asked about the related barriers and challenges that hinder the application of the research and technology advancements identified. The most common responses are shown below.

SMEs make up 98% of the U.S. manufacturing base. Methods are needed to ease SMEs' adoption of new technology. Currently, there are few incentives to replace existing systems.
Access to actual data is impeded by both technological limitations and intellectual property/security concerns. The use of digital thread data to inform standards and qualifications depends on confidence in the digital thread, which is presently lacking.
Industry reluctance is a challenge; major changes will require buy-in at multiple levels.
Access to the available workforce—for example, solutions that require expertise across multiple disciplines—is a growing challenge.
Profitability and unreasonably short requirements for return on investment (ROI) hinder new technology adoption.

Workforce Development

Many of the questions above elicited concerns about the workforce. Participants were asked explicitly about the training and education needed to digitalize the U.S. manufacturing sector. The most common responses are summarized below.

There is a need for training in new technologies such as data analytics, AI/ML, digitization, IoT, and robotics. The skills needed to use these technologies must be incorporated into science, technology, engineering, and mathematics (STEM) education at all levels.
Programs are needed to educate workers currently on the shop floor about new technologies, and feedback should be incorporated. Trainers should also include shop floor workers.
Curricula should include hands-on, problem-based learning to give students practical experience.
Engineering education tends to be siloed by traditional disciplinary roles. Industry hiring tends to follow the same trend. Approaches for cross-training/interdisciplinary engineering education must be accelerated, in collaboration with industry, which will create a market for new skills.

> The federal government should work with community colleges to develop a future workforce. Family support (childcare and eldercare) and student loan relief for two-year college students could be provided, as well as financial aid, allowing students to earn credentials without having to go into debt.

Regional Collaborations

Participants were asked about aspects of their enterprises that are regional in nature. In particular, participants were asked what challenges or opportunities related to manufacturing digitalization are specific to their geographic regions, rather than an industry sector.

Participants described the regional nature of workforce development, noting the availability of excess workers in areas that have seen the manufacturing industry decline and the potential role of local educational institutions. Participants also described the limiting role of poor broadband internet access for SMEs located in rural and underserved communities.

Participants were asked about possible regional collaborations or ecosystems that would allow their organizations to further exploit the benefits of digitalization. From the responses provided, participants consider institutions such as MxD (Manufacturing x Digital), the Manufacturing Demonstration Facility at ORNL, and the Manufacturing USA Institutes as successful examples of regional collaborations. There are other models that can be informative, including business incubators that lead to transformational thinking and U.S. Department of Agriculture (USDA) programs with facilities and resources in almost every county of the United States.

Key Takeaways from the Digitalization Session

The following represent key takeaways, summarized from all aspects of the digitalization session:

- Several key drivers and strategic imperatives are motivating the application of digitalization in manufacturing.
- Key R&D initiatives can be pursued to add value to the U.S. manufacturing industry.
- The use of data in digitalization needs to support a clear business case.
- Advances in digitalization can allow humans to focus on higher-level processes in manufacturing, instead of manual and repetitive tasks.
- Several technologies are expected to have significant impacts on manufacturing digitalization:
    - AI and ML are expected to affect manufacturing by guiding experiments, optimizing processes, enhancing collaboration, and assisting materials discovery.
    - Technologies and practices are needed to enable and promote data sharing and improve cybersecurity and shared data governance.
    - Digital twins can be used to operate and optimize individual machines and whole manufacturing operations.

    - Computer vision augmented reality, and mixed reality applied to productivity (including energy) will enhance product personalization and enable remote manufacturing.

Participants shared many observations about workforce development needs:

- The workforce requires improved education on data analytics, AI/ML, digitization, the IoT, robotics, and data interpretation. Interdisciplinary training must be developed in collaboration with the industry.
- Training should be available to students and the present workforce (upskilling). Implementation should include community colleges and affordability options for families.
- Curricula should include hands-on, problem-based learning to give students practical experience.
- Workforce development challenges can be regional in nature. For example, some areas have seen the manufacturing industry declines, and local educational institutions may play key roles in a workforce renaissance.

Although effective manufacturing institutions exist, regional collaborations can be expanded through additional programs, including business incubators and manufacturing extension programs.

Cybersecurity Considerations

The cybersecurity discussion was motivated by a need to deploy standards, protocols, and best practices to secure the U.S. manufacturing sector; guarantee safety, integrity, and confidentiality; and empower effective data sharing and digitalization.

Participants explored these topics through keynote presentations, a moderated Q&A session, and a facilitated discussion. The outcomes from each portion of the technical session are summarized below.

Summary of the Presentations

The following presentation summaries are provided.

<table>
<tr><th>Presenter Name</th><th>Institution</th><th>Role</th></tr>
<tr><td>Lin Nease</td><td>PointNext Services, Hewlett Packard Enterprise</td><td>Hewlett Packard Enterprise Fellow, IoT Chief Technology Officer</td></tr>
<tr><td colspan="3">Presentation Title:
Manufacturing Transformation and Cyber Security (A Call to Action)</td></tr>
<tr><td colspan="3">Presentation Abstract:
As manufacturers embark on strategic digital transformation initiatives, one of the biggest barriers to their success is cybersecurity in the operations environment. For years, industrial operators have relied on “air gaps” and obscurity to protect their production assets. These approaches had started to fall short even before the transformations. Given that connected operations will be required for advanced manufacturing, manufacturers not only need to address these prior cybersecurity shortfalls but also must address the process and technology gaps associated with new, advanced manufacturing. This session addressed both of these types of gaps and discussed what manufacturers must consider moving forward securely.</td></tr>
<tr><td colspan="3">Key Presentation Points:
A new architecture is needed to solve challenges in digital operations transformations.
Purdue modeling is incomplete for the 2020s; too much data and workflow now passes outside of the model, specifically IoT direct sensing and ML inference. New standalone apps emerge to use these data.
These data are sensitive yet flow over ad hoc plumbing, frequently ending up on the cloud.
One issue is knowing how to get the right sensor on the equipment of interest.
When looking at edge AI, the protection surface is huge, with thousands of micro edge devices. Patching thousands of devices is not tenable.
The most complex networks in the enterprise include campuses (workers with smartphones, and laptops), data centers, operations technology, and new IoT technologies.</td></tr>
</table>

• Software-defined OT will help by enabling OT logic to be monitored and patched and to use modern operating systems (OSs) and platforms. This technology approach also bridges life cycle differences between IT and OT and enables new types of resilience. • Software-defined OT also creates challenges by extending the radius of services logic and adding complexity.

Presenter Name	Institution	Role
Suzanne Lightman	National Institute of Standards and Technology	Senior Cybersecurity Specialist

Presentation Title:

Cybersecurity and Manufacturing: The Scary Present and Possible Future

Presentation Abstract:

This past year has seen significant cybersecurity incidents around manufacturing—and with a commensurate government response. What are the approaches that the federal government is considering? What resources are being offered to manufacturers to assist them in securing their systems? This talk explored the cybersecurity issues, from ransomware to lack of expertise, that faces the manufacturing sector. Among the topics covered were the performance goals coming from the Department of Homeland Security (DHS), the definition of critical software developed by NIST, the issues around pulling cybersecurity expertise from the IT side, and what is on the horizon.

Key Presentation Points:

- NIST is working with industry and science to advance innovation and improve the quality of life.
- There is a rising interest in industrial systems, and the interested parties include not only industry and government but also hackers. There is a rise in ransomware, with recent high-profile incidents that affected railways and meatpacking plants.
- The recognized issues are the complexity of systems and the lack of resources, both capital, and people.
- In OT, every channel is a means of entry and therefore needs to be considered. There are many different entrances that all need special protection (unlike in IT, where all doors and windows providing access may be the same).
- It is important to look at where people interact with systems. People are often the weak link in the worst attacks.
- The Executive Order on Improving the Nation's Cybersecurity in May 2021 covered supply chain cybersecurity and software labeling and assurance.
- The National Security Memorandum on Improving Cybersecurity for Critical Infrastructure Control Systems in July 2021 covered critical infrastructure cybersecurity goals across all sectors, with preliminary goals out by September 22, 2021.
- NIST defines critical software as any software that has, or has direct software dependencies upon, one or more components with at least one of these attributes:
    - Is designed to run with elevated privilege or to manage privileges.
    - Has direct or privileged access to networking or computing resources.
    - Is designed to control access to data or operational technology.

- Performs a function critical to trust.
- Operates outside of normal trust boundaries with privileged access.

- Help is available in various resources:
  - NIST Manufacturing Profile
  - Cybersecurity Framework Profile
  - NIST 1800 Series
  - NIST Cyber Supply Chain Risk Management
  - National Initiative for Cybersecurity Education
  - Manufacturing Extension Partnership
  - Stop Ransomware
  - DHS Computer Emergency Readiness Team

Summary of the Q&A Session

The following themes were discussed during the Q&A session. The raw results can be found in the separate Data Collection Report.

- **Prioritization:** It is important for a manufacturer to get a new set of eyes to see what is going on in its network, then determines how to reorganize systems and networks and what to update.

- **Lessons learned:** Approaching cybersecurity from ground zero is not ideal. Organizations should know what they have and what is important to them. Topology is different for every manufacturer.

Summary of the Facilitated Discussion

Participant discussions indicated that cybersecurity is a growing concern for manufacturers, though not many would regard it presently as a top concern within their organizations.

Participants identified several key cybersecurity innovations that are likely to have impacts on manufacturing in the next 10 years. A summary of the responses is provided below.

Defensive AI technology to "automate" cybersecurity expertise Development of cyber-physical OSs with cybersecurity built in at both coding and firmware levels Active prevention of cyberattacks
Business process innovation: required two-factor authentication and password changes Cybersecurity certification (International Organization for Standardization [ISO]) in purchasing relationships Requirements for ISO 90001 certification for quality (forcing a supply chain to change its behavior through purchasing terms and conditions)
Advanced protocols for security and data protection, including zero-knowledge protocols, zero trust/secure access service edge (SASE), and post-quantum cryptography
Domain-specific modeling and programming language for cybersecurity Android-like OSs for factory systems

Data life cycle (when data can be deleted and thus not be at risk any longer)

Participants were asked to identify standards, protocols, and cybersecurity frameworks that are being applied within manufacturing settings. It was noted that standards and protocols are very context- and organization-dependent and can range from McAfee antivirus software on computers used by small businesses to advanced IT systems. In some instances, no standards or protocols are being applied. Workshop attendees stated that their organizations applied good intersections of IT and OT cybersecurity standards and protocols; protocols referenced by attendees included NIST 800-XX, ISO 15408 common criteria, International Electrotechnical Commission (IEC) 62443, and MTConnect.

Participants were asked whether cybersecurity concerns can conflict with, compete with, or complement efforts related to resource efficiency or decarbonization. Participants noted that these different concerns compete for limited resources within organizations. At times, people and money can be dedicated only to one goal or the other.

Participants discussed cybersecurity challenges associated with managing IT and OT in a manufacturing context. Several concerns emerged. Companies often employ different teams to manage OT and IT, and the OT and IT teams rarely communicate with each other. In addition, ensuring cybersecurity also requires that vendor-provided equipment meet cybersecurity requirements, even as those requirements change over time.

When asked about the cybersecurity training and education needed to prepare the future workforce, participants stressed the importance of degrees, certifications, and training for line workers.

Participants were asked about cybersecurity challenges or opportunities specific to their geographic regions, rather than their industry sectors. The consensus was that cybersecurity is a global problem, and places experiencing regional differences are driven largely by politics rather than technical considerations.

Key Takeaways from the Cybersecurity Session

The following are key takeaways, summarized from all aspects of the cybersecurity session:

- Traditional approaches to cybersecurity involved keeping OT devices offline, an approach that can no longer be applied with the proliferation of edge devices in manufacturing. This advancement requires a new architecture for ensuring cybersecurity.
- Increasingly, ransomware attacks are being targeted at manufacturing facilities, which are complex and often lacking in capital and human resources. The U.S. federal government has taken notice, and resources are being provided by DHS, NIST, and others.
- Innovations in software, firmware, AI, business processes, protocols, and data management are all expected to enhance the cybersecurity of the manufacturing sector.

- Some of the greatest hindrances to enhancing cybersecurity within organizations involve the internal competition for resources (including people) and the stark divisions between personnel and processes for managing IT versus OT.

Enhancing Resource Efficiency in Manufacturing

The resource efficiency technical session explored ways to minimize the negative environmental impacts of manufacturing, including through conserving energy and natural resources. The session included a keynote presentation, moderated Q&A session, and facilitated discussion. The outcomes from each portion of the technical session are summarized below.

Summary of the Presentations

Presenter Name	Institution	Role
Mark Besser	Symphony IndustrialAI	Senior Vice President

Presentation Title:

Improvements to energy efficiency are a classic people, process, and technology equation

Presentation Abstract:

There are many aspects to consider when strategizing the efficient use and long-term sustainability of natural resources in manufacturing. This is a classic people, process, and technology discussion, which requires that all three elements be present for a stable strategy and sound execution. This talk discussed some of the issues and challenges at hand and potential ideas and solutions.

Key Presentation Points:

- People, processes, and technology all work together when building truly sustainable results. Technology cannot be the sole focus.
- Additional considerations include:
    - Economic and policy impacts
    - Climate change
    - Corporate culture
    - Beyond the four walls (e.g., raw material quality)
    - Impact of packaging and transportation
    - Small- to medium-sized businesses and contractors
- Technology trends and challenges in connectivity, big data, 3D printing, autonomous operations, AI/ML, and augmented and virtual reality are creating new paradigms for manufacturing.
- Necessary infrastructure includes network/bandwidth, hardware, software, communication, storage, security, integration, cloud, and scale.
- The process needs to be better, faster, and cheaper. Reaction time is too slow and cannot respond to drastic market changes. It is important to make sure the correct problems are being measured and addressed.
- Workforce availability is a well-documented challenge. Other considerations regarding "people" include tribal knowledge being locked in the aging workforce, whether workers have the right skills, the ability to share openly when things go wrong, and energy as a focus on the work floor.

Summary of the Q&A Session

The following themes were discussed during the Q&A session. The raw results can be found in the separate Data Collection Report.

- **Environmental key performance indicators (KPIs):** Environmental performance should be included in process KPIs to be faster and cheaper. This is an example of considering measuring approaches and whether the right metrics are being used. A global view is important for adopting these sustainable manufacturing processes.
- **Level of automation:** Automation systems can simultaneously decrease labor requirements while increasing overall system complexity. The right balance is needed.
- **Labor pool:** New technology represents one approach for enticing younger professionals into the manufacturing sector, though much of what happens on the manufacturing line does not involve new technology. Cultural issues within a company can be a larger deterrent than technology.

Summary of the Facilitated Discussion

Participants were asked about their organizations' greatest challenges to resource efficiency efforts. Respondents indicated overwhelmingly that economic concerns, including funding, justification, and ROI, were the primary challenges affecting efficiency-related decisions. Additional details are summarized in the table below.

It is not very clear how the enhancement of resource efficiency will affect other aspects of production, profitability, competitiveness, overall sustainability, or benefits management.
Efficiency has lower priority than feature richness, reliability, innovation against competitors, etc.
It can be difficult to balance the cost and complexity of sustaining existing systems (installed base) and finding time to take on new initiatives.
Domain expertise is not shared broadly; training is needed at all organizational levels.

Participants were asked particularly about specific technology gaps hindering the implementation of resource efficiency strategies within their organizations. A summary of the responses is provided in the table below.

Lack of quantifiable metrics and data to do quantitative optimization, modeling, and resource reallocation
Difficulty identifying sources of inefficiency and learning about potential solutions
Poor interoperability with existing (often legacy) systems, controls, equipment, and information systems
Cost and complexity of intermittent renewable energy sources and battery systems

The labor involved in waste reduction/scrap reprocessing
Lack of appropriate materials for harsh environments to harness high- and ultra-high-temperature waste heat in manufacturing plants (e.g., waste heat recovery from electric arc furnaces)
Need for sensors for harsh environments to collect vital data to control and optimize processes (e.g., sensors to monitor the steel slab inside temperature or electric arc furnace exhaust gas composition in the steel industry or the level of fermentation in fermentation tanks in the brewing industry)
Approaches to scaling up bench-scale technologies (carbon capture, electrocatalysis, etc.) to get them to the state of a favorable ROI If not scalable, ways to bridge the valley of death gap, when there is no demand yet (governmental funding, tax incentives, etc.)

Participants were asked what additional tools, definitions, standards, or protocols they would need to assist their organizations in implementing strategies to enhance resource efficiency. Responses are summarized below.

Standards harmonization is needed. From 2008–2010, NIST ran the Smart Grid Interoperability Panels to harmonize between a plethora of standards. A similar approach is needed for Smart Manufacturing. Government convening would be valuable to ensure openness. Standards should also be developed for calculating carbon savings and enabling information exchange between systems.
There is a need for tools for assessing more precisely the effectiveness of the strategies a specific organization intends to implement, e.g., tools that are tracking and accounting for where resources are being used and lost across all the different types of resources (energy, water, material).
There is a need to be much clearer about what data, what problem statement, what model, and what transformations are being utilized. There are layers. A common vocabulary of terms and concepts would be useful.
The technical and financial accounting worlds must be bridged. Groups such as the Sustainability and Financial Accounting Standards Boards could be engaged in this effort.
Assistance is needed with digitizing data, data availability and security, selection of platforms, formulation of optimization strategies and criteria, and moving from priorities to implementation.
Some resource efficiency metrics across the supply chain could help. Manufacturers would like a blend of Energy Star, post-consumer recycled content, economic value-added assessment for labor, etc. that allows them to assess the efficiency of suppliers and show efficiency successes to customers. Such a metric or metrics could improve supply chain transparency. The end consumer could use this metric to choose the most efficiently produced product.
It would be helpful to share best industrial practices with other companies and academia. Data should be aggregated, verified, and curated (e.g., by national labs) and made available.

When asked about their internal efforts to track and monitor resource efficiency efforts, over half of the companies present indicated that they do not baseline and track their water, energy, and material use, though half indicated that they do employ models to describe or better understand their energy, water, or material use.

Regarding baselining studies and modeling efforts related to resource efficiency, participants indicated that the following have been used within their organizations.

Surveys, trend analyses, and studies are used to track energy performance and other parameters such as water and material consumption.
Modeling is used to characterize energy use and identify strategies for improvement.
Life cycle analysis (LCA) is applied to some aspects of operation, such as water reclamation. New York State provides external expertise to assist organizations with LCAs. However, the industry does not always disclose the consumption data necessary for accurate LCA models.
Several organizations have worked with local utilities and DOE Industrial Assessment Centers.

Participants noted the following challenges when attempting to baseline, track, or model their organizations' resource efficiency.

It can be difficult to obtain meaningful data to develop KPIs and assess performance.
Getting raw data can require high-resolution instrumentation across all production systems. Many sensors must be installed and networked and must be able to survive the harsh environment of a manufacturing facility.
Knowledge and experience needed to do the work effectively may be lacking.
Implementation approaches are often top-down instead of non-hierarchical (flat) and involve individual, rather than collective, efforts.
Organizational histories of similar studies are lacking—non-existent or spotty and outdated.
Decision makers often do not support these studies, as the value proposition is not clear or well understood.

Participants noted the following strategies as being effective in increasing management support for resource efficiency efforts.

Robust analysis that presents results in terms that resonate with management: "turning green into gold"
Green New Deal, etc. Shareowner awareness/activism on efficiency "Carbon shaming"
Better Plants (for large energy users) and Industrial Assessment Centers (for small businesses)

Participants noted the following R&D efforts as necessary to enhance resource efficiency efforts within manufacturing facilities, from the shop floor to the networked enterprise level.

An integrated system to track requirements and model, simulate, measure, and automatically adjust manufacturing parameters to enhance efficiency New AI-guided, highly efficient manufacturing tools equipped with real-time feedback loops and sensors (e.g., using lasers for both manufacturing and measurements)
Tools and case studies to quantify and make cases for resource efficiency that resonate with specific industries (not generalizations)
At the manufacturing level, new energy-efficient materials with enhanced performance and lower environmental impacts
Methods, tools, and IT/OT technologies to efficiently collect, store, access, and utilize data to support effective manufacturing decision-making (based on standard KPIs and tailored internal metrics of interest, which will vary based on the internal/external audience)

Participants were asked to comment on resource efficiency training and education needed to prepare the manufacturing workforce of tomorrow, as well as the skill and tool gaps that currently exist. A summary of the responses is provided below.

Students must be able to use and understand LCA tools and be equipped with cyber manufacturing knowledge.
Employees need to be able to think in systems and have experience identifying opportunities for optimization.
Corporate financial management controls access to resources, so employee training should include not only technical issues but also accounting principles.
Students need to understand how and when (and when not) to use and rely on data to improve their decision-making. This cannot be done in a vacuum, so students must also understand and know how to access the expertise available across the human resources of their organization. Typically, this training comes "on the job."
Training is needed in energy auditing, water auditing, materials tracking, etc.
More hands-on training is needed. There are challenges to conducting this training at the manufacturing sites because of safety issues and impacts on production. Therefore, training sites, demonstration sites, and pilot facilities are needed to show advanced technologies in action.
Issues such as intellectual property and export control remain challenges in terms of educating the workforce in the state of the art. Organizations are often teaching content that is at least 5–10 years behind the current advances.
Childcare and tuition assistance should be available to students learning technologies necessary to support our economy. Workers should earn appropriate salaries. The country has a paycheck gap, not a skills gap or worker gap.

> Industry organizations should increase their budgets for employee training. The current mindset—"If we train them, they may find other jobs"—should change. It is overly negative.

Key Takeaways from the Resource Efficiency Session

The following are key takeaways, summarized from all aspects of the resource efficiency session:

- The greatest hindrance to implementing resource efficiency efforts appears to be an inability to find economic justification and resources to support efforts. Internal organizational efforts compete with each other for staff and financial resources. Some of these efforts have clearer connections to profitability, competitiveness, or organizational KPIs.
- Though modeling, direct measurement, and LCA analyses have been performed by some organizations, the value proposition for doing so can be unclear, and the equipment needed to support these efforts can be complex.
- Though there are many technologies for enhancing resource efficiency, effective metrics, data, and tools are needed to fully analyze these technologies' potential and impact within manufacturing and throughout the supply chain.
- Specific technologies are expected to have positive impacts on resource efficiency in manufacturing:
    - Waste heat recovery for industrial processes
    - Sensors that operate under harsh conditions to support process control and optimization
    - Real-time observability and feedback to optimize manufacturing processes while they are operating
    - New energy-efficient materials with enhanced performance and lower environmental impacts

There is a need for training, broadening domain expertise, and sharing best practices across the industry. Advancing knowledge in these ways would improve understanding of opportunities, quantification of their benefits, and implementation of solutions.

Opportunities in workforce development to support resource efficiency include:

- Increased education on key topics, such as LCA, cyber manufacturing, systems thinking, accounting principles, data-driven decision-making, energy and water auditing, and materials tracking
- More hands-on training, training sites, demonstration sites, and pilot facilities to show advanced technologies in action

- Childcare and tuition assistance for students, competitive pay for workers, and increased employee training budgets

Decarbonization of the Manufacturing Industry

AMO's mission includes a focus on decarbonization and the role it plays within the U.S. manufacturing sector. During the technical session, participants discussed manufacturing decarbonization through a keynote presentation, moderated a Q&A session, and facilitated discussion. The outcomes from each portion of the technical session are described below.

Summary of the Presentation

A summary of the presentation is provided below.

Presenter Name	Institution	Role
David S. Scholl	Oak Ridge National Laboratory	Director, Transformational Decarbonization Initiative
Presentation Title: Decarbonization to address climate change and maintain competitiveness		
Presentation Abstract: The goals of reaching net-zero emissions by 2050 and limiting the global impacts of climate change will require enormous changes in every sector of the economy. The U.S. manufacturing sector has an opportunity to lead the way in adapting existing approaches and in developing the infrastructure and workforce that will be needed for the low-carbon economy of the future. This talk outlined the scale of the decarbonization challenge that society faces, explored near-term opportunities and threats in manufacturing, and highlighted the impetus for large-scale negative carbon technologies to offset critical sectors that will be hard to decarbonize.		

Key Presentation Points:
• The two main challenges in reaching net-zero emissions are quantity (effecting impacts at the gigaton scale will require enormous changes) and timing (considerations must be made over decadal time scales).
• Roughly 30% of GHG emissions are from industry.
• Certain sectors are more difficult to decarbonize: iron and steel, cement, load-following electricity, shipping, and aviation. Carbon-negative technologies are needed in these sectors to achieve net zero.
• One technology opportunity is electrifying manufacturing, as many industrial processes rely on process heating or cooling and many chemical processes rely on thermally driven catalysts and separations.
    ○ In principle, thermal catalysts can be replaced with photo or electrocatalysis.
    ○ There are many opportunities to implement process intensification.
• There is an opportunity in non-fossil feedstocks, as essentially all chemicals are sourced from fossil feedstocks. Possible strategies include recycling, upcycling, bio-sources, CO_2 as a carbon source, etc.		

- Tackling structural materials is another large opportunity, as reducing GHG emissions in the cement, iron, and steel sectors will be critical. Both high- and lower-tech solutions should be considered.
- Negative-carbon technologies such as direct air capture must be implemented at gigaton scales.
- The workforce associated with coal-fired power plants is an important consideration when discussing decarbonization.

Summary of the Q&A Session

The following themes were discussed during the Q&A session. The raw results can be found in the separate Data Collection Report.

- **Language around decarbonization: "**Net-zero carbon equivalent" is a better phrase than "decarbonization" since methane, nitrous oxide, and hydrofluorocarbons are also included. Impacts are typically referenced in terms of CO_2 equivalents.
- **Supply chain:** It is important to consider the entire chain, as no one solution fixes everything. The value of a reverse supply chain is not obvious at the moment, but a productive way of doing it must be found to enable a circular economy. The value of a circular economy is not clear for all areas.
- **Renewable energy and carbon capture:** There is an abundance of energy available from geothermal in Iceland, so many direct CO_2 capture technologies are deployed there. It makes sense to pair renewable generation with carbon capture technology, where possible.
- **Attractiveness of decarbonization:** Decarbonization may be difficult, but it is necessary to meet net-zero goals. Decarbonization is needed to mitigate climate change, as CO_2 must be reduced by gigaton levels. The United States should become a technology leader in this space and then begin helping developing countries.
- **DOE lab programs:** The National Energy Technology Laboratory is an Office of Fossil Energy and Carbon Management lab and is leading decarbonization efforts. ORNL is an Office of Science lab and is working on CO_2 utilization and innovations for direct air capture.

Summary of the Facilitated Discussion

Participants were asked about the challenges their organizations experience in pursuing manufacturing or supply chain decarbonization efforts. Responses are summarized below.

Manufacturing needs a decarbonization framework to better understand the contribution of specific processes.
Carbon-neutral technologies have higher costs than traditional technologies. For-profit businesses are reluctant to spend extra unless forced. Currently, there are no incentives to promote the adoption of costly technologies.

Available data (such as scope 3 accounting) on the supply chain is lacking. A clear techno-economic analysis is needed.
The impact of decarbonization needs to be better measured. Trust in the numbers used is important. Often, LCA methods are incomplete, data are not verified, and tools are not easily accessible to the right people, including those who can make decisions on decarbonization.
Answers are complex, but people are always looking for simple, cross-cutting solutions, such as hydrogen and carbon capture, utilization, and storage.
Multi- and cross-disciplinary effort and expertise are lacking or unavailable to address this complex problem.
For discrete manufacturing, it is difficult to think of direct decarbonization, but the impact can be through an indirect reduction in energy consumption (improved efficiency, productivity, and quality, hence reducing the energy footprint).
Policy support on imports may be needed to avoid domestic carbon emissions by outsourcing overseas.

Participants discussed specific technology gaps that hinder the implementation of decarbonization efforts in their organizations. Participant contributions are summarized below.

Many companies (especially SMEs) do not understand the energy footprints of their equipment. We need technology to measure actual CO_2 emissions in real-time, including in harsh environments, and use those data for improvements.
Renewable electricity has a real cost to the bottom line, as the cost is 30%–50% higher than carbon-based electricity. Unless the calculations have included the real costs of carbon emissions over time, the economics of renewables do not make sense.
Under-utilized technologies must be scaled up and integrated at commercial facilities.
Alternatives are needed for high-energy processes: factory heating, painting, high-temperature natural gas burning process options, etc.
Modular, low-cost, point capture equipment is needed.
In energy-intensive manufacturing environments, validation of scope 2 emissions is needed. Oftentimes, estimates are used in place of direct measurements, but estimates often do not account for significant variation, such as the energy mix to produce electricity, which can vary temporally. The same need for validation applies to scope 3 emissions.

Participants were asked if additional tools, definitions, standards, or protocols were needed to assist their organizations in implementing decarbonization strategies. Responses are summarized below.

A revenue-neutral tax mechanism to price carbon should be implemented—something like George Schultz's carbon tax—after which the market can decide/respond. An acceptable target is around $50/ton. Alternatively, there could be tax breaks for decarbonization efforts.
Better protocols for tracking decarbonization through supply chains are needed.
Commonly accepted protocols for carbon accounting are needed.
Organizations would benefit from easy-to-use analysis and decision-making tools, as well as tools to design around sustainable systems at larger scales (circular economies). The tools should consider recycling resources across a community (e.g., energy from water utilities and reclaimed water from the community). Manufacturing is resource-intensive, but there are many opportunities for recycling within municipalities.

Attendees were asked whether their organization baselines and tracks its GHG emissions, including scope 1, scope 2, and scope 3 emissions. The responses were split, with half of the respondents saying yes and the other half saying no.

Participants were asked to describe any baselining studies or modeling efforts related to decarbonization that their organizations have employed, including descriptions of the goals, methodologies, and outcomes, where possible. The results are summarized below.

LCA under ISO 14000 series standards is being used to identify where the carbon hotspots are (but not being used for reporting).
The REMADE Institute tracks the energy and emissions impacts of its projects, both at project start and completion. This allows the Institute to update the impacts based on what the projects actually achieved.
One organization did a full CO_2 inventory (in Excel) of all its processes and equipment for 40 factories. The inventory took about nine months. The results are used to forecast and prioritize.
Strategic energy management has shown high potential for managing energy use, which is related to carbon. However, only 17 energy-/carbon-intensive sites globally have achieved ISO 50001.
Colleagues at Autodesk developed a carbon accounting (finance-based) methodology: http://images.autodesk.com/adsk/files/greenhouse_gas_white_paper000.pdf.

Participants described the "availability of reliable data" as the greatest challenge their organizations face when attempting to baseline, track, or model emissions.

When asked about R&D efforts needed to enhance decarbonization efforts within manufacturing facilities and across the manufacturing supply chain, participants emphasized the existence of under-utilized technology and the need for support in commercializing these technologies at scale.

Participants were asked what training and education related to decarbonization were needed to prepare the workforce to implement the decarbonization strategies that had been discussed. Responses are summarized below.

Training is needed in LCA, systems thinking, and data science.
There is a universal lack of understanding of what "decarbonization" means. Decarbonization can be nuanced, as it can have many "colors" (CO, CO2, CH4, and other GHGs).
Engineering education should require coursework related to decarbonization.
Corporate technical and financial employees will have to be trained in compliance with GHG reporting standards once they are established and accepted.
There is a need for more manufacturing engineers and engineering resources.
Sustainability is one of the top drivers for post-millennial people under age 21. Decarbonizing and fixing the manufacturing sector is a great motivating factor for getting young people into manufacturing. This is an opportunity, not a challenge.
Organizations need the ability to work within and across disciplines (the proverbial T-shaped engineer).

Key Takeaways from the Decarbonization Session

The following are key takeaways, summarized from all aspects of the digitalization session.

- There are many potential pathways for pursuing decarbonization in manufacturing:
  - Use of carbon-negative technologies in carbon-intensive industries, such as iron and steel, cement, load-following electricity, shipping, and aviation
  - Manufacturing electrification, including process heating or cooling, replacement of thermal catalysts with photo or electrocatalysis, possibly coupled with process intensification
  - Non-fossil feedstocks, recycling, upcycling, bio-sources, CO_2 as a carbon source, etc.
- Manufacturing needs a decarbonization framework to better understand the contribution of specific processes.
- There are many challenges preventing manufacturing decarbonization at scale:
  - Lack of real-time measurement of carbon emissions
  - Lack of visibility into the supply chain carbon footprint
  - Need for modular, low-cost, point capture equipment
  - Need for better protocols and processes to verify the performance of carbon reduction technologies

- Workforce development needs for supporting decarbonization in manufacturing include expanded education in LCA, systems thinking, data science, decarbonization, GHG reporting standards, and interdisciplinary collaboration.

Advanced Materials and Modeling for Energy Optimization

In the materials and modeling session, participants discussed the vast opportunities to use system models for real-time digital continuity between materials design and selection, product design, manufacturing engineering, operations, and the supply chain. The potential for optimization is vast.

Participants explored these topics through a keynote presentation, moderated Q&A session, and facilitated discussion. The outcomes from each portion of the technical session are described below.

Summary of the Presentation

A summary of the presentation is provided below.

Presenter Name	**Institution**	**Role**
Nasreen Chopra	Applied Materials	Managing Director

Presentation Title:

Advanced Materials and Manufacturing – The role of equipment design and modeling in smart manufacturing

Presentation Abstract:

Manufacturing has been evolving since the early days of the Industrial Revolution. The drive for higher productivity, lower cost, and better quality has been a consistent mantra, motivating detailed optimization studies and disciplined execution throughout the last two centuries. The semiconductor industry, which is young compared to some others, is perhaps the most dramatic example of phenomenal success in manufacturing that has revolutionized the everyday lives of people. So what makes now so different? This talk discussed the enabling role of equipment, the importance of modeling, and the need for advanced materials to meet the simultaneous challenge of people and the planet.

Key Presentation Points:

- The tenets of manufacturing are man, machine, material, and market, with a focus on increasing productivity and quality while reducing cost.
- There are issues across industries regarding what the substrate should be, how to set up the line, and how to handle materials.
- Looking at solar manufacturing as a case study, the decrease in costs from 1970 to 2020 can be attributed to the change from batch to in-line processing, the change from single-lane to multi-lane processing, and other process improvements. Equipment drove the growth in solar module production.
- Semiconductor materials exploration has been focused recently on structure-property relationships.

- Using the Cynefin model (a conceptual framework used to aid decision-making) (Snowden and Boone 2007), manufacturing issues are moving from being complicated to complex, so problems are becoming more probabilistic than deterministic.
- Modeling is critical in informing a direction and/or helping with decision-making.
- Moore's Law serves as a great roadmap for the industry to follow.

Summary of the Q&A Session

The following themes were discussed during the Q&A session. The raw results can be found in the separate Data Collection Report.

- **Workforce:** Students become experts in certain materials and modeling but need to have a systems-level view when they enter the industry to help them make bigger impacts. Additionally, materials engineering is a key need for the semiconductor industry, as materials engineers tend to be trained in systems thinking.
- **Energy impacts:** It is important to think about where and how the energy enters the system. Customers ask whether the electricity comes from renewable resources. DOE must talk to the industry so that federally funded innovations are applicable and more likely to be adopted within manufacturing facilities. It is also important to focus not only on energy use at manufacturing facilities but also on the impacts associated with that use.
- **GHG management approach:** Calculating chemical impact should include consideration of certain gases with very high GHG equivalents used in semiconductor manufacturing. The goal is to reduce chemical impact, not just chemical usage. Education is important in this regard since the semiconductor industry has been focused on performance and yield.

Summary of the Facilitated Discussion

This section provides a summary of responses to focus questions that were presented to workshop attendees during the facilitated discussion on materials and modeling.

Participants anticipate that advances in materials are expected to make the most impact in the fabrication and production stages of manufacturing, and some attendees believed that new materials will also affect product design. However, it was generally agreed that issues in supply chain management will be largely unaffected.

Participants were asked about specific materials advances with the potential to make the greatest impact in manufacturing in the next 10 years. Attendees noted that there is usually a 20-year delay between materials discovery and manufacturing for commercial markets, so the graphene nanomaterials and new battery cathode/anode materials discovered in the 2000s will be reaching manufacturing over the next 10 years. Other materials and materials-based topics mentioned are listed in the table below.

Alternatives to gases with high global warming potential in production
Smart materials, advanced composites, and metamaterials
Semiconductor materials for heterogeneous integration and packaging (all other manufacturing sectors depend on chips)
Theory-driven materials discovery Integrated science for structure, property, and behavior of materials
Advanced modeling, simulation, visualization, and computing for materials
AI and knowledge graphs for materials substitution

Participants were asked what they believed were the greatest challenges to applying advanced materials in manufacturing applications. The responses are summarized below.

There should be proven ROI, which is often difficult to predict when materials are produced at a small scale. Depending on whether the material is replacing an existing functionality in products or providing new functionality, there will be different pathways and challenges.
Efficient equipment, production lines, and recycling/recovery streams must be developed to accommodate new advanced materials in cost-effective, environmentally responsible ways.
Over-engineered materials pose challenges for manufacturing processes.
Lead time and inflexibility of manufacturing processes are a challenge. Often, materials are discarded because their use would require changes to a manufacturing line. Drop-in replacements are often unrealizable. A middle ground is needed.
Experience in high-scale, real-world deployments is lacking. There will be a reluctance to use advanced materials in life-critical applications until there are many years of deployment experience.
There is limited knowledge/understanding across other life cycle stages.

Participants were asked what research and technology improvements are needed to encourage the use of advanced materials in manufacturing applications. Below is a summary of responses.

Complete LCA of advanced materials is needed to demonstrate that new materials do not result in lower life cycle sustainability (triple bottom line) performance than conventional materials.
The properties of new materials must be fully characterized: strength, durability, environmental impact, energy use, etc. The results can be used to drive digital twins of the associated manufacturing processes and applications.
Researchers should explore how advanced materials can be integrated into products and what new products can be enabled by these advanced materials.

There is a need for reconfigurable and modular manufacturing processes with the ability to use AI to optimize the process for the new product. Adopting adaptive manufacturing can deal with some uncertainty in terms of materials composition, variability, and scalability.
A better understanding is needed of "What is manufacturing?" to the foundational research community, including universities and the R&D arms of many large companies. Researchers should be able to address issues of cost and scalability early in the materials discovery and adoption phase.
A national database of materials information models is needed. There should be ways to encourage data sharing between direct competitors despite an economic motivation not to share.
All manner of non-destructive evaluation, sensing, and integrated computational materials engineering (ICME) can provide the industry with real-world validation to enable business decisions. Until technologies can be truly validated, their adoption will be limited (or at least challenging).

Participants were asked what training and education related to advanced materials are needed to prepare the manufacturing workforce of the future, as well as what skill gaps currently exist. The following responses were provided.

Training to create expertise into how advanced materials can be integrated into products
Training related to computational science, modeling, and LCA, often to earn certificates (not necessarily standalone degrees)
Transferrable technical ("hard") skills, regardless of the specialization The ability to program, and perform data analytics, AI/ML, etc.
ML/data analytics for materials discovery
Pre-graduation industrial internships

Participants were asked what modeling and analytical advances they believed will make the greatest impact in manufacturing in the next 10 years. Responses are summarized below.

Multi-scale, physics-based models, especially when combined with IoT sensors to link the physical world with the simulation
An understanding of how product LCA and advanced materials can affect the footprints of pathways, including not just how the materials and products perform but also how they fit into a larger ecosystem
Real-time materials property prediction during manufacturing, based on real-time sensing and modeling, to allow tuning of manufacturing parameters in real time
Impacts of the data and analytics on profitability, without which none of the other attributes (environmental, social, and governance considerations, new products, etc.) will be achieved

Participants provided their thoughts regarding the greatest challenges to using advanced modeling and analytical approaches in manufacturing applications. Attendees noted that many programs, such as JMP, Oracle, and Excel, have built-in AI/ML capabilities. However, doing AI and ML without incorporating physical modeling might produce decisions that would violate the laws of thermodynamics, which would lead to suboptimal decisions. Other challenges are listed below.

Data sharing, trust, and sovereignty, especially between economic competitors
Lack of uncertainty analysis
Ways to present complex (real-time) data in a readily usable/interpretable way
Data accessibility and usability
Student training (irrespective of discipline) in ICME tools, similar to training in computer-assisted design, manufacturing, and engineering tools
A domain-specific language for materials modeling

The table below summarizes participant thoughts regarding the research and technology improvements needed to encourage the use of advanced modeling and analytical approaches in manufacturing applications.

Education is important. AI/ML and modeling is a knowledge proliferation problem, as much as a research problem. The post-millennial generation grew up on model-based design; Minecraft and Roblox are the most widely used digital design tools in the world, and they are physics-based modeling tools. Gamers should be encouraged to work in modeling.
Atomic-scale modeling must bridge to a large (manufacturing) scale. Bridging this computational gap, either through high-performance computing (HPC) or hybrid models using AI/ML, can prove the value of using advanced modeling and analytical approaches within the manufacturing community.
There is a need for usable tools for non-domain experts. Materials modelers can create sophisticated models/tools, but it is not clear that design/manufacturing engineers can use them.
Product development and relevant product standards are needed.
The long cycle time to get reasonable results is a barrier, so access to computing through the edge and the cloud will be important.
Open data sets with good metadata and process information are needed.

Key Takeaways from the Materials and Modeling Session

The following are key takeaways, summarized from all aspects of the materials and modeling session.

- It is anticipated that materials discovery and materials substitution will be greatly aided by advances in AI/ML, simulation, modeling, knowledge graphs, and theory-driven materials exploration.
- Advances are expected in smart materials, advanced composites, metamaterials, and semiconductors.
- There are major challenges hindering the integration of new materials into manufacturing processes. New materials may require process changes, which drive cost. A clear and worthwhile value proposition and ROI must precede these changes.
- Several factors drive new material adoption:
    - Complete LCAs and proven improved sustainability and equivalent performance
    - Full materials characterization and integration into digital twin systems
    - Open sharing of materials data and a national database of materials information
    - Real-world performance validation
- Workforce development could be supported with training related to computational science, modeling and LCA, programming, data analytics, AI/ML, and ICME tools. These can be made available to students and the workforce through certification programs and industrial internships.
- Improvements in modeling and analytics are expected to bring the following advances to manufacturing:
    - The integration of manufacturing processes with sensing, feedback, multi-physics modeling, and materials properties prediction and tuning, all in real-time
    - The ability to predict advanced materials' impacts on the LCA of products, their footprint, and larger ecosystems
- The industry faces several challenges related to modeling:
    - Combining AI/ML with physics-based models
    - Addressing issues around data sharing, trust, sovereignty, the impact of economic competition, and data accessibility and usability
    - Providing uncertainty analysis or quantification
    - Advancing modeling in manufacturing

  - Bridging the computational gap between atomic-level and manufacturing-scale modeling
  - Enhancing computational access through HPC, edge computing, cloud, AI, and ML
- There is a need for usable tools for non-domain experts, including open data sets with good metadata and process information.

Adaptable and Flexible Supply Networks for Energy Productivity

The discussion on supply networks considered several factors, including the need to fortify the U.S. manufacturing sector against perturbations and disturbances and to deal with variability and variations. Opportunities exist to strengthen the sector's ability to avoid, withstand, and recover from adversity, while allowing for the production of faster, cheaper, better, and greener products, processes, and services.

During this session, participants explored these topics through two keynote presentations, a moderated Q&A session, and a facilitated discussion. The outcomes from each portion of the technical session are described below.

Summary of the Presentations

Summaries from each presentation are provided below.

Presenter Name	Institution	Role
Venkat Venkatasubramanian	Columbia University	Professor, Department of Chemical Engineering
Presentation Title: A Framework for Analyzing Efficiency–Robustness Tradeoffs in the Design of Adaptable Complex Supply Networks		
Presentation Abstract: Complex dynamic networks play a crucial role in many socio-technical applications, such as global supply chains, electric power grids, transportation networks, and the Internet. Typically, the design and architecture of such networks have emphasized their efficient performance and cost minimization more than their robustness and resilience to attacks and failures. However, the recent failures of the Texas power grid and the near-collapse of the global supply chain during the pandemic demonstrated the importance of robustness and resilience. Toward those goals, Columbia University has developed a conceptual framework that helps model and analyzes efficiency–robustness tradeoffs in network design. This talk presented an overview of this conceptual framework and discussed the tradeoffs to be made between efficiency, robustness, and cost for the long-term sustainability of such systems, and described a variety of model network topologies such as star, circle, hub, small-world, scale-free, and von Neumann networks.		
Key Presentation Points: • Approximately 85% of global supply chains have faced a reduction in operations due to the pandemic. Companies overestimated their ability to handle severe disruptions. • Supply chains are complex dynamic networks involving people, processes, equipment, policies, and incentives. The network structure is a critical factor in operational success.		

- While many engineered systems are built for efficiency, systems in nature are often optimized for resilience, providing valuable lessons for supply chain design.
- Network topology governs operational efficiency and resilience. These two factors often represent opposite extremes.
- Network efficiency and robustness can be formally described in the context of an optimization problem.
- By assigning a measure of relative significance to both parameters, optimal network modules can be generated for a system of varying node numbers, given assigned costs for various system parameters.
- Relative significance can be evaluated by comparing the cost of system operation to the cost of system disruptions.
- A formal analytical framework, such as the one presented, allows for the systematic study of network topologies and modeling of the effects of hostile environments.

Presenter Name	Institution	Role
Soundar Kumara	The Pennsylvania State University	Professor of Industrial Engineering

Presentation Title:

Self Sufficiency and Resilient Supply Chains

Presentation Abstract:

COVID-19 has shown us the drawbacks of our supply chains and exposed our vulnerabilities. This talk focused on the research aspects related to resilient supply chains, keeping in mind the mantra of self-sufficiency. Dr. Kumara discussed previous work using network science to build resilient and adaptive supply chains. The research-driven discussion highlighted how intelligent and digital technologies can play an important role in driving the future and touched upon economics-based models for self-sufficiency. The discussion pointed to some models for educating and upskilling the nation's workforce. The talk focused on discrete part manufacturing.

Key Presentation Points:

- Better predictions can increase the supply chain's adaptivity.
- A resilient supply chain is defined by its capacity for resistance and recovery, while an adaptive supply chain responds quickly to sudden changes in demand.
- Resilience in supply chains can be built through topology or redundancy.
- Redundancy is costly, but building topology cannot be scaled if the network is too large.
- Insights can be taken from pandemic supply chain stories related to collaboration, open-source sharing, the tradeoff between profit and public welfare, supply chain resilience, and the manufacturing supply chain collaboration platform.
- Many nodes and layers are interacting in supply chains.
- Networks can help with understanding cascading effects at system and component levels.

Summary of the Q&A Session

The following themes were discussed during the Q&A session. The raw results can be found in the separate Data Collection Report.

- **Structures in nature:** It could be argued that the most important piece of information in nature is DNA, which has a ring plasmid structure. The objective is to minimize the effects of external shock and ensure good protection (for robustness rather than efficiency). Looking at the plasmid, the double helix, and the structure of food webs, the alpha value is between 0.7 and 0.8, a good balance of robustness and efficiency.
- **Challenges to SMART small and medium-sized manufacturers[5]:** The metrics that manufacturers care about must be considered. The company context and focus are important. Small manufacturers often are not interested in high-end technology but rather in reduced maintenance and downtime.
- **Fixed vs. dynamic topology structure:** These are two extremes, star, and ring, but most networks are a combination. The more efficiency is emphasized, the more the structure shifts toward the star. One issue is the design of the structure or topology. Changes cannot be made in real-time in the supply chain, so finding the best way to reroute is important. Another issue is the switching cost, which can be considerable.
- **Role of government:** The government has generously funded a good deal of academic work in supply chain optimization. An interesting question is self-organization and whether, if pieces are assembled, they will self-organize. An example is neurons. By themselves, they are not aware, but if 100 billion come together, the collective becomes self-aware.

Summary of the Facilitated Discussion

During the facilitated discussion on supply networks, participants were asked about the most likely factors to cause manufacturing supply chain disruptions and the greatest vulnerabilities. Participants mostly attributed disruptions to cyberattacks, software bugs in supply chain software, natural disasters, climate events, global conflicts, pandemics, and other lower-probability, high-impact events.

Participants were asked what research and technology advancements can allow U.S. manufacturing and supply chains to become adaptable and flexible, increasing their resilience and ability to respond to disruptions. Participants emphasized the need for technologies that enable real-time supply chain visibility, paired with predictive models and simulations that help determine the impacts of "what if" scenarios. The discussion also examined the need for flexible processes, rapid retooling, upskilling the workforce, and data interoperability.

[5] SMART goal parameters are Specific, Measurable, Achievable, Relevant, and Time-Bound.

Key Takeaways from the Supply Networks Session

The following are key takeaways, summarized from all aspects of the supply networks session:

- Supply chains are complex, dynamic networks involving people, processes, equipment, policies, and incentives. The network structure is a critical factor in operational success, which determines the operational efficiency and resilience of the supply chain.
- A resilient supply chain is defined by its capacity for resistance and recovery, while an adaptive supply chain responds quickly to sudden changes in demand. Resilience in supply chains can be built through topology or redundancy, while better predictions can increase supply chain adaptivity.
- While many engineered systems are built for efficiency, systems in nature are often optimized for resilience, providing valuable lessons for supply chain design. Many natural systems present a good balance between robustness and efficiency.
- Supply chain topology structures can be dynamic, though switches often cannot be made in real-time, and changes can come at great expense.
- Reductions and savings in maintenance and downtime are important metrics for incentivizing businesses to make investments in supply network improvements.
- Cyberattacks, bugs in supply chain software, natural disasters, climate events, global conflicts, pandemics, and other lower-probability, high-impact events were noted as the most likely incidents to disrupt supply chains.
- Participants described real-time supply chain visibility, predictive models and simulations, flexible processes, rapid retooling, upskilling the workforce, and data interoperability as key innovations for enhancing the adaptability and flexibility of U.S. manufacturing supply chains.

Summary of Workshop Takeaways

This section synthesizes the key takeaways from all the technical sessions held during the workshop and discusses the next steps from the perspective of AMO.

Key Challenges

The main challenges identified during the workshop are listed below.

Digitalization

- The use of data in digitalization needs to support a clear business case.
- Some of the greatest hindrances to enhancing cybersecurity within organizations involve the internal competition for resources and people and the stark divisions between personnel and processes for managing IT versus OT.
- Cyberattacks, bugs in supply chain software, natural disasters, climate events, global conflicts, pandemics, and other lower-probability, high-impact events are the most likely incidents to disrupt supply chains.

Resource Efficiency

- Manufacturing needs a decarbonization framework to better understand the contribution of specific processes.
- The greatest hindrance to implementing resource efficiency efforts appears to be an inability to find economic justification and resources to support efforts. Internal organizational efforts compete with each other for resources, and some have clearer connections to profitability, competitiveness, or organizational KPIs.
- Though some organizations have performed modeling, direct measurement, and LCA analyses, the value proposition for doing so can be unclear, and the equipment needed to support these efforts can be complex.
- Though many technologies exist for enhancing resource efficiency, effective metrics, data, and tools are needed to fully analyze the technologies' potential and impacts within manufacturing and throughout the supply chain.

Decarbonization

There are many challenges preventing manufacturing decarbonization at scale:

- Lack of real-time measurement of carbon emissions
- Lack of visibility into the supply chain carbon footprint
- Need for modular, low-cost, point capture equipment

Better protocols and processes are needed to verify the performance of carbon reduction technologies.

Materials and Modeling

Integrating new materials may require manufacturing process changes, which drive cost. A clear and worthwhile value proposition and ROI must precede changes in materials.

Modeling Challenges

- Combining AI/ML with physics-based models
- Addressing issues around data sharing, trust, sovereignty, the impact of economic competition, and data accessibility and usability
- Providing verification, validation, and uncertainty analysis

Research Opportunities

Research opportunities identified throughout the workshop are aggregated below.

Digitalization

Several technologies are expected to have significant impacts on manufacturing digitalization:

- AI and ML are expected to affect manufacturing by guiding experiments, optimizing processes, enhancing collaboration, and assisting materials discovery.
- Technologies and practices are needed to enable and promote data sharing and improve cybersecurity and shared data governance.
- Digital twins can be used to operate and optimize individual machines and whole manufacturing operations.
- Computer vision augmented reality, and mixed reality applied to productivity (including energy) will enhance product personalization and enable remote manufacturing.
- Innovations in software, firmware, AI, business processes, protocols, and data management are all expected to enhance manufacturing sector cybersecurity.

Resource Efficiency

Specific technologies are expected to have positive impacts on resource efficiency in manufacturing:

- Waste heat recovery for industrial processes
- Sensors that operate under harsh conditions to support process control and optimization
- Real-time observability and feedback to optimize manufacturing processes while they are operating
- New energy-efficient materials with enhanced performance and lower environmental impacts

Decarbonization

There are many potential pathways for pursuing decarbonization in manufacturing:

- Use of carbon-negative technologies in carbon-intensive industries, such as iron and steel, cement, load-following electricity, shipping, and aviation
- Manufacturing electrification, including process heating or cooling, replacement of thermal catalysts with photo or electrocatalysis, possibly coupled with process intensification
- Non-fossil feedstocks, recycling, upcycling, bio-sources, CO_2 as a carbon source, etc.

Materials and Modeling

- It is anticipated that materials discovery and materials substitution will be greatly aided by advances in AI/ML, simulation, modeling, knowledge graphs, and theory-driven materials exploration.
- Advances are expected in smart materials, advanced composites, metamaterials, and semiconductors.
- Advances in modeling and analytics are expected to bring the following advances to manufacturing:
    - The integration of manufacturing processes with sensing, feedback, multi-physics modeling, and materials properties prediction and tuning, all in real-time
    - The ability to predict advanced materials' impacts on the LCA of products, their footprint, and larger ecosystems
- Needs for advancing modeling in manufacturing include:
    - Bridging the computational gap between atomic-level and manufacturing-scale modeling
    - Enhancing computational access through HPC, edge computing, cloud, AI, and ML
- There is a need for usable tools for non-domain experts, including open data sets with good metadata and process information.
- Real-time supply chain visibility, predictive models and simulations, flexible processes, rapid retooling, and data interoperability as key innovations for enhancing the adaptability and flexibility of U.S. manufacturing supply chains.

Workforce Development Needs

Workforce development suggestions were included in almost every technical session throughout the workshop. The various recommendations are aggregated below.

Participants shared many observations about workforce development needs for digitalization:

- The workforce requires improved education on data analytics, AI/ML, digitization, IoT, robotics, and data interpretation. Interdisciplinary training must be developed in collaboration with the industry.

- Training should be available to students and the present workforce (for upskilling). Implementation should include community colleges and affordability options for families.
- Curricula should include hands-on, problem-based learning to give students practical experience.
- Workforce development issues can be regional in nature. For example, some areas have seen declines in the manufacturing industry, and local educational institutions have a potential role in workforce development.

Opportunities in workforce development to support resource efficiency include:

- Increased education on key topics, such as LCA, cyber manufacturing, systems thinking, accounting principles, data-driven decision-making, energy and water auditing, materials tracking, decarbonization, GHG reporting standards, and interdisciplinary collaboration
- More hands-on training, training sites, demonstration sites, and pilot facilities to show advanced technologies in action
- Childcare and tuition assistance for students, competitive pay for workers, and increased employee training budgets

Suggestions concerning workforce development needs related to materials and modeling include training related to computational science, modeling and LCA, programming, data analytics, AI/ML, and ICME tools. These can be made available to students and the workforce through certificate programs and industrial internships.

Workshop Guiding Questions and Their Responses

The organization of the TRANSSFORM workshop was guided by a set of key questions. This section attempts to synthesize responses to these questions, based on the information gathered during the workshop.

1. Question:

What research and technology advancements will allow the U.S. manufacturing enterprise to capitalize on the growing ability and capability to collect and utilize data to build upon the integration of existing stand-alone and emerging technologies and increase future efficiency (energy, material, water) for enabling decarbonization and addressing climate change and competitiveness?

Response:

The research opportunities described in Section 10.2 describe the required technical advancements that will enable the advanced manufacturing future imagined through TRANSSFORM.

2. Question:

What research and technology advancements can allow U.S. manufacturing and the supply chain to become adaptable and flexible for resilience and the ability to respond to disruptions? What are your organization's or industry's greatest vulnerabilities to supply chain disruptions?

Response:

Cyberattacks, bugs in supply chain software, natural disasters, climate events, global conflicts, pandemics, and other lower-probability, high-impact events were noted as the most likely incidents to disrupt supply chains.

Participants described real-time supply chain visibility, predictive models and simulations, flexible processes, rapid retooling, upskilling the workforce, and data interoperability as key innovations for enhancing the adaptability and flexibility of U.S. manufacturing supply chains.

3. Question:

What research and technology focus can increase the availability and access to new manufacturing technologies, materials, designs, and approaches, including advanced modeling and analytical approaches? How can new technology solutions help with the rapid transition from design to manufacturing for materials, processes, and components in priority areas?

Response:

Advances in modeling and analytics are expected to bring the following advances to manufacturing:

- The integration of manufacturing processes with sensing, feedback, multi-physics modeling, and materials property prediction and tuning, all in real-time.
- The ability to predict advanced materials' impact on the LCA of products, their footprint, and larger ecosystems.

Needs for advancing modeling in manufacturing include:

- Bridging the computational gap between atomic-level and manufacturing-scale modeling
- Enhancing computational access through HPC, edge computing, cloud, AI, and ML

There is a need for usable tools for non-domain experts, including open data sets with good metadata and process information.

4. Question:

What strategies can help the United States implement new business models, structural changes, and cultural shifts toward energy and resource efficiency realized through design and manufacturing approaches? What challenges does your organization experience in the integration of new technologies together with existing technologies? What additional tools, definitions, or standards are needed to assist you in developing and implementing such strategies?

Response:

Energy and resource efficiency are generally considered secondary concerns to manufacturing enterprises, falling behind industry competitiveness and profitability. Tying environmental concerns to other business concerns can create a cultural shift. Businesses must incorporate environmental goals into their organizational and process KPIs.

Participants acknowledged that issues exist when attempting to integrate new technologies into existing processes. Problems occur primarily when established manufacturing lines are forced to change in ways that incur significant costs. A clear financial justification is needed to enable such changes to be implemented.

The industry would benefit from tools that enable effective modeling and estimation of the impacts of new technologies on organizational KPIs and economics. Many technologies currently exist but fail to find applications, owing to the complexity associated with the upfront analysis and financial justification.

5. Question:

What challenges or opportunities are specific to your geographic region, rather than an industry sector? Are there possible regional collaborations or ecosystems that would allow your organization to become more efficient (in energy, material, and water use) or allow for supply chain flexibility?

Response:

In general, workshop participants noted that regionality was not a primary factor related to the technical issues discussed. However, in a few instances, regional concerns were highlighted.

In particular, participants noted that workforce development is highly regional, providing opportunities for collaboration between industry, government, universities, and other regional institutions.

Participants noted the success of regional manufacturing advancement initiatives, including MxD (Manufacturing x Digital), the Manufacturing Demonstration Facility at ORNL, and the Manufacturing USA Institutes. It was also noted that other regional organizations may present effective models for supporting manufacturing advancements, including business incubators, which are located in various regions throughout the United States and contribute to innovation ecosystems. Similarly, the USDA implements programs nationally and has deep reach into counties across the country, through its agricultural extensions. A similar model could deepen the reach of DOE in supporting manufacturing innovation.

6. Question:

What training and education are needed to prepare the workforce to implement the above? What skill gaps currently exist?

Response:

Section 10.3 summarizes the workforce development needs and provides suggestions for actions that can be taken to fill the existing gaps.

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Appendix A. List of Terms

TRANSSFORM (Transformative, Resilient, Adaptive, Nimble, Sustainable, Smart, Flexible, Optimal, Robust, and Model-based)

Definitions from various sources: (Institute of Electrical and Electronics Engineers, Association for Computing Machinery, American Society of Mechanical Engineers, textbooks, handbooks, and research publications)

- **T**ransformations in manufacturing require a multidisciplinary understanding to discover new approaches that fully integrate modeling, data analytics, and characterization and reduce life-cycle energy and resource impacts.
- **R**esilience encompasses the system's ability to avoid, withstand, and recover from adversity.
- **A**daptive systems are complex systems that can continuously monitor values and trends of the external environment or internal variables (through increased sensing capabilities), optimizing their goals according to certain rules and complex control logics, and able to self-optimize manufacturing performances and realize intelligent and adaptive behaviors.
- **N**imble manufacturing focuses on faster, cheaper, better, and greener products, processes, and services.
- **S**ustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also enhances employee, community, and product safety.
- Smart manufacturing is the business, technology, infrastructure, and workforce practice of optimizing manufacturing through the use of engineered systems that integrate operational technologies and information technologies (OT/IT). These integrated engineered OT/IT systems are referred to as "cyber-physical systems." The "smart" concept is a process of securely integrating manufacturing operations technology with information, communication, and computation technologies, through mathematically and algorithmically defined multi-sensor data fusion, for on-time and real-time prediction and control.
- **F**lexible manufacturing system is a production method that is designed to easily adapt to changes in the type and quantity of the product being manufactured. Machines and computerized systems can be configured to manufacture a variety of parts and handle changing levels of production. Flexibility in manufacturing means the ability to deal with slightly or greatly mixed parts, allow variation in parts assembly and variations in process sequence, change the production volume, and change the design of certain products being manufactured.

- **O**ptimal manufacturing is the practice of using data to build better, cheaper, greener products, faster, with the goal of being more competitive.
- **R**obustness refers to the operation of a system under a given range of perturbations or disturbances, whereas resilience refers to the restoration of a system under unexpected extreme and rare events.
- **M**odel-based manufacturing engineering refers to real-time digital continuity between product engineering, manufacturing engineering, and manufacturing operations.

Appendix B. Full Agenda

DAY 1: September 8, 2021, | 10:30 AM – 5:45 PM EDT	
Time	Activity
10:30 – 11:00	**Workshop Introduction and Overview** Welcome and Opening Remarks Workshop Overview and Ground Rules
11:00 – 11:15	**Keynote Presentation** Chad Schell, U.S. Department of Energy, Advanced Manufacturing Office
11:15 – 12:00	**Presentations on Government Initiatives in Future Manufacturing** Bruce Kramer, Senior Advisor, National Science Foundation Mike Molnar, Founding Director, Office of Advanced Manufacturing National Institute of Standards and Technology
12:00 – 12:30	**Combined Q&A Session** Session Moderator: Dr. Emmanuel Taylor, Senior Energy Consultant, Energetics Incorporated
12:30 – 1:00	Break – East Coast Lunch
1:00 – 1:30	**Digitalization Keynote Address and Q&A Session** Session Moderator: Sudarsan Rachuri, Federal Program Manager, U.S. Department of Energy, Advanced Manufacturing Office Session Speaker: Dr. Sujeet Chand, Senior Vice President, and Chief Technology Officer, Rockwell Automation
1:30 – 2:45	**Digitalization of Manufacturing, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
2:45 – 3:15	Break – West Coast Lunch
3:15 – 3:35	**Cyber Security Keynote 1** Lin Nease, Chief Technologist, IoT Advisory Practice, Hewlett Packard Enterprise, PointNext
3:35 – 3:55	**Cyber Security Keynote 2** Suzanne Lightman, Senior Cybersecurity Specialist, National Institute of Standards and Technology
3:55 - 4:05	**Combined Q&A Session** Session Moderator: Dr. Steven Shooter, Science, and Technology Policy Fellow, U.S. Department of Energy, Advanced Manufacturing Office
4:05 – 4:15	Break
4:15 – 5:30	**Cyber Security Considerations, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
5:30 – 5:45	**Day 1 Closing Remarks**

DAY 2: September 9, 2021, | 10:30 AM – 5:15 PM EDT	
Time	Activity
10:30 – 11:00	**Workshop Introduction and Overview** Welcome and Opening Remarks Workshop Overview and Ground Rules
11:00 – 11:30	**Review of Day 1 Discussions and Outcomes**
11:30 – 12:00	**Resource Efficiency Keynote Address and Q&A Session** Session Moderator: Alberta Carpenter, Strategic Analysis Lead for Advanced Manufacturing, National Renewable Energy Laboratory Session Speaker: Mark Besser, Senior Vice President, Symphony IndustrialAI (formerly Savigent)
12:00 – 1:15	**Enhancing Resource Efficiency in Manufacturing, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
1:15 – 1:45	Break – East Coast Lunch
1:45 – 2:15	**Decarbonization Keynote Address and Q&A Session** Session Moderator: Sudarsan Rachuri, U.S. Department of Energy, Advanced Manufacturing Office Session Speaker: Dr. David S. Sholl, Director, Transformational Decarbonization Initiative, Oak Ridge National Laboratory
2:15 – 3:30	**Decarbonization of the Manufacturing Industry, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
3:30 – 4:00	Break – West Coast Lunch
4:00 – 5:15	**National Strategic Plan for Advanced Manufacturing, Roundtable Discussion** Mike Molnar, Director, Office of Advanced Manufacturing, The National Science and Technology Council, Subcommittee on Advanced Manufacturing Said Jahanmir, Advanced Manufacturing National Program Office, The National Science and Technology Council, Subcommittee on Advanced Manufacturing Diana Bauer, Advanced Manufacturing Office, Department of Energy, The National Science and Technology Council, Subcommittee on Advanced Manufacturing
5:00 – 5:15	**Day 2 Closing Remarks**

DAY 3: September 10, 2021, | 10:30 AM – 5:00 PM EDT	
Time	Activity
10:30 – 11:00	**Workshop Introduction and Overview** Welcome and Opening Remarks Workshop Overview and Ground Rules
11:00 – 11:30	**Review of Day 2 Discussions and Outcomes**
11:30 – 12:00	**Advanced Materials and Modeling, Keynote Address and Q&A Session** Session Moderator: Mahesh Mani, Technology Manager, U.S. Department of Energy, Advanced Manufacturing Office Session Speaker: Nasreen Chopra, Applied Materials
12:00 – 1:15	**Advanced Materials and Modeling for Energy Optimization, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
1:15 – 1:45	Break – East Coast Lunch
1:45 – 2:05	**Adaptable and Flexible Supply Networks, Keynote 1** Professor Venkat Venkatasubramanian, Department of Chemical Engineering, Columbia University
2:05 – 2:25	**Adaptable and Flexible Supply Networks, Keynote 2** Soundar Kumara, Professor of Industrial Engineering, The Pennsylvania State University
2:25 – 2:45	**Combined Q&A Session** Session Moderator: Samantha Reese, Senior Engineer, and Analyst, National Renewable Energy Laboratory
2:45 – 4:00	**Adaptable and Flexible Supply Networks for Energy Productivity, Facilitated Discussion** All Workshop Attendees May Actively Participate, Instructions Will Be Provided
4:00 – 4:30	Break – West Coast Lunch
4:30 – 4:45	**Priority Research Directives**
4:45 – 5:00	**Closing Discussion**

Appendix C. National Science and Technology Council Special Session – Summary

The following section summarizes the discussion held to inform the draft development for the National Strategic Plan for Advanced Manufacturing, which is currently being developed by the National Science and Technology Council, Subcommittee on Advanced Manufacturing. Representatives from the subcommittee led a discussion around a set of prepared focus questions. The discussion questions, and a summary of participant responses, can be found below.

Question 1: Which emerging science and technology areas will be key to the next generation of advanced manufacturing? What should be the near-term and long-term technology development research and development (R&D) priorities for advanced manufacturing, the anticipated timeframe for achieving the objectives, and the metrics in assessing progress toward the objectives?

Response: One of the most common themes in the discussion was advanced interfaces such as augmented or virtual reality that can synthesize human expertise with AI/ML to drive innovation and allow design and manufacturing to occur anywhere. Reliable and secure cyberinfrastructure was also seen as a desirable technology. Other opportunities listed included commercializing new technologies, using science to inform manufacturing-related policies, developing a set of national technology priorities, and promoting decarbonization of the manufacturing industry.

Question 2: What are examples of technological, market, or business challenges that may best be addressed by public-private partnerships, and are likely to attract both participation and primary funding from industry?

Response: Respondents identified some broad areas that could benefit from public-private partnerships, such as long-term strategic research or systems-level research to improve manufacturing agility and interoperability. They also identified specific problems that could be solved by public-private partnerships, such as improving the capabilities of sensors. However, some respondents were concerned that public-private partnerships would be counterproductive in many situations. One noted that public-private partnerships added overhead costs to research, while another observed that public-private partnerships were often stymied by intellectual property laws to protect proprietary technology.

Question 3: How can federal agencies and federally funded R&D centers supporting advanced manufacturing R&D facilitate the transfer of research results, intellectual property, and technology into commercialization and manufacturing for the benefit of society to ensure sustainability, national security, and economic security?

Response: Respondents stated that federal agencies should balance public good and industry benefit to ensure that private partners can make money from new technology, set new standards to encourage industry to take up new technology, expand AMO's lab-embedded entrepreneurship program (LEEP), and learn how to better manage intellectual property and human capital.

Question 4: How would you assess the state of the domestic advanced manufacturing workforce in the United States? How can federal agencies and federally funded R&D centers develop, align, and strengthen all levels of advanced manufacturing education, training, and certification programs to ensure a high-quality, equitable, diverse, and inclusive workforce that meets the needs of the sector and drives new advanced manufacturing jobs into the future?

Response: Respondents noted that highly educated individuals rarely contribute their expertise to the U.S. manufacturing industry. They observed that community colleges and online courses are underutilized, undergraduate courses have gaps in areas that would be beneficial to manufacturing, and Ph.D. students rarely work with manufacturing companies. They suggested engaging community colleges and online programs in the manufacturing sector and working to attract more graduating students to the field.

Question 5: How can the federal government assist in the development of regional public-private partnerships to achieve greater distribution of advanced manufacturing clusters or technology hubs, particularly in underserved regions of the country?

Response: Respondents advised that the federal government invest more in small manufacturers, consult with small manufacturers to find out what they need, and identify gaps between state and federal priorities. They also noted that COVID-19 may have changed the concept of regionality, allowing the government to connect distant areas through digital communication, augmented reality, and virtualization.

Question 6: How do you assess the adequacy of the domestic advanced manufacturing supply chain and industrial base? How can federal agencies assist small and medium-sized manufacturing companies to adopt advanced technologies and to develop a robust and resilient manufacturing supply chain to ensure that future products are made in all of America by all of America's workforce? What are some infrastructure barriers and challenges in promoting manufacturing in all regions of the country?

Response: While some respondents felt that manufacturing industrial supply chains and the manufacturing base were continuously improving, others were concerned that large parts of the country were being ignored by the modern manufacturing industry. One recommended that the government engage manufacturing institutes to help map out supply chain needs.

Question 7: The current Strategy for American Leadership in Advanced Manufacturing has three top-level goals, each with objectives and priorities:

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

Are these goals still appropriate for the next four to five years? Are there additional top-level goals to consider?

Response: Respondents advised the Strategy for American Leadership in Advanced Manufacturing to consider networking as a major goal. The government should develop regional centers to facilitate collaboration between manufacturers and research centers on work that is relevant to local communities and businesses and serve as a support ecosystem for manufacturing. Respondents also suggested building international partnerships to improve the supply chain and prioritizing sustainability and carbon neutrality.

Question 8: Is there any additional information related to advanced manufacturing in the United States, not requested above, that you believe the Office of Science and Technology Policy should consider?

Response: No comments were noted in response to this question.

Appendix D. List of Participants

Workshop Organizing Committee:

- Dr. Sudarsan Rachuri, Advanced Manufacturing Office
- Dr. Mahesh Mani, Advanced Manufacturing Office
- Mr. Chad Schell, Advanced Manufacturing Office
- Dr. Paul Syers, Advanced Manufacturing Office
- Dr. Steven Shooter, Oak Ridge Institute for Science and Education Fellow, Advanced Manufacturing Office
- Dr. Emmanuel Taylor, Energetics Incorporated
- Dr. Alberta Carpenter, National Renewable Energy Laboratory
- Dr. Samantha Reese, National Renewable Energy Laboratory

Workshop attendees are listed in the table below.

First Name	Last Name	Company/Organization
Aaron	Fluitt	Argonne National Laboratory
Abhai	Kumar	U.S. Department of Defense / ANSER
Al	Jones	National Institute of Standards and Technology
Alberta	Carpenter	National Renewable Energy Laboratory
Alexander	Orlov	Stony Brook University
Alison	Gotkin	Raytheon Technologies Research Center
Anastassija	Konash	Rochester Institute of Technology
Ankit	Shah	University of South Florida
Attila	Yavuz	University of South Florida
Binil	Starly	North Carolina State University
Blake	Marshall	Advanced Manufacturing Office
Bob	Slattery	Oak Ridge National Laboratory
Brandon	Wood	Lawrence Livermore National Laboratory
Bruce	Kramer	National Science Foundation
Byeong-Min	Roh	The Pennsylvania State University

First Name	Last Name	Company/Organization
Candice	Mitchell	U.S. Army Corps of Engineers, Engineer Research and Development Center
Chad	Schell	U.S. Department of Energy
Changwon	Suh	Advanced Manufacturing Office
Charles	Byers	Industry IoT Consortium
Christopher	Hovanec	U.S. Department of Energy
Christopher	Saldana	Georgia Institute of Technology
Claudette M	Rosado-Reyes	MSRDC
Clifford	Ho	Sandia National Laboratories
Conrad	Leiva	Clean Energy Smart Manufacturing Innovation Institute (CESMII)
Craig	Blue	Oak Ridge National Laboratory
Cyrus	Wadia	Amazon
Damodar	Shanbhag	Applied Materials
Dana-Marie	Thomas	National Renewable Energy Laboratory
Daniel	Mosher	Raytheon Technologies Research Center
David	Ailor	American Coke and Coal Chemicals Institute -
David	Miller	National Energy Technology Laboratory
David	Sholl	Oak Ridge National Laboratory
Dawn	Tilbury	University of Michigan
Diana	Bauer	Advanced Manufacturing Office
Don	Ufford	National Institute of Standards and Technology, Office of Advanced Manufacturing
Dongping	Lu	Pacific Northwest National Laboratory
Edgar	Lara-Curzio	Oak Ridge National Laboratory
Eliezer	Colina Morles	University of Illinois, Urbana-Champaign
Emmanuel	Taylor	Energetics Incorporated
Eswaran	Subrahmanian	Carnegie Mellon University
Ethan	Rogers	Advanced Manufacturing Office
Fazleena	Badurdeen	University of Kentucky

First Name	Last Name	Company/Organization
Fernando	Villarreal	Legrand North America
Gen	Satoh	Raytheon Technologies
Gordon	Smith	Electrolux AB
Greg	Krumdick	Argonne National Laboratory
Haresh	Malkani	Clean Energy Smart Manufacturing Innovation Institute (CESMII)
Hongyue	Sun	University at Buffalo
I.S.	Jawahir	University of Kentucky
Ignasi	Palou-Rivera	RAPID Manufacturing Institute for Process Intensification/ American Institute of Chemical Engineers
Ilya	Kovalenko	University of Michigan
Itoro	Atakpa	Energetics Incorporated
James	Jonza	3M Company
James	Moyne	University of Michigan
Jan	Vandenrbande	PARC
Janis	Terpenny	The University of Tennessee
Jim	Davis	The University of California, Los Angeles/Clean Energy Smart Manufacturing Innovation Institute (CESMII)
Joe	Cresko	Advanced Manufacturing Office
John	Dyck	Clean Energy Smart Manufacturing Innovation Institute (CESMII)
John	McCook	Savigent
John W.	Sutherland	Purdue University
Jose	Garcia-Bravo	Purdue University
Junhyuk	Choi	National Institute of Standards and Technology
Karl	Haapala	Oregon State University
Karthik	Nithyanandam	E16
Karthik	Ramani	Purdue University
Katherine	Morris	National Institute of Standards and Technology
Kathryn	Peretti	U.S. Department of Energy
Kenta	Shimizu	Energetics Incorporated

First Name	Last Name	Company/Organization
Kevin	Jurrens	National Institute of Standards and Technology
Kira	Barton	University of Michigan
Lili	Shi	Pacific Northwest National Laboratory
Lin	Nease	Hewlett Packard Enterprise
Lisa	Fronczek	National Institute of Standards and Technology
Magdi	Azer	The REMADE Institute
Mahesh	Mani	Advanced Manufacturing Office
Mark	Besser	Savigent Software – Symphony Digital Manufacturing
Mark	Johnson	Clemson University
Maureen	Tholen	3M Company
Michael	Pease	National Institute of Standards and Technology
Michael	Rinker	Pacific Northwest National Laboratory
Michael Cai	Wang	University of South Florida
Mike	Molnar	National Institute of Standards and Technology
Mingjie	Bi	University of Michigan
Nabil	Nasr	The REMADE Institute
Nancy	Diaz-Elsayed	University of South Florida
Nasreen	Chopra	Applied Materials
Neal	Rakow	3M Company
Nehika	Mathur	National Institute of Standards and Technology
Noah	Last	National Institute of Standards and Technology
Ozge	Kaplan	U.S. Environmental Protection Agency
Paige	Shee	Georgia Institute of Technology
Paul	Syers	Advanced Manufacturing Office
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Robert	Gao	Case Western Reserve University
Robert	Hershey	Robert L. Hershey, P.E.
Robert	Praino	Chasm Technologies
Robert	Sandoli	Office of Energy Efficiency and Renewable Energy
Robin	Miles	Lawrence Livermore National Laboratory
S. Manian	Ramkumar	Rochester Institute of Technology, College of Engineering Technology
Sachin	Nimbalkar	Oak Ridge National Laboratory
Sagar	Kamarthi	Northeastern University
Sai	Nelaturi	PARC
Said	Jahanmir	National Institute of Standards and Technology
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Sankaran	Mahadevan	Vanderbilt University
Santanu	Chaudhuri	Argonne National Laboratory
Satish	Bukkapatnam	Texas A&M University
Shane	Terry	Oak Ridge National Laboratory
Shanshan	Yao	Stony Brook University
Sharon	Nolen	Eastman Chemical Company
Shekhar	Chandrashekhar	International Electronics Manufacturing Initiative (iNEMI)
Shreyes	Melkote	Georgia Institute of Technology
Soundar	Kumara	The Pennsylvania State University
Sreekant	Narumanchi	National Renewable Energy Laboratory
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Sujit	Das	Oak Ridge National Lab
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Tatha	Bhattacharya	ArcelorMittal
Thomas	Kurfess	Oak Ridge National Laboratory
Thorsten	Wuest	West Virginia University
Venkat	Krovi	Clemson University
Vinod	Kumar	GE Aviation
Wei	Wang	Pacific Northwest National Laboratory
Xiao	Zhu	University of Michigan, Ann Arbor
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Yash	Parikh	Carnegie Mellon University
Yinlun	Huang	Wayne State University
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