U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

ADVANCED MATERIALS &
MANUFACTURING
TECHNOLOGIES OFFICE

Near Net Shape Workshop Report

Technical and Business Challenges for Infrastructure-Scale Near Net Shape Components

February 2024

Disclaimer

Foreword

The U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Advanced Materials and Manufacturing Technologies Office partners with industry, small businesses, universities, and other stakeholders to catalyze research, development, and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

Authors

The authors of this report include the following individuals from the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Advanced Materials and Manufacturing Technologies Office:

- Alaa Elwany
- Christopher Hovanec
- Nick Lalena.

Acknowledgments

Special thanks to the Manufacturing Demonstration Facility at Oak Ridge National Laboratory (ORNL) for hosting this workshop as well as staff and contractors of the Advanced Materials and Manufacturing Technologies Office for their support in making this event possible, including:

- Adam Stevens, ORNL
- Bob Slattery, ORNL
- Jessie McPeters, ORNL
- Sudarsanam Babu, University of Tennessee Knoxville/ORNL
- William Peter, ORNL
- Jack Holmes, Nexight Group
- Dylan Smith, Nexight Group.

The authors owe additional gratitude to the participants (listed in Appendix C) for their attendance and invaluable contributions through presentations and discussion.

This report was prepared for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Advanced Materials and Manufacturing Technologies Office.

List of Acronyms

AI	artificial intelligence
AM	additive manufacturing
AMMTO	Advanced Materials and Manufacturing Technologies Office
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EO	executive order
ICME	integrated computational materials engineering
LCA	life cycle assessment
MDF	Manufacturing Demonstration Facility
ML	machine learning
MRL	manufacturing readiness level
NDT	nondestructive testing
NNS	near net shape
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
SMMs	small and medium manufacturers
STEM	science, technology, engineering, and mathematics
TRL	technology readiness level

Table of Contents

1 Introduction 1
1.1 Background and Workshop Objective 1
1.2 Motivation 1
1.2.1 Role of Near Net Shape Components in U.S. Clean Energy Generation Goals ... 1
1.2.2 Declining NNS Domestic Manufacturing Capability 2
1.2.3 Exacerbated Limitations in the Case of Large NNS Components 3
2 Domestic Supply Chain of Large NNS Components 4
2.1 Relevance of Large NNS Components to Clean Energy 4
2.1.1 Wind Energy 4
2.1.2 Nuclear Energy 5
2.1.3 Hydropower 5
2.1.4 Other Industries 5
3 Workshop Structure and Format 6
4 Outcomes and Recommendations 7
4.1 Key Insights From Preliminary Survey 7
4.2 Panel Session Outcomes and Summary 9
4.3 Breakout Sessions Outcomes and Summary 10
4.3.1 Challenges 10
4.3.2 Technology Development Needs 12
4.3.3 Supply Chain Needs 13
4.3.4 Demonstration, Transition, and Scale-Up Needs 14
4.3.5 Education and Workforce Development Needs 15
5 Conclusion 16
References 18
Appendix A. Workshop Agenda 19
Appendix B. Preliminary Survey Results 21
Appendix C. Workshop Participants 25
Appendix D. Detailed Workshop Inputs 27

List of Figures

Figure 1. (left) End-use markets for metal castings products in the United States (Dawnbreaker 2022) and (right) U.S. emissions-free electricity generation share by source in 2019 (DOE Office of Nuclear Energy 2020) 2
Figure 2. (left) Number of domestic production facilities and the U.S. share of global plants; (right) number of domestic foundries 2
Figure 3. Domestic U.S. metal casting production in million metric tons (MMT; left axis) and as a percentage of global production (right axis) [4]. 3
Figure 4. NNS component weights by material or alloy versus the number of domestic foundries 4
Figure 5. (left) Proportion of large NNS component applications across different sectors, and (right) weight thresholds beyond which acquiring NNS components domestically is impractical or impossible 7
Figure 6. (left) Survey participants evaluated their organizations' ability to produce or procure a large NNS component domestically within 12 months. (right) Survey participants indicated the percent of large NNS parts their organizations procure from various countries. 8
Figure 7. Average lead times for receiving a large NNS part after ordering 8
Figure 8. (left) Number of survey responses evaluating reliability of the domestic large NNS supply chain, and (right) the urgency of developing domestic manufacturing capabilities 9

List of Tables

Table A-1. Workshop Agenda 19
Table C-1. List of Workshop Participants 25

1 Introduction

1.1 Background and Workshop Objective

In 2021, President Biden issued Executive Order (EO) 14017, spurring the federal government to build more secure and diverse U.S. supply chains, including energy supply chains, to ensure economic prosperity and national security (White House 2021). In response to EO 14017, the U.S. Department of Energy (DOE) published *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition* (Igogo 2022) to outline the challenges and opportunities facing the energy supply chain along with key strategies to secure America's position as a clean energy superpower in the years and decades to come. The expansion of domestic manufacturing capabilities is identified as one of the common risks and vulnerabilities for which DOE should develop comprehensive strategies to secure supply chains for the clean energy transition. The report states that "*examples of manufacturing capabilities of concern include … large iron and steel castings for wind turbines, hydropower turbines, and nuclear reactor components.*"

In addition to this comprehensive strategy report, DOE developed 13 deep-dive assessments on specific technologies and crosscutting topics (DOE no date [a]), in which the importance of castings and forgings was prevalent. The Energy and Water Development Appropriations Bill of 2023[1] further emphasizes the role of large castings and forgings in producing large near net shape (NNS) components for clean energy production. The bill directed the DOE's Advanced Materials and Manufacturing Technologies Office (AMMTO), in collaboration with the Office of Nuclear Energy, the Wind Energy Technologies Office, and the Water Power Technologies Office, to provide a briefing to Congress on the potential for developing and commercializing novel manufacturing processes for producing large NNS metallic components, including but not limited to those traditionally fabricated using large castings and forgings.

The objective of this workshop was to convene industry leaders to gather information in support of the congressional briefing on the technical and economic viability of producing large metallic NNS components in the United States.

1.2 Motivation

1.2.1 Role of Near Net Shape Components in U.S. Clean Energy Generation Goals

NNS components generally offer multiple benefits, including lower embodied energy, fewer processing steps, increased geometric complexity, reduced parts count and less joining, increased throughput, unique mechanical performance, and, in some cases, reduced cost. As a result, NNS components find applications across the entire industrial sector, as shown in Figure 1 (left). An NNS component is typically not the final product but rather an enabler (e.g., tooling) and/or necessary part of a larger system (e.g., wind turbine component). Many complex systems used in different applications require NNS components. Hydropower, nuclear, and wind energy generation are clear examples of applications that cannot operate without them. These energy sources collectively account for approximately 95% of all clean energy generation in the United States (Figure 1 (right)). Hence, NNS components are on the

[1] Explanatory statement for the energy and water development appropriations bill, 2023: https://www.appropriations.senate.gov/imo/media/doc/EWFY23RPT.PDF

critical path toward meeting U.S. goals of 100% clean electricity by 2035 and net-zero emissions by 2050.

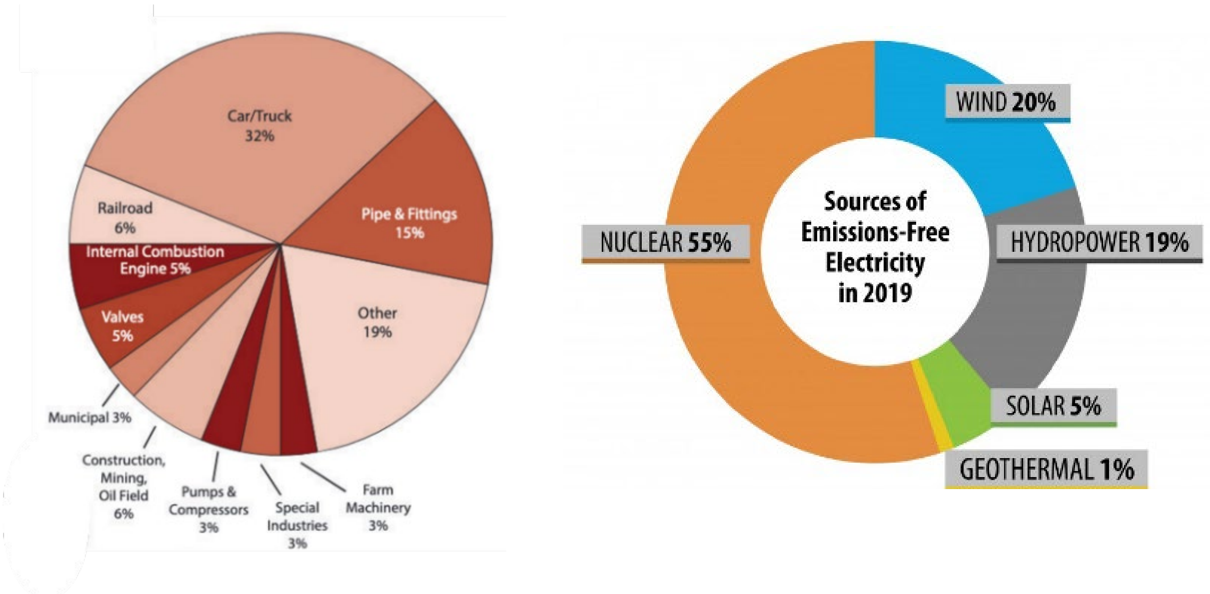


Figure 1. (left) End-use markets for metal castings products in the United States (Dawnbreaker 2022) and (right) U.S. emissions-free electricity generation share by source in 2019 (DOE Office of Nuclear Energy 2020)

1.2.2 Declining NNS Domestic Manufacturing Capability

The overall health of the domestic NNS manufacturing base has been in decline over the past four decades. NNS components have traditionally been produced using casting and forging processes. The number of casting and forging facilities (i.e., foundries and forging houses) in the United States has steadily declined since at least the 1980s (Figure 2 (left)). More than 40% of the foundries in the United States either closed permanently or moved overseas since 2000 (Figure 2 (right)). Over that same time period, the United States' share of global foundries shrunk by more than 60%.

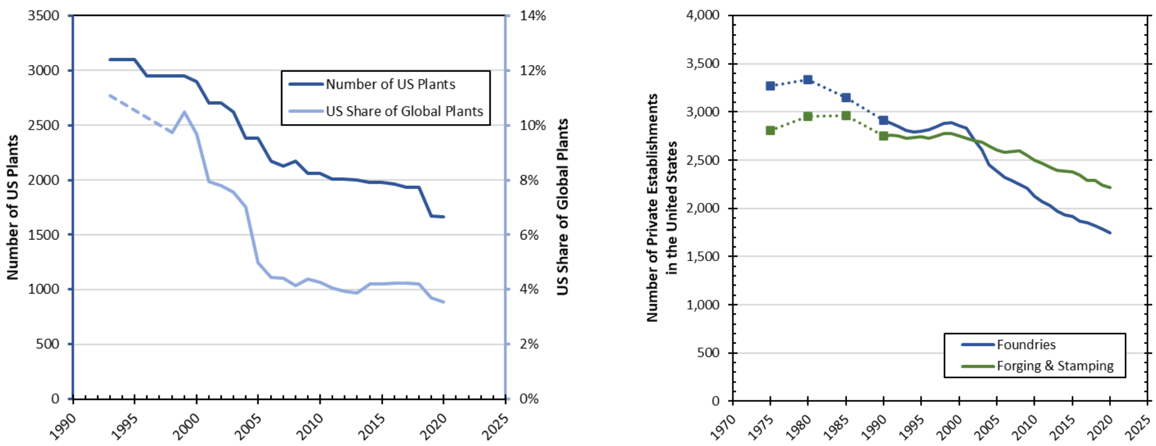


Figure 2. (left) Number of domestic production facilities and the U.S. share of global plants; (right) number of domestic foundries

Production throughput has consequently followed similar trends. In the 2000s, the output of domestic foundries shrunk by ~25% while the United States' share of global production shrunk by ~55% (Figure 3). Although the trends for casting and forging facilities already indicate the need for action, the trends observed for the overall NNS manufacturing base are significantly worse for clean energy production applications, as discussed later in this report. Furthermore, additive manufacturing (AM) and powder metallurgy are not advancing at a fast enough pace to compensate for the negative trends in the casting and forging industries.

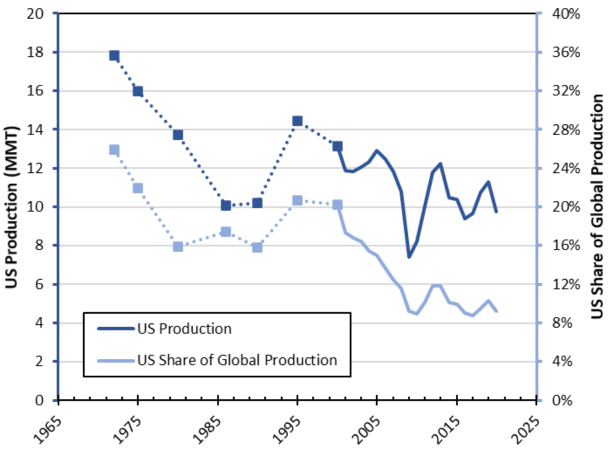


Figure 3. Domestic U.S. metal casting production in million metric tons (MMT; left axis) and as a percentage of global production (right axis).

1.2.3 Exacerbated Limitations in the Case of Large NNS Components

The majority of domestic foundries in 2016 produced castings that were less than 50 pounds (lb); foundries capable of producing castings over 1,000 lb represented the smallest category among domestic foundries (Figure 4). If binning by weight was continued above 1,000 lb, the number of foundries capable of producing castings above 10,000 lb would likely be in the single digits. The limitations of the current NNS domestic manufacturing base are further exacerbated by the fact that NNS components for clean energy applications can reach weights exceeding 70,000 lb (and for many other manufacturing applications, components are typically larger than 1,000 lb).

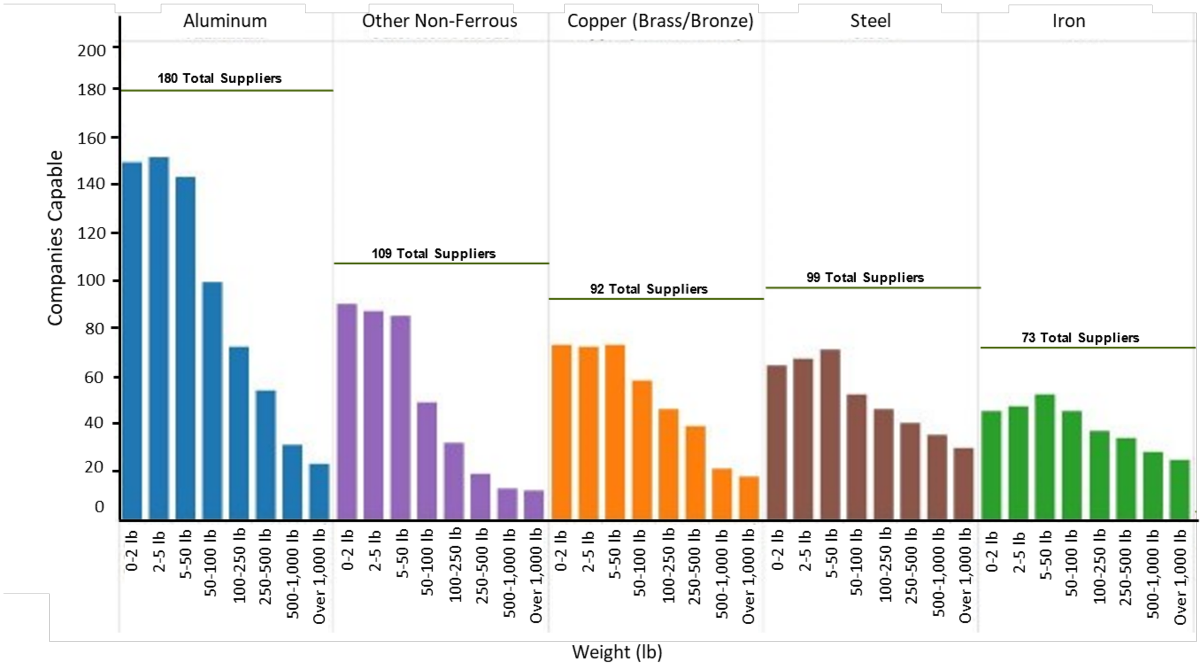


Figure 4. NNS component weights by material or alloy versus the number of domestic foundries

The domestic manufacturing base is not positioned to competitively meet the demands of different sectors that require NNS metallic parts. The problem is further exacerbated in the case of large NNS parts (e.g., 70,000 lb/35 tons, or larger) and has resulted in increased cost, long lead times, and reliance on foreign supply chains to acquire such parts. It also inhibits the ability to manufacture large complex systems needed in critical sectors, including clean energy production, transportation, industrial machinery, tooling, durable goods, and infrastructure. These limitations are the manifestation of a decades-long decline in the competitiveness of the domestic casting and forging industry, coupled with the slow, widespread adoption of alternative processing methods (e.g., powder metallurgy hot isostatic pressing, AM, and diode laser cladding, among others).

2 Domestic Supply Chain of Large NNS Components

2.1 Relevance of Large NNS Components to Clean Energy

In addition to the comprehensive strategy report (Igogo 2022) that DOE developed in response to EO 14017, a series of deep-dive assessments on specific technologies and crosscutting topics were also developed (DOE no date [a]). The importance of large NNS components, including those produced by castings and forgings, for clean energy generation was emphasized in many of these deep-dive reports.

2.1.1 Wind Energy

The *Wind Energy: Supply Chain Deep Dive Assessment* (Baranowski et al. 2022) states that the domestic supply chains for large forgings and castings for both land-based and offshore wind turbines are currently not competitive. The report identifies critical components (e.g., rotor hub, nacelle bedplate, generator shaft, tower flanges, and rings for bearings) fabricated by casting and/or forging and notes that there is limited to no domestic capacity for producing these large NNS components. Domestic capabilities to manufacture large NNS components for offshore wind turbines are relatively more limited than those for land-based wind turbines due to the increased size and performance requirements. The report recommends research, development, and demonstration investments in alternative manufacturing methods (such as AM) and production facilities for large NNS components.

2.1.2 Nuclear Energy

The *Nuclear Energy: Supply Chain Deep Dive Assessment* (Finan et al. 2022) addressed supply chain challenges for both the current fleet of light-water reactors and future advanced reactor designs. While these power generation stations are constructed using both castings and forgings, the report emphasizes large forgings such as vessels, shells, pressurizers, and steam generators. Currently, there is no domestic capacity to produce these large NNS components; all are produced overseas. The report projects that there will be significant domestic and global demand for large forged and cast components to support the nuclear industry for the foreseeable future. The importance of NNS manufacturing for the future of nuclear power generation was also acknowledged in DOE's Pathways to Commercial Liftoff reports (DOE no date [b]).

2.1.3 Hydropower

Future demand for hydropower includes both the scheduled refurbishment of existing equipment and the production of new installations (domestically and globally). The *Hydropower Supply Chain Deep Dive Assessment* (Uría-Martiínez 2022) states that large steel castings and forgings are very difficult or impossible to source domestically and have extremely long lead times. Turbine original equipment manufacturers (OEMs) are not able to procure castings over 10 tons (20,000 lb) domestically; the situation is similar for large forgings, although there is at least one U.S. supplier that can provide them. Almost all NNS components needed for hydropower systems (e.g., turbine runners, wicket gates, headcover, generator shaft) are supplied by foreign manufacturers. Further development of AM processes is identified as an alternative to importing large castings and forgings.

2.1.4 Other Industries

In response to EO 14017, the U.S. Department of Defense (DOD) issued *Securing Defense-Critical Supply Chains* in February 2022 (Office of the Deputy Secretary of Defense 2022). The breadth and scale of the defense supply chain is large enough to represent the overall domestic manufacturing base. Therefore, this report has been included to serve as an assessment of the domestic manufacturing base (e.g., transportation, durable goods, tooling, machine equipment) that is not in direct support of clean energy generation or DOD-specific applications. The report identifies four areas that were determined to be critical supply chain vulnerabilities, one of which is "castings and forgings." The report notes the importance of a robust casting/forging industry and associated supply chain to provide reliable, timely delivery of components used in diverse systems. The casting and forging section of the report concludes with a set of recommendations, including expanding interagency activities. A partnership with the DOE's Manufacturing Demonstration Facility was specifically identified to develop processes to supplement casting/forging capabilities, including additive and hybrid manufacturing processes, metrology, and the development of technical data packages.

3 Workshop Structure and Format

On Nov. 3–4, 2022, Oak Ridge National Laboratory in Knoxville, Tennessee, hosted the workshop sponsored by AMMTO. The workshop brought together 57 attendees from organizations representing large industries, small and medium manufacturers (SMMs), federal agencies, and industrial and government research laboratories.

The first day of the 2-day workshop included two keynote sessions by industry and government leaders to set the stage and articulate workshop objectives and goals, a focused panel session in which four panelists from the public and private sectors shared their perspectives and held an open dialogue on challenges and opportunities with workshop participants, and a series of seven short lightning talks by industry and government representatives to share their organizations' engagement in the NNS space.

The remainder of the first day and the second day of the workshop included three breakout sessions, each consisting of two-to-three parallel tracks to run highly interactive discussions among workshop participants. To ensure alignment of the discussions with workshop objectives and goals, targeted lists of questions were sent to the participants prior to the workshop, and the interactive discussions were guided by these questions and coordinated through a session moderator. Participants were given the option to preregister for specific sessions based on their interests, expertise, and organizational goals before the workshop. The breakout sessions followed a thematic scheme:

- <u>Challenges</u> related to NNS manufacturing, with the following parallel tracks:
  - Challenges and Economic Considerations in the Supply Chains Related to Castings and Forgings.
  - Challenges With Respect to NNS Manufacturing for Clean Energy Production.
  - Challenges With Respect to NNS Manufacturing for the Rest of the Manufacturing Base.
- Emerging technologies to discuss potential <u>solutions</u> to the challenges identified, with the following parallel tracks:
  - Emerging Technologies to Support the Castings and Forgings Sectors.
  - New Emerging Technologies for NNS Manufacturing.
  - Emerging Technologies to Improve the Resilience of NNS Manufacturing Supply Chains.
- <u>Implementation</u> pathways of the solutions proposed, with the following parallel tracks:
  - Technology Demonstration, Transition, and Scale-Up Needs.
  - Education and Workforce Development Needs.

The interactive discussions were led by a moderator for each parallel track in the breakout sessions, with coordination and logistical support from Nexight Group. During these discussions, the questions shared with the participants prior to the workshop were presented by the track moderator to gather insight from participants. In addition to the interactive verbal discussions, participants were given access to enter written responses to the discussion questions for further analysis through the XLEAP Facilitation Software.

The workshop agenda with detailed session and presentation information, expanded preliminary survey results, and workshop participants can be found in Appendices A, B, and C, respectively. Copies of the plenary, panel, and lightning talk presentations are publicly available on the workshop's webpage.[2]

4 Outcomes and Recommendations

The interactive discussions and participants' written responses to the pre-workshop questions during breakout sessions were synthesized to identify key takeaways, systematically summarize the contents of these responses, and develop specific recommendations and calls for actions. The outcomes and recommendations are summarized in the next sections.

4.1 Key Insights From Preliminary Survey

Following the plenary and panel sessions on Day 1 of the workshop, and prior to holding the interactive breakout sessions, a survey was given to workshop participants. The objective of this survey was to gather quantitative data to help define the needs and challenges from the users' perspectives. Key insights from this survey are summarized in the next paragraphs.

The need for large NNS components in clean energy generation (wind, nuclear, and hydropower) accounted for 54% of the responses, with the remaining 46% attributed to the remainder of the industrial base (left side of Figure 5). One important outcome from the survey was to quantitatively determine what is meant by a "large" NNS component. The right side of Figure 5 shows the weight thresholds beyond which domestically manufacturing or procuring NNS components becomes impractical or impossible for surveyed organizations.

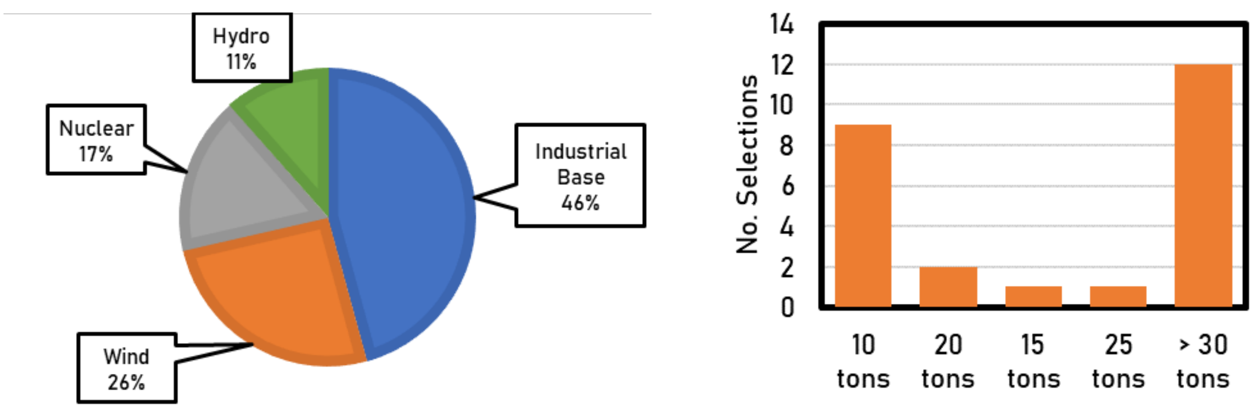
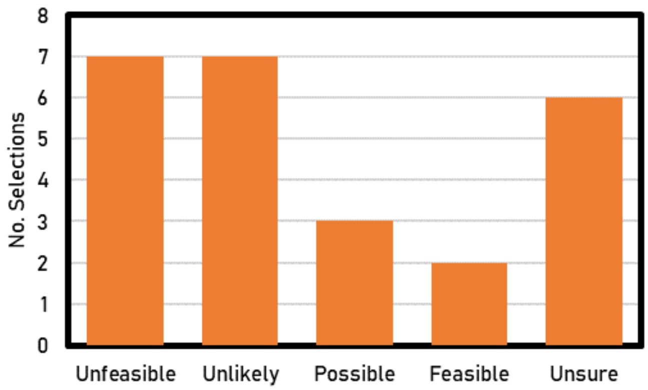


Figure 5. (left) Proportion of large NNS component applications across different sectors, and (right) weight thresholds beyond which acquiring NNS components domestically is impractical or impossible for survey respondents

[2] Workshop: Technical and Business Challenges for Infrastructure Scale Near Net Shape (NNS) Components. https://isnnsc.ornl.gov/presentations/

More than 50% of survey participants indicated that their organizations are unable to procure large NNS components domestically, and that 72% of the large NNS components used in their respective industries are outsourced from overseas (Figure 6).



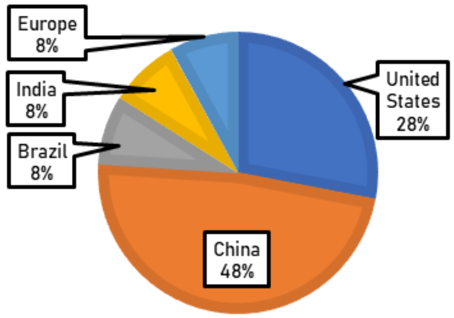


Figure 6. (left) Survey participants evaluated their organizations' ability to produce or procure a large NNS component domestically within 12 months. (right) Survey participants indicated the percent of large NNS parts their organizations procure from various countries.

Furthermore, the lead time for receiving a large NNS part (domestically or globally) after placing the order was longer than 12 months for approximately 57% of the survey participants (Figure 7).

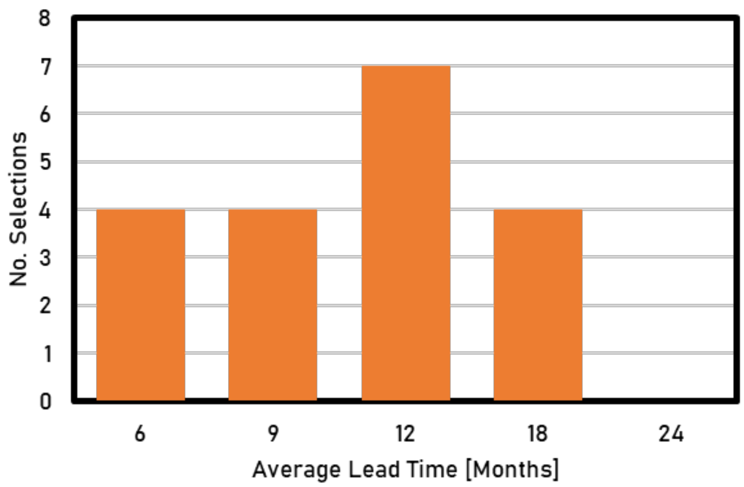


Figure 7. Average lead times for receiving a large NNS part after ordering

As an overall assessment of the domestic manufacturing base's health for large NNS components, only 12.5% of the participants viewed the domestic NNS supply chain as being reliable, and there was full consensus regarding the urgent need to domestically produce large NNS components, with 100% of the survey responses indicating moderate-to-high degrees of urgency (Figure 8).

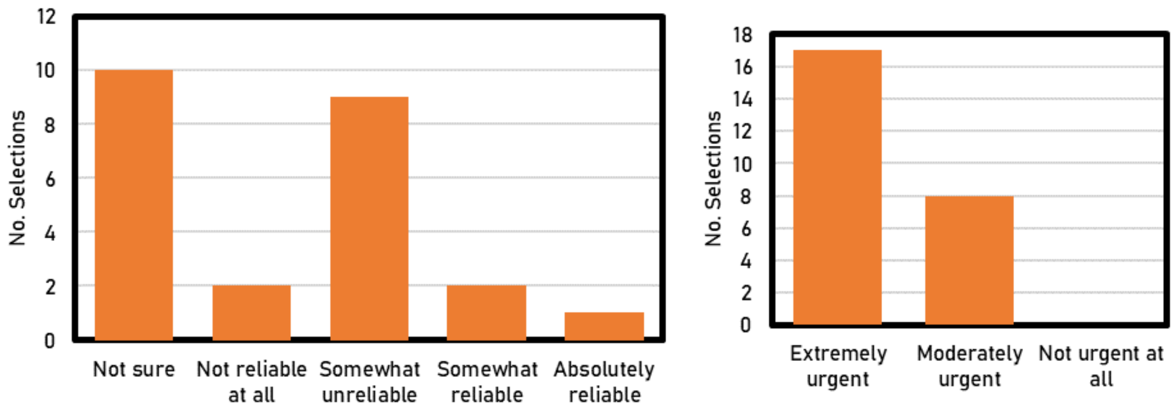


Figure 8. (left) Number of survey responses evaluating reliability of the domestic large NNS supply chain, and (right) the urgency of developing domestic manufacturing capabilities

4.2 Panel Session Outcomes and Summary

Recommendations include:

- Identify opportunities to automate processes where in-person workforce availability and training are bottlenecks.
- Explore best practices from other industries, such as automotive, for mitigating risk around new technology development (casting and forging industry is risk-averse).
- Build additional machining cells as an easy infrastructure win for expanding domestic capacity; this would help alleviate competition between government and industry for current capacity.
- Have DOE more clearly articulate how its goal of net-zero carbon emissions will provide a demand signal for industry.

During the panel discussion, the speakers identified several high-priority hurdles to competitively producing large NNS components domestically. Financial challenges were the most significant, such as the costs involved in navigating the complexities of overseas supply chains, the time offset in cost reduction not being as significant as expected, and companies hesitant to spend on capital expenditures due to business risk. Additionally, workforce demands pose challenges related to both the supply of a workforce and the bottleneck for training facilities (producing educators and students and selecting the best training facility sites). Testing and evaluating these components without causing damage is a high-priority hurdle that may be addressed through a data analytics approach.

The panelists also discussed the availability of technical training and the role of government versus industry in providing this training. The U.S. Navy takes responsibility for providing training it deems relevant, as industry members do not have the resources. AMMTO takes a similar approach and invests heavily in workforce training; however, the office faces challenges in tracking the impact of these investments. Rather than focusing solely on in-person training, there should be a push toward identifying what work can be automated, especially since industry facilities are not the most pleasant places to work.

The discussion then turned to the needs of SMMs and approaches to drive their investments in technologies. Financial risk is the most significant challenge facing these companies. The government should adopt processes from other, larger industries—such as the advanced product quality process in the automotive industry—to mitigate risk. Sharing this risk may help mitigate some of the reservations SMMs have about early investing.

In terms of quick wins, panelists discussed the high demand for domestic capacity driven by the high cost of logistics. Building machining cells is an easy infrastructure win that can achieve a good return on investment. The government is competing with industry for capacity, and there is a need to diversify suppliers.

Finally, the panelists addressed the topic of managing the rapid rate of technology innovation and its associated risks. There must be balance in investments between proven and game-changing technologies. There are some steps being taken, such as the venture capital model, which disrupts manufacturing by putting products into operation to prove out systems and iterate quickly. Collaboration and problem-solving is a powerful way to drive innovation in the industrial base.

4.3 Breakout Sessions Outcomes and Summary

Key outcomes across the three breakout sessions (comprising a total of eight parallel tracks) are summarized in this section for ease of readability. Detailed discussions and participants' input for each parallel track are available in Appendix D. The outcomes were categorized into five categories: (1) challenges, (2) technology development, (3) technology demonstration, transition, and scale-up, (4) supply chain, and (5) workforce development.

4.3.1 Challenges

Summary recommendations:

- Redesign government purchase commitments and procurement contracts (e.g., current contracts lock in prices that do not escalate with inflation)—industry needs a clear demand signal to reduce the risk associated with new materials and processes.
- Collect data and perform life cycle assessment (LCA) for new/alternative manufacturing systems to demonstrate their competitiveness and ability to meet specific performance requirements.
- Fund additional research around new materials for additive manufacturing that can replace existing materials.
- Conduct studies to better understand the operational factors that could adversely affect product quality and process reliability/repeatability.

4.3.1.1 Economic Challenges

High cost of labor, small labor pools, and stringent environmental, health, and safety regulations make domestic manufacturing economically challenging. Because procurement decisions are primarily based on low costs rather than quality, domestically sourced parts are unattractive. The barriers to reestablishing the domestic manufacturing base are significant, as nonrecurring costs to create the first article can amount to 4 times the cost of the final production article. Additionally, the U.S. government subsidizes fewer industrial capital expenditures than other governments do. Today, the U.S. manufacturing base is not cost-competitive for castings over 1 ton. Costs are even more significant in the nuclear energy sector where large components are only produced overseas. Raw materials, such as high-quality powders for powder metallurgy products, suffer price inflation and supply chain volatility.

4.3.1.2 Logistical and Supply Chain Challenges

On-site, or expeditionary, manufacturing of large parts is not feasible: there is little to no available footprint at OEMs to install on-site manufacturing capability for large NNS parts. Further, manufacturing process steps to produce large NNS components are not collocated. Components must be shipped to different, remote locations for forging, machining, welding, and other processing steps. Oversized components, such as wind turbine blades, are difficult to move by road or rail and are subject to special permitting, regulations, and hazards. Supply chain issues are prevalent for wire and powder feedstocks since manufacturers only produce feedstocks after orders are placed.

Component approval timelines are frequently delayed due to a lack of early and continued engagement from OEMs with component manufacturers. OEM specifications are also becoming more stringent to hedge against litigation. Specifications are unclear, and there is a lack of available resources to enable manufacturers to respond to specification interpretation questions with authority. There is also a lack of long-term commitment for procuring parts at sufficient production volumes. Companies refrain from taking risks associated with "one-offs."

4.3.1.3 Technological Challenges

There is insufficient data for meeting specific performance requirements for large, domestic NNS components and a lack of testing infrastructure and funding mechanisms to promote technology integration. It is very difficult to conduct effective qualification and certification because there is insufficient trust and understanding of operational factors that adversely affect product quality and process repeatability. In foundries, even slight process changes can potentially ruin parts. The manufacturing industry is conservative and slow to adopt new technology—companies will accept castings that produce internal flaws because they are viewed as safer than additively manufactured parts. Within conventional NNS component manufacturing, existing automation capabilities are not being implemented. For example, flash removal and metal pouring into molds is still done manually. There are also constraints on melt and ladle capacity.

Development of new materials for additive manufacturing is lagging due to insufficient research and long approval times for new alloys and/or manufacturing processes. Additively manufactured parts are expected to have similar microstructures to previous manufacturing processes and match legacy properties, though this should not be the case. Materials and alloys of interest include refractory alloys with high melting temperature (>2,000°C), SA508 steel, stainless steel, ductile iron, Ti 8-1-1, and 7000-series Al. Alternate manufacturing routes have not demonstrated competitiveness, due in part to a lack of LCA capabilities. Nondestructive testing (NDT) and heat treatment requirements increase lead times. Modeling capabilities must be improved for powder metallurgy hot isostatic pressing.

4.3.1.4 Workforce Challenges

The high cost of domestic labor is exacerbated by high educational costs. There is a need to control labor costs while maintaining manufacturing productivity, job stability, and good income. However, there is a shortage of trained workforce (engineers, metallurgists, etc.)

capable of producing repeatable critical parts. Manufacturing locations are limited to locations with the labor concentration while volatile demand affects job stability and prevents workers from entering manufacturing.

Many SMMs do not have dedicated staff who can handle growing cybersecurity requirements. There are also challenges in training the workforce in industry-specific skills. For example, there is a lack of training schools where people can go to learn skills like mold design and solidification. Further, there is a lack of knowledge transfer from senior employees to the next generation.

4.3.1.5 Manufacturing Capacity Challenges

The number and capacity of domestic foundries has been declining for years. The current manufacturing base is at capacity and not motivated to expand for small market applications. For example, U.S. nuclear component manufacturers are not subsidized and will not invest in maintaining certifications for such a small market. Infrastructure-scale parts may be as large as 40–60 tons; however, parts above 10 tons are impractical to produce domestically, and parts above 15 tons are nearly impossible. Additionally, postprocessing machining capacity is scarce for very large parts.

4.3.2 Technology Development Needs

Summary recommendations:

- Advance data-driven monitoring, inspection, and modeling capabilities to facilitate qualification and certification of large-scale parts.
- Enable distributed manufacturing processes (i.e., creating large-scale parts in sections, on-site feedstock production, and mobile part finishing).
- Improve capabilities of AM and hybrid manufacturing (i.e., AM for superalloys and refractories, faster material deposition, improved finishing capabilities, and localized control of material properties).

4.3.2.1 Advanced Manufacturing Technologies

These technologies include AM (e.g., advancements in directed energy deposition of large-scale superalloys and refractory alloys) and hybrid manufacturing, including all ancillary technologies (joining, deposition, removal, and forming). These are technologies and processes that can build (and finish) parts larger than the build volume. New deposition techniques feature extremely high throughput, and precision manufacturing at high temperatures will help achieve material property control. Sectional creation of large-scale parts leverages distributed manufacturing, and mobile machining centers using robotic machining reduce lead time. These technologies also feature on-demand creation, processing, and recycling of AM raw feedstock.

4.3.2.2 Robotics and Automation

The automation of many of these processes can aid in labor, quality assurance, and integration. Data-driven flexible automation with hybrid processes are high-speed and AI-controlled, and they can perform automated quality assurance techniques. For example, automation can provide in situ monitoring and control as a proxy for nondestructive inspection. Robotics-driven automation can also augment physical labor such as grinding, blasting, and cutting. Additionally, collaborative systems can connect users with automated technologies and replace proprietary automation controls with open systems to enable cross-sector integration.

4.3.2.3 Sensors and Data Management

In situ monitoring with higher quality and lower costs calls for real-time embedded sensors. For example, routine inspections may be replaced by embedded sensors and structural health monitoring. In terms of managing data, capture methodologies and data analytics should be used to leverage sensor data to its full potential. Software tools that efficiently analyze and make decisions using large data sets should be employed, as they heighten confidence. While there should be an open data source to support modeling and data analytics on the factory floor, cybersecurity systems must be trusted for secure information transfer across critical manufacturing outfits.

4.3.2.4 Modeling, Testing, and Other Software Tools

There is a need for improved process modeling and simulation tools such as Magma, Procast, Deform, and Forge. To enable location-specific material performance and track defect locations, among other uses, high-fidelity physics and solidification models for large-scale processes should be implemented. Integrated computational materials engineering (ICME) can be used in predicting mechanical performance and targeting processing conditions. Other tools include topology optimization for complex geometries and multifunctional components and rapid development capability for damage tolerant alloys/materials. Digital technologies can include digital twin development and closed-loop integration, digital tools and probabilistic methods to accelerate model-based qualification and certification, and in situ nondestructive technologies and standards, such as digital radiography.

4.3.3 Supply Chain Needs

Summary recommendations:

- Consolidate customer demand signals and relay them to the suppliers; consolidate supplier capabilities and relay them to the customers.
- Implement government-funded qualification and certification efforts.
- Enable existing facilities to accommodate large NNS parts and create emergency backups of critical components with short lead times.

4.3.3.1 Analyses and Resources

Given the limited 3-year timescale to drive research, development, and deployment priorities, landscape assessment should be implemented to identify casting and forging activities with the highest impact. A strategic list of national needs for large manufacturing facilities and a database of current capacity at existing and legacy suppliers are necessary resources for analysis. Additionally, acquisition and demand signal tools for primary metal producers may help assess opportunities for maintaining and expanding operations well within their capabilities.

4.3.3.2 Industry Coordination

Coordination within the industry can help streamline innovation and output. Watchdog organizations can help prevent monopolies that slow down innovation, and clearing house organizations can consolidate the demand signals from customers and relay them to manufacturers. Additionally, conferences, workshops, and tours of practitioner facilities will improve coordination within the industry.

4.3.3.3 Capacity Expansion

To expand capacity, a volume obligation/commitment should be made along with additional infrastructure for existing plants to accommodate large NNS components. Factories can be reconfigured to serve multiple industries, and there is strong demand for building a pig iron plant in the United States.

4.3.3.4 Government Support

The government should provide support by funding qualification and certification efforts, as well as user facilities to streamline industry adoption. The government is also responsible for supporting SMMs that have limited resources. Beyond funding and resource allocation, the government should maintain backups of critical components and develop emergency backup parts with short lead times.

4.3.4 Demonstration, Transition, and Scale-Up Needs

Summary recommendations:

- Form public/private partnership with agile entities focused on rapid demonstration throughout the NNS component value chain.
- Frequently engage with industry throughout TRL timeline to ensure technologies will transfer.
- Collaborate with qualifying entity from beginning stages of project to accelerate qualification and certification, especially if there is concern that existing standards will not be valid for new manufacturing processes.

4.3.4.1 Demonstration

There are various methods to demonstrate industry capabilities. This could include hosting a contest to quickly produce an infrastructure-scale part that meets all mechanical and quality requirements. Other options would be developing advanced, infrastructure-scale equipment for machining NNS parts, direct casting/drawing of wire feedstock to demonstrate additive manufacturing, and facilitating qualifications for additive friction stir deposition. Sensors embedded in 3D-printed sand molds may help validate a solidification model and develop an understanding of density of sensors required. Ultimately, the drive is toward public/private partnerships with agile entities focused on end-to-end rapid demonstration.

4.3.4.2 Technology Transition

To successfully transition technologies, industry must be involved early to make sure the technology is transferable. Industry must also independently fund TRL 8 to enable systems that are completed and qualified. Nonprofits should invest in earlier TRLs. TRLs below 5 are expensive, as the return on investment is most desirable in less than 2 years, and many NNS applications must realize solutions in less than 5 years.

4.3.4.3 Scale-Up

To scale up these operations, strategic federal investment in public/private partnerships with long signal response must be maintained. Moving away from "power pointing" and toward activating end-to-end technical and workflow demonstrators will spur innovation cycles. There is a need to determine if existing standards are valid for new manufacturing processes and to connect product integrity to system-level performance and reliability. Cost-effective nondestructive evaluation should be made more readily available, and the qualification and certification process should be accelerated through collaborating with a qualification entity from the beginning stages of the project. Reducing bureaucracy and improving practicality and efficiency is a vital goal.

4.3.4.4 Teaming Opportunities

Opportunities to share and collaborate across agencies and programs are beneficial. Federally funded programs with limited cost may share requirements to incentivize the industrial base. Interagency collaboration should exist at the federal level; for example, forming a DOE and DOD working group. In the private sector, AM supply chains should be presented with teaming opportunities. For example, wire producers, large-scale AM manufacturer, and machining would make up one team. Generally, a private technology council with a track record of implementing technologies at large scale should be formed.

4.3.5 Education and Workforce Development Needs

Summary recommendations:

- Nurture competencies in science, technology, engineering, and mathematics (STEM) concepts (especially mechanical skills, computer science, and technical communication) at primary education levels.
- Incentivize training and apprenticeship programs for new workers and retraining programs for incumbent and displaced workers; trainings need to be valuable and appealing.
- Foster workforce diversity by using communications software and social media to share success stories of people from diverse backgrounds (especially those historically discouraged from pursuing STEM education) working in manufacturing.

4.3.5.1 Critical Workforce Competencies

The workforce in these industries should be competent in materials science, technical communication, basic coding, and mechanical skills. The increasingly software-driven environment demands basic coding skills, while hands-on experience with various manufacturing techniques remains vital. Diversity of thinking, knowledge, and skill sets is necessary, as manufacturers must have a breadth of knowledge in different manufacturing areas.

4.3.5.2 Workforce Development Programs

To further develop the workforce, improvements should be made to workforce availability and diversity of skill sets by enabling communication across disciplines. Training programs should be made valuable to workers and comparable to a university education. Small companies should be incentivized with state and local funding to train their employees, as they are currently reluctant to provide time for training because it takes employees off the factory floor. Finally, methods for existing and established workers and industry leaders to give back to younger generations should be formed.

4.3.5.3 K–12 and Postsecondary Education

To get students excited about industry manufacturing, internship programs should be created to engage with students during their educational career. Gaps in educational resources at primary education levels should be addressed, and technical/mechanical concepts should be made more approachable for students. Educators should be better informed of the opportunities available to their students so they can properly advise them on potential options. Students should not be discouraged from pursuing fields that are interesting to them.

4.3.5.4 Diversity, Equity, and Inclusion

Diversity of thought requires diversity, equity, and inclusion in representation. Underrepresented/underserved communities should be courted into the field. Agriculturally focused communities that have not considered manufacturing may have many potential employees. People from diverse backgrounds should have their stories developed and shared to promote these ideas and serve as a call to others. To better serve those currently employed, focus should be on developing training and conducting outreach focused on supporting women in STEM, as well as developing programs for retraining incumbent workers (age 40+) to meet the needs of today's manufacturing work. Most programs today are geared toward students, and these opportunities should be made accessible for everyone.

5 Conclusion

The production of large metallic NNS components in the United States is critical for expanding domestic manufacturing capabilities and securing supply chains for the clean energy transition. Though NNS components are critical for applications such as hydropower, wind, and nuclear energy generation, the domestic NNS manufacturing base has steadily declined over the last several decades as production has moved overseas. To address this gap, AMMTO is collaborating with DOE's Office of Nuclear Energy, Wind Energy Technologies Office, and Water Power Technologies Office to assess the potential for developing and commercializing novel manufacturing processes for producing NNS components.

The workshop brought together stakeholders representing large industries, small and medium manufacturers, federal agencies, and research laboratories for 2 days of information sharing and dialogue. Workshop sessions were framed around identifying challenges, potential solutions, and implementation pathways related to domestic NNS innovation. Through the survey, participants provided insight into common applications, weight thresholds, and average lead times that underscored current issues with the NNS supply chain. The panel discussion highlighted cost and workforce hurdles while recommending the industry explore best practices from other sectors and search for quick wins such as building additional machining cells.

Key recommendations from the workshop include the need to improve manufacturing processes as well as enable technologies such as robotics and automation, sensors, and modeling tools. For supply chain needs, attendees identified the potential role of the federal government in developing a strategic list of national needs, supporting qualification and certification efforts, and facilitating industry coordination. Similarly, DOE can support technology demonstration and scale-up by forming a dedicated public-private partnership and engaging with industry frequently throughout the TRL timeline. Finally, for education and workforce development, attendees indicated a need to incentivize training and apprenticeship programs and nurture interest in manufacturing careers among K–12 students.

Following the workshop, AMMTO has started working on a briefing to Congress on the technical and economic viability of producing large metallic NNS components in the United States. AMMTO also released a Funding Opportunity Announcement that will award $15–$30 million to projects that advance near net shape manufacturing techniques.

References

Baranowski, Ruth, Aubryn Cooperman, Patrick Gilman, and Eric Lantz. 2022. *Wind Energy: Supply Chain Deep Dive Assessment.* Washington, D.C.: U.S. Department of Energy. DOE/OP-0013. https://doi.org/10.2172/1866032.

Dawnbreaker. 2022. *Market Research Study: Domestic Casting Industry*. Rochester, NY: Dawnbreaker. https://science.osti.gov/-/media/sbir/pdf/Market-Research/AMO---Metal-Casting-August-2022-Public.pdf.

Finan, Ashley, Andrew Foss, Michael Goff, Christine King, and Christopher Lohse. 2022. *Nuclear Energy: Supply Chain Deep Dive Assessment*. Washington, D.C.: U.S. Department of Energy. DOE/OP-0009. https://doi.org/10.2172/1871579.

Igogo, Tsisilile. 2022. *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition*. Washington, D.C.: U.S. Department of Energy. DOE/OP-0014. https://doi.org/10.2172/1871491.

Office of the Deputy Secretary of Defense. 2022. *Securing Defense-Critical Supply Chains: An Action Plan Developed in Response to President Biden's Executive Order 14017*. Washington, D.C.: Office of the Deputy Secretary of Defense. https://apps.dtic.mil/sti/pdfs/AD1163223.pdf.

U.S. Department of Energy (DOE) Office of Nuclear Energy. 2020. "U.S. Emissions-Free Electricity Generation Share by Source – 2019." https://www.energy.gov/ne/articles/us-emissions-free-electricity-generation-share-source-2019.

U.S. Department of Energy (DOE). No date (a). "Securing America's Clean Energy Supply Chain." https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.

U.S. Department of Energy (DOE). No date (b). "Pathways to Commercial Liftoff: Liftoff Reports." https://liftoff.energy.gov/.

Uría-Martiínez, Rocío. 2022. *Hydropower: Supply Chain Deep Dive Assessment*. Washington, D.C.: U.S. Department of Energy. DOE/OP-0007. https://doi.org/10.2172/1871571.

White House. 2021. "Executive Order on America's Supply Chains." https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/?utm_source=link.

Appendix A. Workshop Agenda

Table A-1. Workshop Agenda

Date and Time	Topic	Location
Day 1 (Thursday, Nov. 3, 2022): Setting the Stage: Plenary Presentations		
8:00 a.m.	Arrive at Manufacturing Demonstration Facility (MDF) for Badging	2350 Cherahala Blvd, Knoxville, TN 37932
8:30 a.m.	Welcome by Oak Ridge National Laboratory (ORNL) leadership	
8:45 a.m.	Welcome by Advanced Materials and Manufacturing Technologies Office (AMMTO) director/program manager	
9:00 a.m.	Keynote 1: Challenges in the NNS Manufacturing and Supply Chain in the U.S. – David Gandy, EPRI	
9:20 a.m.	Q&A	
9:30 a.m.	Keynote 2: Domestic NNS Manufacturing for Clean Energy Production – Juan Cilia, GE Renewables	
9:50 a.m.	Q&A	
10:00 a.m.	Break	
Day 1 (Thursday, Nov. 3, 2022): Panel Session Invited representatives from the public and private sectors will have a focused panel session in which they will share their perspectives and open dialogue with workshop participants on challenges and opportunities.		
10:15 a.m.	Panelists' Introduction Brian Began, American Foundry Society Matt Gratias, Relativity Space Matthew Draper, U.S. Navy Rick Lucas, Desktop Metal Ron Aman, EWI	
10:20 a.m.	Panel Discussions	
10:50 a.m.	Moderated discussions with panelists	
Day 1 (Thursday, Nov. 3, 2022): Lightning Talks and Working Lunch Invited organizations will briefly share their organizations' engagement in the NNS space as part of a lightning talk session. A portion of lunch will be devoted to an overview of the XLeap facilitation tool to be used as part of the interactive breakout sessions 1–3 on Day 2.		
11:30 a.m.	Invited Lightning Talks Slade Gardner, Big Metal Additive Jeff Rieman, Form Alloy Brian Wright, Elyria-Hodge Jiten Sha, PDA LLC Westley Downs, MELD Brandon Ribic, America Makes	

	Glenn Daehn, HAMMER ERC	
12:30 p.m.	Working Lunch Overview of XLeap tool.	
Day 1 (Thursday, Nov. 3, 2022): Breakout Session 1: Challenges Related to Near Net Shape (NNS) Manufacturing In this session, we will discuss the *challenges* related to NNS manufacturing in three different parallel tracks broken by application.		
1:30 p.m.	First Breakout Session Track 1: Challenges and Economic Considerations in the Supply Chains Related to Castings and Forgings Track 2: Challenges With Respect to NNS Manufacturing for Clean Energy Production Track 3: Challenges With Respect to NNS Manufacturing for the Rest of the Manufacturing Base	
3:00 p.m.	Break	
3:15 p.m.	Optional MDF General Tour	
4:30 p.m.	Adjourn	
Day 2 (Friday, Nov. 4, 2022): Breakout Session 2: Emerging Technologies **In this session, we will discuss potential solutions to address the challenges identified earlier in Breakout Session 1 in three different parallel tracks broken by processes.**		
8:00 a.m.	Arrive at MDF	
8:15 a.m.	Day 2 Introduction	
8:30 a.m.	Second Breakout Session Track 4: Emerging Technologies to Support the Castings and Forgings Sectors Track 5: New Emerging Technologies for NNS Manufacturing (e.g., Powder Metallurgy, Additive Manufacturing) Track 6: Emerging Technologies to Improve the Resilience of NNS Manufacturing Supply Chains	
10:00 a.m.	Break	
Day 2 (Friday, Nov. 4, 2022): Breakout Session 3: Implementation Pathways In this session, we will identify the needs and pathways to implement some of the solutions proposed in Breakout Session 2 to advance U.S. competitiveness in NNS manufacturing.		
10:15 a.m.	Third Breakout Session Track 7: Technology Demonstration, Transition, and Scale-Up Needs Track 8: Education and Workforce Development Needs	
Day 2 (Friday, Nov. 4, 2022): Final Summary and Next Steps: AMMTO program managers and ORNL leadership will summarize details and next steps related to the workshop report, request for information (RFI), and action items. They will also suggest how the participants can play a role		

in developing our infrastructure and capability for manufacturing and qualification of industrial-scale near net shaped metallic components in rapid fashion and at low cost relevant to our aspirational goals of clean energy by 2050.		
11:45 p.m.	Working Lunch: Final Summary/Next Steps	
12:45 p.m.	Adjourn	

Appendix B. Preliminary Survey Results

1. What is your organization's focus application for large NNS components?

Application for large NNS components		
No.	Item	Selections
1	Industrial Base	16
2	Wind	9
3	Nuclear	6
4	Hydro	4

2. What is the threshold at which manufacturing or procuring large NNS components domestically becomes impractical or impossible?

Threshold for domestic large NNS components		
No.	Item	Selections
1	Greater than 30 tons	12
2	10 tons	9
3	20 tons	2
4	15 tons	1
5	25 tons	1

3. What alloy family is most relevant to your applications? Select all that apply.

Alloy family most relevant to your applications		
No.	Item	Selections
1	Stainless steel	24
2	Nonferrous alloy	20
3	Low-alloy steel	19
4	Carbon steel	15
5	Iron	12
6	Low-carbon steel	11

4. Which technology is of the greatest interest to your organization and/or application? Select all that apply.

Technology of greatest interest		
No.	Item	Selections
1	Additive Manufacturing	24
2	Hybrid Manufacturing	20
3	Casting	17
4	Forging	11
5	Powder Metallurgy	11
6	Other (please specify)	5

Other responses include:

- Process innovation and hybridization
- Automation
- In situ melt pool data
- Polymer composite
- Welding and joining.

5. If you needed to produce or procure a large (15+ ton) NNS component domestically within the next 12 months, could you?

Feasibility of domestic large NNS components		
No.	Item	Selections
1	No	7
2	Unlikely	7
3	Unsure	6
4	Probably	3
5	Definitely	2

6. Where are the majority of the large NNS components used in your industry manufactured?

Location of large NNS components manufacturing		
No.	Item	Selections
1	Overseas (please state which country)	15
2	Domestically	7

Overseas locations include:

- China
- India
- Brazil
- Europe (e.g., Italy).

7. What is the average lead time for receiving a large NNS component once ordered?

Average lead time		
No.	Item	Selections
1	12+ months	7
2	6+ months	4
3	9+ months	4
4	18+ months	4
5	24+ months	0

8. How reliable is the current supply chain for large NNS components?

Reliability of current supply chain for large NNS components		
No.	Item	Selections
1	Not sure	10
2	Somewhat unreliable	9
3	Not reliable at all	2
4	Somewhat reliable	2
5	Absolutely reliable	1

9. How urgent is the need to domestically produce large NNS components?

Urgency to domestically produce large NNS components		
No.	Item	Selections
1	Extremely urgent	17
2	Moderately urgent	8
3	Not urgent at all	0

10. What is the estimated cost to develop a manufacturing process/method to produce a full-scale NNS demonstration component (technology readiness level [TRL] 7) within 2–3 years?

Estimated cost		
No.	Item	Selections
1	$9–$12 million	9
2	$3–$6 million	5
3	$6–$9 million	5
4	$0–$3 million	2

11. What starting TRL is needed for industry to internally fund and complete development of a manufacturing process/method for large NNS components?

Starting technology readiness level (TRL)		
No.	Item	Selections
1	TRL 5	7
2	TRL 7	7
3	TRL 6	6
4	TRL 8	3

12. How desirable is it to be able to produce components on-site?

Desirability of producing component on site		
No.	Item	Selections
1	Desirable	17
2	Neutral	8
3	Necessary	0

13. How important is partnering across the supply chain when developing a manufacturing process/method for large NNS components?

Importance of partnering across the supply chain		
No.	Item	Selections
1	Necessary	15
2	Desirable	9
3	Neutral	1

14. Do you see value in private-public partnership models for NNS manufacturing?

Value of private public partnership models		
No.	Item	Selections

1	Yes	21
2	Not sure	3
3	No	1

15. What would be your preferred method for continued engagement with DOE and/or information gathering?

Preferred method for continued engagement with DOE		
No.	Item	Selections
1	Periodic meetings/workshops	25
2	Roundtable discussions	18
3	Requests for Information (RFIs)	9

Appendix C. Workshop Participants

Table C-1. List of Workshop Participants

First Name	Last Name	Affiliation
Consortia/Trade Groups		
Brian	Began	American Foundry Society
Greg	Kramer	American Foundry Society
Brandon	Ribic	NCDMM/America Makes
Government		
Joe	Baker	Nexight Group
Robert	Bartolo	Allegheny Science and Technology (AST)
Tyler	Christoffel	DOE Wind Energy Technologies Office
Matthew	Draper	U.S. Navy
Alaa	Elwany	DOE AMMTO
Daniel	Fisher	TVA
Jesse	Geisbert	US Navy
Jack	Holmes	Nexight Group
Christopher	Hovanec	DOE AMMTO
Colin	Sasthav	DOE Water Power Technologies Office
Dylan	Smith	Nexight Group
Aaron	Wiest	Submarine Industrial Base
Industry		
John	Adams	Dienamic Tooling Systems

Ronald	Aman	EWI
Dana	Beyeler	ELLWOOD Group, Inc.
Juan Pablo	Cilia	General Electric
John	Cory	Magotteaux
Chase	Cox	MELD Manufacturing
Huijuan	Dai	General Electric
Brian	Downey	MELD Manufacturing
Westley	Downs	MELD Manufacturing
Patrick	Dunne	3D Systems
Mark	Evers	GKN Aerospace USA
Daniel	Galicki	BWX Technologies
David	Gandy	EPRI
Slade	Gardner	Big Metal Additive
Lillie	Ghobrial	GE Renewable Energy
Matt	Gratias	Relativity Space
Nanci	Hardwick	MELD Manufacturing
Rick	Lucas	Desktop Metal
Jeff	Riemann	FormAlloy Technologies, Inc.
Ayman	Salem	MRL Materials Resources LLC
Jiten	Shah	Product Development & Analysis (PDA-LLC)
David	Weiss	Eck Industries, Inc.
Brian	Wright	Elyria & Hodge Foundry Group
National Laboratories		
Anders	Andersson	Los Alamos National Laboratory
Nicolas	Argibay	Ames National Laboratory
Andrea	Jokisaari	Idaho National Laboratory
Meimei	Li	Argonne National Laboratory
Mirko	Musa	Oak Ridge National Laboratory
Peeyush	Nandwana	Oak Ridge National Laboratory
Ryan	Ott	Ames National Laboratory
Brian	Post	Oak Ridge National Laboratory
Mitchell	Rencheck	Oak Ridge National Laboratory
Robert	Slattery	Oak Ridge National Laboratory
Isabella	van Rooyen	Pacific Northwest National Laboratory
Joshua	Vaughan	Oak Ridge National Laboratory
Dawn	White	Oak Ridge National Laboratory

Universities		
Sudarsanam	Babu	University of Tennessee, Knoxville
Glenn	Daehn	The Ohio State University
Dustin	Gilmer	University of Tennessee, Knoxville
Bradley	Jared	University of Tennessee, Knoxville
Orlando	Rios	University of Tennessee, Knoxville
Tony	Schmitz	University of Tennessee, Knoxville

Appendix D. Detailed Workshop Inputs

Breakout Session 1: Challenges Related to Near Net Shape (NNS) Manufacturing

Track 1: Challenges and Economic Considerations in the Supply Chains Related to Castings and Forgings

1. What is the size/weight threshold at which manufacturing or procuring large NNS components domestically becomes impractical or impossible?

- Iron: Weight threshold is 220,000 lb.
  - Iron castings are produced regularly up to 160,000 lb.
  - However, some participants have not seen anything above 100,000 lb.
  - Some have struggled to source castings over 40,000 lb.
- Low-alloy steels: Several manufacturers can pour 90,000–100,000 lb.
  - Size is limited to 12 ft tall and 25 ft long.
- Stainless steel: Forgings limited to 40 tons domestically.
- Nickel-aluminum-bronze: U.S. entities can pour >250,000 lb.
- Nonferrous metals (e.g., aluminum): Limited to 5,000 lb.
- Castings (in general): Effective limit is >100,000 lb (many facilities are tied up by Navy and others).
  - Size is limited to 48 ft × 36 ft × 36 ft (height is not an issue due to crane).
- Carbon steel forging: Not domestically available larger than 100 tons.
  - 13-ft diameter carbon steel forgings needed for nuclear industry.
- Laser powder bed fusion is limited when parts are larger than 16 in. in each dimension.

    - Other additive manufacturing (AM) technologies have larger build envelopes (20–30 ft).
- Freight, ingot size, and ingot lifting are limiting factors for dimensional size.

2. Identify the most significant supply chain challenges and risks that your organization faces with respect to producing or procuring large NNS components.

Procurement Process

- Relationship between procurement policies and long lead times.
- Lack of early and consistent engagement from original equipment manufacturers (OEMs) with component manufacturers.
- Delays in approval timelines from the OEMs.

Materials and Feedstock Availability and Cost

- Raw materials availability and price inflation (e.g., quality atomized powders in large quantity (for powder metallurgy products)).

Demand and Risk

- Lack of long-term commitment/orders (at sufficient volume)—companies do not want to take risks on "one-offs" and little-used materials (e.g., titanium 8-1-1).
- Getting domestic suppliers to buy American (or at least from Five Eyes[3] nations).
- OEMs make decisions based on lowest cost rather than quality.

Standards, Specifications, and Requirements

- Increasing and tighter OEM specifications (e.g., due to fear of litigation).
- Lack of clear specifications, and lack of available resources to answer specification interpretation questions with authority.
- Nondestructive testing (NDT) requirements and resources.

Workforce

- Lack of trained workforce (engineers, metallurgists, etc.) capable of producing repeatable critical parts (labor gap).
- Training school gap—where do people go to learn skills like mold design and solidification?
- Many subject matter experts do not have dedicated staff who can handle growing cybersecurity requirements (government fines can scare small businesses away).

---

[3] The Five Eyes Intelligence Oversight and Review Council includes Australia, Canada, New Zealand, the United Kingdom, and the United States (https://www.dni.gov/index.php/ncsc-how-we-work/217-about/organization/icig-pages/2660-icig-fiorc).

- Lack of knowledge transfer to capture senior employees‘ knowledge for the next generation.

Technology Challenges

- Melt and ladle capacity are constraints.
- Pouring/filling automation is a challenge.
- Lack of powder metallurgy hot isostatic pressing modeling capabilities.

3. What are typical lead times on large components that you order from your suppliers? What is driving the long lead times for large NNS components?

Lead Times

- 12 months is typical; drivers are approvals from the OEMs and value-added activities such as NDT.
- 10 months for a foundry to get something as simple as sand processing equipment.
- 9 months for raw materials.
- 24–48 months for large forgings used for nuclear applications; acquisition from overseas (e.g., Japan) is the main reason.
- 6–12 months for nuclear components.
- 20 months for hydropower turbines (final delivered product).

Drivers

- Limited foundry capacity due to the decline of foundries along with a manufacturing resurgence.
- NDT and heat treatment are bottlenecks that drive lead times.
    - Industry is not willing to do NDT in house.
- Pig iron shortages impact the availability of all other sources of scrap.
    - Steel mills have more buying power than foundries; they get the materials when there are shortages, and others have to source from farther away.
- Current system is at capacity and not motivated to expand for small-market applications (e.g., nuclear).
- Manufacturing steps are not collocated; components ship to different sites for forging, machining, welding, etc.

4. What percentage are transportation and logistics costs relative to your total acquisition costs? Is there significant value in being able to manufacture components near or on-site?

- This is not a driver (or at least overstated) when sourcing from NAFTA (North American Free Trade Agreement) countries.
- On-site manufacturing is not feasible.
    - There is minimal-to-no available footprint at OEMs to install on-site manufacturing for NNS parts.
    - OEMs should focus on redesigning pieces to make them easier to transport.
- For nuclear, transportation costs are significant because components are produced overseas.
- This can be a significant factor for steel ingots, specifically.
- Labor is the bottleneck, not logistics; shipping is necessary to target the labor concentration.
- As an international foundry organization, supply chain issues allowed us to take local market from overseas competition.

5. Where is the highest concentration of large component suppliers/manufacturers globally?

- Overseas: China; then Japan, Korea, and India.
- Domestic: Ohio, Massachusetts, Pennsylvania, Illinois (Chicago), Washington (Seattle, large stainless steel forging), West Virginia/North Carolina.
- Nuclear (overseas): South Korea, Japan, Germany, Italy (large forging), France (large forging), U.K.
- Nuclear (domestic): Scot Forge, North American Forgemasters, Lehigh Heavy Forge.

6. What is the cost-per-pound threshold at which manufacturing or procuring large NNS components domestically becomes impractical or impossible?

- Cannot answer, alloy-specific.

7. What is your organization’s current or projected demand for large components, and do you anticipate this demand to grow over the next decade?

- 80 gigawatts (GW) to replace existing nuclear structure; >4,000 GW (internationally) over next 25 years.
- Nuclear: current demand is ~10 components/year. Scrap rate of 0% is required. Demand will grow over the next decade for microreactors.

8. Do the domestic postprocessing and raw materials supply chains meet your organization’s needs? Identify operations/processes/materials of the most concern.

- Melt alloys are typically not domestic; scrap steel is available, but often gets shipped to China. This indicates they are paying more for raw materials yet can still be low cost.

9. What are the consequences to your business associated with supply chain risks?

- Shutting down production without available alloys or power.

Track 2: Challenges With Respect to NNS Manufacturing for Clean Energy Production

1. What is the size/weight threshold at which manufacturing or procuring large NNS components domestically becomes impractical or impossible?

- The part volume is possibly a bigger barrier than weight, as oversize objects such as wind turbine blades are very difficult to move by road, rail, etc.
- United States is currently not competitive cost-wise for any castings over 1 ton.
- Parts above 10 tons are impractical; parts above 15 tons are nearly impossible.
- Infrastructure-scale parts may be as large as 40–60 tons.

2. Identify the most significant challenges to domestically produce or procure large NNS components for clean power generation applications?

Logistics

- Transportation logistics are very difficult; large parts are subject to special transportation permitting, transportation hazards, regional regulations, etc.
- Depending on type of solution, facilities may need to be near deployment site (for example, near the coast for offshore wind).
- Need high part volume for wind; sometimes turbine blades are made at a suboptimal size so they are easier to transport.
- Transporting components in pieces and creating assembly sites near the installation site could mitigate logistical problems.

Economics

- Embrace of low-cost overseas labor has undermined U.S. manufacturing competitiveness.
- High costs from labor, infrastructure, testing, logistics, raw material, industry plus government collaboration.
- Overseas manufacturing is heavily subsidized; political barriers exist for domestic competitiveness.
- Demonstrating demand and volume for foundries and machining companies? Trustworthy demand signals.

Infrastructure

- Lack of domestic machining capabilities for very large parts.
- Do there need to be additional companies for machining and surface finishing?

- No capacity for very large castings (>30 tons); part volume may be a more significant barrier than weight.
- Demonstrating new alternative technology (additive, hybrid) at low cost and at scale in United States.
- Is there a data set of foundries in the United States? What capacity can they produce? Is the data set up to date?

3. What factors are making foreign producers/suppliers more competitive at manufacturing large NNS components?

Sociological

- High cost of domestic labor and shortage of skilled workers.
- Foreign countries often have governmental policy support.
- Countries in the EU handle environmental regulations and high labor costs while maintaining manufacturing productivity.
    - Culture of workforce development in Germany and Spain makes manufacturing jobs attractive.
    - There is better job stability, livable salaries, government intervention, more favorable attitudes to manufacturing jobs.

Political

- Cheaper labor and subsidized capital expenditures in foreign countries.
- Some overseas manufacturers have more lax environmental regulations.
- Proactive governmental intervention was significant in China's development of casting and forging infrastructure.

Economical

- Wind orders follow cyclical tax credit cycle and affect manufacturing stability.
- Volatile demand prevents workers from entering manufacturing.

Technological

- Automation capacity exists, but it is often not applied. For example, flash removal and pouring metal into molds is usually done manually.
- Life cycle assessment (LCA) for new/alternative manufacturing systems to demonstrate competitiveness.
- Lack of machining capabilities.
- Database for production bottlenecks could help facilitate solutions.

4. What are the top design and/or performance requirements that make domestic manufacturing of large NNS components challenging?

Infrastructure

- Size is a constraint. For example, in nuclear applications, there are no facilities capable of casting large vessel heads (4-m diameter) in a single piece.
- Size is also a constraint for postprocess machining.

Workforce

- Limited skilled work force and limited interest in manufacturing careers.
- Better availability of foreign subject matter experts to help guide customer specifications may help foreign manufacturers meet U.S. specifications.

Communication

- Each component design/material combination may have separate requirements. There is a need for better communication between customers and manufacturers.
- Lines of communication between U.S. customers and foreign manufacturers may be more established than with domestic manufacturers.

Data and Technology

- There are insufficient data for meeting specific performance requirements for large, domestic NNS components.
- Limited personnel and software tools to do computational analysis.
- Feed for topology optimization to facilitate complex geometries and multifunctional parts.
- Need for automated, scalable post-machining.

5. Identify the barriers to adopting new technologies that could increase competitiveness, such as automation, digital manufacturing, machine learning (ML)/artificial intelligence (AI), and hybrid processes?

Business Cases

- Few funding opportunities directed at large casting parts and fewer companies in the industry.
- Lack of industrial partnerships in United States to bring multiple industries together.
- Foundries need successful business models to follow. Interdisciplinary approaches could show successful business case for domestic manufacturing in other industries.

Risk

- Cultural perceptions of failure prevent risk-taking.

- In foundries, slight deviations from the established process can ruin a part. Any process changes are high-risk.
- Low trust in new tech that has not been proven in the field.

Demonstration

- Lack of testing infrastructure and funding mechanisms to promote technology integration.
- Need to show business case (LCA) for new AM processes and do demonstrators in the field.
- Need for rapid development of codes/standards/to address the introduction of each technology.

Workforce

- Lack of required skills and expertise with high educational costs.
- Domestic manufacturing jobs are unstable and unattractive.
- Lack of general knowledge in designing for AM impacts system performance.

Machining

- Large-scale machining capacity is critical. New large-scale casting technologies are useless if there is no capability to finish the parts.
- Automation and digitalization can increase throughput, especially for offshore wind, targeting labor and cycle time issues.

6. What factors are preventing NNS processes from manufacturing components at or near the installation site (e.g., print a component on-site)?

- A lot of the emerging processes/solutions need continued investment, LCA, scale-up and demo to commercialize.
- Significant investment and knowledge required for a single company to get started in casting and forging.
- Geographical constraints: need rivers/lakes for cooling water.
- Large NNS components require large footprint casting/forging facilities.

7. Identify your organization's highest priority NNS component types and/or alloy family.

- Refractory element alloys with high melting temperature (>2,000°C) and low-temperature ductility (e.g., to enable higher-temperature gas turbine operation).
- High-performance alloys with advanced cooling structures.
- Ductile iron for offshore wind large castings.

- What are the American Foundry Society's database of capabilities?

Track 3: Challenges With Respect to NNS Manufacturing for the Rest of the Manufacturing Base

1. What is the size/weight threshold at which manufacturing or procuring large NNS components domestically becomes impractical or impossible?

- Lead time is a hindrance rather than size/weight for an additive team. Worktables have a 6,000-lb (3 tons) capacity and are sized 6 ft by 12 ft.
- There are trends where sales of larger powder bed fusion machines are increasing at a more rapid rate in comparison to smaller build envelopes, which is a suggestion that there is demand for larger-scale product manufacturing capability.

2. Identify the most significant challenges to domestically producing or procuring large NNS components for the rest of the manufacturing base?

- Supply chain issues with wire feedstock—no wire on the shelf with five suppliers in the United States due to the manufacturers only producing feedstock when order and money are deposited. Powder and wire have a similar lack of accessibility at scale.
- The nonrecurring cost to create the first article can be 4 times the cost of the final production article. Even when the production rate is a quantity of one. Customers are unwilling to pay the up-front development costs for AM.

3. What factors are making foreign producers/suppliers more competitive at manufacturing large NNS components?

- Many foreign producers have lower costs of labor, a larger labor pool, and lack environmental, health, and safety regulations compared with U.S. industrial base.
- U.S. business model may be challenging, as other governments may heavily subsidize companies, which makes U.S. manufacturing more challenging in advanced technologies.
- There are different economic models, collaboration approaches, intellectual property controls, and standards that allow organizations in Asia and Europe to execute expansive effort, whereas some of the most widely used AM equipment producers are in Europe. Many automations and controls equipment are also produced overseas.

4. What are the top design and/or performance requirements that make domestic manufacturing of large NNS components challenging?

- From a materials perspective, additive must have exact same microstructure as previous manufacturing process and match legacy properties.
  - Compare raw additively manufactured titanium.
- No one working on new materials that replace existing desired materials (aluminum 750).

5. Identify the barriers to adopting new technologies that could increase competitiveness, such as automation, digital manufacturing, ML/AI, and hybrid processes?

- Manufacturing is conservative and slow to adopt new technologies. Castings have been used for many years in numerous industrial applications with variable porosity and internal part flaws, but it is often viewed as a “safer” technology compared to AM. Some AM systems output detailed in situ process monitoring data to give confidence in the build quality, whereas traditional castings and forgings have no such data. Adoption of in situ process data should serve as a confidence-enhancer.

6. What factors are preventing NNS processes from manufacturing components at or near the installation site (e.g., print a component on-site)?

- Quality management systems, one cannot do manufacturing for quality on ships/trucks/etc.
    - Temperature accessibility, and environment leads to a challenge.
    - Material quality and physical challenges.
- Trust and understanding of operational factors for the manufacturing site, which may adversely affect product quality and process reliability/repeatability. It is very difficult to qualify and certify now.

7. Identify your organization’s highest priority NNS component types and/or alloy family.

- Forged steel, copper alloys, and nuclear materials like Inconel.

Breakout Session 2: Emerging Technologies

Track 4: Emerging Technologies to Support the Castings and Forgings Sectors

1. Identify the top three emerging technologies for enabling the competitive manufacturing of domestic NNS components.

Manufacturing Technologies and Processes

- Additive manufacturing (e.g., for 3D-printed molds).
- Hybrid manufacturing, including all relevant technologies (joining, deposition, removal and importantly deformation).
- Robotics-driven automation replacing labor (e.g., grinding, blasting, cutting).
- Partial closed die step forging techniques.

Sensors and Data Management

- Real-time and embedded sensors and in situ monitoring.
- Data capture methodologies and data analytics (to leverage sensor data to its full potential).
- AI-driven tools.

Modeling, Testing, and Other Tools

- Integrated computational materials engineering (ICME) for use in predicting mechanical performance and targeting processing conditions.
- Digital radiography (including standards).
- Enhanced solidification modeling tools to track inclusion and defect location.
- Digital tools and probabilistic methods to accelerate qualification/certification (e.g., model-based inspection).
- Topology optimization for complex geometries and multifunctional components.
- Acquisition and demand signal tools for primary metals producers to assess opportunities to maintain/expand operations well within their capabilities.
- Rapid development capability for damage tolerant alloys/materials, which extend our ability to readily inspect given current supply chain nondestructive evaluation capacity strengths.

2. What are the technological advancements needed to enable and accelerate the technologies identified in Question 1 for >10-ton parts (assume a time frame of 3 years)?

Manufacturing Technologies and Processes

- New deposition techniques that enable extremely high throughput.
- Robotic grinding, blasting, and welding.
- Ability to build parts larger than the build volume.
- Understanding the controlling process variables.
- Additive/hybrid techniques combined with robotics (hydropower repair/maintenance and upgrades).
- Collaborative robotics.

Sensors and Data Management

- Embedded sensors (higher quality, lower cost).
- Need an open source of data the community can use to support modeling and data analytics in the factory.

Modeling, Testing, and Other Tools

- Improve the simulation tools (Magma, Procast, Deform, Forge).
- Improve physics models for large scale.
- Improvements to solidification modeling to predict segregation.
- Digital twin.

- Complete closed-loop system integration.
- Advanced design tools for gating and risers (which may be enabled by AM technologies).
- Landscape assessment (Defense Logistics Agency/DOE/DOD) to identify casting/forging activities with greatest benefit/impact given limited timescale (3 years) to drive research, development, and demonstration priorities.

3. What are the top three considerations you would prioritize when selecting an emerging technology for large NNS components?

- Improving productivity and yield while reducing cycle time (without compromising quality).
- Business case (cost, labor requirement, fundability).
- Supply chain risks and resilience (e.g., onshore production).
- Environmental friendliness.
- Implementation to gain wide adoption.
- Workforce development potential (can workers be upskilled to use technology).
- Final metal properties.

4. Identify any current or legacy domestic capabilities for producing large NNS components. Identify opportunities to make these facilities/processes more efficient, competitive, and/or larger in scale.

- Aging plants need additional infrastructure to handle larger parts (larger castings need larger facilities).
    - Location must have access to transportation, materials supply, and workforce.
- Existing facilities need volume obligation and commitment to invest.
- Turning on a facility that is not active and bringing equipment/facility up to operational readiness can take 3 years or more.
- A greenfield facility can be cheaper than updating/reclaiming a legacy site.
- Specific facilities: Scot Forge, North American Forgemasters, and Lehigh Heavy Forge (nuclear components).

5. What is the estimated cost to develop a manufacturing method/process capable of producing a full-scale NNS metallic component at TRL 7 (system prototype demonstrated in relevant environment)?

Key Considerations

- This question cannot be answered globally; it is dependent on technology and the criticality of the application.
    - DOE should ask this question specifically to each stakeholder.
    - Could also ask about the cost to onshore production instead.
- Manufacturing readiness level (MRL) question is perhaps the better question
- There will be cost to develop technology and cost for companies to set up facilities in the United States.
- This answer will be higher fidelity for the existing casting/forging industry compared to emerging markets.

Estimates

- >$500 million based upon quick internet search around Carpenter Technology's new facility in Huntsville, Alabama.
- $2–$50 million to transition manufacturing technology; hundreds of millions of dollars for new facility.
- There are published numbers for how much it should cost to advance a technology to a certain TRL level.

6. What extent of postprocessing do large NNS components typically undergo for your application? Identify opportunities to reduce the amount of postprocessing.

- 80%+ of the time for manufacture is in postprocessing.
    - Automated processes and qualified rework processes will improve throughput and yield.
- Processes: shakeout (de-gating), heat treatment, machining, welding/joining, coating.

7. What capabilities would a new or emerging technology bring that traditional manufacturing processes would not have?

- Accurate modeling can enable location specific material performance and requirements.
- Design margin (e.g., higher damage tolerance), productivity improvement (yield, throughput).

Track 5: New Emerging Technologies for NNS Manufacturing

1. Identify the top three emerging technologies for enabling the competitive manufacturing of domestic NNS components.

Additive Manufacturing

- Additive friction stir deposition. Additive forming, binder jet of sand molds, directed energy deposition. Multimaterial additive manufacturing.

Artificial Intelligence

- High-speed, AI-controlled, direct robotic deposition. Data-driven, flexible automation with hybrid processes.
- Human worker/operator augmentation with AI-enabled in situ process monitoring (automated flaw detection) for large-scale metal directed energy deposition.
- Automated quality assurance techniques (e.g., in situ monitoring used as a proxy for nondestructive inspection).
- Robotically controlled AI systems.

2. What are the technological advancements needed to enable and accelerate the technologies identified in Question 1 for >10-ton parts (assume a time frame of 3 years)?

Materials

- Much higher deposition rates.
- Directed energy deposition of large-scale superalloys/refractories.
- Raw material supply chain improvements—reduced cost materials.

Sensor Detection and Qualification

- Improved in situ sensing (and reduced cost of those sensors).
- Qualification efforts that are funded.

Modeling

- Generally, AM technologies are developed and demonstrated. Barrier to scale-up investment is ability to have confidence in the final part.
- Physics-based predictive models for large-scale processes.
- Software tools to efficiently analyze and make decisions using large data sets.

3. Is expeditionary manufacturing achievable for large metallic NNS components? Identify opportunities/technologies that would enable the manufacturing of components on or near the installation site.

Challenges

- Cannot do manufacturing without a factory with a controlled environment.
- Fabrication cannot get a quality stamp compared to manufacturing.

Solutions

- Yes, for applications that don't require major postprocessing (testing, heat treat, machining, etc.).
- Something "expeditionary" would have to factor in environmental changes and how they affect the process.

- Mobile machining centers. May require use of less robust machine tools like robots. More research to allow accurate machining with robotic machining.
- Airships move 100 tons (Lockheed project).
- Remove transportation logistic restrictions of waterways and roads.

4. What are the top three considerations you would prioritize when identifying or selecting an emerging technology for large NNS components?

- Cost of producing the components.
- Demonstrated products/technologies are easier to accept.
- Mobility.

5. What extent of postprocessing do large NNS components typically undergo for your application? Identify opportunities to reduce the amount of postprocessing.

- Heat treatment, NDT, and finish machining.
- In situ monitoring techniques to drive down post-build NDT.
- Determine the “good enough” functional requirement thresholds for surface quality versus “because that’s always been the spec.” Revisit specs to determine applicability on an application-specific basis. Can sometimes remove 95% of postprocess work by redefining requirements.
- Additive process with fine/coarse resolution to potentially avoid some machining.

6. What is the estimated cost to develop a manufacturing method/process capable of producing a full-scale NNS metallic component at TRL 7 (system prototype demonstrated in relevant environment)?

- “Near” net shape already exists, or close to it; <$10 million.
- Under $10 million, over $1 million for setting up.
- Capital cost of equipment alone ($1–$5 million).
- Rather than focus on development of processes, invest in the processes already available.
- Can get to TRL 5 with $3 million, TRL 6 with $10 million, and TRL 7 with $20 million—relativity.
- Estimate $100–$200 million to develop large-scale metal AM technologies capable of producing NNS. However, to go from NNS to net shape at industrial scale at TRL 7 would require investment of $1–$1.5 billion to solve the postprocessing challenges (machining, etc.).

7. What capabilities would a new or emerging technology bring that traditional manufacturing processes wouldn’t have?

- Faster (rapid), better (design optimization), cheaper (less waste/assembly), Made in the USA.
- Ability to automatically label and store data that can be leveraged as training sets for AI/ML algorithm development—further acceleration to technology development. With additive as well there is pedigreed data for every square inch of material.
- Complex internal build capability.
- New designs with optimized performance, optimized flow, optimized reliability; integrated components with fewer-piece parts.
- Better material efficiency, better performance parts, better performing devices.

8. Are there any specific challenges or topics from Breakout Session 1 that need further discussion?

Materials

- Wire feedstock for additive manufacturing is more expensive than cast part feedstock. Powder is even more expensive.
- Availability of alloys and wire feedstock supply chain for base alloys (steel) is stable, but more expensive than casting overseas.

Government

- Government-funded user facility to help industry adopt technology.
- Government should understand that funding should be large and focused— large budgets that get distributed over consortia do not cut it.

Track 6: Emerging Technologies to Improve the Resilience of NNS Manufacturing Supply Chains

1. Identify opportunities to enable the domestic NNS manufacturing sector to be less reliant on foreign supply chains.

Workforce Development

- Improve workforce availability and diversity of skill sets by enabling communication across disciplines (for example, through software and social media).
- Support efforts to revive trade/skilled worker training and develop new methods of replacing traditional apprenticeship programs.
- Developing collaborative systems through data analytics to help machines and humans work together effectively and efficiently.
- How to provide capabilities to small and medium-sized companies with limited resources.
- Watchdog organizations could help prevent monopolies that hamper innovation.

- A clearinghouse organization could consolidate the demand signals from customers and relay them to manufacturers.

Technology Development

- Novel creation, processing, and recycling of feedstock materials for AM processes.
- Precision manufacturing at high temperatures for induced material property control.
- Continuous support for material development with emphasis on technology transfer.
- Hybrid manufacturing and design optimization to minimize material use.
- In situ nondestructive evaluation technologies in hybrid systems to assure quality.
- Faster material and process qualifications to bring technologies to market more quickly.

Manufacturing Capacity

- Sectional creation of large-scale parts to leverage distributed manufacturing.
- Compiling current capacity at existing/legacy providers. How much capacity do we need to add?
- Databases of manufacturing across the country with their specialty and capabilities could connect customers with manufacturers.

Data Transfer

- Improved data sharing without competitiveness.
- Cybersecurity process for trusted information transfer across critical manufacturing outfits, including setting up ITAR (International Traffic in Arms Regulations) processes.
- Federated learning could support data transfer without exchanging proprietary information.

2. Identify opportunities to leverage cross-sector (e.g., power generation, heavy equipment, defense, marine/shipping) manufacturing needs to strengthen the overall domestic manufacturing base for large metallic NNS components.

Workforce Development and Education

- Cross conference or workshops.
- Continuous education programs interdisciplinary training and education.

Technology Development

- Scalable finishing systems (e.g., machining) whose limits are not defined by contained build volume.

- Most automation control solutions are proprietary, or very poorly documented. Open control systems would enable cross-sector automation and integration.
- Make technologies more accessible, not necessarily more advanced.
- Mining previous inventions for future applications.
- Provide incentives for academic institutions or research organizations to use their findings in practical applications. There is very little incentive to go any further than the first publication.

Communication

- Raising visibility of problems in manufacturing.
- Share advancements and progress. Physics solutions are commonly analogous, even across some disciplines.
- Develop strategic national list of needs for large manufacturing facilities.

Manufacturing Capacity

- Modular manufacturing to ease burden of manufacturing and transportation of large parts.
- Provide approaches to assist companies working on defense, nuclear, ITAR, and EAR (Export Administration Regulations) products, to maintain separate information and data to make their capacity available.

3. Identify the most impactful opportunities for reducing component lead time. What is a reasonable lead time target for delivering large NNS components to a customer?

- Two-year lead time for nuclear components. Current lead time is 10 years.
- Lead time for DOD components is several weeks.
- Automotive industry wants new car models every year, meaning lead times of 1 month.

Qualification

- Ensure specifications are focused on performance and not necessarily all the aspects that can be measured.
- Developing understanding of manufacturing product quality. Understanding compliance requirement for different products.

Critical Components

- Having backups of critical components (i.e., configuration management).
- Having quick lead times for emergency backup parts while waiting for replacement components with high lead times.

Manufacturing Capacity

- Manufacturers are encouraged to fill 100% of capacity, which creates backlogs. Incentivizing and/or de-risking excess capacity could reduce lead times.
- Reconfigure factories to be more to serve multiple industries by repurposing material, equipment, or plants for new applications.
- Flexibility in the way or method of manufacturing.
- Companies' metrics of success are based on profitability and not productivity.

Fault Detection

- Replace routine inspections with more accurate structure health monitoring and embedded sensors.
- Feature complexity is associated with analogous measurement complexity. Can this be reduced, eliminated, or performed in situ?

4. Identify the technology solutions and/or interdependency coordination to realize potential cost benefits of a robust domestic supply chain for large NNS components.

Technology Solutions

- Improved process modeling tools/computation for hybrid systems.
- Shared materials models for process modeling.
- Leverage existing competencies and resources.
- Identify crosscutting, transformative technologies and make them accessible.

Collaboration

- Faster turnaround of IP/patent claims.
- Remove unnecessary bureaucracy. More time (and therefore cost) is often spent negotiating than working.
- Customer commitment. Need assurances from customers and consistent demand.
- Know needs are for the various industries so that nationally strategies can focus on the synergetic processes.
- Change contracting model of shared risk, encouraging collaboration and interdependency, and not just the final produced component.
- Enable industry to share data more freely without losing profitability.

Technology Transfer

- Business incentives to encourage companies to implement new processes.
- Engineering and research centers to help bring technologies to market.

5. How can we simplify transportation and logistics of the value chain to reduce costs and/or enable on-site manufacturing?

- Feedstock on demand.
- Machines that can use flexible feedstocks.
- Digital manufacturing needs to be covered and supported with knowledge management in mechanistic understanding.

Breakout Session 3: Implementation Pathways

Track 7: Technology Demonstration, Transition, and Scale-Up Needs

1. Identify supply chain segments that need to be engaged to successfully demonstrate, transition, and scale up a domestic NNS manufacturing capability. Identify teaming mechanisms and/or best practices across the supply chain.

Teaming Opportunities to Improve Supply Chain

- Cooperative Research and Development Agreements; via this method no funds are exchanged and there is no contract; services/materials are traded with IP rights.
- Teaming mechanisms should be federally funded programs with limited cost share requirements for team members to engage and incentivize the industrial base.
- DOE and DOD collaboration, intra-agency office collaboration.
    - Federal interagency working group—DOE, DOD, NSF, U.S. Navy etc. See other task forces (U.S. Department of Homeland Security, joint program offices, DOE/DOD Wind Radar federal working group).
- Teaming in AM supply chain: wire producer, large-scale AM parts manufacturer, machining provider, casting provider, contract assembly/installation provider, end-use customer.

Demonstration Project Concepts

- Public/private partnership with agile entities focused on end-to-end rapid demonstration.
- Host a contest to quickly produce an infrastructure-scale part that meets all mechanical and quality requirements.
- Production processes to manufacture mooring lines and tethers for offshore wind.
- Use sensors embedded in a 3D printed sand mold to validate a solidification model, developing understanding of density of sensors required.

Workforce

- Need to include community colleges, universities, trade schools, etc. to help foster workforce.
- Identify and reduce barriers that prevent existing workforce demographics from entering the labor market (i.e., childcare, citizenship status, etc.).

Logistics

- Infrastructure to transport these components can be time-consuming to build/operationalize. Need to highly consider location/region of various nodes within these supply chains for optimal placement.

Standards and Performance

- If a certified and deliverable product is a major goal of this effort, we need to foster system-level-performance understanding vs. focusing on just a part or qualification.
- Need to start with the end goal in mind—e.g., we need a White Sands for other industries where we can effectively test our developments.

2. What starting TRL is needed for industry to independently fund and complete development and subsequent commercialization of a manufacturing process/method for large NNS components?

Technology Readiness Level

- TRL 6, as TRL 5 and lower can result in considerable cost and delay. (ROI in <2 years required for NNS)
- TRL 4 industry can begin buying articles, but continued funding needs to carry to TRL 5, 6, and 7.
- TRL 8 is required for industry to independently fund further development. Actual system completed and qualified.
- Nuclear industry example: DOE's Advanced Reactor Development Program (ARDP) award to develop a nuclear fuel concept from TRL 3 to commercialization for $200 million over 7 years.
- Industry involvement needs to happen early on to make sure technology is transferable. Manufacturers looking at next-gen technology need a pipeline to advance the technology.

Demand for New Technology

- The motivation to invest in technology starts with demonstrated demand.
- The technology must be embedded in a supply chain and a market sector with a business case.
- If OEMs are not going to purchase domestically, there is little incentive to invest.

Risk

- Need to underwrite industry purchases with tax credits, which could fuel innovation in AM companies, build workforce, and advance TRL/MRL organically.
- Risk/reward can change the TRL/MRL required.

    - ORNL's MDF allows companies to explore a technology at an early stage to see if it's something they want to continue with.

3. Identify technology/component demonstration opportunities that could be performed within a ~3-year window that would meaningfully impact the domestic manufacturing base. What is needed to accelerate these development efforts?

Digital Technologies

- Digital foundry (public/private partnership). Activate tangible end-to-end demonstrators to communicate capability and accelerate iteration/innovation cycles.
- Develop a digital repository of material properties for a given alloy with a given process.

AM Technologies

- Additive friction stir deposition can be used to produce parts in the materials and scale required by NNS. Investments need to be made to enable qualification in specific materials.
- Direct casting/drawing of wire feedstock to demonstrate wire cost reduction.
- Develop capability for digitally controlled deformation to complement additive manufacturing.
- DOE/DOD fund and enable multiple AM systems in the United States that could handle the parts for offshore wind and target the fundamental AM issues.

Finishing Technologies

- Develop advanced, infrastructure-scale finishing machine, capable of machining current cast NNS parts.
    - Finishing capabilities could improve confidence in domestic capability and spur some spontaneous individual efforts in industry.
    - Existing CNC machines for Francis turbines in hydropower applications may be an ideal candidate.

4. Is qualification/certification a significant barrier to putting a component into service? If so, identify opportunities/actions needed to accelerate the qualification/certification process (e.g., digital data sets, coordination with codes and consensus standards).

Barriers

- Current standards were based on old processes and may not apply for new processes.
    - Counterpoint: Existing qualification/certification standards and processes can be applied to AM parts without modification for some applications.
- A qualified part, material, or process does not necessarily mean the product will be readily certifiable. Need to connect product integrity to system-level performance and reliability.

- Professional society code development rigidity and government/industry reliance on those codes are barriers.
- The current process is expensive; could be mitigated by increasing the availability and lowering the cost of performing these activities.
- Need resource to test more at system level with limiting risk or consequence of failure.

Advanced Sensing

- The availability of advanced and multiple sensing technology requires capabilities to turn sensing data into confidence in qualified parts.
- Need a mechanism to use sensor data to support qualification/certification.

Data Management

- Need publicly available testing database to compile results.
- Certification/qualification reviewers need a way to review large amounts (several gigabytes) supporting data that is uncomplicated and understandable.

Technical Opportunities

- Validated ICME.
- Availability radiography, computed tomography, or other volumetric nondestructive evaluation as a cost-effective service to accelerate the acceptance (qualification/certification) of parts.

Collaboration

- Need for strong collaboration with qualifying entity from the beginning stages of the project.
- There is often very little difference in approval time, process, or reporting for $50,000 collaborations vs. $5 million collaborations. Incentivize rapid collaborations (even for lower dollar amounts) to foster collaborations.
- Government-owned, contractor-operated (GOCO) could be a useful model to come back to.
- Form and partner with a private tech council with a track record of implementing revolutionary technologies at large scale.
- Maintain significant strategic federal investment in public/private partnership with very long signal response.
- “Stop power pointing, start prototyping”: Activate end-to-end technical and workflow demonstrators that spur innovation cycles.

- A learning tool for better understanding the qualification/certification process is desirable.

Track 8: Education and Workforce Development Needs

1. What are the most impactful workforce competencies needed to realize a strong NNS manufacturing base?

- Materials science with hands-on experience and technical communication competencies.
- Diversity of thinking, knowledge, and skill sets: manufacturers must have a breadth of knowledge in different manufacturing techniques.
- Basic coding skills are necessary to understand advanced processes, which are increasingly software-driven.
- Mechanical skills have been lost because of digital technology and difficult-to-repair technology.
- For additive friction stir deposition, retraining CNC machine operators would be a useful pilot development program.

2. Do currently available curricula, programs, and delivery mechanisms related to NNS manufacturing meet your EWD needs?

- Making training programs valuable to workers and comparable to university education.
- Companies are reluctant to give additional training to their employees, since time away from the factory floor results in decreased productivity. Need to incentivize small companies to be able to train employees.
- Erosion of trust in federal institutions. Better that incentives come from state and local level.

3. Identify professional or continuing education programs in NNS manufacturing.

- DOD's and Institute of Advanced Learning and Research's Danville workforce training facility.
- America's Cutting Edge (ACE): UT, ORNL, IACMI.
- Excellence Training Center (ETC) at Youngstown State University (YSU).
- YouTube.
- DIY/maker communities.
- Free online courses and training programs with certifications for data analytics and machine learning.

4. Identify most important diversity, equity, inclusion, and access considerations in the NNS manufacturing base/workforce?

Demographic Considerations

- Reaching out to underrepresented/underserved communities. Underprivileged communities (urban or rural) do not have opportunities for jobs, skills, training.
- Diversity of experience/background can drive dramatically different training/education requirements.
- Reaching out to historically agriculturally focused communities who have not previously considered manufacturing.
- Workforce training and outreach focused on supporting women in STEAM.
- Most training programs are geared toward students, but there are many people aged 40+ who could be retrained to meet the needs of today's manufacturing work.
- Accessibility of success stories for people from varied backgrounds.

Primary Education

- Disparity of educational resources at primary education levels.
- School programs can demonstrate concepts opportunities in STEM from an earlier age.
- Making technical concepts more fun and approachable would also make them more accessible.
- Educating educators to better inform students of opportunities available to them.
- Helping younger generation understand that manufacturing is not what it used to be.

Secondary Education

- How to engage in mentoring with several hundred students at once?

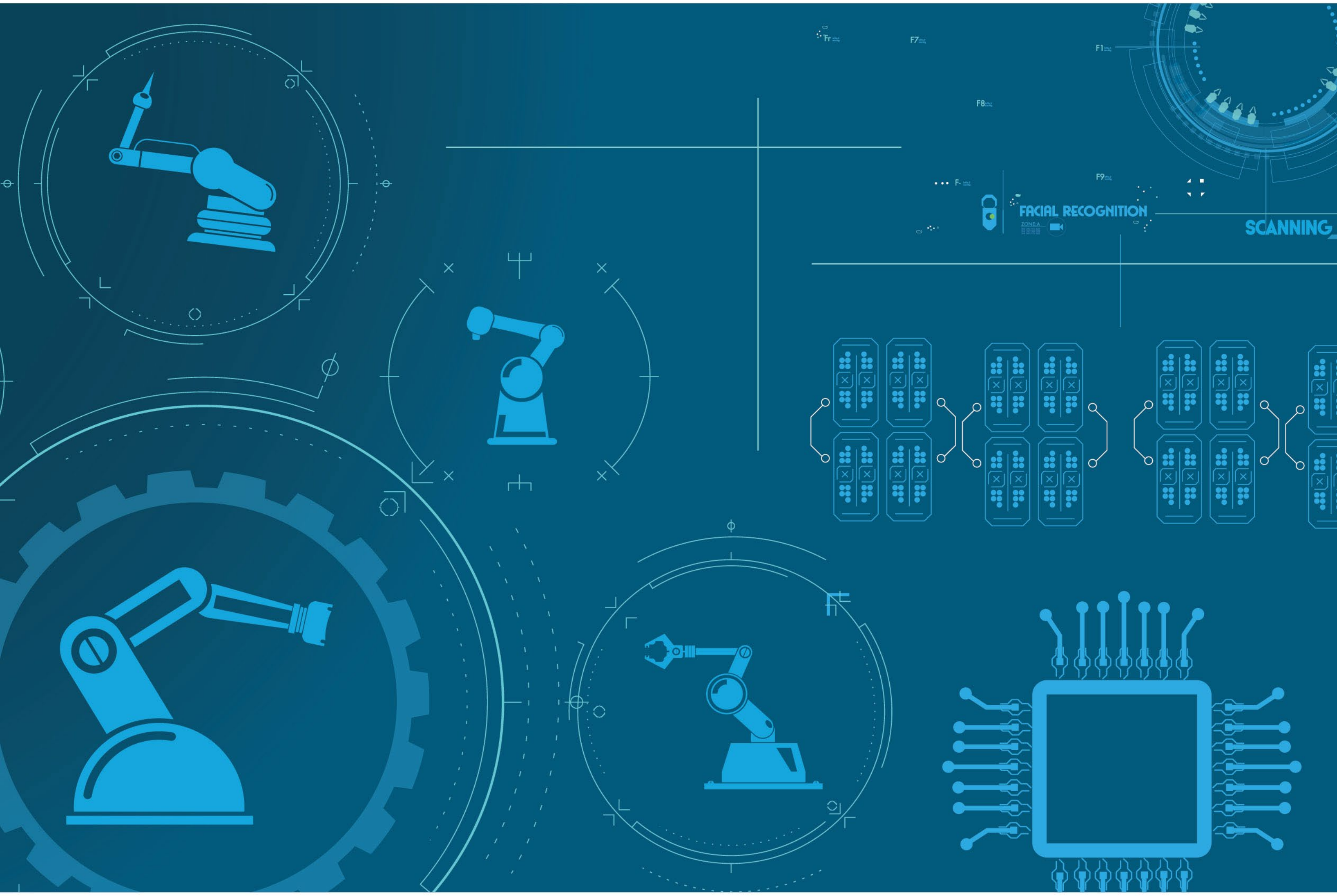
5. What are good models to grow and sustain a talent pipeline for the NNS manufacturing base?

- The word "pipeline" does not have the desired outcome. Talent "garden" is a much better metaphor. Gardening is a more inviting terminology and implies an element of nurturing.
- Internship programs to engage with students during their educational career. Enables training while students are being educated.
- Stop discouraging students from pursuing fields that are interesting to them.
- How can established workers and industry leaders give back to the younger generations?
- Improve expectations of "success." Encourage non-four-year degree paths for students.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

ADVANCED MATERIALS &
MANUFACTURING
TECHNOLOGIES OFFICE



For more information, visit: energy.gov/eere/ammto

DOE/EE-2691 • February 2024