U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Manufacturing Office

Workshop on Integrated Sensor Systems for Manufacturing Applications

Workshop Report

January 25-26, 2021

Within the DOE Office of Energy Efficiency and Renewable Energy (EERE), the Advanced Manufacturing Office (AMO) partners with industry, small business, academia, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

This document was prepared for DOE/EERE's AMO as a collaborative effort by DOE AMO, Boston Government Services, and Energetics.

Disclaimer

List of Acronyms

AI	Artificial intelligence
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AM	Additive manufacturing
AMO	Advanced Manufacturing Office
BES	Basic Energy Sciences
BS	Bachelor of Science
CEO	Chief executive officer
CESMII	Clean Energy Smart Manufacturing Innovation Institute
CMOS	Complementary metal oxide semiconductor
CRS	Congressional Research Service
CPU	Central processing unit
CTO	Chief technical officer
DOE	U.S. Department of Energy
DRAM	Dynamic random-access memory
HVACR	Heating, ventilation, air-conditioning, and refrigeration
EERE	U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy
EPA	Environmental Protection Agency
IoT	Internet-of-things
IEEE	Institute of Electrical and Electronics Engineers
FOA	Funding opportunity announcement
GE	General Electric
GPU	Graphics processing unit
GWP	Global warming potential
HFC	Hydrofluorocarbon
HPC	High performance computing
IP	Intellectual property
MIT	Massachusetts Institute of Technology
ML	Machine learning
MS	Master of Science
NRE	Non-recurring engineering
NSF	National Science Foundation
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory

PI	Principal investigator
PhD	Doctor of Philosophy
R&D	Research and development
RD&E	Research, development, and engineering
RD&D	Research, development, and demonstration
RF	Radio frequency
RFI	Request for information
ROI	Return-on-investment
SBIR	Small business innovation research
SC	Office of Science
SIA	Semiconductor Industry Association
SLAC	Stanford Linear Accelerator Center
SNR	Signal-to-noise ratio
SRC	Semiconductor Research Corporation
SWE	Society of Women Engineers
TI	Texas Instruments
VP	Vice President

Executive Summary

The Department of Energy's Advanced Manufacturing Office (AMO) held a virtual Workshop on Integrated Sensor Systems for Manufacturing Applications on January 25th and 26th, 2021. The workshop brought together over 140 leading scientific and technical experts to identify opportunities and technical challenges for applied research and development (R&D) that can advance the state of the art for integrated sensor systems. The workshop featured perspectives from sensor equipment manufacturers, facility operators, and system integrators and included breakout discussions on four main topic areas: 1) sensing platforms and materials; 2) energy sources and power conditioning; 3) analog and digital circuits and communications; and 4) monolithic and hybrid integrated sensor systems. Several themes that emerged throughout the workshop are interconnected and contribute toward the vision of developing sensor systems that can increase the competitiveness of U.S. manufacturing.

This workshop report summarizes the presentations, panel discussions, and breakout group discussions that took place at this event. Note that the results presented here are a snapshot of the viewpoints expressed by the experts who attended the workshop and do not necessarily reflect those of the broader sensor system development community.

Discussions at the workshop focused on exploring issues in three major areas: 1) technology applications, benefits, and metrics of integrated sensor systems; 2) research challenges for advanced sensor systems; and 3) R&D pathways to develop next-generation sensor systems.

Based on the common themes identified during the workshop, a number of high priority areas emerged:

Harsh Environments: Increasing sensor system capabilities in harsh operating conditions was highlighted as one of the greatest needs for manufacturing applications. Currently, the environments in which sensor systems can operate are very limited. Harsh service conditions lack robust sensor systems to provide high-fidelity spatio-temporal data critical to manufacturers. Manufacturers must accept current sensor capabilities and sacrifice spatio-temporal data by placing sensor systems outside of these environments. Stability of materials used in transducers and packaging must be improved for wide deployment in these environments. Extensive research into novel transducer and packaging materials is required to significantly improve sensor system stability, performance, and lifetime in harsh operating conditions. However, these materials must be compatible with current semiconductor manufacturing infrastructure. Alternative solutions leveraging non-traditional sensor operation include mobile sensors that reduce the time within the harsh environment and disposable sensors that are only designed to operate for short periods of time.

Wireless Technology: There was wide agreement that wireless capabilities are necessary for future

Figure ES-1: Priority Research Areas

- **Harsh environments:** Improving sensing capabilities in harsh operating conditions by developing robust materials for transducers and packaging and utilizing novel operating techniques
- **Wireless technology:** Deploying robust, reliable wireless sensor systems by developing novel materials, circuits, and energy harvesting techniques
- **Edge computing:** Increasing energy efficiency by limiting data transmission off-node through development of advanced analog hardware and computational strategies
- **Standards:** Establishing industry-wide standards in communication, data processing, and testing for improved component and system-level integration and validation
- **Increased industry coordination:** Coordinating a sensor industry consortium to accelerate commercialization by centralizing funding and research efforts

integrated sensor systems and that further advancements in wireless technologies are needed to meet performance requirements for many manufacturing applications. Wireless technology will enable easier retrofit of advanced sensor systems on legacy manufacturing equipment, significantly reduce the spatial burden of wired connections, and provide the freedom of integrating sensor systems where desired. Power handling of both wireless communication and wireless energy transfer, the sheer amount of data generated at the sensor node, limitations on usable frequency spectrum, extreme electromagnetic noise, and lack of reliability were identified as some the primary barriers that need to be overcome for widespread wireless sensor system deployment in manufacturing environments. Because of this, hard-wired sensor systems are still the preferred or only option in most cases. Improvements in analog circuits, use of wide bandgap semiconductors, and development of local energy harvesting techniques were identified as priority research targets to accelerate wireless deployment. As sensor nodes become more complex by integrating wireless and edge computing components, novel integration and power management schemes will become critical to address this complexity.

Edge Computing: Data transmission was highlighted as one of the most energy intensive operations and identified as a major obstacle in deploying wireless communication in integrated sensor systems. Efficient generation and transmission of actionable information, while disposing of unnecessary data, can be achieved by pushing data analysis and computation to the edge. However, to best accomplish this, advances in computational hardware will be required. Current analog electronics lack the necessary signal processing capabilities and rely on digital components for processing, which is more computationally intensive and generates enormous amounts of raw data in cases where high fidelity is needed. Development of novel edge computing strategies and analog hardware will significantly reduce latency, reduce power consumption, increase reliability, and ultimately, improve energy efficiency. As noted above, incorporation of these components at the node will add a layer of complexity in power management and integration.

Standards: Developing standards for communication and data processing will enable significant acceleration in wireless sensor system design and deployment. In numerous discussions throughout the workshop, participants voiced their concerns over the lack of standards in the sensor industry, limiting integration of sensors and auxiliary components and pathways for innovation. As the electronics industry pushes for more internet-of-things (IoT) devices and wireless capabilities, standards in communication and data processing will be paramount to establishing interoperability across different sensor components and building confidence and interest from both system developers and users. In addition, developing standard testing protocols was identified as a key priority to validate and deploy new sensor technology. As it stands, there is no industry standard for testing, often leading to inconsistent testing and validation methods.

Increased Industry Coordination: Coordinating a sensor industry trade association or consortium was identified as a mechanism to address many of the cross-cutting challenges raised during the workshop. The sensor consortium can act as a centralized organization to develop technology roadmaps; distribute sensor R&D funding; coordinate the development of standards in communication, data processing, and testing; provide a pathway for new technology commercialization; and establish programs focusing on workforce development.

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Background and Workshop Proceedings

On January 25th and 26th, the Department of Energy's Advanced Manufacturing Office (AMO) held the first in a series of workshops on different topics related to semiconductor research and development (R&D). This workshop focused on integrated sensor system R&D for manufacturing applications. As AMO is housed within the office of Energy Efficiency and Renewable Energy (EERE), the workshop addressed not only industry needs and R&D opportunities, but also the impacts that improvements in sensor systems can have on energy efficiency and greenhouse gas production. The output of this workshop will inform AMO's future portfolio of R&D investments, provide perspectives on trends, drivers, and challenges for next generation semiconductor sensor systems, and help the stakeholder community understand the opportunities on the horizon.

Workshop Series

Semiconductors power key products that are rapidly growing in importance in all sectors of the economy including consumer goods, finance, transportation, and manufacturing. Advances in semiconductor technology are critical for global competitiveness as well as economic and national security. According to an October 2020 Congressional Research Service (CRS) report, the semiconductor industry in 2019 had $424 billion in sales with the U.S. accounting for roughly half (Platzer, Sargent, and Sutter 2020). The CRS divides the industry into four segments, shown in Figure 1. Because of its economic importance and the potential for its products to improve quality of life and reduce energy use in other sectors, growth of the semiconductor industry is desired; but innovation is needed to ensure this growth is accompanied by major improvements in energy efficiency. In the past, semiconductor industry and product energy-use was flat or declining due to efficiency innovations, but energy inefficiencies increasingly limit performance (SIA 2019).

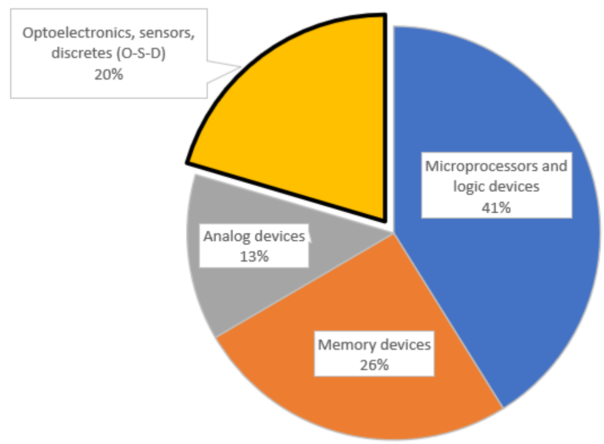

Figure 1: Market segments of the semiconductor industry and the breakdown of sales, in percentages. Sensors (grouped with optoelectronics and discretes — referred to as O-S-D) account for 20% or nearly $85 billion in sales.

Multiple trends in semiconductor related energy use are combining to make increased energy efficiency a top priority for the industry. These trends include the decreasing of energy consumption of semiconductor manufacturing processes; the decreasing of energy consumption per chip; and the acceleration of the use of microelectronics in products and processes—which, ultimately, drives the overall energy use of semiconductor industry processes and products.

The semiconductor industry's emphasis on energy efficiency of its products and manufacturing processes aligns with AMO's goal to reduce the lifecycle energy use of manufactured products in general. Furthermore, deployment of advanced, integrated sensor systems can reduce manufacturing energy use while increasing productivity and competitiveness of the US manufacturing industry, accelerate decarbonization of energy intensive industries through electrification, spur domestic job creation in the semiconductor industry, and combat the climate crisis through reduced energy consumption across all sectors that utilize semiconductor technology. Based on this strong alignment of goals, AMO believes that it can play an important role in integrated sensor system R&D for manufacturing and help manufacturers remain internationally competitive.

Workshop Motivation

The segment of the semiconductor industry with the most direct impact on manufacturing energy use is sensor systems. Sensor systems capable of automatic, real-time adjustments will greatly increase precision, reduce equipment downtime, and even enable a far greater degree of material and product customization. Moreover, these sensors will enable automated control systems used by manufacturers to achieve higher precision, lower costs, improved performance, and increased energy efficiency of existing operations. Sensors are also critical to obtaining the large amounts of data required by machine learning enabled analysis methods that continue to improve our understanding of materials and processes, and in turn, our ability to control them. Integrated sensor systems are also key to enabling industry decarbonization efforts such as the substitution of highly controlled electric powered processes for fossil powered thermal processes.

Semiconductor devices, fabrication methods, and system integration approaches provide foundational technology for a variety of integrated sensor systems from sensing platform, signal- and power-conditioning, to communicating. Low-power consumption sensor systems are critical for enabling wireless operation of large numbers of networked sensor system arrays.

AMO analysts estimate that deployment of smart manufacturing – for which sensor systems are a necessity – could reduce up to 15% of all manufacturer's energy use. While the integrated sensor systems themselves use additional energy, it is a tiny fraction compared with the significant energy savings estimated. Still, integrated sensing platforms need to become more energy efficient in order to operate and communicate wirelessly. Low-power sensors that operate on harvested and stored energy avoid the considerable burden of integrating hard-wired connections to provide energy and communication pathways to each sensor node. Despite this burden, nearly all manufacturing sensor systems are still hardwired due to the lack of commercially available wireless sensor systems.

As the manufacturing environment becomes more complex and manufacturers integrate more sensors to better monitor and control manufacturing processes, advanced integrated sensor technology will become critical in reducing the "data deluge" through local data processing and increasing energy efficiency through limited data transmission. As this data comes in as analog signals, improvements in analog electronics are key to enabling computing "at the edge" needed to dramatically increase sensor systems' ability to reduce this data deluge. The Semiconductor Research Corporation's (SRC) 2020 Decadal Plan notes advances in analog electronics, including 100,000x reduction in data communicated by integrated sensor technology, as one of its five seismic shifts necessary to maintain America's position as a global leader in innovation (SRC/SIA 2021).

Workshop Overview

To better understand the need for integrated sensor systems in manufacturing and the federal role in this area, the U.S. Department of Energy (DOE) held the Workshop on Integrated Sensor Systems for Manufacturing Applications on January 25-26, 2021. Representatives from industry, academia, the DOE national laboratories, and non-governmental organizations gathered virtually to hear presentations and participate in informative panel discussions with subject matter experts, as well as contribute to topical breakout discussion/brainstorming sessions.

This workshop report summarizes the attendees' input on the needs, challenges, and opportunities in the development of integrated sensor systems from presentations, panels, and breakouts. In this report, the terms "sensor" and "sensor system", although related, do not mean the same thing. The "sensor" is the element or device that senses the desired phenomena and converts it to an electrical signal while the "sensor system" includes all support components that digitize, process, and communicate the data associated with that signal. In other words, the sensor system includes all of the auxiliary components including electrical circuitry, packaging, and wiring of sensor modules and intermediate data routers.

Below is a brief overview of the workshop agenda. More detailed summaries of the talks are included in Appendix B.

Day 1

On the first day of the workshop, participants learned about the industry needs for advanced, integrated sensor systems. The morning featured introductory talks by Technology Manager and workshop series organizer Tina Kaarsberg and AMO (acting) Office Director Valri Lightner, as well as talks by chief technology officer (CTO) of the Clean Energy Smart Manufacturing Innovation Institute (CESMII) Haresh Malkani and the vice president (VP) of Research of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Xudong Wang.

Dr. Kaarsberg gave an overview of the workshop highlighting the urgent need for energy efficiency in both semiconductor products themselves and in manufacturing products and processes—especially in light of the Biden-Harris Administration's ambitious climate impact reduction goals. Director Lightner summarized how integrated sensor systems can greatly help in achieving AMO's goals for reducing manufacturing energy use and provided several examples of past AMO-supported R&D for sensors. Ms. Lightner also provided a general overview of AMO and its mission in reducing energy impact. Both discussed how the workshop aligns with AMO's guiding principles and the importance of participant feedback on how federal investment can push this field forward.

Haresh Malkani and Xudong Wang provided industry perspectives of the current needs in sensor technology and highlighted the challenges the industry faces in development and deployment of integrated sensor systems. Dr. Malkani gave a brief overview of CESMII and the needs of advanced sensing technology in smart manufacturing. Dr. Wang discussed the applications and importance of sensors in the heating, ventilation, air-conditioning, and refrigeration (HVACR) and water heating industry.

The afternoon of the first day included three panel sessions that featured perspectives from three major categories of industry stakeholders that leverage integrated sensor systems: System Developers & Integrators; Facility Owner/Operators; and Sensor Equipment Developers.

The first panel focused on perspectives of developers that assemble the integrated sensor systems. These manufacturers do the critical work of choosing the individual types of sensing data needed and integrating the sensors to gather this data into complete systems. The second panel focused on perspectives of facility owners & operators, which are the primary users of integrated sensor systems for manufacturing. The third panel focused on perspectives of sensor equipment developers.

Day 2

The morning of the second day focused on the research and development pathways necessary to advance integrated sensor systems. Dr. Yarom Polsky, the section head for Energy Systems, Integration, and Controls at Oak Ridge National Laboratory (ORNL), discussed the lab's rich history and future outlook on sensor technology for manufacturing, including a new systems engineering paradigm driving major advancements in integrated sensor systems. Following Dr. Polsky, Jim Wieser, Chair of SRC's Chapter on Analog electronics and Director of University Research and Technology at Texas Instruments spoke about SRC's Decadal plan for Semiconductors and the need for data reduction through edge computing for sensors and other applications.

In the afternoon, attendees were broken up into parallel breakout sessions for more targeted technical discussions on applications, challenges, and opportunities. During the breakout sessions, the participants were divided into the following four parallel breakout groups to specifically discuss and address critical aspects of the integrated sensor system and how to enable their integration into larger systems for manufacturing applications.

- **Breakout Group 1: Sensor Platforms and Materials**, focused on novel materials, designs, and processes for new sensors and sensing platforms.

- **Breakout Group 2: Energy Sources and Power Conditioning**, focused on energy sourcing and power conditioning needs and the energy challenges associated with wireless integrated sensor systems.
- **Breakout Group 3: Analog and Digital Circuits and Communication**, focused on the computing and communication needs of sensor systems.
- **Breakout Group 4: Monolithic and Integrated Sensor Systems,** focused on emerging technologies and opportunities around integrating individual sensor components with other supporting components as well as technologies necessary to retrofit mature manufacturing equipment.

The discussions in each breakout group occurred in three segments:

Breakout Session 1: Technology Applications, identifying how each sensor technology would be deployed as part of the system, including the most important potential applications areas and use cases.

Breakout Session 2: Challenges, identifying existing and emerging challenges for each aspect of the integrated sensor system. Current workarounds to existing challenges were identified.

Breakout Session 3: R&D Pathways, identifying the R&D pathways necessary to overcome the challenges identified in Breakout Session 2.

The day concluded with the technical chairs of each breakout session reporting their conclusions. The workshop agenda is shown in full detail in Appendix A. The remarks made by speakers, panelists, and participants have been combined across all workshop sessions and organized topically and presented in Chapter 2: Summary of Results.

Summary of Results

A. Integrated Sensor System: State-of-the-Art

Sensor systems currently deployed in most manufacturing environments all use wires for both communication and power; use silicon-based components that limit the range of environments in which they can operate; and are mainly designed and manufactured by large original equipment manufacturers (OEMs). They primarily collect data and send it to an external database or the cloud for analysis by an engineer or technician. These systems require manual input to make changes to the processes. Real-time automated process improvement is still a far-off goal for such systems. Furthermore, electromagnetic noise, unreliable networks, and the lack of advanced computing capabilities at the sensor node – to reduce data transmission needs – limit deployment of wireless communication in integrated sensor systems.

Advancements sensor systems have made in recent years have not kept pace with the progress in mainstream semiconductor technologies[1] due to a confluence of factors. Most of the physical sensors that makes up a sensor system use standard complementary metal oxide semiconductor (CMOS) manufacturing processes and therefore a large majority of sensor design and production is limited to large foundries that require high volume sales to achieve a return-on-investment (ROI) for their considerable R&D expenditures. At the same time, sensors for sensor systems – especially for manufacturing applications – often require application specific customization and integration of specialized materials, which increases their non-recurring engineering (NRE) costs and limits their demand volume. This has resulted in a paucity of sensor R&D funding and caused sensors to lag behind other semiconductor industry products in innovation. Most of the advanced capabilities such as in-situ materials characterization or film property monitoring are not available for wide deployment in manufacturing environments and are primarily limited to small-scale research facilities.

B. Technology Applications, Benefits, and Metrics

A major topic of focus throughout the workshop was technology applications of integrated sensor systems. At various points, speakers, panelists, and attendees mentioned specific application areas; the benefits of using integrated sensor systems in these areas; and the metrics to quantify the identified benefits. These points have been captured and summarized in the Table 2-1 below. The participant responses from Breakout Session 1 that did not fall under applications of sensor systems for manufacturing or were not directly relevant to the workshop are captured in Appendix C.

Most of the applications raised in the workshop leveraged the process monitoring and control capabilities of advanced sensor systems, instead of post-production testing and validation. Future sensor systems can enable measurement of traditionally hard-to-measure, in-situ parameters such as real-time defect counts in additive manufacturing, chemical reactions rates and environmental conditions, and various materials properties during deposition and crystal growth. Advances in edge computing will enable real-time, dynamic control to ensure processes are always within specifications. Finally, robust transducer and packaging materials will enable sensor systems to be utilized in harsh service conditions, providing manufacturers with critical spatio-temporal data within their process chambers.

The benefits derived from developing more advanced sensor systems can be grouped into the following three categories:

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[1] Technologies such as central processing units (CPU), graphics processing units (GPU), memory technologies, and integrated circuits (IC) for mobile applications

Manufacturing process benefits: The most tangible benefits from improving advanced sensors systems for manufacturing are those that affect the manufacturing processes themselves. Developing sensor systems to have in-situ characterization and dynamic process control capabilities can eliminate backend testing by ensuring the process stays within process specification at all times. This reduction in time spent on backend testing and overall scrap (out-of-spec product) rate will improve manufacturing competitiveness. Additionally, with more accurate and capable processes, tool downtime can be minimized and open-loop, quality control testing may even be eliminated.

Sensor system benefits: Developing sensor systems with more robust materials and novel integration schemes will improve sensor stability in continuous manufacturing environments, where many sources of interference exist, and open up new sensing opportunities in harsh environments.

Energy benefits: Increasing edge-computing will decrease total system energy usage through reduction in data transmission, which in turn, will increase energy efficiency of the sensor system. Advanced sensor systems with heightened sensing resolution and dynamic process control will help reduce the process intensity of many manufacturing processes.

Discussion during the workshop also touched on the metrics used to quantify the benefits above, which are divided into major categories, summarized here:

Financial metrics: Financial metrics, such as profit-margin, ROI, capital deployments, and operating expenses, were recognized as the most compelling metrics for demonstrating the value that advanced sensor systems can provide. Given the role sensor systems play in the overall manufacturing ecosystem and the fact that their specific applications differ across different industries and manufacturing processes, financial metrics can rarely be directly tied to sensor system outputs. Therefore, the additional metrics described below are used to link sensor systems to financial impacts. However, it can be reasonably predicted that sensor systems that are able to function as intended in harsh service conditions, accurately monitor and control manufacturing processes to continuously keep them within specified parameters, and have the ability to identify defects in-situ will allow for significant reduction in operating costs and waste material. Determining the relationships between various types of metrics will enable a more direct calculation of financial impacts.

Manufacturing metrics: Broadly speaking, throughput, yield, and process capability (c_p, c_{pk}) are all standard manufacturing process metrics that can be measured to evaluate the efficacy of deploying an advanced integrated sensor system. Comparisons to baseline c_{pk}'s for specific manufacturing processes can be made to quantify the benefits that sensor systems provide.

Energy metrics: Sensor system energy efficiency and manufacturing plant energy usage are two metrics that manufacturers can directly measure. Future sensor systems with advanced capabilities in edge computing will see drastic increases in sensor system energy efficiency but also reduction in manufacturing plant energy usage through more sophisticated and real-time process control. This in turn, can reduce the energy intensity of manufacturing processes.

Performance metrics: Data processing rates and communication fidelity will be two critical metrics to evaluate when edge computing and wireless communication become widely available in sensor systems. With the development of more robust materials, novel energy sources, and power conditioning, sensor system stability and lifetime will be useful metrics as well.

Commercialization metrics: Sensor systems that have higher resolution measurements, continuous feedback, and in-situ measurement capabilities will allow for faster development time for R&D deployment in manufacturing products and shorter time-to-market.

Table 2-1: Applications, benefits, and metrics of integrated sensor systems

Applications

- Environmental monitoring in ceramic firing furnaces
- Strain and displacement sensing in steel slab casting
- Defect detection in additive manufacturing
- Process monitoring control for thin film deposition in semiconductor processing
- Manufacturing equipment condition monitoring for continuously operating manufacturing environments
- In-situ characterization of material properties
- Retro-fitting existing manufacturing equipment with new sensor systems

Benefits

Manufacturing Process Benefits

- Eliminate backend testing
- In-situ materials characterization
- Real-time, dynamic process control
- Improve manufacturing competitiveness by reducing cost and improving energy efficiency
- Autonomous optimization of manufacturing processes
- Reduced scrap rate

Energy Benefits

- Increased energy efficiency
- Reduced energy intensity in manufacturing
- Reduction in energy usage through reduced data transmission
- No dependence on battery technology

Sensor System Benefits

- Improved stability
- Energy harvesting in harsh environments
- New materials for sensing in new/harsh environments

Metrics

Financial

- Capital deployments
- National GDP
- Revenue
- ROI of sensor system
- Work hours saved

Manufacturing Metrics

- Throughput
- Product yield
- Tool downtime
- Process capability (c_p, c_{pk})
- Quality control pass/fails

Energy Metrics

- Plant energy usage
- Sensor system energy efficiency
- Manufacturing energy intensity

Performance Metrics

- Data processing rates
- Communication fidelity
- Sensor system stability
- Sensor system lifetime

Commercialization Metrics

- Time to market
- Development time

C. Challenges

At multiple points in the workshop, speakers, panelists, and participants discussed current and emerging development opportunities, anticipated advantages, and barriers to realizing advanced integrated sensor systems. Sensors for harsh environments and wireless technology for power and communication consistently arose in discussions and were regarded as presenting the greatest need for advancement in order to realize increased benefits and deployment in manufacturing applications. Generally, the challenges discussed throughout the workshop can be categorized into five themes which are summarized here:

Harsh environments: The environments in which sensor systems can operate is very limited. Harsh service conditions such as high temperature, high pressure, high mechanical stress, and corrosive chemical environments lack robust sensor systems to provide high resolution spatio-temporal data critical to manufacturers. The greatest challenge facing broader deployment is the stability of the materials used in sensor systems; current transducer materials are not robust enough to withstand the harsh environments for long durations. Furthermore, research into packaging materials has lagged behind that of transducer materials, becoming the limiting capability when choosing a suitable environment for the sensor system. When placing sensor systems in harsh environments, there is an additional challenge of powering the system; traditional, wired connections typically cannot withstand the sensing environment. Due to the lack of sufficiently robust materials and challenges in powering sensor systems, manufactures are often left to sense the harsh environment from outside the tool sacrificing critical spatial and/or temporal fidelity on their processes.

Wireless technology: The plenary speakers and panelists all stated that wireless sensing technology is the path forward for integrated sensor systems; however, there are significant challenges before realizing this future. Current power handling capabilities cannot sustain both wireless communication and wireless energy transfer for significant periods of time. The sheer amount of data generated at the sensor node and limitations[2] on usable frequency spectrum typically make wireless communication unpractical for sensor nodes. Furthermore, wide deployment of wireless sensor systems will require appropriate network management to ensure continuous communication and network connectivity while accommodating numerous wireless nodes. This was cited as a key bottleneck when implementing wireless communications throughout a manufacturing environment. Limitations in energy transmission, concerns over electromagnetic interference, and nascent technologies limit deployment of wireless power transfer in manufacturing environments. Finally, implementation of wireless communication and wireless power transfer will present significant integration challenges in incorporating all the necessary components while maintaining a small sensor system footprint.

Edge computing: Pushing data analysis and computation to the edge will help overcome some of the challenges for wireless technology summarized above. Increasing the computational power and speed of individual sensor nodes will significantly reduce their data transmission load and thereby significantly reduce their energy usage. The primary challenge is to efficiently generate and transmit only actionable information from the glut of data generated while disposing of the rest, which will likely require specialized hardware, including some mix of analog or application specific circuitry. However, current analog electronics have limited signal processing capabilities and require digital components to process these signals, creating enormous amounts of raw data. Similar with wireless technology, challenges may arise when integrating edge computing components into the sensor system. Finally, researchers will need to find the balance between edge and cloud computing for optimized performance.

Lack of standards: There was significant discussion regarding the lack of standards in sensor system technology. Sensor systems components from various manufacturers all use different standards in

[2] Limitations were mentioned as being both environmental – in terms of background noise, blocking materials or other factors – and technical – in terms of the frequency range and precision that typical communication technologies in sensor systems can achieve.

communication, data transmission, and data processing, making it virtually impossible to properly integrate them with each other into the same system, which significantly limits pathways for innovation. Standards in these areas will be critical when wireless sensors see wide deployment in manufacturing settings for seamless integration into a cohesive sensor network. Furthermore, as internet-of-things (IoT) devices become more prevalent and expected for a wider range of uses, formalized standards will need to be developed to integrate different components optimized for specific applications with common supporting components. In this way, standards can motivate modular development and customization of the integrated sensor system. Finally, standardization in testing will also be critical in validating new sensor technology and aid in commercialization by providing common metrics and testing protocols.

Sensor funding: Due to the low ROI of sensors, there is a general lack of private R&D funding to push the sensor field forward. Participants noted many times the general lack of R&D funding in sensors has hindered cutting edge research and has made commercialization of new technologies more challenging. With the dearth of leading-edge sensor systems, manufacturers are limited to the available, mature sensor technologies, further entrenching legacy sensor technology. This stems partly from the complexity of development and production of custom sensors; there is rarely a one-size-fits-all solution to designing, fabricating, and integrating sensor systems so the overall cost of developing new technologies is too high.

Table 2-2: Challenges
Harsh Environments
• Sensor packaging materials are not as robust as the sensor transducer material, becoming the limiting capability in choosing suitable environments. • Sensor system materials, including transducer material, packaging materials, and auxiliary components, are not stable in harsh environments. • Current sensor technology is not capable of measuring parameters of interest. • Lack of in-situ metrology necessitates costly post-processing characterization.
Wireless Technology
• Data transmission is consuming too much power limiting sensing capabilities. • Wireless technology as an energy source is still too immature for widespread adoption in mature manufacturing plants. • Spectrum limitations for wireless communication. • Wireless communication fidelity due to large sources of interference from manufacturing environment and the high volume of wireless sensors. • Widespread adoption of wireless power transmission to sensor systems. • Development of robust energy scavenging or intermittently available power to sensor systems. • Communicating and coupling large amounts of generated data into machine learning algorithms with simple human interfaces and outputs. • Battery lifetime, weight, and size challenges for battery-powered sensor systems, as an intermediate solution to wirelessly powered sensors. • Complex power conditioning with integration of wireless technology and edge compute components.
Edge Computing
• Balancing the pressure of computing at edge vs cloud with considerations for power conditioning, sensor system integration, and sensor system footprint. • Efficient contextualization and generation of actionable data at very low power.

• Minimization of energy consumption at sensor node. • Optimization of analog sensors to have programmable matched filter to signals. • Limited performance of analog devices in detecting, conditioning, and processing of sensor data. • Developing an energy efficient, parallel computing architecture • Complex power conditioning with integration of wireless technology and edge compute components • Difficulty integrating local compute components to reduce data transmission.
Lack of Standards
• Standards for communication, data processing, data transmission, and testing will need to be formalized for proper deployment of sensors from a variety of vendors. • With the increase in data generation, standardization of data management and security will be critical.
Sensor Funding
• Very small or non-existent private sector investment in sensor R&D due to low ROI, makes investigating next generation sensor technology difficult. Federal funding is necessary. • Due to funding considerations, there is a limited number of technical people to develop, deploy, and service advanced sensor systems.

Current Workarounds and Advantages of Emerging Technology

After identifying challenges, participants noted the current workarounds to mitigate associated barriers and identified the advantages of emerging technology over existing options. Again, the discussion focused around the five over-arching themes mentioned above.

Harsh environments: Currently, the most common workaround is to simply use the sensor systems (toolset) that are available. Sensor systems are not robust enough to be placed directly in the harsh environment itself and are typically placed outside the tool, sacrificing critical spatio-temporal resolution. This also greatly limits the precision and sensitivity of the system by limiting the area available for sensing. As interest in materials for harsh environments grow, sensor technology can integrate these material insights into new sensor system designs. The use of robust materials will allow for sensing more directly located in the process environment itself along with increased stability and operational lifetimes for sensor systems in conventionally placed locations. Furthermore, advanced materials may allow for multi-modal sensing and increased sensing capabilities. Smaller system footprints could further increase the number and types of locations where sensors can collect data.

Wireless technology: Wireless power conditioning and communication technologies are currently too immature for widespread adoption in manufacturing environments. Hard-wired sensor systems serve as the primary workaround for both power and communication before wireless is widely available. Integrated sensor systems must be designed with wires but with the wireless future in-mind. Battery powered sensor systems can serve as an alternative workaround, but size and battery lifetime are large burdens for widespread adoption. Advances in energy harvesting through wireless technology and local phenomena, such as vibrations, environmental heat, and ambient light, could greatly reduce the number of wired connections in integrated sensor systems. Improved digital filtering and advanced analog circuit components with low signal-to-noise ratio (SNR) can enable more robust wireless communication technologies for future adoption in electromagnetically noisy manufacturing environments.

Edge computing: There are no workarounds mitigating challenges surrounding sensor contextualization. As of now, sensor systems do not locally compute and transmit the entirety of the generated data; therefore, reduction of data can only be achieved through limiting the use of the sensor system. Data is sent to the cloud or local networks where engineers analyze and act on the data. Advances in local compute strategies and components will drastically reduce energy requirements for integrated sensor systems by reducing the data transmission load, reducing latency, and reducing power consumption. Reduction in energy requirements may equate to an overall reduction in sensor system footprint, increase in reliability, and energy efficiency. The ultimate goal of edge computing is to enable real-time decision making without a significant increase in energy burden to the manufacturer.

Lack of standards: The lack of standards came up many times in all breakout group discussions. As it stands, sensor system users simply deal with the lack of standards and work around this impediment. Industry groups have tried to develop common standards with extremely limited success and participants strongly pushed for federal leadership in this area. The development of standards for communication, data transmission, data processing, and testing could greatly improve sensor system integration, compatibility between sensor systems, and accelerate R&D commercialization efforts.

Sensor funding: Sensors are considered to be low value by manufacturers and are inherently low volume compared to other semiconductor markets segments like memory and logic devices so there is little R&D investment to improve sensor platforms and incorporate new materials. Advances in sensor technology are largely constrained by the needs of the semiconductor industry. As novel materials and increasingly complex device designs are implemented, the semiconductor industry will require next generation sensor systems, advancing the state-of-the-art in sensor technology. With little to no private investment and only modest federal investment for sensor R&D, sensor researchers are only exploring a small subset of possible options in sensor technology. With larger infusions of funds, researchers in academia and industry can explore the breadth of sensor materials, components, and integration schemes to drive innovation and keep US manufacturing competitive.

D. R&D Pathways and Additional Federal Support

Throughout the workshop, speakers, panelists, and participants discussed the potential R&D solutions to overcome the identified challenges. Four overarching R&D areas were identified, which are summarized here:

Harsh environments: Advanced materials development in novel transducer and packaging materials is necessary to significantly increase sensor system stability and performance in harsh environments. Robust materials will allow sensor systems to be placed within the sensing environment and enable precise spatio-temporal process monitoring of the local environment. Advanced packaging and integration techniques that protect the sensitive components that do not need to interact with the surrounding environment will enable a wider array of sensor technologies that are capable of operating in harsh environments. However, the challenge is to choose materials and integration schemes that are compatible with existing semiconductor manufacturing infrastructure and to allow deployment in harsh environments without hindering sensitivity. Non-traditional sensor operation methods may provide alternative solutions to developing robust, novel materials. These include mobile sensors that are able to reduce time spent in the harsh environment by moving in and out of such environments and cheap, disposable sensor systems that are only designed to operate for a short time.

Wireless technology for power: Widespread deployment of wide bandgap materials in power integrated circuits (IC) could significantly advance current wireless power capabilities. With its wider operational range, voltage standoff, and higher efficiencies, enabling smaller, lighter, and longer lifetime devices, wide bandgap materials are well suited for wireless capabilities in integrated sensor systems for manufacturing. As battery technology enables longer lifetime while limiting size and weight, batteries may be an optimal intermediate technology before wireless power is widely adopted. Energy harvesting from local environments and beamed microwave power can also be leveraged. As sensor nodes integrate wireless and edge computing components, novel power management schemes will become critical in handling this newfound complexity.

Wireless technology for communication: Extreme electromagnetic noise and lack of reliability were cited as reasons that manufacturers were reluctant to use wireless technology for sensor system communications. Improved analog electronics and digital filtering were noted as possible solutions addressing these concerns. Communication is inherently orders of magnitude more energy intensive than edge computing so the need to communicate data off-node should be minimized. Advancements in analog circuits with high signal-to-noise (SNR) ratio and linearity could enable wireless communication technologies in manufacturing facilities that may present noisy electromagnetic environments. Poor wireless network reliability is a problem far beyond the scope of the integrated sensor systems but must be solved before wireless sensor systems can be become widespread.

Edge computing: Development of novel edge computing strategies can significantly increase the energy efficiency of the sensor system by reducing the data transmission load. A hierarchical and heavily parallel computing strategy, focusing on analog electronics as mentioned in the SRC's decadal report, is just one method for an improved sensing-to-action computational strategy. This method will drastically improve edge computing capabilities to enable sensor systems with improved energy efficiency and speed while maintaining a small footprint. As noted above, with the local integration of edge computing components, wireless technology, and the transducer, power conditioning will be important to supply the integrated sensor system components with the proper power levels and characteristics to function efficiently.

Increased industry coordination and collaboration: The lack of industry coordination in sensor system development, design, and manufacturing, including the lack of a trade association was noted multiple times in multiple sessions. Increased collaborative efforts focusing on the cross-cutting challenges identified in the workshop can connect stakeholders and help bridge the gap between R&D and production to aid in the commercialization of sensor technology. Possible collaborative efforts mentioned include establishing common sensor testbeds for part validation as well as standards in communication, data processing, and data transmission, which are necessary for widespread, high-level integration of sensor systems in manufacturing environments. Finally workshop participants emphasized the importance of outreach programs and university courses and recommended increasing them to expand sensor expertise in the workforce.

Table 2-3: R&D Pathways

Harsh Environments

- Advanced materials development for transducer and packaging materials for sensor systems in harsh environments
- Advanced integration schemes and packaging methodology to allow for sensing in harsh environments
- Evaluate 1D and 2D and other functional materials for harsh environments; challenges in material synthesis, contamination, integration and scale-up must be addressed before 1D/2D materials-based devices can be commercialized.

Wireless Technology for Power and Communication

- Development of better analog circuits and digital filtering for noisy electromagnetic environments
- Widespread deployment of wide bandgap electronics for power ICs and auxiliary sensor components.
- Development of wide bandgap-based high-power lasers for power over fiber
- Novel power management methodologies for advanced capabilities in sensor fusion, edge computing, and wireless technology (both wireless energy transfer and wireless communication).
- Integration with more reliable (WiFi 6.0) communication systems

Edge Computing

- Novel local compute strategies (e.g., with analog, machine learning (ML)) to increase computation at the edge and dramatically reduce data transmission.

- Next generation analog and digital electronics enabled by ultra-precision fabrication.
- Novel power management methodologies for advanced capabilities in sensor fusion, edge computing, and wireless technology (both wireless energy transfer and wireless communication).

Increased Industry Coordination

- Development of standards for communication (industry/sensor specific robust – especially for transmission) and data processing
- Creation of a common testbed/platform for sensor system validation as part of an R&D commercialization effort
- Expanded workforce and education efforts, especially in analog electronics

E. Conclusion

Sensor systems are critical in reducing manufacturing energy use. By actively tracking process variables, real-time adjustments can be made to increase precision, reduce equipment downtime, and ultimately, increase energy efficiency of existing operations. However, advances in sensor systems are limited by the lack of investment in sensor R&D, low ROI, and requirements for a high degree of application specificity limiting sensor production primarily to large OEMs.

The workshop identified sensor systems for harsh environments, wireless technology for both communication and power transmission, edge computing, and the lack of standards as the areas of greatest opportunity for the development of next-generation sensor technology. Innovations in semiconductor materials and circuits will be required to address the specific R&D challenges in deploying sensors for harsh environments and developing the necessary technology for wireless communication, wireless power transmission, and edge computing.

Sensor systems inherently involve the combination of many different technologies and therefore require expertise in many different technical areas. Increasing interdisciplinary collaborative efforts to develop more diverse advanced sensor systems would address many of the cross-cutting challenges that manufacturers, integrators, and users face. Additionally, workforce development efforts will be critical to building the interdisciplinary knowledge and skills necessary for both producers and users of sensor systems to remain competitive. Collaborative efforts such as standards bodies, common testbeds, and public-private-partnerships to leverage both academic and industry expertise will help pave the way for development of robust, next-generation integrated sensor system technology for manufacturing and help manufacturers increase energy efficiency, reduce process intensity, and remain internationally competitive.

References

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SIA. 2019. *Comments of the Semiconductor Industry Association (SIA): Request for Information Regarding Basic Research Initiatives for Microelectronics*. Washington, DC: SIA

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Appendix A. Agenda

Day 1 - Monday, January 25			
Time (ET)	**Segment**	**Speaker/Panelist**	**Topic**
11:00 – 11:05 AM	Welcome	Tina Kaarsberg (AMO)	Opening Remarks
11:05 – 11:20 AM	Plenary Talk 1	Tina Kaarsberg (AMO)	Introduction to Workshop and Workshop Series
11:20 – 11:40 AM	Plenary Talk 2	Valri Lightner (AMO)	Introduction to AMO Mission & Portfolio
11:40 AM - 12:05 PM	Plenary Talk 3	Haresh Malkani (CESMII)	Smart Manufacturing possibilities enabled by advanced sensor systems
12:05 – 12:30 PM	Plenary Talk 4	Xudong Wang (AHRI)	The importance of sensors in building system operations
12:30 - 1:00 PM	Break		
1:00 – 1:45 PM	Panel Discussion 1	• Brandon Lucia (CMU) • Tom Spears (Open Additive) • John Middendorf (Arctos) • Scott Whitlock (Flexware Innovations)	System Developer/ Integrator Needs
1:45 - 2:00 PM	Break		
2:00 – 2:45 PM	Panel Discussion 2	• Adam Stevenson (Saint-Gobain) • Xiaolin Lu (Texas Instruments) • Loucas Tsakalakos (GE Research)	Facility Owner/ Operator Needs
2:45 - 3:00 PM	Break		
3:00 – 3:45 PM	Panel Discussion 3	• Amir Bayati (Applied Materials) • Eugene Chow (Xerox PARC) • John Baniecki (SLAC) • Mitchell Hsing (Inchfab)	Sensor System Equipment Developer Needs
3:45 - 4:00 PM	Break		
4:00 – 4:55 PM	Discussion		Connecting the points shared across the three panels
4:55 – 5:00 PM	Closing Remarks	Tina Kaarsberg (AMO)	Reminding attendees on the structure of Day 2

<table>
<tr><th colspan="4">Day 2 - Tuesday, January 26</th></tr>
<tr><th>Time (ET)</th><th>Segment</th><th>Speaker/Chair</th><th>Topic</th></tr>
<tr><td>11:00 – 11:05 AM</td><td>Welcome</td><td>Tina Kaarsberg (AMO)</td><td>Opening Remarks</td></tr>
<tr><td>11:05 – 11:30 AM</td><td>Plenary Talk 1</td><td>Yarom Polsky (ORNL)</td><td>The wide variety of sensor systems being developed for advanced manufacturing</td></tr>
<tr><td>11:30 – 11:55 AM</td><td>Plenary Talk 2</td><td>Jim Wieser (Texas Instruments)</td><td>SRC Decadal Plan for Semiconductor Research</td></tr>
<tr><td>11:55 AM - 12:20 PM</td><td>Breakout Logistics</td><td>Tina Kaarsberg (AMO) & Emmanuel Taylor (Energetics)</td><td>Breakout Preview</td></tr>
<tr><td>12:20 - 1:00 PM</td><td>Break</td><td></td><td></td></tr>
<tr><td>1:00 – 2:00 PM</td><td>Parallel Breakout Sessions (hr 1)</td><td rowspan="5">A: Nick Lalena (AMO)
B: Al Hefner (AMO)
C: Tina Kaarsberg (AMO)
D: Paul Syers (AMO)</td><td rowspan="5">• A: Sensing platforms and materials
• B: Energy sources and power conditioning
• C: Digital and analog circuits and communication
• D: Monolithic and hybrid sensor system integration</td></tr>
<tr><td>2:00 - 2:20 PM</td><td>Break</td></tr>
<tr><td>2:20 – 3:20 PM</td><td>Parallel Breakout Sessions (hr 2)</td></tr>
<tr><td>3:20 - 3:40 PM</td><td>Break</td></tr>
<tr><td>3:40 – 4:40 PM</td><td>Parallel Breakout Sessions (hr 3)</td></tr>
<tr><td>4:40 – 5:00 PM</td><td>Closing Remarks</td><td>Tina Kaarsberg, Nick Lalena, Al Hefner, and Paul Syers (AMO)</td><td>Major takeaways from breakout sessions and final remarks</td></tr>
</table>

Appendix B. Workshop Speakers and Panelists

Plenary and panel sessions featured invited experts from AMO, academia, the national laboratories, and industry. Tina Kaarsberg and Valri Lightner set the stage for the workshop and discussed AMO's goals and how the semiconductor R&D workshop series fit into them. Haresh Malkani and Xudong Wang gave overviews of the sensor needs in smart manufacturing and the HVACR industry, respectively. Following these talks, three industry panels discussed the sensor needs of various industry stakeholders. Finally, Yarom Polsky and Jim Wieser provided their perspectives on sensor R&D required to meet industry needs and to achieve AMO's energy efficiency goals as well as the semiconductor industry as a whole. Each of the talks and industry panels are summarized below.

Advanced Manufacturing for Integrated Sensor Systems: Semiconductor R&D Series Overview

Bio: Dr. Tina Kaarsberg is a technology manager in AMO leading activities related to nanoscience and technology in biological, chemical, and physical systems, especially metals and semiconductors. Dr. Kaarsberg has two decades of experience in government at DOE and on Capitol Hill and is a Fellow of the American Physical Society.

Tina Kaarsberg introduced the workshop series on semiconductor R&D with emphasis on energy efficiency. Currently, three key trends are motivating semiconductor energy efficiency research: the exponential growth of semiconductor production and use as economic activity becomes increasingly virtual; the steady increase in energy efficiency has slowed; and semiconductor energy consumption will quadruple by 2025 without energy efficiency focused technology improvements. Energy efficient technology will be required in the next decade to avoid the market dynamic limit and continue to increase gross world product. With the alignment of the semiconductor industry's goals with AMO's primary mission of improving energy efficiency in manufacturing, reducing product lifecycle energy, and strengthening of the domestic workforce, AMO can help the semiconductor industry achieve its own goals of reducing manufacturing energy use and improving device energy efficiency through technical partnerships. Dr. Kaarsberg then outlined AMO's five goals, below, and how the semiconductor R&D workshop series aligns with them.

Goal 1: Improve the productivity, competitiveness, energy efficiency, and security of U.S. manufacturing

Goal 2: Reduce the lifecycle energy and resource impact of manufactured goods

Goal 3: Leverage diverse domestic energy resources and materials in U.S. manufacturing while strengthening environmental stewardship

Goal 4: Transition DOE-supported innovative technologies and practices into U.S. manufacturing capabilities

Goal 5: Strengthen and advance the U.S. manufacturing workforce

The first workshop in the series addresses Goal 1. The second workshop in the series, on ultra-energy efficiency devices and atomically precise manufacturing techniques, address Goal 2. Future workshops in the series will address other aspects of energy efficiency.

Two laws were passed in 2020 highlighting the importance of semiconductor R&D at the federal level. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act of 2020 authorized semiconductor R&D to be coordinated by a cabinet level committee and authorized the creation of a Manufacturing USA Institute for semiconductor manufacturing R&D. The Energy Act of 2020 specifically noted smart manufacturing technologies and development of technologies in automation, monitoring, computation, and sensing as an enabling technology to reduce greenhouse gases and authorized an industrial emissions reduction program at the DOE. The incoming administration shifted some offices and housed EERE and the Office of Science under the same leadership, which bodes well for future research opportunities in semiconductors and materials. Dr. Kaarsberg concluded her talk by reiterating the workshop objectives and outcomes.

Advanced Manufacturing for Integrated Sensor Systems

Bio: Valri Lightner is the Acting Office Director of the Advanced Manufacturing Office at the US Department of Energy. Valri Lightner has been a technology development manager for the federal government for 35 years. Ms. Lightner's team manages research, development and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity. The program is executed through collaborations of industry, academia, and government. Ms. Lightner previously worked in the Loan Programs Office where her team provided the technical management of a portfolio including vehicle manufacturing and innovative energy projects. Ms. Lightner also led public-private research and development partnerships in cellulosic biofuels, fuel cells for transportation, and pulp and paper energy efficiency.

Valri Lightner gave a high-level overview of AMO and how the semiconductor workshop series fit in with the greater AMO mission. AMO partners with industry, academia, states, and National Laboratories to catalyze R&D and adopt advanced manufacturing technologies. AMO supports private-public partnerships in three general areas. R&D Projects supports early-stage proof of concept projects; R&D Consortia supports research through seven advanced manufacturing consortia, each with its own area of expertise; and Technical Partnerships supports development and validation of technologies and practices in the manufacturing environment. AMO's portfolio is shaped both through a holistic top-down and a bottom-up systems approach to enable the highest potential for impact. The portfolio, the widest at DOE, consists of four fundamental areas: materials, processes, energy systems, and manufacturing enterprise.

Decarbonization of industrial manufacturing and the availability of clean energy technology in the U.S. supply chain is of critical importance to the new administration. As the manufacturers move towards Industry 4.0, integrated sensor systems will be foundational in providing IoT connectivity and artificial intelligence (AI)/ML interfaces for increased automation. These advances will shape the future of manufacturing by reducing both manufacturing energy use and product lifecycle energy use. Ms. Lightner then shared two, AMO funded, success stories of advanced sensor deployment in manufacturing processes. They highlight the need and impact of integrated sensor systems in manufacturing. Finally, she concluded her talk by sharing two ways to get involved with AMO. Small business innovation research (SBIR) grants provide funding for small business development in cutting edge technology. She noted that sensor technology has been historically funded and highlighted the great need from manufacturers for all types of sensors. In addition, high performance computing (HPC) has regular calls for funding opportunities to support modeling efforts to optimize energy intensive and complex processes.

In response to a question regarding the relationship between Basic Energy Sciences (BES) in the Office of Science (SC) and AMO, she noted that AMO partners with BES to show how the foundational work conducted at BES provides the basis for the applied work being done at AMO. With the restructuring of the DOE offices to have SC and AMO under the same Under Secretary, there is good communication between the two offices to make sure there aren't any duplicative work being done.

Enabling Smart Manufacturing through Integrated Sensing

Bio: Haresh Malkani is the CTO of the Clean Energy Smart Manufacturing Innovation Institute (CESMII). Haresh oversees the technology mission, roadmap and objectives of CESMII and is responsible for developing the institute's project portfolio for Smart Manufacturing technologies spanning advanced sensors, controls, modeling, analytics and platforms for manufacturing. He also oversees the development and application of the nation's first open, collaborative Smart Manufacturing Innovation platform for industrial applications. Dr. Malkani brings three decades of experience in industrial RD&E covering development and deployment of Smart Manufacturing technologies. Prior to joining CESMII, he was the Director of Digital Manufacturing &

Automation Technologies at Arconic/Alcoa where he was responsible for developing the organization's strategy for smart manufacturing and deploying solutions that drove productivity across the company's discrete and hybrid operations. He holds an M.S. and Ph.D. in Mechanical Engineering from Northwestern University, and a B.S. in Mechanical Engineering from Maharaja Sayajirao University (India).

Haresh Malkani gave a brief overview of CESMII and the needs of the advanced sensing technology in smart manufacturing. CESMII is a DOE funded research consortium enabling manufacturing productivity, energy productivity, and competitiveness through smart manufacturing innovations. The CESMII integrated roadmap comprises of four interconnected pillars that define the key priorities of the institute: smart manufacturing business practices, smart manufacturing enabling technologies, smart manufacturing innovation platform, and smart manufacturing ecosystem and workforce education.

Smart manufacturing business practices focuses on facilitation of smart manufacturing adoption across the manufacturing industry and provides strategies and risk mitigations to make smart manufacturing implementation more feasible. Smart manufacturing enabling technologies develops smart manufacturing building block technology and helps to fund the gaps in necessary research areas to create robust systems for integration into smart manufacturing systems. Smart manufacturing innovation platform allows for integration of smart manufacturing building blocks in a pilot manufacturing environment and allows for a common test bed for enabling technologies. Finally, the smart manufacturing ecosystem and workforce education provide training and educational resources to build smart manufacturing skills for the future workforce.

Dr. Malkani then described the five smart manufacturing building blocks in more detail. Sensing captures the desired data, contextualization processes the data into useful information, analytics provides insights from the data, modeling generates intelligence, and control allows for actionable responses. To maximize smart manufacturing capabilities, it is critical that these building blocks have a platform to communicate and can move "data-in-context" between the components. One of CESMII's primary focuses is on developing this platform for its members to solve real world problems. Dr. Malkani noted that CESMII works to take a broad view of many disparate challenges to create a common framework for the smart manufacturing platform to be applicable across many problems.

Dr. Malkani concluded his talk with three industry examples highlighting the need for advanced sensor systems to enable smart manufacturing. These examples showcased the advancement in building block technology and how the ability to sense in traditionally unmonitored environments can improve energy efficiency and process control.

Sensors in HVACR and Water Heating Industry

Bio: Dr. Xudong Wang is the Vice President of Research at the Air-conditioning, Heating and Refrigeration Institute (AHRI). Dr. Wang has 11 years of professional experience in the HVACR industry. He is responsible to closely work with AHRI Members to develop and manage research programs and projects addressing common issues and challenges that the industry faces. He has initiated and managed multiple research programs and projects related to assess low GWP refrigerants' performance, compatibility, and safety.

Xudong Wang discussed the applications and importance of sensors in the HVACR and water heating industry. Currently, residential, and commercial buildings constitute 40% of the nation's total energy demand and require 75% of all electricity use. Within this, HVACR and water heating systems makeup roughly 50% of a building's primary energy consumption. As the HVACR market steadily increases, there are significant opportunities for energy savings and emissions reductions in this industry alone. Dr. Wang outlined four primary drivers for the need in advanced sensing in the HVACR and water heating industry: government regulations, grid-interactive efficient buildings, customer demands, and workforce shortage.

Two key regulations impacting the HVACR and water heating industry are the minimum efficiency level of HVACR systems and the hydrofluorocarbon phase-down. A new standard in the Energy Policy and

Conservation Act will require higher seasonal efficiency for air conditioners and heat pumps, effective 2023[3]. Additionally, the EPA has mandated a reduction in hydrofluorocarbon (HFC) production and consumption, the primary refrigerant in air-conditioning and refrigeration equipment, to move towards less global warming potential (GWP) chemicals. This will require a whole new suite of sensors to monitor these chemicals.

The growing demand for grid interactive efficient buildings will require advanced sensor technology to enable precise demand management and make better use of energy. Customer demands from IoT appliances to increased comfort and freshness with reduced energy expenditure will require advanced sensor technology. Finally, due to a workforce shortage in skilled technicians, HVACR and water heating manufacturers must try to automate diagnostic evaluation and fully digitize the repair process. In all of the key trends mentioned above, advanced sensing technology is necessary.

Finally, in addition to the advancement of sensing technologies, auxiliary components such as the ease of integration (plug and play), cybersecurity, novel test methods for sensor performance, standardizations in communication protocols, data formatting, and sensor naming and placement must all be considered in future systems. Sensors have been an integral part of the HVACR and water heating industry and the importance will only increase as our society moves towards a more complex and connected world.

ORNL Activities and Perspectives on Sensing for Manufacturing

Bio: Yarom Polsky is the Section Head for Energy Systems and Controls and a distinguished member of the R&D staff at the Oak Ridge National Laboratory. He serves as the group leader for the Sensors and Embedded Systems Group and the Geothermal Technologies Program. Dr. Polsky oversees staff developing sensing and measurement technologies for a wide variety of applications. His personal research has ranged from using neutron imaging to understand fluid flow in geothermal systems, to applying diffraction techniques to measure the strain inside rocks.

Yarom Polsky discussed Oak Ridge National Laboratory’s rich history and future outlook on sensor technology for manufacturing. Oak Ridge has engaged in a broad range of sensor R&D, largely focusing on manufacturing inspection and control. The old paradigm of sensor development focused on three primary aspects: the physical observable process, sensor hardware, and analysis and processing of the signal. Dr. Polsky stressed that a new systems engineering paradigm focusing on the entirety of the integrated sensor system must be employed to create next generation sensor technology. These include connected systems, data analytics, quantifiable quality metrics, real-time, flexible decision making, real-time product assessment, and reproducibility across applications.

Dr. Polsky noted by using this new paradigm, a common workflow can be established to tackle a wide range of manufacturing sensor challenges. He shared two, one from additive manufacturing and one from carbon fiber manufacturing. Oak Ridge developed a custom-made system integrating IR thermal imaging, digital image correlation, and a stereoscopic vision system to significantly improve quality characterization of additively manufactured parts within the tool. Furthermore, Oak Ridge has developed a number of in-line materials characterization methods at their Carbon Fiber Technology Facility to enable a closed-loop manufacturing control. In both examples, Dr. Polsky stressed that a common workflow established from the systems engineering approach enabled heightened monitoring and control of the manufacturing process. Dr. Polsky concluded by noting that all of the integrated sensor system pieces must be fine-tuned to enable real-time, flexible optimization of manufacturing.

[3] Olivia, Clark, and Kevin Jarzomski. “Efficiency Requirements for Residential Central AC and Heat Pumps to Rise in 2023 - Today in Energy - U.S. Energy Information Administration (EIA).” U.S. Energy Information Administration, 30 July 2019, www.eia.gov/todayinenergy/detail.php?id=40232.

SIA-SRC Decadal Plan for Semiconductors

Bio: Jim Wieser serves Texas Instruments as Director of University Research and Technology within the university relations organization in close collaboration with the CTO Office. Mr. Wieser has also been an active member of the SRC-SIA Decadal Plan for Semiconductors committee chairing the analog focus area workshop and report. In his Director role at TI, he identifies and drives strategic technology initiatives, research strategy and aligns university research to the needs of the company. His semiconductor experience spans over 40 years in the areas of design, product development management and technologist. He is an IEEE Senior Member and SRC Executive Technical Advisory Board member for TI.

Jim Wieser discussed SRC's Decadal plan for Semiconductors and how sensor technology fit into it. Mr. Wieser began by outlining the five pillars in the Decadal plan: analog electronics, memory and storage, communication, hardware enabled security, and energy efficient computing. Sensor technology fits in the first pillar on analog electronics. The primary goal of the analog electronics pillar was to reduce the data deluge. Currently, data is generated at an exponential rate, while data consumption remains steady which points to massive amounts of unused or redundant data. SRC has created a goal of 100,000:1 data reduction through better design of the integrated sensor system. Data communication is the bottleneck; if only the necessary data was transmitted, the data deluge could be significantly reduced.

Mr. Wieser noted that a bio-inspired system may be a path forward. The body is very hierarchical and the brain efficient. The brain allows for massive parallel computing by processing locally, in-turn reducing computational load and increasing energy efficiency. Sensor systems can adopt this hierarchical architecture to tackle the "always-on" sensor challenge. This hierarchy allows for only the absolutely necessary components to stay on with incredibly low power consumption. Once the sensor is triggered, signal sent out from the edge can alert other parts to wake up and sense. Heterogenous packaging will allow for best performance and best power by allowing for more flexibility and not being constrained to a single material system.

Mr. Wieser concluded his talk by highlighting the research required to achieve a reduction in the data deluge: holistic solutions to study the entirety of the analog system and its response; heterogenous integration to blend the best technology in an energy, size, and cost-efficient manner; optimum power management for proper control and conversion for efficient and fast energy response; leveraging human systems as a model for future systems; and developing a flexible, scalable platform and technology to integrate the many different technologies into a cohesive technology.

INDUSTRY PANEL: System Developer and Integrator Needs

Participants:

Brandon Lucia: Associate Professor of Electrical and Computer Engineering at Carnegie Mellon University. Dr. Lucia's research cuts across the layers of the computer engineering system "stack", bridging the gap between programming languages, software and hardware computer systems, and computer architecture. Dr. Lucia's lab has done foundational work to define the area of intermittent computing on battery-less, energy-harvesting devices. Dr. Lucia's work finds new ways to design reliable, low-latency, high-throughput parallel edge computing systems on Earth and in space, in the emerging field of orbital edge computing. His work is pathfinding in the application of intermittent computer systems for high-reliability applications, and in 2019, with collaborators, Dr. Lucia successfully launched several intermittent computing chip-scale satellites "chipsats" into Earth's orbit. Dr. Lucia's work has led to an NSF CAREER Award, 9 Best Paper (or equivalent) Awards, the IEEE Technical Committee on Computer Architecture "Young Architect Award", and the Bell Labs Prize.

John Middendorf: Chief scientist at ARCTOS-USA's 3D innovation lab (3DI). He heads a top-notch team that is looking to change the additive manufacturing (AM) industry. In August 2018 his team delivered its first two commercial products: A Selective Laser Melt (SLM) system and a sensor package with multiple types of in-process monitoring sensors. They are currently working on several additional commercial products. After getting his PhD in THz technologies at Wright State University, he moved to Mound Laser & Photonics Center inc. where after a flurry of mergers and acquisitions, last year, he and his lab became part of ARCTOS. Says Dr. Middendorf "All in all, my team and I are really quite blessed. We work with state-of-the-art sensors, build our own 3D printers, and are solving really important problems for the manufacturing industry. How can you beat that?"

Tom Spears: Chief Scientist and Director of Research & Technology at Open Additive, a spinout of a major defense-oriented firm. Dr. Spears leads technology development and product innovation in AM processing, sensing and analytics, and process control. He is highly experienced in the laser powder bed fusion arena, having served in technology and product leadership roles in both large OEM and small business settings since 2013. Dr. Spears has been lead or co-inventor on more than 20 awarded and submitted patents. His doctorate is in Physics from the University of Chicago.

Scott Whitlock: President and CEO of Flexware Innovations, a manufacturing systems integrator which has been in operation for over 25 years. Prior to founding Flexware in 1996, Mr. Whitlock was a Senior Electrical Engineer at Indiana Automation, Inc. in Noblesville, Indiana. Mr. Whitlock was also a Software Sales Engineer at Advanced Interface Solutions (AISI) briefly. He holds a bachelor's degree in Electrical Engineering Technology from Purdue University. He is a past board member for the Indiana Chamber of Commerce. He is also a past advisory board member for Purdue University's Technology Assistance Program (TAP) as well as current advisory board member for Purdue's Electrical and Computer Engineering Technology (ECET) program in the College of Technology. Mr. Whitlock also served on the Board of Heritage Christian Schools in Indianapolis, Indiana and as a partner in The Jubilee Village Project.

The panelists discussed the sensor needs of system developers and integrators. The panel strongly highlighted the need to efficiently extract actionable information from collected data to reduce data transmission loads. Data transmission is the most energy intensive operation and often requires an increase in sensor system size to accommodate this action. Locally computing can aid in reduction of data transmission by reducing data movement. Often, local compute hardware requires significantly less energy than data transmission components. Reducing the data transmission rate will greatly reduce the energy required by the sensor and therefore allow for smaller sizes and less power conditioning. The panel noted that the design and integration of sensors are highly dependent on the application and that a one-size-fits-all approach or design is not yet feasible. Furthermore, self-integration is more desirable for complex applications but OEM integrated sensors are acceptable for generic use. Finally, the discussion turned towards wireless solutions and their feasibility. The panelists agreed that large manufacturing environments are currently all hardwired so introducing wireless sensors will be easier and cheaper to integrate. However, these environments are often noisy and full of interference so wireless technology will require significant development before widespread adoption in mature manufacturing facilities.

INDUSTRY PANEL: Facility Owner and Operator Needs

Participants:

Xiaolin Lu: Fellow and the director of Texas Instruments Kilby Labs responsible for driving research activities on connected sensors, embedded AI, timing and clocking technologies for industrial internet and automobile applications. Dr. Lu is well-known as an embedded system and software expert inside and outside TI and has given keynote and plenary talks at numerous technical conferences. In addition, she is the author/co-author of more than 60 U.S. issued patents and the recipient of the special recognition awards: 2016 Asian American Engineer of the Year, Society of Women Engineers (SWE) and National Women of Color award in the Technical Innovation – Industry category.

Adam Stevenson: R&D Manager for Saint-Gobain developing engineered ceramics. Dr. Stevenson's current work is focused on developing ceramic material solutions for defense, chemical, sanitary, mining, automotive, and energy industries.

Loucas Tsakalakos: Senior manager of strategic technology partnerships at GE Global Research. He is the director of GE-wide horizontal technology platform in the area of Photonics & Optics, overseeing technology development and insertion strategy, roadmaps, and technology R&D programs. His portfolio includes leading Sensing Systems and Solutions (Industrial IoT) technology programs and serving as a co-leader of GE-wide Sensor Synergy Council. Loucas received his BS degree (1995) from Rutgers University, and his MS (1998) and PhD (2000) degrees in Materials Science and Engineering (with minors in Solid State Physics and Microelectromechanical Systems) from the University of California, Berkeley. His expertise is in the integration of heterogeneous thin film and nanostructured materials systems for micro- and nano- device applications; he also has extensive experience in the characterization of materials.

The panelists discussed the sensor needs in large manufacturing environments or systems. The panelists noted that monitoring of the manufacturing process and the manufacturing equipment themselves were two primary areas where advancements were needed to stay competitive. More specifically, sensor technology in harsh environments was one area where large advancements in sensing capabilities were needed. All panelists noted that using advanced sensor technology could improve energy efficiency of their processes and equipment and would be cost-effective. The need for retrofitting mature manufacturing equipment with new sensing technology was also a primary concern. Wireless sensors would be the easiest and cheapest to integrate but network compatibility has proven to be a large obstacle in seamless integration. As mentioned in the sensor system integrator panel, noisy, interfering environments will further hinder widespread adoption. Furthermore, sensor systems taking advantage of edge computing could significantly reduce power consumption and data security concerns. All panelists noted the need for advanced sensor systems in manufacturing facilities but stressed that it would be a long, tough road to implementation.

INDUSTRY PANEL: Sensor System Equipment Developer Needs

Participants:

Amir Bayati: Systems Engineer & Senior Director of PMTS at Applied Materials based in Santa Clara, California. Previously, Dr. Bayati was the Chief Technology Officer at Heliotrope Technologies and led Managing Equipment Technology Development at First Solar before that. Dr. Bayati has extensive experience and expertise in many advanced processing technologies and process integration across a wide range of semiconductor technologies.

Eugene Chow: Principal scientist and manager of the microsystems research group in the electronic materials and devices laboratory at PARC (a Xerox Company). The group leverages microsystems technology for applications in printing for manufacturing, electronics and biomedicine. Recent projects include micro-assembly for device integration, microsprings for electronics packaging and test, and microjets for drug delivery. Dr. Chow leads research projects at PARC with support from Xerox, other companies and the government, and has over 100 patents granted/filed. He earned a B.S. from U.C. Berkeley in engineering physics, and did his graduate work at Stanford University (M.S. engineering management, M.S. and Ph.D. in electrical engineering).

John Baniecki: Senior Staff Scientist at SLAC National Accelerator Laboratory. He has over 20 years of experience in semiconductor device fabrication and process integration challenges for complex metal oxide thin films in industry and academia. He graduated with a Ph. D in Electrical Engineering from Columbia University where his research, conducted at the IBM T.J. Watson Research center, focused on integration challenges for high dielectric constant thin films used in storage node capacitors for Gbit DRAM. From August 2000, he was employed at Fujitsu Laboratories, Atsugi, Japan and worked on a variety of scientific and process integration challenges for a wide range of devices including ferroelectric memories, decoupling capacitors, voltage tunable filters, thermoelectrics, solar to fuel synthesis, and neuromorphic memories. He holds 59 US patents in these areas, is a professor of Special Appointment at Tokyo Institute of Technology, the Senior Editor of the Journal of Electronic Materials, and has more than a hundred peer viewed publications as well as numerous invited presentations.

Mitchell Hsing: Co-founder and CEO of the startup company Inchfab. For the last several years, Inchfab has been working to develop a complete platform of ultra-low-cost micro- and nanofabrication equipment to enable the economical production of electronic, mechanical, chemical, and biological devices, such as sensors, actuators, optical, RF, and mixed-signal technologies. Dr. Hsing earned a Ph.D. in the Microsystems Technology Laboratory at M.I.T. where he focused on the development of a set of low-cost fabrication tools for the production of micro-/nano- devices. He co-founded Inchfab in 2019 to commercialize his research with the ultimate goal of changing the manufacturing paradigm of the microelectronic industry. Born and raised in California, Hsing completed his undergraduate education at the University of California, Irvine with a B.S. in electrical engineering and physics.

The panelists discussed the needs of sensor system equipment developers. Future integrated sensor systems will require advanced capabilities such as multiple sensing modalities, the ability to function in harsh environments, and be highly precise and robust while requiring the system to be relatively low cost. Panelists agreed that in order to integrate these capabilities, heterogenous integration and advanced packaging techniques of the sensor system will be required. Development of standards will aid in the ease of integration between components fabricated by different manufacturers. Furthermore, customizable electronics will enable modularity and allow sensor system equipment developers the flexibility in fabricating new sensor technology from existing product lines. Wireless technology is a critical need for equipment developers for communications and as an energy source while also reducing the number of wired connections. As the other two panels noted, wireless technology needs to be more robust for widespread adoption in manufacturing equipment.

Appendix C: Other Technology Applications

The participant input from Breakout Session 1 for technology applications of integrated sensor systems that were not manufacturing related applications are summarized below. Participant input is included and loosely organized for completeness.

Table C-1: Other Applications of Integrated Sensor Systems	
Grid Monitoring and Control • Power quality monitoring • Power management for communication networks • Power grid electronics, including smart grid • Electric vehicle charging networks	**Other Applications** • Sensing broad RF spectrum for communications • High speed antibody testing • Proximity sensing in vehicles • Solar inverters • Medical electronics • Room occupancy detection and counting for automated environmental building control.

Appendix D. Workshop Participants

Name	Organization
Moinuddin Ahmed	Argonne National Laboratory
Emad Andarawis	GE Research
Viktor Balema	Ames Laboratory
Douglas Barlage	
Diana Bauer	US Department of Energy
Amir Bayati	Applied Materials
Necmi Biyikli	University of Connecticut
Craig Blue	Oak Ridge National Laboratory
Charles Boohaker	Southern Company
Antonio Bouza	US Department of Energy
Vince Bowen	Idaho State University
Sabine Brueske	Energetics
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Bond Calloway	University of South Carolina
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Qin Chen	Applied Materials
Mark Cheng	University of Alabama
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Eugene Chow	Xerox PARC
John Christensen	OSD Manufacturing Technologies Office
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Ayman EL-Refaie	Marquette University

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Mitchell Hsing	Inchfab
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Tim McDonald	Infineon Technologies
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Chang-Yong Nam	Brookhaven National Laboratory
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Guocang Wang	Ames Laboratory
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Albert Wang	NSF
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Brian Willis	University of Connecticut
Todd Younkin	Semiconductor Research Corporation
Qiuming Yu	Cornell University
Yao Yu	Texas Instruments
Andriy Zakutayev	National Renewable Energy Laboratory
Chunlei Zhang	Applied Materials
Yuepeng Zhang	Argonne National Laboratory
Yuhao Zhang	Virginia Tech

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