Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

Direct Thermal Energy Conversion Materials, Devices, and Systems

Materials for Harsh Service Conditions

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Process Intensification

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Sustainable Manufacturing - Flow of Materials through Industry

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Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF
ENERGY

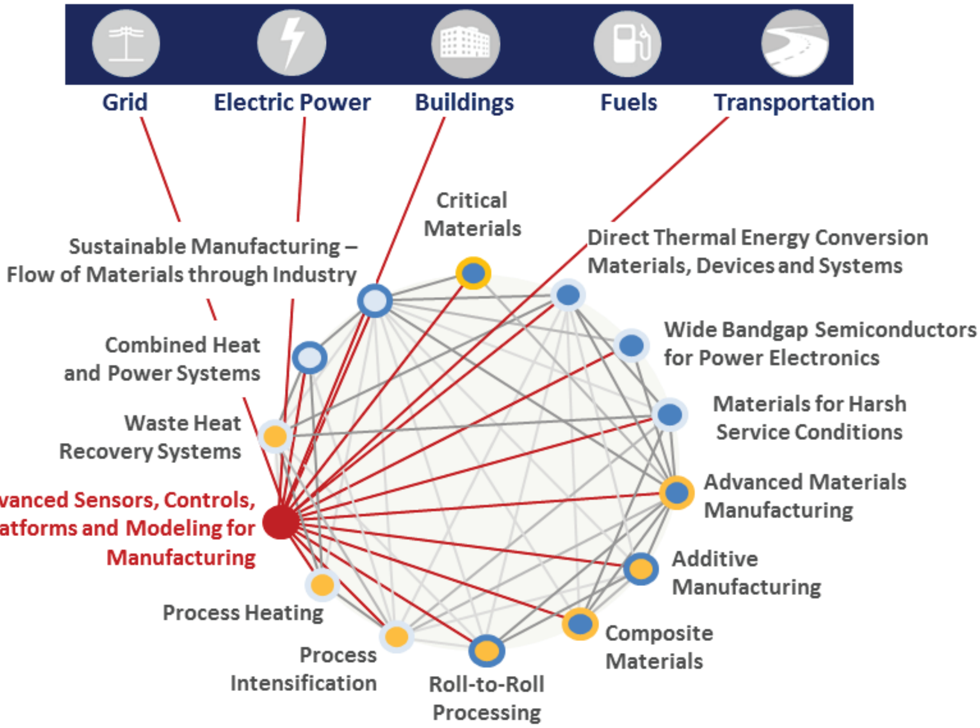
Quadrennial Technology Review 2015

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Advanced Sensors, Controls, Platforms and Modeling for Manufacturing is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **Connections spanning all manufacturing technologies, including:** integrated sensors and controls for increased manufacturing throughput, efficiency, and quality control; computational models for simulations and accelerated materials development	■ **Grid:** advanced metering; sensors for power flow ■ **Electric Power:** grid integration ■ **Buildings:** advanced sensors for lighting and HVAC ■ **Transportation:** vehicles engine control systems

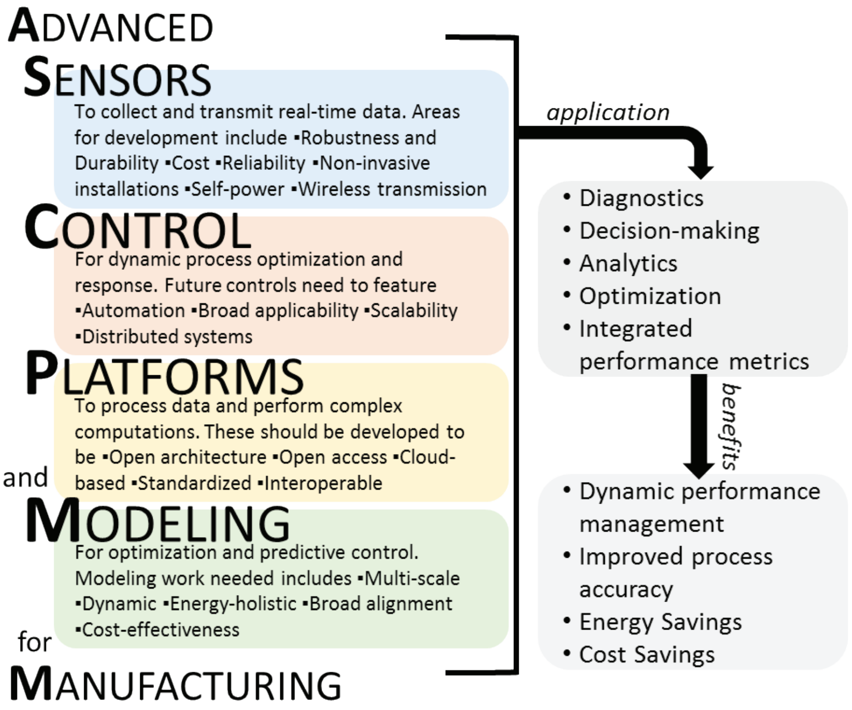
Introduction to the Technology/System

Overview of Advanced Sensors, Control, Platforms, and Modeling for Manufacturing

The applications of advanced networked data and information technologies for manufacturing, referred to here as Advanced Sensors, Control, Platforms and Modeling for Manufacturing (ASCPMM), have the potential to transform the entire manufacturing supply chain — from extraction of materials at mines, through commodities, to finished products. ASCPMM technologies enable the extensive application of data for the optimization of enterprises and multi-company supply chain ecosystems, where data from advanced sensors and sensor systems form the basis for process control applications, decision work flows, and enterprise and supply chain optimization. A networked, open architecture, open access, and open application data platform combined with "plug-and-play" capabilities facilitates the application of ASCPMM technologies.

ASCPMM technologies include infrastructure, software, and networked solutions for sensing, instrumentation, control, modeling and platforms for manufacturing applications. These technologies interact in machine-to-plant-to-enterprise-to-supply-chain ecosystem applications of real-time data and models that are networked for enterprise and ecosystem optimization, as well as monitoring, diagnostics, enterprise/ecosystem analytics, and integrated performance metrics. Figure 6.C.1 defines the technology needs associated with ASCPMM and demonstrates how these technologies come together to perform tasks and realize benefits often associated with the term "smart manufacturing."

Figure 6.C.1 ASCPMM Technologies and Their Combined Applications and Benefits



To collect and transmit real-time data. Areas for development include ▪Robustness and Durability ▪Cost ▪Reliability ▪Non-invasive installations ▪Self-power ▪Wireless transmission

For dynamic process optimization and response. Future controls need to feature ▪Automation ▪Broad applicability ▪Scalability ▪Distributed systems

To process data and perform complex computations. These should be developed to be ▪Open architecture ▪Open access ▪Cloud-based ▪Standardized ▪Interoperable

For optimization and predictive control. Modeling work needed includes ▪Multi-scale ▪Dynamic ▪Energy-holistic ▪Broad alignment ▪Cost-effectiveness

- Diagnostics
- Decision-making
- Analytics
- Optimization
- Integrated performance metrics

- Dynamic performance management
- Improved process accuracy
- Energy Savings
- Cost Savings

When aligned with business objectives, new business models, and communication networks, ASCPMM technologies can be used to address next generation manufacturing performance, efficiency, safety, environment, energy, and product goals. ASCPMM enables a greater opportunity for accelerated product variation and new products with tighter tolerances through the real-time management of products, energy, productivity, and costs at the level of the factory and enterprise and the supply chain ecosystem. The integrated advancement of energy, performance and productivity can provide manufacturing cost savings through an optimized product development cycle.

A holistic systems approach, from raw materials to end-user services, can be used to identify manufacturing pathways that optimize production rates and minimize excess production at each manufacturing step.[1] ASCPMM is related to intelligent efficiency (the application of sensors, real-time controls, and optimization applications to achieve energy efficiency in particular operations), because both terms refer to the use of information communication technology (ICT) to achieve efficiency goals. ICT represents the network and information technologies used for securely storing, transferring, and manipulating data. ASCPMM technologies use real-time software and data applications to achieve multiple-objective optimizations across manufacturing enterprises and ecosystems. Figure 6.C.2 shows the relationship between ASCPMM, intelligent efficiency, ICT, and the Internet of Things (IoT),[2] which addresses the standards-based connection and integration of devices and device data over a network. It has been estimated that investments in ASCPMM could generate cost savings and new revenues that add $10–$15 trillion to global gross domestic product over the next 20 years.[3] Over that period, the U.S. manufacturing sector could realize savings of $15 billion in annual electricity costs, with average company energy demand reducing by 20%.[4]

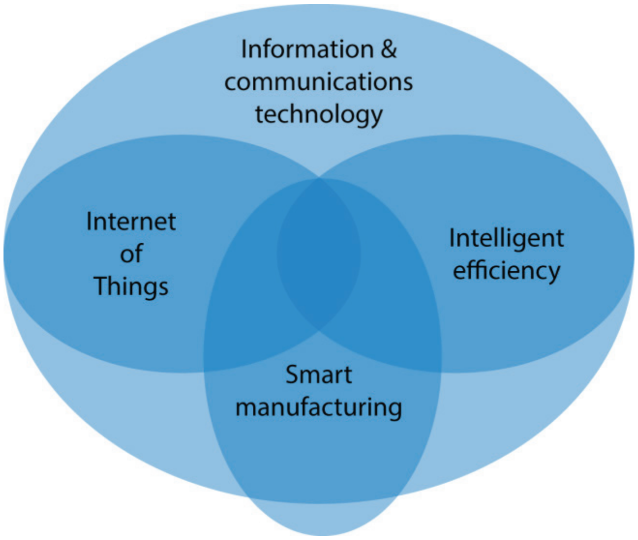
Challenges and Opportunities

While aspects of ASCPMM have been successfully implemented in several key industries (e.g., the chemicals industry is highly instrumented), there are technological, cost, and knowledge barriers to broader ASCPMM implementation across manufacturing. Barriers include the following:

- *Low or underdeveloped value proposition.* Investments in process control and IT are viewed as optional and noncritical. One-off, compartmentalized ASCPMM implementations that do not scale IT or manufacturing function involve costly infrastructure and staffing that are not easily extended. Sensors, software, and the overall development and implementation of an application can be costly. The

Figure 6.C.2 Relationship of ICT, IoT, intelligent efficiency, and ASCPMM (smart manufacturing). Subsets of ICT include intelligent efficiency (energy savings resulting from ICT-enabled connection of sensors, devices, systems, facilities, and users), smart manufacturing (superior productivity resulting from the integration of all aspects of manufacturing), and IoT (machine-to-machine interaction through the Internet).[1]

Credit: American Council for an Energy-Efficient Economy (http://aceee.org/research-report/ie1403)



value (return on investment [ROI]) for an incremental, compartmentalized application is often low and causes challenges owing to high costs, long paybacks, and ROIs that are interdependent with other manufacturers. Without commitments on the value of data as an asset, the enabling tools and software products, or the necessary workforce skills, the development of real-time data-driven software applications for control, decision making, and/or optimization can be a difficult and expensive set of tasks. Such tasks include building secure IT infrastructure, factory and application data integration, integrating and interfacing with multiple vendor products, configuring data and models, and testing and validation.

- *Actual or perceived interference with operations.* Energy-intensive industries, while relatively advanced, often rely on continuous production where materials being processed, either dry bulk or fluids, are continuously in motion, undergoing chemical reactions or mechanical or heat treatment. These plants typically operate 24/7, with infrequent maintenance shutdowns, such as semiannually or annually. Some chemical plants operate for more than two years without a shutdown, while blast furnaces can run four to ten years without stopping for a major revamp.[5] These long uninterrupted production cycles make it difficult to install sensor and IT assets, which in turn can pose challenges with developing the necessary data, model, and control configurations for an application.
- *Technological limitations*. Instrumentation and sensors used in ASCPMM today may not be suitable for certain processes and process conditions. Technological advances in sensing and control may have to endure high temperature, high pressure, and/or harsh environments. For example, a sensor used to monitor ultra-supercritical boilers must withstand a temperature of over 700°C and pressure of 5000 psi. A gasifier environment not only has similar high temperature and pressure but also serious corrosion and erosion issues. Sensor reliability is also a key issue, because current batch and semi-continuous manufacturers are traditionally averse to adding process monitoring sensors that can be invasive and are believed to have high false-alarm rates. These sensors must also be affordable and able to extract sophisticated data as well as ideally be noninvasive, highly reliable, and able to transmit wirelessly in real time.
- *Hardware/software incompatibility and technology "lock-in."* Existing process and control equipment and software are not consistently forwards or backwards compatible, or compatible from one manufacturer to another. This means that upgrading to ASCPMM technologies requires creating custom work-arounds anytime compatibility across systems is needed, a difficult barrier for any individual company to address alone. Further, many manufacturing facilities have already invested in process and control assets that remain serviceable and economically viable. As a result, the turnover rate of these assets can be slow, making technology advancement slow. For example, blast furnaces and associated distributed control systems are used for decades before they are retired or replaced. As a result, technology advancements are often evolutionary rather than revolutionary. The need for retrofit technologies that align with manufacturer needs is an existing challenge.
- *Cybersecurity and risk concerns*. Many manufacturers' organizational and business structures are inherently resistant to ASCPMM advancements. Perceived and real risks of increasingly IT-dependent operations, and the associated perceived and real cyber-security risks, often enhance the organizational resistance to more automation. In addition, lack of workforce skills and manufacturer technical readiness relative to available technologies can be limiting.

Public and Private Roles and Activities

ASCPMM was specifically called out in the White House Advanced Manufacturing Partnership (AMP) 2.0 Steering Committee as one of three highest priority advanced manufacturing technology areas in need of federal investment.[6] Manufacturing practitioners want and need the following: (1) to use products from multiple software, control and factory platform vendors; (2) a way to transition and use new technologies faster as new

ASCPMM technologies are developed through any source; (3) better ways of reusing applications; (4) better ways to scale, access and use IT infrastructure on an as-needed basis; (5) a more flexible range of vendor and open source product options; and (6) ways to take advantage of data and experiences with applications. However, most individual companies lack the resources to scale these capabilities for enterprise and supply chain/ecosystem applications. Government participation can facilitate technology development and commercialization of ASCPMM to U.S. manufacturing industries, for example through public-private partnerships.[7,8]

Some nations are also heavily investing in new manufacturing technologies. Japan's National Institute of Advanced Industrial Science and Technology received 63% of their funding (~¥58,000, or $580M) in FY2012 from the Japanese Government to advance the state of Japanese manufacturing.[9] EU nations are investing significantly in ASCPMM technologies, in what they refer to as Industrie 4.0 and with a combination of public and private funding to advance the development and deployment of these technologies.[10] Germany's Fraunhofer-Gesellschaft Institute also receives significant funding from the government (€382M, or ~$500M) to advance the state of German manufacturing.[11] With the U.S. government playing a role in mission-oriented, pre-competitive research and in infrastructure capabilities, energy-intensive industries and energy-dependent supply chains can benefit from accelerated adoption of ASCPMM strategies through enterprises and across ecosystems—with national benefits in the form of energy reduction, greater industry competitiveness, productivity and safety, and a boost to the sensor and automation industry.

Technology Assessment and Potential

The Opportunity Space for ASCPMM Technologies

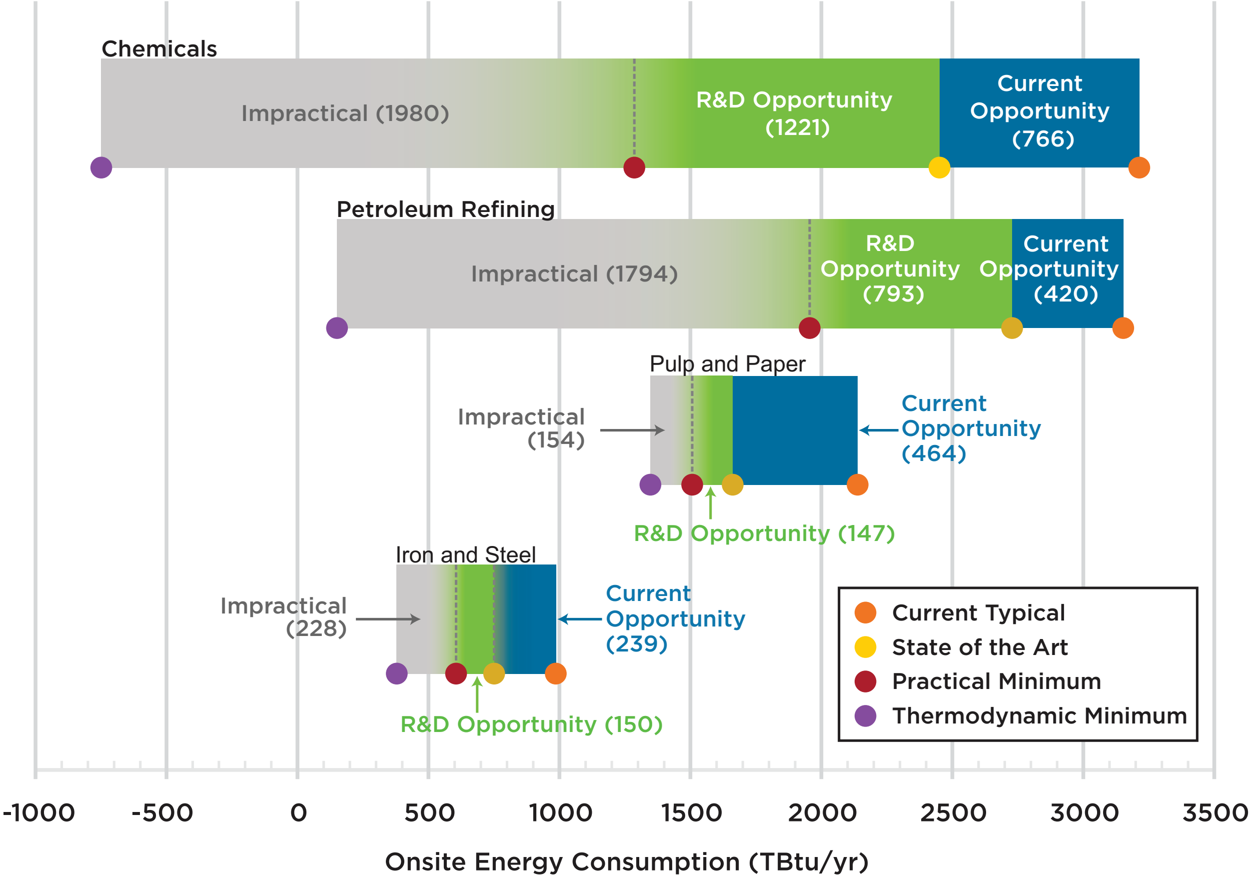
There are a myriad of energy, economic and performance opportunities when data for sensors, tools and infrastructure are managed as an asset. For example, ASCPMM technologies can be used to optimize efficient equipment turnarounds and start-ups, reduce maintenance times, increase machines' capacity factors, improve operational and quality control, make it possible to manage variations better, operate with tighter risk tolerances, and address alarm and abnormal situations earlier with operational, control, diagnostic and predictive monitoring. The benefits of ASCPMM have been demonstrated in multiple manufacturing sectors, where benefits include improved business logistics, increased daily output, more rapid innovation, and faster product launches and transitions. For example, modeling and simulation in the aluminum industry led to an estimated $200M annual savings owing to reduced metal use,[12] and automated process control implemented at refineries resulted in at least $2.5M/year in benefits per major refining unit.[13]

The opportunity space for ASCPMM technologies spans continuous, semi-continuous, batch, discrete, and hybrid manufacturing operations, with significant energy and energy cost savings opportunities in energy-intensive industries and energy-dependent supply chains and across energy-impacted product life cycles. For example, the current and future technological energy savings potentials of the four largest energy-consuming industrial sectors in the United States are shown in Figure 6.C.3. While ASCPMM technologies alone do not account for these savings potentials, they are part of the technology systems platforms needed to attain the maximum energy savings potential.

Performance Advances and Benefits of ASCPMM Technologies

Advanced low-cost and sensor and associated infrastructure technologies are fundamental to greater data harvesting and utilization for manufacturing enterprises, supply chains, and ecosystems. There are a number of pathways that can lead to more pervasive ASCPMM technology adoption across applications and industries. If coupled with high fidelity time-dependent physics-based computational models, advanced sensors can enable greater deployment of real-time model predictive control in advanced and energy-intensive manufacturing processes to optimize and manage energy at the factory level rather than individual process control points. Ultra-low power/low-cost sensors can allow for greatly expanded data collection on different devices across the

Figure 6.C.3 Bandwidth Diagrams Illustrating Energy Savings Opportunities in Four Energy-Intensive U.S. Manufacturing Industries. Current opportunities represent energy savings that could be achieved by deploying the most energy-efficient commercial technologies available worldwide. R&D opportunities represent potential savings that could be attained through successful deployment of applied R&D technologies under development worldwide.[14] ASCPMM technologies alone do not account for the energy savings, but are an underlying component of the technology systems needed to attain these savings.



manufacturing supply chain.[15] Embedded input/output devices can provide bidirectional information transfer for networked computing and analysis.[16] "Cloud" architectures[17] can allow for data collection, contextualization, and data merging that are readily combined with advanced optimization algorithms.[18] Advanced tracking of parts and material lots can provide identifiers for customer-to-source tracking.[19] The expanded development and qualification of sensor systems and infrastructure can enable benefits such as the following:

- *System optimization*. When implemented in each stage of energy-intensive manufacturing processes, integrated digital control systems with embedded, automated process controls, operator tools, and service information systems can optimize plant operations, energy consumption, and safety. These components can be used to collect and analyze large quantities of performance data to identify relationships between operational performance and energy use and to provide predictive control modeling.[20] Real-time communication between each step in a given manufacturing process and a data customized infrastructure then allows system-wide algorithms to simultaneously operate each manufacturing component to anticipate and meet productivity demand while minimizing energy use.
- *Customization*. Expanding the communication network to consumer demand can promote customized product manufacturing. Advanced inventory tags can be used to track items from production to final customized fabricated products. Real-time communication can adjust production rates based on changes

in consumer orders. In energy-intensive manufacturing sectors, this customization can control for energy and material use. ASCPMM technologies will allow advanced manufacturing technologies, such as digital manufacturing, to reach their full potential, via on-demand additive manufacturing of products from electronically communicated digital designs. This has the potential to disrupt supply chains, enabling more distributed manufacturing, which can in turn transform the transportation requirements of different goods and services.

- *Predictive maintenance.* Asset management using predictive maintenance tools, statistical evaluation, and measurements will maximize plant reliability, contributing to greater productivity and energy efficiency. Data collection can be used for fault detection and diagnostics to predict when manufacturing parts will need repair or replacement, minimizing downtime.
- *Distributed control systems*. Increased network communication among different components throughout the manufacturing process enables distributed control systems, with one or more control points for each component subsystem (e.g., for a complex oil refining process that consists of various unit operations). Distributed control has mainly two advantages over centralized control. First, there is a reduction in computational burden on any individual controller, owing to the system decoupling. Under the distributed control scheme, the local operations decisions can be evaluated by taking only local process conditions into account. Only the proposed decisions are broadcast to other subsystems for system-level coordination. At the system-level, local operation decisions can then be incorporated within global optimization framework. The second advantage is system robustness. A fault that occurs to any of the subsystems can be more easily isolated and corrected under distributed control.
- *Smart energy management system (EMS)*. Smart EMSs provide a cost-effective solution for managing energy consumption. Smart systems integrated within the industrial EMS and externally with the smart grid could further enable real-time energy optimization and create entirely new ways of energy load management, potentially allowing for increased excess energy production for return to the grid and other ancillary benefits. These systems are based on the integration of existing wired/wireless communication technologies combined with smart context-aware software that can offer a complete solution for automation of energy measurement and device control.[21]
- *Flexible manufacturing system*. ASCPMM provides a level of flexibility to react in case of operational changes, whether predicted or unpredicted. Data collection and analytics can be used to develop production scenarios that will help anticipate the best operating conditions to meet changes in product demand.
- *Track and trace*. Supply chains that aim to integrate track and trace capabilities into their systems often employ ASCPMM technologies. These systems use inventory tags and Global Positioning System data, paired with advanced system architecture, to track the current state of parts at any time while simultaneously tracing the past states and the origin of the part. Through accurate, comprehensive real-time data collection and communication, this data enables optimization of business operations within manufacturing and on to delivery processes, inventory management, optimized maintenance, compliance and safety.
- *Cloud-based platforms*. Cloud computing has been used in several key areas of manufacturing, such as IT, pay-as-you-go business models, production scaling with demand, and flexibility in deploying and customizing solutions. Cloud computing can support manufacturing because distributed resources are encapsulated into cloud services and managed in a centralized way to maximize energy productivity and process energy efficiency. Clients can use cloud services according to their requirements. Cloud users can request services ranging from product design, manufacturing, testing, management, and all other stages of a product life cycle.[22]

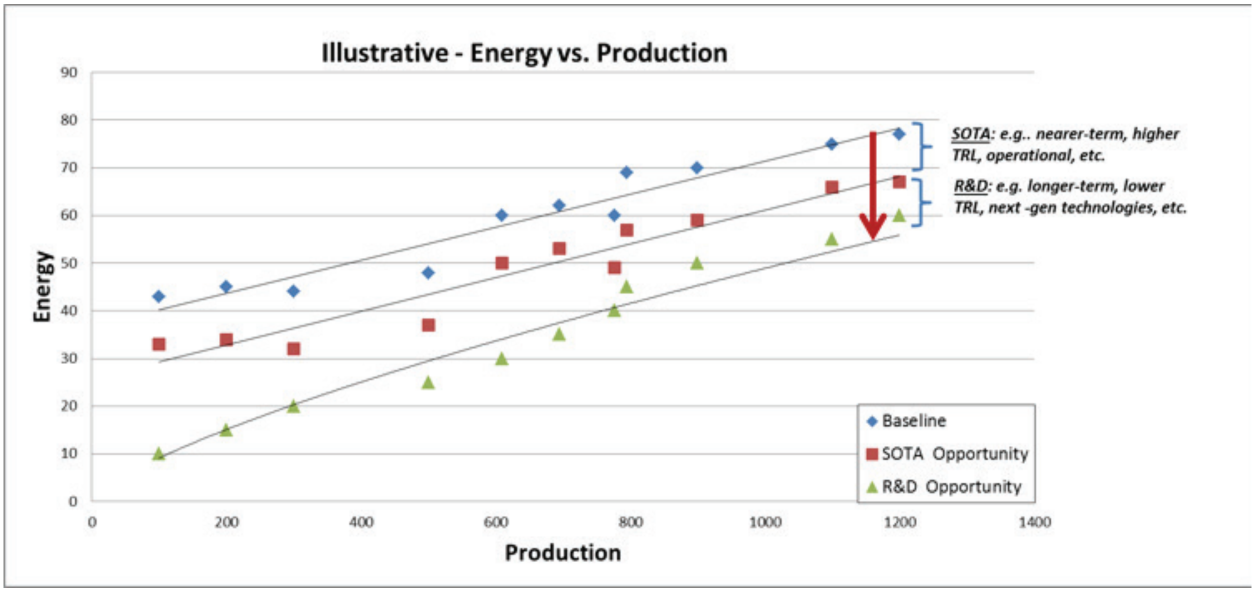
While these performance advances derived from ASCPMM technologies can result in a range of operational benefits, the impacts need to be measured and verified, which requires rigorous analytical methodologies. Industrial energy consumption and energy intensity[23] can depend on a number of factors, some of which are beyond the control of the manufacturer (e.g., weather), while others are attributable to production levels (for example, increased production leads to increased energy consumption). In order to accurately account for energy improvements attributable to energy improvement strategies, the baseline energy consumption must be normalized to account for the influence of independent variables.

Candidate energy performance metrics (i.e., energy performance indicators) typically correlate energy with a key manufacturing-related variable such as production (see Figure 6.C.4 for an illustrative example). It is critical that metrics associated with energy-associated improvements are based on methodologies that can demonstrate improvement while controlling for the influence of other variables.[24]

Figure 6.C.4 also highlights several energy and production issues that ASCPMM technologies can address. Especially in the energy-intensive industries, economies-of-scale influence design such that the highest efficiencies occur at high, steady-state operation. At reduced production capacity, efficiencies decline (e.g., owing to equipment standby losses when production is not occurring but equipment is still consuming energy). ASCPMM technologies can drive maximum benefit derived from the deployment of state-of-the-art (SOTA) manufacturing technologies, as well as longer-term opportunities that will result from deployment of next-generation technologies currently under R&D, including the following:

- Nearer-term, higher technology readiness level (TRL) SOTA technologies that can improve the operational efficiency of manufacturers, many of which are relatively low-cost opportunities that have the potential to be enabled by ASCPMM technologies.
- Longer-term, lower TRL next generation technologies that have the potential to extend the energy-associated improvements beyond the current SOTA opportunity. This benefit has the potential to be amplified when operational and design improvements are coupled with ASCPMM technologies that intensify processes and optimize efficiency over a wide range of manufacturing production levels,

Figure 6.C.4 Illustrative Only Example of the Baseline Approach to Characterize Energy-Associated Improvements. SOTA is the nearer-term opportunity for SOTA technologies to improve current energy use; R&D is the longer-term opportunity for technologies still under development.



leading to more efficient energy utilization as production capacity fluctuates. When coordinated with other associated approaches, such as process intensification (see the Technology Assessment 6.K *Process Intensification*) and modular processing approaches, improved and future designs can operate more efficiently across a wider range of production capacities, allowing for more flexibility in operations ranging from production scheduling to energy management.

Broader application of ASCPMM technologies has great potential in many manufacturing sectors, as outlined in the AMP 2.0 Annex Report with the following examples:[25]

- With advanced sensing and model-based optimization techniques, an aerospace metal-parts manufacturer expects to save on the order of $3M per year on furnace operations alone in a plant that includes both continuous and discrete processes.
- A chemicals company projects 10%–20% energy savings for a hydrogen production plant with improved sensors and modeling, translating to a reduced natural gas cost of $7.5M per year.
- A plant provides ancillary power services for the Independent System Operator (ISO), using demand-response and direct-load control for frequency regulation of the grid. Reported revenue to the plant is over $1M annually.
- A three-mill cement grinding plant reduced specific energy consumption by as much as 5% with a customized model-predictive control approach.
- A robotic assembly plant for a large automotive original equipment maker anticipates reducing energy consumption by 10%–30% by using optimization tools for robot motion planning.

Technology and System Integration Needs for Improvement

Important technical system integration challenges to realize the energy benefits of ASCPMM have been outlined by the AMP working team[6] and are presented below in approximate order of their implementation readiness. Research to address the more challenging gaps is important and can reward nations that succeed in the effort.

Open Standards and Interoperability for Manufacturing Devices, Systems, and Services

Vendor lock-in is a widely acknowledged barrier to innovation in sensing, control, and platforms for manufacturing. Standardization of information and communication has been attempted but with limited success and slow outcomes. It should be noted that standards, even open standards, are necessary but insufficient. Interoperability must also be assured, such as agreements on data definitions, so that data can be readily interpreted between devices and systems.

Advanced Control of Machine Energy Consumption and Waste Streams

In several manufacturing sectors, product quality, throughput, and plant efficiency suffer because of the lack of fast, noninvasive measurement methods. In many cases, samples must be analyzed or tested in a lab, or production must be affected for accurate measurement. Depending on the factory and process, noninvasive/noncontact measurement could take different forms: standoff imaging, disposable embedded sensors, inferential sensing, and others. In all cases, reliable and cost-effective techniques are needed. These same technologies can be implemented to control for and optimize the energy consumption in a plant environment, for continuous, semi-continuous and discrete manufacturing processes.

Energy Optimization of Processes and Integration with Smart Grids, Cogeneration, and Microgrids

Dynamic energy optimization in industrial plants can improve manufacturing efficiency and simultaneously facilitate the integration of renewable generation in the grid. Affordable and accessible energy-holistic manufacturing simulation models will improve both design and operation. Choices of fuel/power use, generate or purchase decisions, integration of storage of different types, and model-based optimization can all be improved over current approaches for a broad swath of the nation's manufacturing base. Steps can be taken with initial interfacing and interoperability between ASCPMM and smart grids to address these needs.

Health Management for Manufacturing Equipment and Systems

Specific techniques for fault diagnosis, detection of incipient problems, and condition-based and predictive maintenance are needed. Techniques developed generally lack rigor and broad applicability. Sector-specific techniques will be needed, but broad classes of facilities equipment that are deployed across many manufacturing sectors can be targeted (e.g., pumps, motors, burners, and furnaces). In addition to plant performance and efficiency, the safety of people and the environment is at stake.

Low-Power, Resilient Wireless Sensors and Sensor Networks

A now long-standing promise of wireless technologies has been pervasive sensing. While wireless sensors and networks have been demonstrated at large scale,[26] the promise remains well short of fulfillment. Encapsulating a radio with the transducer is not sufficient. Power management, possibly with energy harvesting, and reliable and fault-tolerant communication protocols tied with physical measurements are required, and solutions must be robust to the manufacturing environment and work practices.

Integration with Big Data Analytics and Digital Thread

The technology areas discussed in this report are all data- and model-intensive. Advanced sensing, control, and platforms—and their integration—will produce vast amounts of data that can be mined for further models and simulations development; monitoring, control, and optimization techniques; and intelligent decision support systems. Sources of data are multifarious, including weather forecasts, markets, plant historians, real-time process state and part quality data, equipment specifications, supply-chain databases, and others. Just as one example, the integration of storage technologies and the nascent efforts for using weather-based demand prediction for participating in energy markets present an opportunity to integrate Big Data analytics and digital thread technologies to the next level and embed decision support systems to make trade-off decisions on operations and asset utilization. This problem is particularly complicated, owing to the real-time operational criticality of data and problems that ASCPMM is tackling. Data need to be well understood and defined in function and time, working initially with small amounts of well-defined data, establishing function and growing toward large data sets and analytics.

Platform Infrastructure for Integration and Orchestration of Public and Private Data and Software Across Heterogeneous and Human Systems

Cyber-physical platforms integrate computing and communication capabilities in the sensing and actuation functions of components. Public and private applications and data resources need to interconnect to coordinate enterprise views and actions. Many data and information "seams" are not well bridged with existing systems and platform technologies. As the complexity of platform integration grows, there is further need for methods to design and build platform infrastructures while addressing issues of privacy and cybersecurity associated with the shared data.

Software Service-Oriented Platforms for Manufacturing Automation

Manufacturing automation relies predominantly on single-vendor monolithic software architectures. Service architecture approaches can enable the extensive and systematic application of data analytics, models, and software innovations in physical manufacturing (cyber involvement). Such approaches will enable multiple development environments, infrastructures that support composability, and cloud-based orchestration. Appropriate cyber-security considerations must be incorporated from the outset.

Theory and Algorithms for Model-based Control and Optimization in the Manufacturing Domain

The model-based control and optimization paradigm is widely and successfully used in some manufacturing sectors but has had limited application in many others. Industry-specific aspects must be considered if useful tools and technologies are to be developed. Topics of interest include nonlinear, stochastic, and adaptive control; large-scale and enterprise-wide optimization; integration of planning, scheduling, and control; and co-design of manufacturing processes with sensing and control strategies.

Modeling and Simulation at Temporal and Spatial Scales Relevant Across Manufacturing

Models are at the core of many ASCPMM technology gaps. Not only is an increasingly rich diversity of real-time and life-cycle modeling resources important, but also important are the tools and methods to more easily and cost-effectively build, deploy, and maintain models across large heterogeneous systems. Model alignment is also an outstanding need, especially because advanced manufacturing is dependent on models for various functions (e.g., planning, optimization, diagnostics and control).

Cybersecurity

ASCPMM requires troves of data being streamed between sensors and processors and stored on servers. This data, along with the applications and algorithms that employ it, are often proprietary and confidential, and can be potentially harmful if not protected correctly. Initial steps in cybersecurity can be taken in relation to sensitivity of overall function to manufacturing objectives and sensitivity of data and IP in using new control and platform structures.

Potential Impacts

ASCPMM technologies can result in significant near-term benefits to the United States to positively impact quality, yield, productivity and energy efficiency, both within and through interoperability. In the next five years, more extensive application of ASCPMM in large companies is expected, throughout small-to-medium enterprises (SMEs) and across all manufacturing structures (continuous, semi-continuous, batch, and discrete). The footprint of ASCPMM technologies applied for control and enterprise optimization will begin to attain that of the continuous process industries.

The potential impact of ASCPMM is more readily realized in large companies and new manufacturing facilities where available technologies can be readily incorporated. For example, a smart automobile factory could utilize ASCPMM technologies to enable the acceptance of custom orders from dealers and adapt on the spot to customers' preferences, while allowing the company to track parts to their source. See adjacent text box for other examples of ASCPMM technologies in commercial applications. With lower cost sensor and platform infrastructure, many more manufacturers can take advantage of ASCPMM, especially SMEs. In the longer term, new manufacturing processes would be optimally designed simultaneously with their sensor and actuator suites and control strategies. End-to-end supply/demand chains would be integrated and optimized in real time. New sectors, such as bio-manufacturing and nano-materials, will be operationally mature in their application of sensing and control and in their automation platforms.

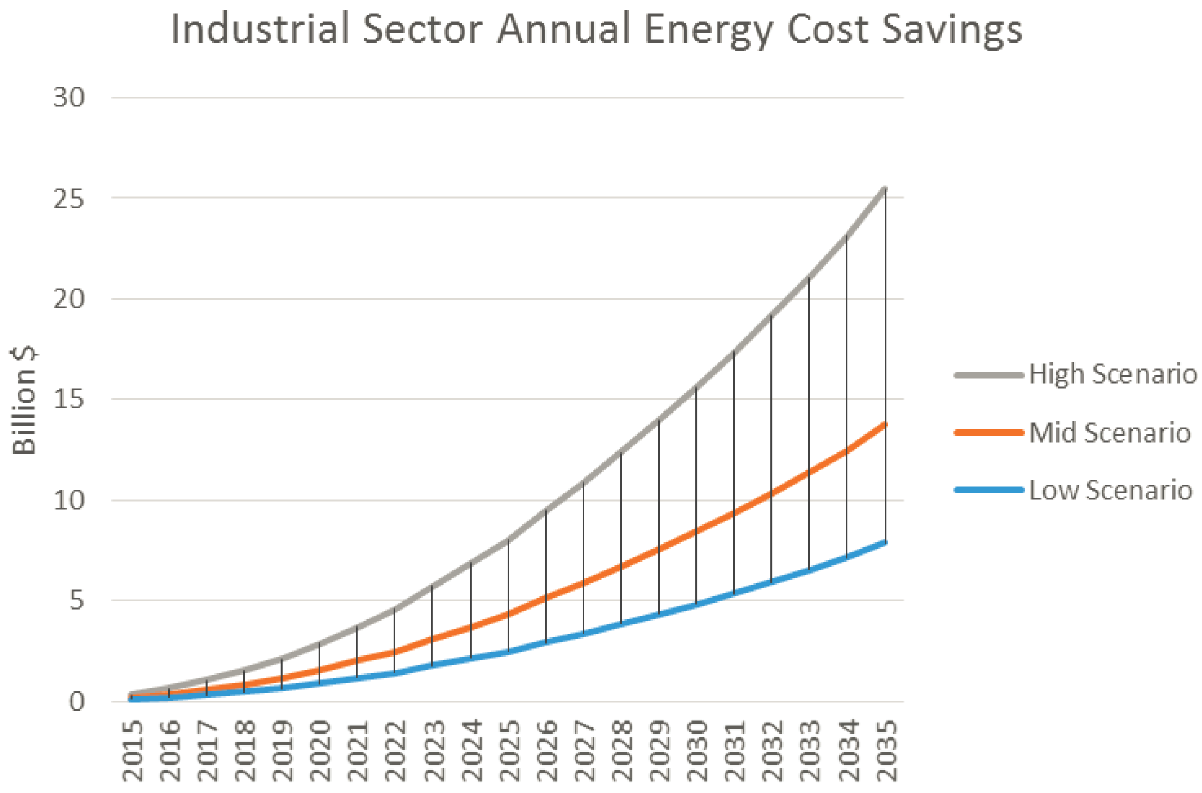
Impacts of ASCPMM Technologies in Commercial Applications

The potential impacts in existing facilities can be seen in larger companies such as ExxonMobil and Procter & Gamble (P&G) that have already begun addressing the technical implementation of ASCPMM.[27] ExxonMobil's first step towards ASCPMM was focused on an integrated information-sharing network. They deployed standards and cyber security, life cycle cost and life expectancy management, remote access and data visualization. The result is a global enterprise network that enables information sharing, management, and data visualization across 100 cogeneration plants in more than 30 facilities. P&G has relied on supercomputing for their initial product design and evaluation. High performance computing arrays host complex, rigorous calculations such as computational fluid dynamics algorithms to model and solve problems, such as the scale-up of the mixing of fluids in commercial scale equipment. This "atoms to the enterprise" approach has allowed P&G to answer critical manufacturing questions such as what if, why not, and how much.

An analysis of the potential efficiency benefits of implementing promising ASCPMM measures was conducted by Rogers in 2013.[4] Assuming a 50% penetration of intelligent controls and an increase in investments of 1% per year over current trends and increasing over 20 years to 3%, it is estimated that the industrial sector could save between \$7 billion and \$25 billion in energy cost per year by 2035, as shown in Figure 6.C.5.

Figure 6.C.5 Estimated Industrial-Sector Energy Cost Savings Resulting from the Implementation of Promising ASCPMM Measures[4]

Credit: American Council for an Energy-Efficient Economy (http://aceee.org/research-report/e13j)



The AMP working team outlined the following specific goal statements related to the integration of ASCPMM technologies:[6]

- Manufacturing automation equipment from different vendors seamlessly interoperates and allows plug-and-play configurations within three to five years.
- Energy use and waste streams per unit output from manufacturing plants are reduced by 20% in three years and 50% in ten years after implementation.
- The deployment cost of sensors falls by an order of magnitude, enabling pervasive real-time measurement solutions within five to ten years.
- Process optimization and control systems adapt automatically and in real time to changes in feedstock, market demands, and plant performance within five to ten years.
- Potential faults and failures are detected and corrected when still incipient, reducing plant downtime by 50% in five years and 90% in ten years.
- Data and information platforms provide extensive access, scalability, reusability and actionable orchestration of analytic, modeling, simulation, and performance metric software resources.

Program Considerations to Support R&D

While several U.S. manufacturing sectors have benefited from advances in sensing and control over the last few decades, penetration of these technologies has not been widespread. In particular, U.S. small and medium enterprises have lagged behind larger organizations on productivity growth, owing in large part to the lack of adoption of such technologies. Beyond technology expertise, implementation is impeded by lack of cost-effective IT platforms and infrastructure and other implementation gaps identified earlier. The following R&D efforts and public–private partnerships can accelerate the integration of ASCPMM into the manufacturing sector.

Universal network protocols are needed to connect devices across various manufacturing sectors. The protocol needs to establish translation across types of sensors and provide “future proofing” that allows for adaptability as new sensor technologies are developed. Universal protocols for software and communication platforms (e.g., open-architecture and open-source) can enable plug-and-play connectivity to ease integration and customization across different ASCPMM components, different manufacturing requirements, and the latest IT hardware and standards.

The potential for systems optimization through sensor distribution vastly increases once sensors can operate and communicate without requiring physical connections. Research is needed to accelerate the development of self-sustaining sensors that require no dedicated power source (i.e., powered through waste heat or physical movement) or specific “WiFi” connection (i.e., communication through cellular or satellite networks). Additionally, research is needed on sensors that can withstand high temperature, high-pressure environments, as well as the development of sensors with embedded knowledge that makes them smarter and easier to integrate into sensor networks employed in manufacturing. Robust sensors have potential application in harsh, energy-related manufacturing processes.

The AMP 2.0 working team recommended a national ASCPMM coordinating committee, with experts from industry, academia and relevant government agencies be established to focus on the following deliverables:[6]

- *Interoperability*. Develop and implement interoperability standards and protocols for key systems with vendor support.
- *Standards and nomenclature*. Develop and propose new methods for addressing relevant industry standards on an as-needed, highly fast-tracked basis working with key standards developing organizations.
- *Technology roadmapping and development of a research agenda*. Develop technology roadmaps and prioritize research investments with government agencies on next generation sensors, process

control, and platform technologies in collaboration with relevant funding agencies (e.g., National Science Foundation, Department of Energy (DOE), National Aeronautics and Space Administration, Department of Defense, Defense Advanced Research Projects Agency, National Institute of Standards and Technology [NIST]) and private sector participants to accelerate development.

- *Coordinating digital and ASCPMM requirements*. Digital design and ASCPMM have distinct requirements that need to be integrated without losing appropriate emphasis on either.

The AMP 2.0 working team also recommended sector-focused demonstration and implementation activities that address the following needs:

- Physical and virtual test beds for technology demonstration and evaluation
- ASCPMM technology evaluation, development, demonstration, and customization services to small, medium, and large enterprises, in collaboration with vendors (for later stage TRL/Manufacturing Readiness Level [MRL] technologies)
- Training and facilitation for technical and managerial staff by linking with industry and technical/community colleges
- Coordination with digital design and advanced materials centers, institutes, and/or initiatives on common infrastructure and technologies so that the full life cycle of technology solutions is integrated at the point of demonstration and delivery

How does DOE differentiate between “Digital Manufacturing” and “Smart Manufacturing?”[28]

Digital manufacturing aims to improve product design and manufacturing processes across the board by using enhanced, interoperable cyber-secure information technology systems across the supply chain. It focuses on modeling and advanced analytics, and utilizing data from design, production and product use to reduce the time and cost of manufacturing, and improve product performance.

Smart manufacturing aims to reduce manufacturing costs from the perspective of real-time energy management, energy productivity, and process energy efficiency. Initiatives will create a cyber-secure networked data-driven process platform that combines innovative modeling and simulation, and advanced sensing and control. Smart manufacturing integrates efficiency intelligence in real time across an entire production operation, with primary emphasis on minimizing energy and material use, particularly relevant for energy-intensive manufacturing sectors.

Risk and Uncertainty and Other Considerations

The consumer and discrete manufacturing industry has in recent years employed ICT-based platforms and sensors to individual stages of decision making and production. This approach has enabled greater plant-wide efficiencies, leading to lower costs and higher productivity and quality in certain manufacturing sectors. However, similar advancements have been slow to migrate to energy-intensive industries owing to differences in manufacturing methods (continuous/semi-continuous and batch processing versus discrete production), low turnover rate of capital assets, an evolutionary (instead of revolutionary) approach to technology updates, and harsh production environments. The following system-level factors currently inhibit implementation of ASCPMM technologies, especially in the small- to medium-enterprise segments of U.S. manufacturing. These challenges are well researched and documented in various publications by NIST and serve as the key reasons for the recent Manufacturing Technology Acceleration Centers pilots and the Manufacturing Extension Partnership program administered by NIST.[29]

- *Complexity and initial cost*. Because technical solutions are complex and interdependent, taking action on comprehensive "horizontal" methodologies comes with a full gamut of investment, market, technology, legacy, security, and organizational changes for manufacturers that will be felt across small, medium and large companies in different ways. Small and medium enterprises in particular face greater challenges in successfully navigating the risks associated with these changes.
- *Rapid changes in technology*. While emerging technologies and models can drive down costs, complexity increases as new cloud technologies necessitate changes in data, information, and modeling products, services, and business models. Additionally, owing to the interdependence of solutions, value chain access is hard for new entrants, inhibiting innovation and the ability to limit risks.
- *Industry know-how*. While many of the technologies encompassed by the ASCPMM space are broad-based, the application is often industry- or even entity-specific. This limits large investment by both technology vendors and potential manufacturers unless value can be demonstrated for the proposed new approaches.
- *Workforce availability*. Owing to complex and interdisciplinary nature of the technologies, workforce talent is limited. An investment in this area can lead to a shift in workforce needs, causing a dearth of workers in some areas and an oversupply of workers in other areas.
- *Security*. The expansion of information transmission with ASCPMM creates vulnerability in privacy for both companies and consumers. Information security protocols will be necessary to address privacy concerns that could hamper the adoption of this information sharing.

Case Studies

ASCPMM Examples

Examples of current ASCPMM benefits are highlighted in table 6.C.1. However, these achievements are still below targets set through initial industry roadmapping efforts, among them 20% increase in operating efficiency and 25% improvement in energy efficiency.[8] In order for energy-intensive industries to achieve widespread energy benefits and operational efficiencies from ASCPMM, innovations and advances will be needed in a number of areas.

Table 6.C.1 Current Benefits from ASCPMM Concepts

Industry	Company	ASCPMM Concept	Benefits
Petroleum Refining	Chevron[14]	Advanced Process Control with Advanced Software for Adaptive Modeling	■ System is optimized for efficient turnaround of refining units ■ \$2.5–\$6.0M/year in benefits per major refining unit ■ Increased capacity and more energy efficient
Cement	Holcim, Capitol Cement, Others[30]	Framework & Architecture to Customize Control Systems Including Predictive Control	■ 70% reduction in programming & trouble-shooting time ■ Resolved 6–10 potentially critical situations per year that would otherwise have caused a shutdown ■ Increased production stability ~36% ■ Reduced energy use 3% (in new facility) ■ Added \$5M/yr to bottom line by improving plant availability 15%
Chemical	Eastman Chemical[31]	Model Predictive Control (MPC)	■ Currently 55–60 MPC applications of varying complexity ■ \$30–\$50M/year increased profit from increased throughput

Applications of ASCPMM Strategic Energy Management

By helping to mitigate deficiencies in the ability to measure and manage energy, ASCPMM technologies show great promise in optimizing and accelerating the uptake of new and emerging manufacturing technologies. In addition, as ASCPMM equipment becomes more advanced and less costly, more types of equipment and plant operations will be monitored at a more granular level to enable greater energy savings, emission reductions, and productivity benefits. ASCPMM technologies are expected to enable these significant improvements in manufacturing facility energy performance and efficiency through the automated control and tailored analysis of data captured from factory networks.

The data-driven approach enabled by ASCPMM technologies is being facilitated by manufacturing facilities adopting a systematic approach to energy management that institutionalizes the important role played by ASCPMM technologies to improve energy performance and optimize operations. While manufacturers have traditionally viewed energy as a fixed monthly expense, a systematic approach to managing energy that continuously monitors energy performance is proving to yield sustained energy savings and reduced operational costs.[32] This type of strategic, data-driven approach to facility energy management reveals the need for improved data collection methods, such as submetering of significant energy uses. Submetered manufacturing processes can provide real-time, equipment-specific energy consumption data and automated process alerts. In addition, equipment submetering also helps to identify equipment that is nearing failure, proactively reducing equipment downtime through preventive maintenance and extending the service life of facility equipment.

One example of a DOE program that emphasizes a systematic approach to energy management in U.S. manufacturing facilities is the U.S. DOE Superior Energy Performance® (SEP™) Program. Launched in 2014, SEP is an industrial energy management certification program that is accelerating the realization of ASCPMM benefits by emphasizing the value of improved data measurement and operational control for enhanced energy performance. SEP utilizes the ISO 50001 energy management standard as its foundation, augmented with quantitative energy performance improvement targets and requirements for third-party measurement and verification (M&V) of energy savings. The SEP Program requires that manufacturers meter, monitor, and record energy consumption data at their SEP-certified facilities.[33] As a result, SEP-certified facilities are installing energy management metering systems to measure, manage, and optimize energy performance as a key performance variable. Such metering and monitoring equipment demonstrates that energy-efficiency activities yield a positive ROI, helping to accelerate the adoption of cost-effective, energy-efficient technologies in manufacturing facilities.[34]

Endnotes

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[28] Functionally, differences in how ASCPMM technologies are approached are exemplified by the differences in how Department of Energy (DOE) and Department of Defense (DOD) are structuring activities within Innovation Manufacturing Institutes. The following table highlights differences between the DOE and DOD Institutes:

	Digital Manufacturing	**Smart Manufacturing**
Federal Sponsor	■ Department of Defense (DOD)	■ Department of Energy (DOE)
Goal: Real-Time Control of Manufacturing Product Design and Manufacturing Processes—How?	■ Interoperable information technology systems across the supply chain	■ A networked, data-driven process platform that combines innovative modeling and simulation and advanced sensing and control ■ Emphasis on optimizing energy-intensive processes
Key Benefits	■ Cost savings ■ Faster time to market	■ Cost savings ■ Energy efficiency and conservation
Focus Areas for Cost Savings	■ Greater accuracy - Design - Construction - Automatic verification and correction	■ Optimized energy use, leading to 10%–20% reduction in cost of production
Applicable Industries	■ All manufacturing	■ Energy-intensive manufacturing sectors - Chemical production - Solar cell manufacturing - Steelmaking
Core Technical and Process Areas	■ Intelligent machines with integrated IT ■ Machine-to-machine communication, across platforms and companies ■ Computer simulation, 3D models, model-based enterprise interoperable systems ■ Design of advanced materials and processes ■ Analytics	■ Advanced sensing, instrumentation, monitoring, control, and process optimization using advanced hardware and software platforms ■ Modeling and simulation technologies
Detailed Description	■ Take information technologies and digital manufacturing and design concepts from lab environment or prototype to standard business practices ■ Establish "digital thread" standards allowing all manufacturing, including small- and medium-sized manufacturers, to pass design and process information up and down the supply chain	■ Robust sensors for high temperature, high pressure environments ■ Algorithms for control and performance optimization ■ High fidelity modeling and simulation of energy efficient manufacturing processes ■ Unprecedented real-time control of energy, productivity, and costs across factories and companies
Cybersecurity Emphasis	■ Systems	■ Devices

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[34] DOE case studies that detail the positive ROI of SEP certified facilities can be accessed at: http://energy.gov/eere/amo/business-case-sep#-case-studies.

Acronyms

AMP	Advanced Manufacturing Partnership
ASCPMM	Advanced sensors, control, platforms, and modeling for manufacturing
DOE	Department of Energy
EMS	Energy management system
ICT	Information communication technology
IoT	Internet of things
ISO	Independent system operator
M&V	Measurement and verification
MRL	Manufacturing readiness level
NIST	National Institute of Standards and Technology
R&D	Research and development
ROI	Return on investment
SEP	Superior Energy Performance Program
SME	Small-to-medium enterprises
SOTA	State-of-the-art
TRL	Technology readiness level

Glossary

Big data	Large data sets that may be analyzed computationally using advanced database and software techniques to reveal patterns, trends, and associations across different systems
Cloud-based	A type of computing that relies on sharing computing resources, often delivered across the Internet, rather than having local computing equipment handle applications
Cyber-physical	A system of interacting computational elements controlling physical entities
Future proofing	The process developing methods to minimize the shocks and stresses from possible future events
Information communication technology	The combination of networks, software, storage, and audio-visual system for telecommunications and computing
Intelligent efficiency	Energy savings resulting from ICT-enabled connection of sensors, devices, systems, facilities, and users
Internet of things	Machine-to-machine interaction through the Internet
Interoperability	The ability for different products and software applications to communicate and exchange data
Open-architecture	Computer architecture or software architecture that is transparent and designed to make adding, upgrading, and swapping components easy for the broader community
Plug-and-play	The capability of software or devices to work perfectly when first used or connected, without requiring any reconfiguration or adjustment by the user.
Smart manufacturing	Superior productivity resulting from the integration of all aspects of manufacturing