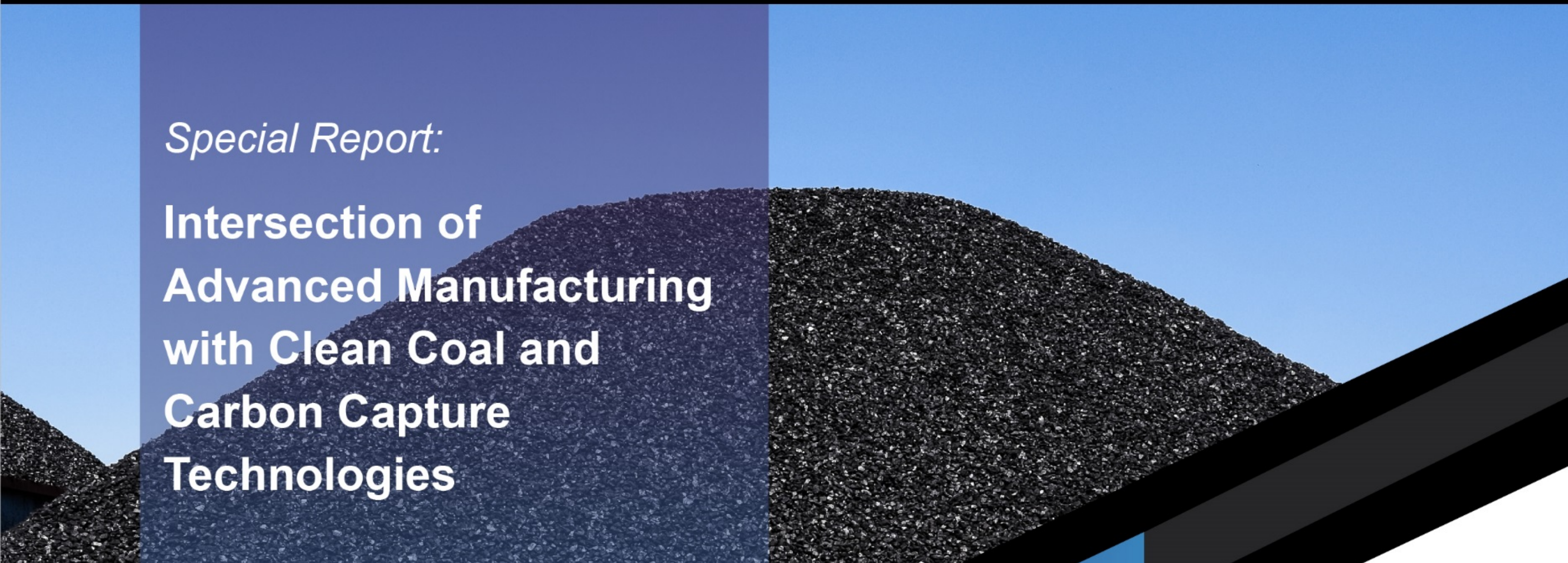
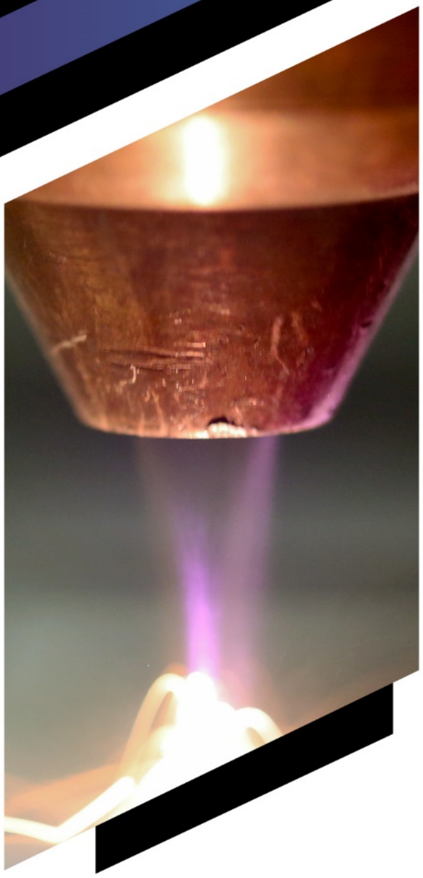


Special Report:

Intersection of Advanced Manufacturing with Clean Coal and Carbon Capture Technologies



October 2019

U.S. Department of Energy
Office of Fossil Energy
Clean Coal and Carbon Management

Foreword

The Office of Clean Coal and Carbon Management (OCCM) within the Office of Fossil Energy (FE) produces a special report each year to explore a topic that cuts across research and development (R&D) programs and leverages the latest developments in science and engineering. For Fiscal Year 2019, OCCM selected for analysis the potential contributions of advanced manufacturing to clean coal and carbon management technology.

This document represents a first step in evaluating the areas in which advanced manufacturing tools and innovations can support and accelerate the attainment of FE goals and objectives. Specifically, collaborative research should lead to novel, high-performance materials and components; transformational diagnostics and maintenance systems; optimized operations; and novel products.

The analysis presented in this report is the product of a broad scoping exercise, which included a workshop held April 30, 2019, in conjunction with the Department of Energy's Advanced Manufacturing Office (AMO) within the DOE Office of Energy Efficiency and Renewable Energy (EERE). OCCM and EERE wish to thank the many experts who attended the workshop and contributed their ideas and insights. These experts represent a range of utilities, national laboratories, government organizations, and companies that specialize in advanced manufacturing. The workshop agenda and list of participants are provided in Appendices A and B.

Abstract

Advanced manufacturing offers a range of tools and technologies that could significantly accelerate progress toward transformational clean coal and carbon capture technologies to provide secure and reliable power and coal-based products that stimulate the U.S. economy.

Cover photos: Coal, AdobeStock 129033427; laser powder-bed fusion metal additive manufacturing process, Lawrence Livermore National Laboratory (LLNL); additive manufacturing at the Manufacturing Demonstration Facility, Oak Ridge National Laboratory (ORNL); fluorescent quantum dots in tubes, Coal Beneficiation Program, National Energy Technology Laboratory (NETL).

Contents

Introduction

FE Objectives

The Office of Fossil Energy (FE) within the U.S. Department of Energy (DOE) Office of Clean Coal and Carbon Management (OCCM) pursues transformational clean coal technologies designed to deliver secure and reliable power, stimulate the U.S. economy, and protect both the environment and human health. To help achieve these goals, OCCM and FE have established three specific objectives:

- **Help Existing Coal Plants Become More Competitive, Resilient, and Flexible:** Enable the existing fleet of U.S. coal plants to economically increase their efficiency, reduce and capture emissions, and rapidly adjust to the dynamic needs of the emerging grid.
- **Design the Coal Plant of the Future:** Leverage advanced technologies to design clean, highly efficient plants that sustainably generate power from coal to serve the future grid. These plants will be compact, modular, resilient, flexible, and equipped to deliver ancillary grid services.
- **Create New Products and Markets:** Reduce the cost of carbon capture, utilization, and storage (CCUS) and help offset remaining costs by developing new products and uses for captured carbon and coal by-products. New businesses and industries will move CCUS closer to commercial viability.

Advanced manufacturing offers an expanding range of enabling tools and technologies that could accelerate progress toward these objectives. Evolving definitions of advanced manufacturing[1] and smart manufacturing[2] incorporate a broad range of innovative tools and methods, including the following:

- High-performance computing and information technologies
- Smart sensors and automated control
- Artificial intelligence (AI), data analytics, and data-driven models
- High-precision, no-waste production processes.

These and other manufacturing technology innovations are enabling significant advancement across the economy. Innovative tools will expedite discovery of new materials; remove traditional component design constraints; expand material and component functionality; lower product costs; increase flexibility; and enable greater product customization, process intensification, and systems optimization.

This document examines the potential for advanced manufacturing techniques to accelerate progress toward all three FE objectives (see Figure 1). The information presented was gathered during a scoping study and one-day workshop held in April 2019 (see Appendix A). Exploring the intersection of advanced manufacturing with clean coal and carbon capture should help guide efforts to achieve affordable, near-term energy security and meet future power and infrastructure needs in a changing energy landscape.

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[1] Paul Fowler of the National Council for Advanced Manufacturing provides the following definition: "The Advanced Manufacturing entity makes extensive use of computer, high-precision, and information technologies integrated with a high-performance workforce in a production system capable of furnishing a heterogeneous mix of products in small or large volumes with both the efficiency of mass production and the flexibility of custom manufacturing in order to respond quickly to customer demands." (Quoted in PCAST, April 2010)

[2] Smart manufacturing is the process that employs computer controls, modeling, big data and other automation to improve manufacturing efficiencies…Smart manufacturing aims to take advantage of advanced information and manufacturing technologies to enable flexibility in physical processes to address a dynamic and global market. Downloaded Oct. 15, 2019, from www.manufacturingtomorrow.com/article/2017/02/what-is-smart-manufacturing--the-smart-factory/9166/

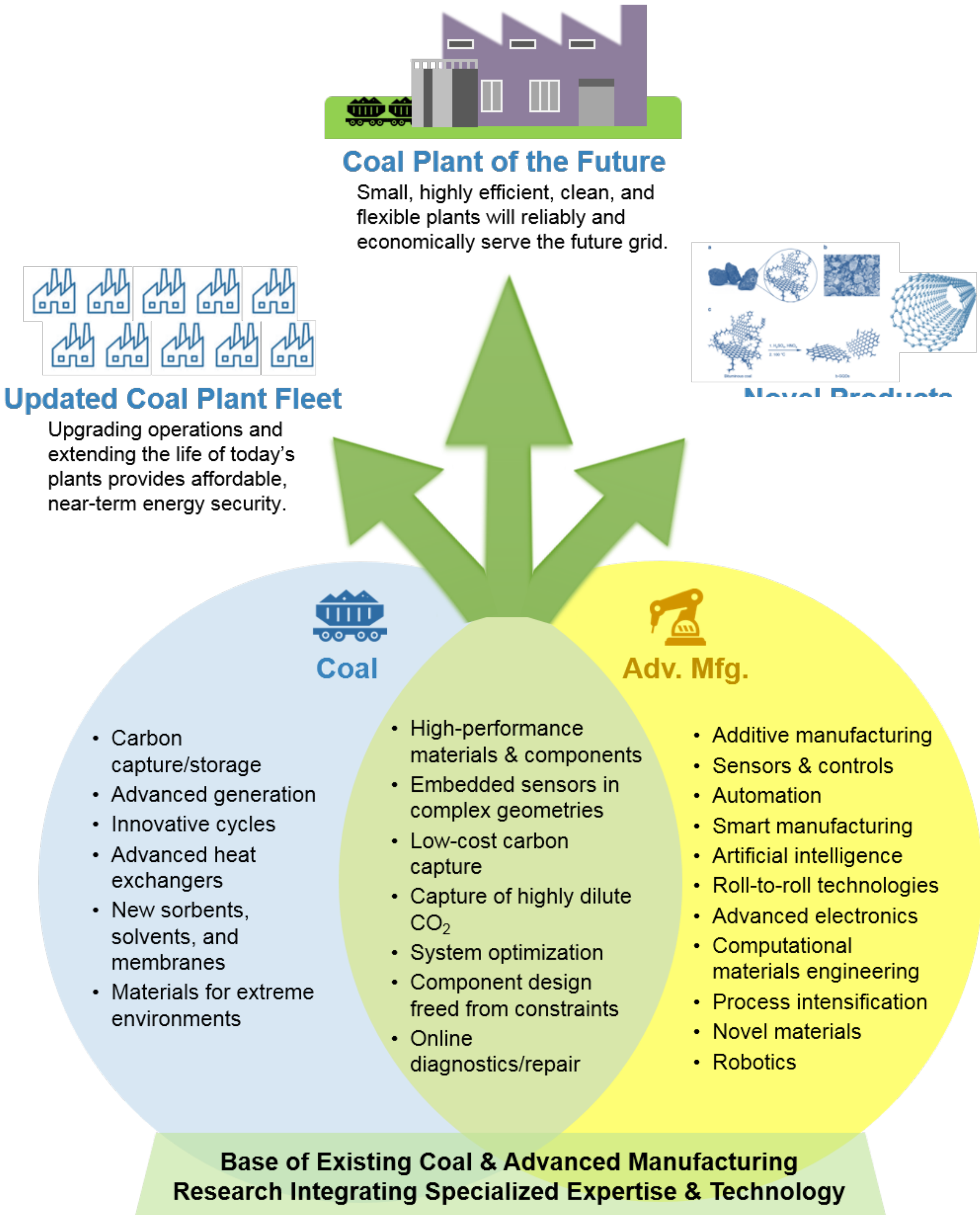


Figure 1. The intersection of advanced manufacturing techniques with clean coal and carbon capture technologies will help to accelerate progress toward the three FE objectives.

Advanced manufacturing techniques offer a variety of energy-efficient and environmentally sound options to economically mass produce modular technological components that can be readily deployed at multiple scales.

Key advanced manufacturing tools, techniques, and processes of interest to FE are briefly described below. The subsequent subsection summarizes a variety of resources available to support FE in leveraging advanced manufacturing capabilities. The section on Challenges and Opportunities identifies major hurdles and potential solutions for upgrading the existing fleet, designing the coal plant of the future, and developing novel coal-based products. The final section suggests potential Future Directions for further analysis and research.

Advanced Manufacturing Capabilities

Advanced manufacturing includes a broad range of tools, technologies, and processes. The category broadly encompasses additive manufacturing (which includes 3D-printing), roll-to-roll technologies, and process intensification (see inset). The latter approach may be particularly useful in facilitating the utilization and capture of carbon dioxide (CO_2), even in dilute streams.

The Advanced Manufacturing Office (AMO) within the DOE Office of Energy Efficiency and Renewable Energy (EERE) develops and evaluates technologies that are broadly applicable to the OCCM research and development (R&D) program (see Supporting Resources and Appendix C). These technologies include advanced and flexible electronics (which could allow sensors to be embedded in critical, geometrically complex components); integrated computational materials engineering; modularization; automation and control; smart sensors; and novel materials development—all potentially expedited using artificial intelligence.

Advanced manufacturing techniques are expected to enable the efficient and economical design and manufacture of components, unrestricted by the limitations imposed by traditional materials and manufacturing processes. Additive processes require no minimum production quantities,

Selected Advanced Manufacturing Methods

Additive manufacturing allows physical, three-dimensional objects to be created directly from a computer design file. 3D printers use a wide variety of materials ranging from polymer composites, metals, and ceramics to foams and gels.
www.energy.gov/eere/articles/what-additive-manufacturing

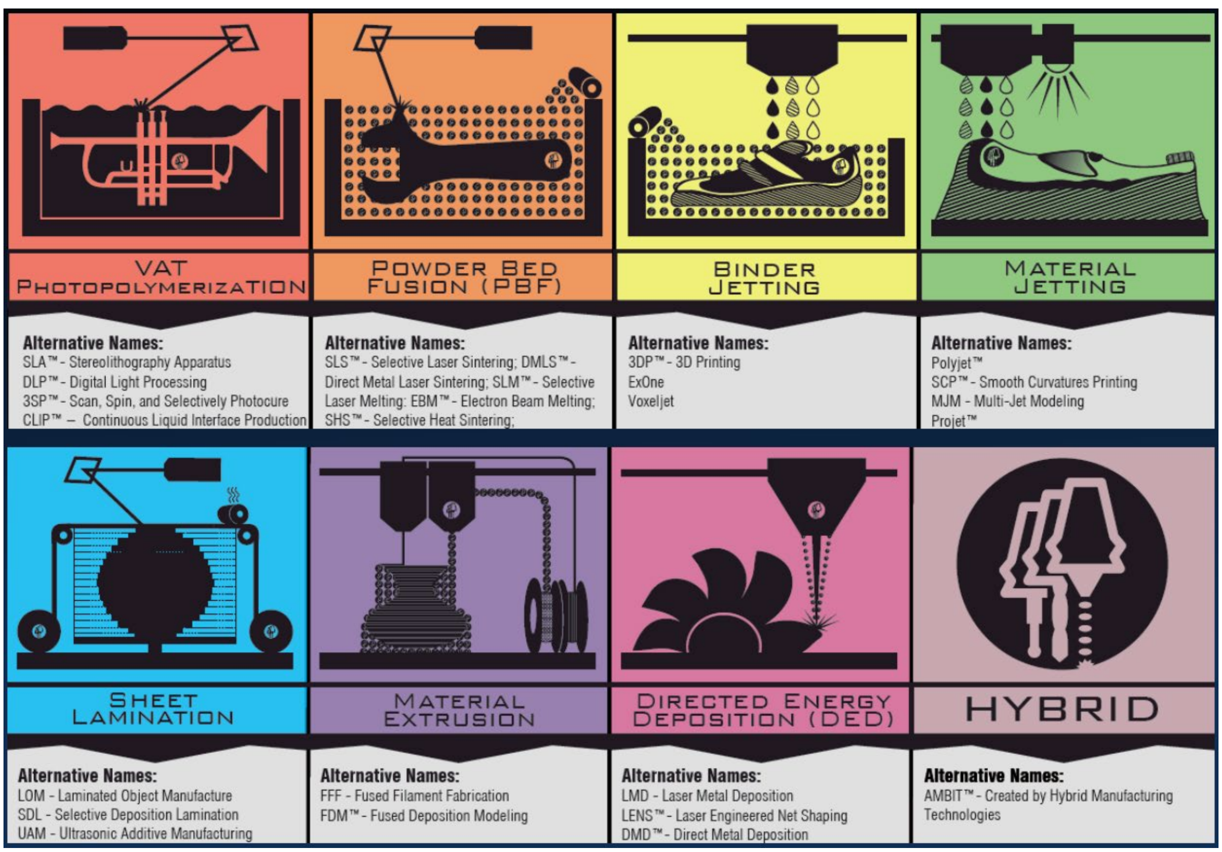
Roll-to-roll (R2R) technologies (e.g., integrated electrospinning) may enable 2D engineered products for use in electrochemical energy storage and conversion, electrolytic hydrogen production, smart flexible sensors, and polymer filtration membranes. (Photo: NREL/PR-5900-68416, M. Ulsh)

Process intensification (PI) involves combining separate unit operations such as reaction and separation, resulting in a more efficient, cleaner, and economical manufacturing process. At the molecular level, PI technologies significantly enhance mixing, which improves mass and heat transfer, reaction kinetics, yields, and selectivity.
Photo: National Energy Technology Laboratory (NETL), www.netl.doe.gov/sites/default/files/2019-05/2019_Annual_Reports/3%20Final%20NETL%20Gasification%20Program%20Overview%20presentation.pdf

allowing a single component to be produced in various materials (plastics, ceramics, or metals) with high accuracy and precision. Process intensification is often guided by models that are developed and continuously updated through the rapid processing of massive data sets (machine learning).

Advanced manufacturing is expected to increase process efficiency and throughput and to accelerate the rate at which new systems and products are developed. For example, heat exchangers that take advantage of novel geometries and surfaces may enhance flows, achieve better mixing, and improve control over critical interactions. Entirely new geometries could drastically reduce the physical size and footprint of heat exchangers, improve performance runtimes, and lower costs. Certain innovations in heat exchanger technology demonstrate the potential to improve performance (efficiency, throughput, etc.) across the fossil power sector.

DOE has long supported R&D of advanced power generation and environmental control technologies, including those focused on CCUS. Advanced manufacturing techniques provide an opportunity to develop carbon capture systems that cost less, utilization systems that convert CO_2 into a range of commercial products, and analytical tools that better support a blended utilization infrastructure with safe and secure storage in diverse geologic formations. All three FE objectives will be advanced by innovations that reduce the size of CO_2 capture systems able to readily and economically convert the CO_2 into high-value hydrocarbons.



The DOE National Laboratories are exploring multiple families of advanced manufacturing processes.
Image: Hybrid Manufacturing Technologies (based on ASTM F2794 definitions), *www.osti.gov/servlets/purl/1368510*

Supporting Resources

Potential collaborative efforts to address the FE objectives are expected to engage world-class expertise and make use of highly specialized equipment and resources. FE plans to leverage its existing R&D programs and projects, the National Laboratories supporting AMO, and the specialized expertise and equipment at AMO Institutes.

FE R&D Portfolio

FE maintains an extensive R&D portfolio that continuously feeds the technology pipeline for OCCM. Existing and future coal plants will derive clear benefits from the technology advancements achieved by FE's research in advanced turbines, solid oxide fuel cells, advanced generation, combustion, and more. In 2019, FE launched the **Coal FIRST** (Flexible, Innovative, Resilient, Small, and Transformative) Power Plant of the Future effort, requesting concept papers on critical components—with $100M in funding for related R&D (see inset).

Through a productive working relationship with AMO, FE is already leveraging some capabilities in advanced manufacturing through its R&D portfolio and in the research that it supports at the DOE National Laboratories. In the FE Crosscutting Research Program alone, 15 active projects (valued at more than $13 million) apply advanced manufacturing to improve coal utilization science and plant optimization technologies.

Additional research projects have been initiated to explore embedded sensors and other novel components for coal plants. In late September 2019, FE announced the award of $56.5 million in federal funding for 32 cost-shared R&D projects, many of which incorporate advanced manufacturing techniques to improve coal system components, focus on process innovations in carbon capture and storage, or support the development of novel coal-derived products (see www.energy.gov/fe/project-descriptions-565m-clean-coal-technologies). Table 1 summarizes an assortment of relevant R&D projects.

Critical Coal FIRST Components

The **Coal FIRST Power Plants of the Future** initiative pursues R&D on the following critical components that may benefit from advanced manufacturing:

- **Coal combustion**, e.g., advanced ultra-supercritical boilers, combustion heaters for supercritical CO_2 (sCO_2) power cycles, direct-injection coal engines, pressurized fluidized bed combustion, chemical looping combustion, staged modular combustion, and pressurized oxycombustion units
- **Compressors/Expanders**, e.g., single-shaft, axial compressor/expander for a coal-fueled, indirect SCO_2 power cycle; integrated combustor/expander with internal blade cooling for a coal-fueled, direct SCO_2 power cycle
- **Gasifiers**, including air separation units, and a 10 to 50 kW syngas-fueled **Solid Oxide Fuel Cell**
- **Miscellaneous**, e.g., sensors, controls, energy storage, polygeneration, syngas engines, and advanced bottoming cycles.

Learn more at: www.netl.doe.gov/node/8692

Table 1. Examples of Ongoing FE-AMO, FE-Industry, and Lab-Based Collaborative Research Efforts

Product or Process	Activity	Technique
Materials Development / Component Design		
Novel gas premix system	Solve hydrogen combustion problem by creating part that better balances ignition delay timing, low-density fuel mixing, and flame speed to reduce NOx.	3D printing
Turbine blades with complex geometries	Create highly detailed castings for the ceramic cores used to make stationery air foils. The castable cores allow manufacture of turbine blades with complex architectures to reduce cooling requirements.	Intricate casting
Materials that can take high thermal and physical stresses	Develop parts deployed in environments ranging from ~500° C to ~ 1,500° C.	Micro-fabrication via 3D printing
Anodes and cathodes	Develop improved anodes and cathodes for use in solid oxide fuel cells (SOFC)	3D printing
Redesign and manufacture steam turbine components	Develop materials and optimize component design to address failure mechanisms and increase the reliability of existing power plant components.	Additive manufacturing
New materials for boilers in existing plants	Evaluate economics of new materials using macro-structurally informed models to clarify degradation of superalloys in boiler components exposed to cyclic loading.	Materials modeling
Advanced ultra-supercritical (AUSC) components	Develop use of wire arc additive manufacturing to cost-effectively produce AUSC components with extended design life under severe service conditions.	Wire arc additive manufacturing
Coatings for AUSC materials	Develop and evaluate corrosion/erosion-resistant coatings for AUSC materials to protect high-pressure steam turbine blades.	Electrolytic co-deposition
Graded composite transition joints	Explore viability of new composites to join dissimilar metals and halt premature weld failures under increased cycling.	Additive manufacturing
Advanced power cycle components and welds	Demonstrate feasibility of fabricating AUSC/sCO_2 turbine components and welds to reduce costs and improve performance.	Hot isostatic pressed technology

Product or Process	Activity	Technique
CCUS Materials and Design		
Mixed matrix membranes for CO_2 capture	Model metal organic frameworks and select for synthesis the candidate membranes most promising for CO_2 selectivity.	Advanced computational modeling
Tailored absorber packings	Print absorber packings tailored for specific carbon capture solvents.	Direct printing
Ionic liquid embedded membranes	Explore additive manufacturing of ionic liquid embedded membranes.	Additive manufacturing
Advanced Sensors & Controls		
Novel, embedded sensors	Use novel sensors to improve thermal management and integrate power plant operations with environmental controls.	Data-driven hybrid models
Thin optical fibers for sensors	Manufacture structures within optical fibers for use in 0.5 mm thickness tubing. (One such fiber can make 100 separate measurements.)	Laser micro-machining of tiny structures
Embedded sensors	Develop sensors that can be placed inside structures, e.g., wireless sensors in refractories. Advanced controls might rely on an embedded sensor that powers itself.	Additive manufacturing
Autonomous nano-sensors for monitoring	Create smart embedded sensors to reduce the cost for long-term security monitoring of carbon storage.	Additive manufacturing
Three types of optical sensor modules (embedded)	Design, fabricate, and test sensors to be installed in inner wall of turbine casing to perform condition-based monitoring of critical operation parameters in coal-fueled steam turbines.	Additive manufacturing
Sensors embedded in rotating blades of low-temperature turbines	Develop sensors that assess/record temperature, position, angle, and derivatives (velocity, acceleration, etc.) to monitor turbine blade vibrations in situ.	Additive manufacturing/ extruded waveguides
Ceramic anchors with embedded sensors	Fabricate and test ceramic anchors with embedded sensors to monitor conditions within coal boilers.	Additive manufacturing
Deep subsurface wireless microsensors	Develop and demonstrate integrated microsensor-based downhole sensing system to measure CO_2 presence.	Autonomous microsensors

Product or Process	Activity	Technique
Maintenance & Repair		
Robotic inspection	Develop robotic inspection technique with “in-place create and replace” or “repair-in-place” capabilities.	Robotics
Predictive maintenance	Develop transformational sensors paired with control algorithms.	Data-driven models
Passive wireless sensors	Develop passive wireless embedded sensors for in-situ monitoring of advanced energy systems.	Direct printing
Repair coal-fired steam turbine components	Reduce routine maintenance, repair, and overhaul costs and improve the operational efficiency of turbines.	Additive manufacturing
Novel Products (and Precursors)		
Precursor extraction during beneficiation	Recover value-added liquid precursors from lower-rank coals for use in developing high-value carbon products.	Patented process
Solid polyurethane foam products	Convert high-volatile U.S. coals to high-value polyurethane (PU) foam (solid) products.	Novel process
Li-ion battery-grade “potato-peel shaped” graphite	Develop scalable processes to economically transform low-cost coal into high-performance, high-value (Li-ion grade) “potato” graphite (a strategic material).	Recently discovered process
Low-cost graphene materials	Produce high-value carbon nanomaterials and carbon sorbents from coal, potentially creating new markets for coatings, composites, and electronics.	Novel technology
Carbon fibers	Develop novel supercritical CO_2 solvated process to transform raw coal feedstocks into pitch and carbon fibers while processing environmentally hazardous intermediates in a closed-loop system.	Vertically integrated continuous manufacturing
High-value coal plastic composite (CPC) decking boards	Use U.S. coal as feedstock to produce lower-cost CPC decking boards with equivalent or better properties than existing wood composite products (meeting specifications).	Continuous process test
High-performance carbon fiber products	Develop and scale efficient processing technology from coal tar pitch to demonstrated product end-uses.	Continuous processing
Quality carbon fiber precursor from pitch	Validate and test high-yield pitch synthesis process to produce lower-cost carbon fiber from U.S. coal.	Continuous process test

Product or Process	Activity	Technique
Industrial carbons & 3D-printable polymers	Use low-temp. microwave plasma coal pyrolysis on coal to make carbon and graphitic materials for industrial electrode applications and polymer composites.	Microwave plasma
High-quality graphene	Produce flash graphene from coal as an economical graphene additive for use in the plastics, steel, aluminum, and concrete industries.	Flash Joule heating

Advanced Manufacturing Institutes

AMO manages public-private R&D consortia or institutes that bring together manufacturers, small businesses, universities, National Laboratories, and state and local governments to pursue coordinated, early-stage R&D in high-priority areas of manufacturing that affect the energy sector. These large public-private partnerships leverage multidisciplinary teams to accelerate innovation in specific industrial manufacturing processes and hasten progress toward national goals.

The U.S. Department of Defense sponsors eight additional institutes engaged in cutting-edge manufacturing research, and the U.S. Department of Commerce sponsors another institute (see Appendix C for more information). Collectively, these institutes expedite the development of new and transformational materials, components, systems, and products and may form shared teams to address issues of mutual interest.

AMO-Funded Institutes

- PowerAmerica (Next Generation Power Electronics Manufacturing Innovation Institute)
- The Institute for Advanced Composites Manufacturing Innovation (IACMI)
- The Clean Energy Smart Manufacturing Innovation Institute (CESMII)
- Reducing EMbodied-energy And Decreasing Emissions (REMADE) Institute
- Rapid Advancement in Process Intensification Deployment (RAPID) Institute.

By strategically planning and prioritizing research efforts, FE hopes to efficiently leverage an appropriate subset of these supporting resources to develop the novel, high-performance components; advanced materials; and transformational diagnostics and maintenance systems required to meet its strategic objectives. Successful collaborative R&D efforts should apply advanced manufacturing to upgrade the existing fleet, design the advanced coal plant of the future, and create new products from coal.

Challenges and Opportunities

The coal industry stands to achieve significant benefits by applying advanced manufacturing techniques and processes to the development and design of new coal plants, retrofit systems for existing plants, and novel products from coal or coal byproducts. In many cases, emerging techniques and highly specialized devices may augment and enhance conventional R&D processes or conventionally manufactured products.

Key themes that emerged during the development of this report center on the need for validated data sets; data-driven modeling to improve process design; and the creation of novel materials, custom components, and automated systems. Real-world applications of advanced manufacturing and smart design will require teams of scientists and engineers who are skilled in advanced manufacturing to work in partnership with subject matter experts. These teams will possess the needed skills and knowledge to identify suitable data sets and produce interdisciplinary analyses and solutions.

Making the Existing Fleet Competitive, Resilient, and Flexible

Existing Fleet Challenges

Coal plants now face fierce competition from low-priced natural gas and increasingly affordable renewable power. In addition, power plants in widespread use today were developed under the operational, technological, and financial constraints that dominated power generation, fossil fuel extraction, and processing from the 1950s through the early years of the 21st century. A large base of coal plant equipment designed to perform well under those constraints is still deployed, yet these plants are expected to serve a rapidly evolving grid with larger fluctuations in demand. Load-following today requires a level of cycling that was not part of the design criteria for many existing coal plants. This mismatch often causes component failure and other issues under some operating regimes.

Wide variations among existing coal plants make it difficult to assess the potential for advanced manufacturing to transform the entire fleet and make all plants competitive, resilient, and flexible. Key distinctions among existing plants include the type of fuel used, planned unit availability, maintenance practices, and past upgrades or overhauls. The uneven status of the existing fleet and the mismatch of equipment to evolving grid expectations (e.g., rapid ramp up/down and power quality services) raise some key questions: What are the baseline requirements for a given power unit? What advantages does advanced manufacturing offer for the near term? Will emerging options for upgrades be worth the investment?

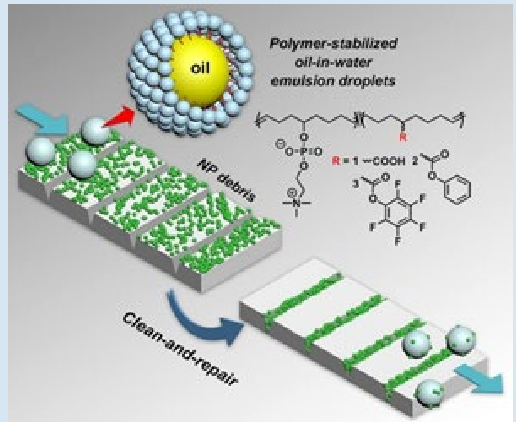
Existing Fleet Opportunities

As aging U.S. coal power plants are upgraded or replaced, new manufacturing methods and novel materials could improve the reliability, resilience, efficiency, and economics of operation. Advanced manufacturing techniques may help OCCM solve critical challenges in upgrading plant performance. For example, major retrofits might allow these plants to switch to supercritical operation or add a supercritical CO_2 topping cycle—enabling higher plant efficiencies and potentially facilitating carbon capture. Improved instrumentation could improve operator control over cycling behavior, provide precise monitoring, and predict overall plant "health."

Advanced manufacturing capabilities could also help the existing fleet of coal plants with on-line repair capabilities or incremental maintenance and parts replacement. Joining old parts to new and ensuring that the welded joints do not fail could enhance reliability and reduce operating costs. Similarly, advances in "smart materials" might provide coal plants with self-healing materials to avoid down time (see example in inset), smart control systems (e.g., valves and gates) to boost efficiency, and shape-changing materials or membranes to support CO_2 capture and sequestration. Real-time sensors made possible by advanced manufacturing will accurately measure and report all critical data (versus the approximations or surrogate data often used today); more precise data measurements can also augment big data and machine learning to accelerate this work.

As discussed below, more specific suggestions or opportunities include the following:

- Develop new repair approaches that focus on on-line, real-time repair
- Develop data, data standards, and machine learning
- Develop targeted technologies, techniques, and practices to meet efficiency and environmental performance goals.



Self-Healing Prospect. In a simultaneous clean-and-repair mechanism, flowing oil-in-water droplets move nanoparticle debris, shown as green spheres, into the cracks. The droplets pick up the nanoparticles, then deposit them in the cracked regions. Image: Todd Emrick, University of Massachusetts, Amherst *www.energy.gov/science/bes/articles/simultaneous-clean-and-repair*

Develop real-time repair approaches

New in-field repair approaches can be developed using advanced manufacturing, especially forms of additive manufacturing. Automated inspection systems could identify potential issues, devise solutions, and arrange on-site robotic repair. Additive manufacturing techniques, including those developed for multi-material, multi-function applications, could be used to produce any plant components requiring replacement (i.e., just-in-time component manufacturing for preventive maintenance). Automated or robotic systems might then remove the old component and build/install the new one according to applicable standards. In this way, robotic systems could make repairs during plant operation—minimizing downtime, allowing more flexible generation, and improving plant profitability.

This technology would require a "qualification" algorithm to validate that the repair meets all applicable standards. Automatic, robotic welding, for example, would reduce repair or replacement costs if the welds could be certified by an automated process. Recognizing that a lack of long-term data may delay industry acceptance of power plant parts and equipment produced using novel processes, methods will be needed to study the behavior and performance of such parts and equipment under actual operating conditions.

Repairing the damage caused by excessive cycling (e.g., valves) will require a better understanding of cycling and its impacts, the progressive effects on materials, and various failure modes. This understanding, which can be built through dynamic modeling of power plants, will help design and implement tailored material solutions (commissioned to precise specifications). The same or similar modeling efforts may also provide the needed data and analysis (described in the next section). Better thermal energy storage is another route to reduce damage from cyclic operations.

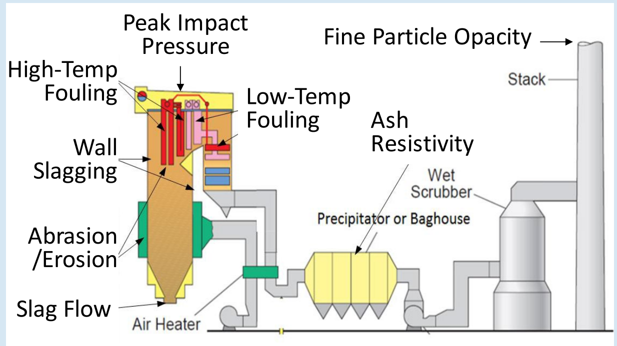
To reduce the frequency with which parts must be replaced, analysts or systems can identify the parts that fail most frequently and find novel ways to improve part durability. Tools or practices for total asset management and maintenance could be developed using data analysis (comprehensive history, issues, operations) and novel test methods. Plants in the existing fleet may be selected for use as testbeds to evaluate new repair technologies and gain new insights on repair or replacement needs.

Data, data standards, and machine learning

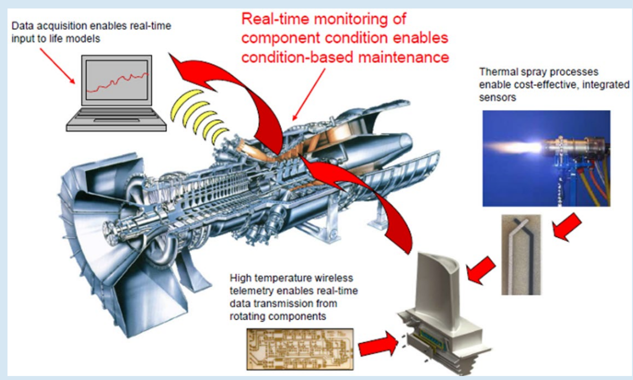
The diversity and uniqueness of existing plants underscore the need to develop dynamic modeling capabilities and characterize plant performance at all scales. Quality data and modeling (digital twins) can help to improve plant management systems, integrate modern maintenance practices, and guide automated repair. Acquiring the needed data streams will require sophisticated sensors that do not damage the system. Both surface and volumetric non-destructive evaluation (NDE) techniques are needed for in-service inspections to forecast remaining part life and verify the quality of repairs. Data-driven models could enhance performance assurance tools, enabling asset management practices (see inset for examples) and tools that support retrofit decisions and subsequent actions.

New models and tools could enable plant operators to accurately understand the economic tradeoffs of cycling operations that damage equipment. These tools could benefit from improved optical or infrared instrumentation coupled with software that enables full-field characterization of flames and temperature distributions. These analyses could be further improved by developing portable instruments to perform NDE of microstructures in the target material.

Data from diverse sources (materials, mechanical properties, manufacturing design) could be integrated into a combined database to support the development and revision of standards; however, the quality and fitness of data for specific uses must be clear.



Optimizing plant performance using real-time analysis of coal composition. Microbeam Technologies Inc. is leading a team using recurrent neural networks and statistics to manage coal quality and boiler operation.
Image: Microbeam Technologies, NETL, #DE-FE0031547



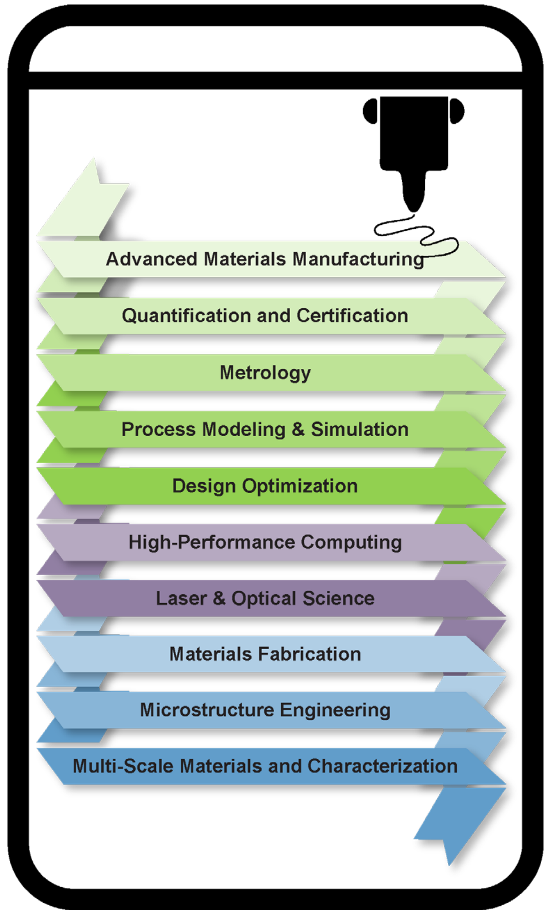
High-temperature wireless telemetry enables real-time monitoring of component conditions. Siemens Corp. is testing integrated sensors and stochastic methods to estimate turbine component life.
Image: Siemens Corporation www.netl.doe.gov/node/1415

Develop targeted technologies, techniques, and practices

New materials are essential to ensure the continued viability, reliability, and cost effectiveness of the current fleet. Materials currently used in advanced manufacturing applications may not be suitable for use under the harsh conditions typical of many fossil fuel-based processes. More robust and reliable materials and sensors would significantly benefit existing coal plant systems and components. There is a need to develop new materials that can better withstand the stresses of cycling operations and extend boiler service life.

Enabling technologies for these new extreme environment materials include new source materials optimized for advanced manufacturing technologies. Existing coal plants particularly need new alloys optimized for production by advanced manufacturing technology, e.g., solidification modeling for new high-nickel alloys.

Many advanced manufacturing techniques currently in use print or otherwise generate products from commercially available materials. This approach often fails to take full advantage of advanced manufacturing capabilities, which have the potential to create products with previously unattainable microstructures or properties. For example, novel technologies and source materials may yield alloy compositions not possible with conventional production practices. The National Laboratories are currently exploring a wide range of source materials and additive technologies (see inset). Needed material enhancements to existing components include ablative heat shielding, aerogels, and embedded sensors.



DOE's National Laboratories pursue research to accelerate development of next-generation advanced manufacturing.

Source: *Spotlight on Additive Manufacturing*, DOE Office of Technology Transitions, July 2019.

Design tool kits that integrate materials, mechanical performance targets, and manufacturing processes could potentially aid the component design process, whether technology system models are available or not; strong standards and a supporting data infrastructure will need to be developed.[3] Tools are also needed to determine which components of existing plants can be repaired or reused (and for what purpose). Such tools may also help determine the feasibility of cloning digital technologies currently in use for applications elsewhere in the system.

Coal-Fired Power Plants of the Future

Plant-of-the-Future Challenges

To competitively produce electricity from coal in the future, marketable new units should be highly efficient, relatively small (50–350 MW), modular, and suitable for siting close to load centers (for distributed generation). These plants must provide auxiliary grid services and operate flexibly (able to

[3] For example, an ASME standard might be developed to provide a framework for assessing the relevance and adequacy of completed verification and validation (V&V) activities that establish the credibility of a computational model. The credibility should be commensurate with the degree to which the computational model is relied on as evidence of device performance, functional characteristics, and/or safety to support a decision, and the consequences of that decision being incorrect. www.asme.org/codes-standards/find-codes-standards/v-v-40-assessing-credibility-computational-modeling-verification-validation-application-medical-devices

ramp up and down rapidly) to compete in domestic electricity markets. In addition, these plants must have near-zero emissions, capturing and profitably utilizing any generated CO_2.

The next generation of advanced coal plants must provide the capabilities and options required to maintain a resilient fleet. High-performance materials and components must operate for long periods under extreme conditions—including high-pressure, high-temperature, vibration, fatigue, and stress states. At the same time, these materials must afford increased resistance to erosion and corrosion.

Automated systems will need to continuously monitor and manage operations to optimize efficiency, service, and cost effectiveness. These systems will exploit new materials, embedded sensors, AI models, and advanced manufacturing technologies to continuously maintain system performance, perform on-line maintenance and repair, and maximize all component service.

Plant-of-the-Future Opportunities

Advanced manufacturing tools and materials remove many traditional design constraints and should pave the way for reimagining the coal-based power plant. Promising tools and techniques for this work include smart sensors to enrich big data and machine learning, process intensification, and system optimization models. Advanced software tools based on these capabilities could help to design and optimize a range of systems for specific power technologies, including solid oxide fuel cells and advanced generation systems (e.g., super-critical CO_2 cycles and direct power extraction systems).

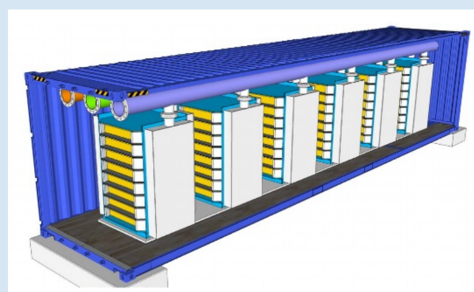
To significantly shorten development timelines, three major opportunities show promise:

- Data-driven optimization of system design and manufacturing
- Components and enabling technologies
- New materials for extreme environments.

Data-Driven System Design and Manufacturing

Novel, modular coal plant designs will take advantage of advanced robotics and use other advanced manufacturing technologies to shorten manufacturing and construction times and manage risk. Consistent designs that can accommodate a range of coal types might reduce capital and maintenance costs across the industry, depending upon the generation technology. Detailed data obtained using new sensors may complement massive data sets from traditional plants to help machine learning systems create useful models and algorithms to guide new plant design.

Success in designing and developing the clean coal power plant of the future will require a systems-level view, advanced manufacturing techniques, and process intensification. Modular carbon capture systems and components (see inset) must demonstrate process intensification and extended service life to reduce operating and life-cycle costs. Up-front integration of a systems concept with innovative manufacturing and design processes can yield purpose-designed components that add value.



Post-Combustion CO_2 Capture: Membrane Technology and Research, Inc. is leading a large-scale demonstration of a simple, compact system design that maximizes flexibility and aims to reduce capture costs to ~$40/ton of CO_2.
DE-FE0031587; FOA 1788. Source: MTR
www.netl.doe.gov/sites/default/files/event-proceedings/2018/co2%20capture/thursday/R-Baker-MTR-Membrane-Large-Pilot-Testing.pdf

Information technology and essential maintenance and operations data, when effectively integrated into algorithms or models, can help keep plants running efficiently. Plant management approaches that rely on just-in-time production of spare parts will need to link to diagnostic systems that synchronize part fabrication and delivery with preventive maintenance needs.

Cybersecurity will be incorporated from the start of development, as the protection of devices is crucial on the end-use edge of the grid.[4] Appropriate standards and protocols will need to make full use of 5G network capabilities (and anticipate those of later-generation networks) to connect all smart components and devices used by coal plants.

Components and Enabling Technologies

Advanced manufacturing techniques, tools, and practices are already beginning to produce novel materials and smart components for selected applications. While experimental data and modeling can generate entirely new insights and pave the way to optimal solutions, clearly defined performance targets and metrics can enhance the likelihood of success in overcoming major hurdles.

In coal-fired power plants, broad target applications for advanced manufacturing include novel configurations for improved heat exchangers (see inset), printed catalysts on novel supports, novel materials, and embedded sensors. Specific enabling advanced manufacturing technologies include full control of spatial relationships during automated manufacturing and multi-material manufacturing techniques for components or systems exposed to extreme environments or conditions. Novel reactors that allow processes to occur at higher rates (process intensification) are a widely recognized need; additional concepts need to be developed and tested. Embedded sensors may give plants the capability to better follow load and instantaneously adjust operational parameters to maintain performance and protect the equipment. The primary role for advanced manufacturing could begin in the design phase, but cost must be a key factor in all subsequent stages of technology development to ultimately produce a unit that is less expensive on a life-cycle basis.

Multi-scale, multi-material component development for heat exchangers

Lawrence Livermore National Laboratory (LLNL) is using additive manufacturing to produce new structures for heat exchangers in supercritical CO_2 fossil-fired power plants. Highly efficient gyroid-configured heat exchangers (Triply Periodic Minimal Surfaces) could improve heat transfer efficiency by an order of magnitude over tubes and flat plates. Only additive manufacturing can build the complex geometric structures of the gyroid designs.

Another advantage of additive manufacturing is that once CAD files for a given part are converted to an .STL file (triangulated representation of a 3D CAD model) the part may be made in various materials.

Printed in stainless steel

LLNL produced the component in nylon, stainless steel, clear polycarbonate, ABS, and Inconel 625. Use of plastics permits cold modeling, visualization of flows and stresses, and ready modification of the CAD files to iterate to a final product design.

www.netl.doe.gov/sites/default/files/netl-file/20180410_1430B_Presentation_FWP-FEW0225_LLNL.pdf

4 "Security can be improved with edge computing by keeping sensitive information within the device and using edge networking devices to reinforce security." Quote from Moxa, Enabling Smart Manufacturing Through Connected Sensors & Machines (Accessed Oct. 15, 2019, at: http://pages.moxa.com/connecting-sensors-and-machines.html

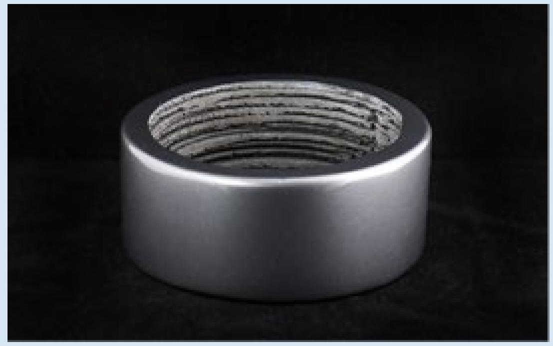
New Materials for Extreme Environments

Power plants of the future are likely to require more robust materials. Advanced manufacturing techniques may provide useful insights on how metallic elements can be arranged to form new alloys for components that can stand up to the harsh conditions of these advanced systems.

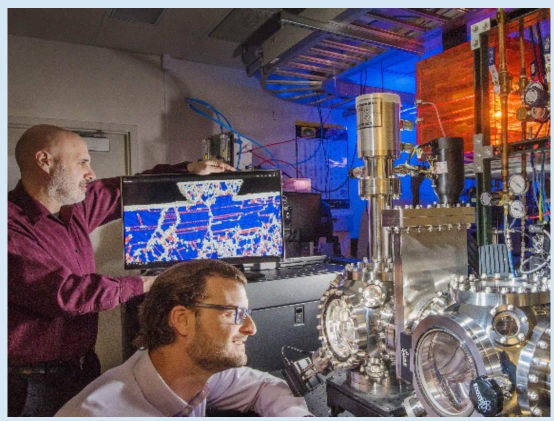
Advanced manufacturing technologies that could create the needed materials and components include a range of additive techniques, but printing will need to move beyond today's commercially available resources. A shift to new source materials (see upper inset) and manufacturing techniques could benefit both design and qualification processes. Innovative materials could elevate performance while maintaining equipment integrity and extending service life. An open database to support information sharing[5] could accelerate progress in achieving these goals.

Materials development efforts require high-quality data and analysis to define the precise material requirements and predict future material properties (see lower portion of inset). Novel, highly efficient coal-fired plants are likely to require materials that can withstand higher temperatures and pressures and the rigors imposed by more flexible operations (increased cycling). Some core enabling technologies may be needed to achieve the material flexibility and resilience required for use in highly variable (range and rate of change) operating conditions.

Recognizing that fossil fuels vary both in composition (particularly mineral matter) and in response to varying operating conditions, new technologies and materials may require accelerated life testing. Perspectives vary on the future ability of advanced manufacturing to produce new target materials that qualify *a priori* for implementation in a coal-fired plant. In the near term, new materials and full-scale



3D-printed permanent magnets with increased density were made from an improved *mixture of materials*, which could lead to longer lasting, better performing magnets for electric motors and sensors. Credit: Jason Richards/Oak Ridge National Laboratory (ORNL), DOE. www.ornl.gov/news/magnets-print-power-repeat-0



Computational tools predict material properties. Sandia National Laboratory's Materials Science team used computational tools to calculate how individual atoms affect the properties of a material, then engineered an alloy believed to be the most wear-resistant metal in the world (100 times more durable than high-strength steel). The key is the diamond-like carbon coating that forms spontaneously.

Photo: Randy Montoya, Sandia National Laboratory (SNL). *https://share-ng.sandia.gov/news/resources/news_releases/resistant_alloy/*

5 Related non-technical topics: Workforce and community development would be essential for the success of such a significant departure from conventional practice. Developing, fabricating, and deploying a significant number of these new power systems would require substantial workforce development. The scientific organizations involved in such an effort could use data and partners that are not participating under current circumstances.

components will need to be evaluated in large-scale testing facilities to clarify their properties, validate component performance requirements, and evaluate joining (interface stability) methods, if applicable.

New Products and Markets

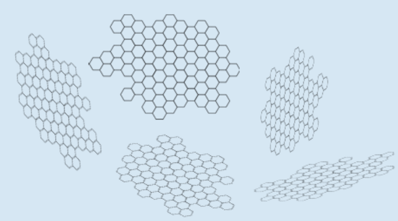
New Product Challenges

Ideally, both upgraded and future coal plants will operate with near-zero emissions as innovative technologies and systems make it cost effective to capture and store even dilute streams of CO_2. Additional innovations will transform the captured emissions and other coal byproducts into high-value products—potentially offering significant advantages over traditional products and creating new market opportunities for coal. New CCUS systems will employ tailored materials and component designs. Advanced manufacturing techniques guided by computational modeling will ensure the economic sustainability of production.

> "With just a few hours of processing, we converted this penny's worth of coal into 1 liter of graphene quantum dots in water, which has a current market value of approximately $50,000."
>
> Christopher Matranga, Materials Engineering & Manufacturing, National Energy Technology Laboratory
> www.netl.doe.gov/node/8826

New Product Opportunities

OCCM's efforts to develop innovative processes and expand the commercial use of coal's carbon and chemical properties should help open new markets. DOE has partnered with industry on some of the world's largest advanced CCUS demonstration projects. Improving carbon capture technologies and exploring new uses for captured CO_2 can facilitate new product development and generate new revenue streams for the industry. DOE has participated in fly ash reuse projects, processes for CO_2 utilization, and the Consortium for Premium Carbon Products from Coal (formed in 1998). More recently, DOE and its partners have begun exploring such new uses for coal as carbon-fiber parts for airplanes, carbon-based building materials, and medical technology devices.



Graphene quantum dots are small, fluorescent nanoparticles with sheet-like structures only one carbon atom thick and a few hundred atoms wide. The tiny size imparts optical and electronic properties to coal-based derivatives. The chemical composition and size of these dots also help them bond with composite materials, interact with the composite, and impart unique properties to the composite.

Source: *www.netl.doe.gov/node/8826*

An analysis of emerging market issues may suggest categories for other new products.[6] For example, the domestic supply of some rare earth elements is limited, and foreign supply chains may be insecure; prices of alternative materials from traditional sources may rise; rapidly expanding markets may threaten to overwhelm existing supplies; or large and lucrative new markets may require a novel material with a critical mix of specific properties (e.g., carbon nanotubes or graphene [see inset]). Identifying and further defining underserved or growing markets would

[6] For products with no current markets but a high potential value, a supply chain and consensus standards are unlikely to exist. These gaps restrict market development. Rare earth elements are a useful example, in that there is no set price (commodity market) and all trades tend to be two-party deals (little or no public data disclosed). Expanding the supply has been difficult. Similar arguments have been made about markets for carbon nanotubes and carbon fiber. Each application tends to define the product specifically for that application—without regard to expanding supply to reduce cost.

inform evaluations of the technoeconomic gaps that might be filled by the right carbon-based products. Using advanced manufacturing to develop technologies or products to close those gaps could significantly reduce both cost and time to market.

Efforts to develop novel carbon products will benefit from success in a wide range of technologies now under development, including new CO_2 capture processes, reactors that optimize existing carbon capture chemistries, new methods to separate fine solids, remote sensing technologies for resource discovery (tied to strong analytic tools), and more secure CO_2 storage. In circular fashion, new materials may also facilitate these developments. Sensor technology is the key enabling technology for many applications focusing on new products and new markets. Some key opportunities for creating novel products from coal and opening new markets include the following:

- Identify supply gaps for high-value materials (or low-value materials in large quantities)
- Find new markets where IT, manufacturing, and supply issues converge
- Create new technologies, produce valuable feedstocks, and improve CO_2 capture and use

Identify Supply Gaps for High-Value Materials

Coal and coal wastes potentially represent a large, low- or no-cost feedstock for domestic materials. Market analyses might identify existing or emerging supply gaps that could be filled by products made from this type of low-cost feedstock (see inset). The technoeconomic analyses frequently used to screen novel manufacturing solutions may also provide insight on promising products that could be made from coal or coal byproducts.

Analytic results may also indicate which resource-to-product pathways might best leverage the carbon resource and available advanced manufacturing options. For example, carbon electrodes that use graphite (with coal as the original source material) might not use millions of tons of coal; however, the product has a high value-added. The real opportunity in advanced manufacturing could simply be small, highly specialized operations that produce high value-added products. Based on market prospects, it may be worthwhile to invest in technologies that more efficiently extract the feedstocks and produce the products. For example, the shift toward tight crude in the existing fossil supply chain adversely affects the asphalt industry, among other industrial markets. Industry access to an alternative supply from coal (fly ash) might create an opportunity to fill this emerging market need.

Many products are manufactured for applications in which high strength and light weight offer significant value. Carbon fiber-reinforced plastics are made by curing carbon fiber-impregnated resin to provide increased strength, and the material is often used in making bicycles, golf clubs, fishing rods, or parts for aircraft, bridges, and automobiles. Strong, lightweight

Possible Applications for Coal-derived Carbon Materials

The molecular structure of coal is ideal for making carbon fiber—giving coal-based feedstocks a technical and cost advantage over petrochemicals and natural gas.
Source: C. Matrenga, NETL.

materials will be needed for the foreseeable future. (The Manufacturing USA LIFT Institute focuses on "light weighting," as described in Appendix C.)

Other interesting opportunities include covetics and nano-diamonds, both of which are relatively new materials with potentially large markets. Covetics are metals infused with small particles of carbon to make them conduct heat and electricity more efficiently than conventional metal alloys (see inset). This superior conductivity could boost the efficiency of heat exchangers, recuperators, and other equipment. Researchers at Argonne National Laboratory (ANL) are using nanodiamonds in a self-generating, very-low-friction dry lubricant that lasts for an extremely long time. The friction is ten times less than that of some nonstick coatings, reducing heat as well as wear and tear on parts and equipment. The lubricant has hundreds of potential applications in industry.[7]

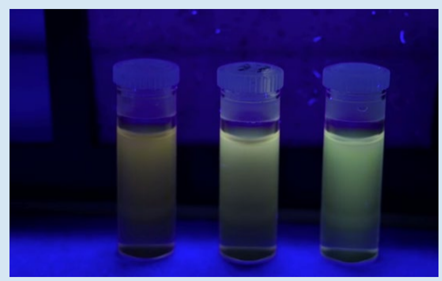
Covetics

The National Energy Technology Laboratory (NETL) is exploring the melt processing of alloys enriched with nano-scale carbon particles to improve their electrical and thermal conductivity. www.energy.gov/sites/prod/files/2019/07/f64/018-Poster19-3%20-%20Melt%20Processing%20of%20Covetic%20Materials_NETL.pdf

Find new markets where IT, manufacturing, and supply issues converge

The future of manufacturing is likely to be more modular and distributed, emphasizing just-in-time processing and mass customization. Studies suggest that nascent markets exist for various carbon products—yet the supply chain is constrained. Under these conditions, crosscutting benefits like a more sustainable net life cycle may make a difference. Products made using highly efficient processes that reduce the carbon footprint and minimize energy and water usage can gain a competitive edge in the market.

Demonstrable quality and product cost are crucial when entering new markets. Researchers are beginning to discover valuable qualities in carbon-based advanced materials from coal (see inset). Competitive cost must be a primary goal in developing new ways to recover a range of industrial elements, minerals, or rare metals. Precision mining and coal preparation or upgrading represent additional opportunities to improve the quality of the coal provided. Major advancements in precision mining or coal preparation can limit variations in coal properties that might affect advanced manufacturing techniques.



Positive Health Impacts from Coal

Unlike most graphene quantum dots, which are expensive and often toxic, coal-derived dots are non-toxic *and* they fluoresce. A team at Rice University is exploring their use in medical imaging and as therapeutic antioxidants to limit damage from free radicals.

Photo: Rice University, L. McDonald, The American Ceramic Society, May 14, 2019. https://ceramics.org/ceramic-tech-today/medical/coal-derived-quantum-dots-offer-basis-for-effective-antioxidant

Create new technologies, produce valuable feedstocks, improve CO_2 capture and use

A mix of advanced manufacturing technologies could help to improve the performance and lower the cost of carbon capture technologies. FE research is already improving CO_2 capture systems, particularly those that use solvents and sorbents. This research would benefit from further process intensification

[7] "Nanodiamonds are forever," in *ArgonneNOW*, S. Vorenberg, May 10, 2018. www.anl.gov/article/nanodiamonds-are-forever

enabled by novel reactor design and materials that enhance capture rates or ease the release of CO_2. It is crucial to lower the cost for chemically transforming CO_2 into valuable carbon-based products.

Keys to improving CO_2 utilization include improving the management of CO_2 storage and increasing the recovery of hydrocarbon resources used for CO_2-enhanced resource recovery. Improved CO_2 storage management will require better sensors and software to rapidly evaluate data from multiple sensors. Downhole CO_2 products (sensors, in particular) need to be durable and reliable; they must work for extended periods in isolation to minimize the cost associated with long-term monitoring of carbon storage sites. These sensors should be wireless, smart, and cloud-based, to assure the public that the CO_2 is stored securely.

"NETL's Coal Beneficiation Program and a dynamic new collaborative effort with universities and sister national laboratories known as the Consortium on Coal-based Carbon Materials Manufacturing (COAL MAT) are leading the way in innovating ways to manufacture carbon products like carbon fiber, and carbon additives for cements and structural composites directly from coal—instead of using petrochemical or biomass feedstocks."

Brian Anderson, Ph.D., Director
National Energy Technology Laboratory
October 01, 2019

www.netl.doe.gov/node/9244

Future Directions

New and emerging advanced manufacturing techniques both support and elevate visions for the coal-fired power plants and coal-derived products of the future. Novel manufacturing techniques, amplified by big data and artificial intelligence, are expected to accelerate progress in all aspects of the technology development continuum, from concept through deployment and market acceptance (see Figure 2).

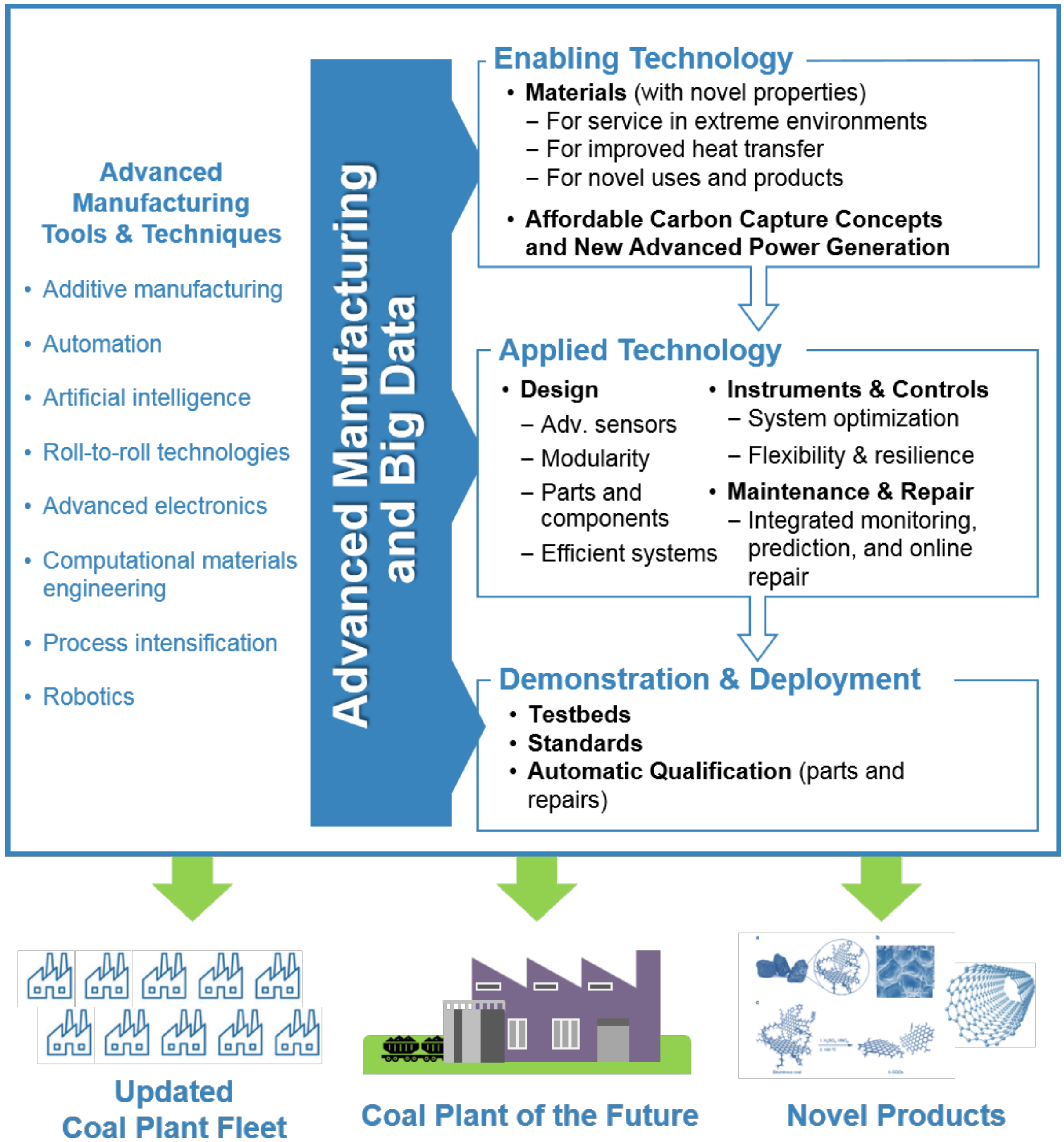


Figure 2. Advanced manufacturing techniques can accelerate progress toward FE's three objectives across the technology development spectrum.

Advanced Manufacturing

As discussed throughout this document, significant opportunities exist to leverage advanced manufacturing knowledge, technologies, and tools in ways that will help FE/OCCM achieve its strategic objectives. DOE programs, labs, and partners are already pursuing many exciting avenues. The results of these early-stage DOE research activities can stimulate further innovation and investment across the economy, but more work remains to expose the full range of opportunities.

Progress on all fronts may be expedited if adequate insights can be gained from the available data (generated by sensors, experiments, or modeling) on target coal plant conditions or operations and desired properties for a part or component (hours of service, dynamic range, etc.). Knowing these target conditions and properties will help to manage the risks inherent in this new approach.

Big Data

Access to large and diverse data sets will enhance learning, and these data sets should be continuously augmented. Sources include historical data sets as well as more precise and detailed data collected by new and continuously improving sensors.

Having the right data is critical to support robust behavior and performance models. This reality drives the need to develop data standards and reference packages of carefully assessed data—and make them readily available to all. Open sources for suitable data can help researchers in conducting the needed analytics and applying a variety of artificial intelligence approaches to extract new insights and develop useful models and algorithms. Open databases of materials properties, especially with respect to additive manufacturing, will also speed industry adoption. Open data sources provide diverse benefits:

- Avoid duplication of efforts
- Build overall confidence in model inputs
- Give the research community clear guidance on needed R&D innovations
- Support standardization (codes, etc.)

New data generated by progressively more accurate sensors, increasingly in real time, must continuously update models that guide decisions or automated systems. For more on this topic, please see the 2018 special report *Big Data+Machine Learning for Clean Coal*, available at: www.energy.gov/sites/prod/files/2018/11/f57/FE20SP%20Special%20Report%20BD%2BML_final.docx

Enabling Technology

Core enabling technologies can help the existing coal fleet operate more efficiently, economically, and sustainably, and the development of those technologies is likely to support the further innovations needed to design novel products from coal and the coal plants of the future.

Materials

Novel materials are essential to improve unit-scale performance within the existing fleet. New alloys may be produced from a-priori modeling or via predictive analysis from failure data to address operations in extreme environments. More durable materials can extend service life and enhance reliability when coal plants operate with significant load variations (necessitating frequent cycling).

The small, modular, highly efficient coal-fired plants of the future are likely to require materials that can handle higher temperatures and pressures than existing plants as well as meet the demands of flexible operations. By taking advantage of advanced manufacturing techniques, developers working on new materials could achieve microstructures that offer properties not previously available. Advanced manufacturing can also enable multi-material component design and expand the use of powder metallurgy to customize components for their intended use. The complex geometries possible with advanced manufacturing could improve heat transfer efficiencies in heat exchangers, recuperators, and similar components of fossil energy systems. These approaches may yield materials suited to endure a range of extreme environments, provide more efficient system components, or produce high-value products from coal.

New Carbon Capture and Advanced Power Generation Concepts

Advanced Carbon Separation System Design and Fabrication. To achieve the three FE objectives and optimize deployment economics, researchers and technology developers will need to improve separation systems through innovative modeling tools, designs, and scalable manufacturing technologies. FE currently funds research on several potentially transformational technologies for the pre- and post-combustion capture, compression, and storage of CO_2 gases. Novel materials, designs, and AI-driven models may suggest still more new approaches that leverage process intensification and other advanced manufacturing techniques to simplify CO_2 capture and make it more affordable. Capital cost reduction for CCUS will be an important next step; ideas include:

- Improve high-efficiency heat exchangers to reduce component size (reducing material costs)
- Improve mass transfer devices to reduce overall component/system size (lowering capital costs).

Advanced Power Generation Systems. FE, its supporting National Laboratories, and industry partners are already analyzing a variety of early-stage concepts that could revolutionize power generation from coal and other fossil fuels or heat sources. Emerging tools, materials, and other outputs of advanced manufacturing could make these revolutionary concepts technically and economically feasible—or inspire entirely new ideas. Modular coal plants of the future would be most likely to take advantage of these novel approaches.

Applied Technology

The specific advanced power generation technologies that will ultimately drive the coal-based power plants of the future are not yet known, making it difficult to predict many of the materials, technologies, and systems required to support them. In the near term, however, advanced manufacturing technologies have the potential to significantly upgrade the efficiency and economics of coal plant operations.

Design

Advanced manufacturing practices may inform the entire system design process from ideation and description of conceptual systems and timelines—through planning and managing research, development, and demonstration—to model-driven operations and maintenance. Extensive use of data is a hallmark of intelligent design practices.

Computer-based optimization and design tools will be needed to develop process-aware design of components. Multi-physics models may be useful in initial design phases and as part of adaptive design capabilities to control costs, minimize resource consumption, manage lifecycle inventories, and track individual risk factors.

Advanced Sensor Design. Coal-based power plants need more durable/sensitive/accurate sensors and data acquisition strategies to enable the use of predictive analytics. Advanced, wireless sensors that can operate for long periods in extreme environments should generate large amounts of more accurate and precise data to inform models, improve operations, and feed analytics that will continuously improve designs, systems, and operations.

Modularity. Advanced manufacturing tools that enable process intensification can help to achieve the modular, high-efficiency designs and installations required to reduce the risks and capital cost of future power plants. Modularity supports distributed generation by providing the flexibility and scalability necessary to improve the economics of technology deployment close to load centers.

Parts and Components. At the scale of individual component parts, comprehensive, verified data sets can support the use of novel materials to deliver levels of functionality not available through conventional methods. As some components may undergo simultaneous development, application of rational design will be important. Rapid development demand methods can be applied to evaluate smaller-scale components to ensure they will perform at scale. This process could prove useful in selecting the process to manufacture novel materials, particularly if bridging across time and spatial scales is likely to be an issue. Thinner, optimized, custom designed, replacement components could lower the cost of replacement parts and enable automated, just-in-time repair using robotics.

High-Efficiency Systems. As novel power generation concepts evolve and demonstrate feasibility, advanced manufacturing design tools should be better able to assist designers in process intensification and optimization. Based on the state of the art, these tools may suggest material specifications and the most efficient operating parameters tailored to the diverse range of coal, load, and climate characteristics.

Instruments and Controls

Advanced sensors are needed to measure the true metric of interest, not a surrogate measurement based on available technology or parameters. Real-time machine learning can use data gathered by an integrated network of advanced sensors and processed by advanced control algorithms to improve detection, interpretation, controllability, and response. Sensors delivering reliable data to knowledge-generating algorithms can greatly enhance all facets of R&D on coal technologies.

Maintenance and Repair

Whether keeping existing plants on-line under cycling conditions or maintaining optimal performance of a new plant, condition-based maintenance and on-line repair will become essential to reliable operations. Non-destructive methods could be developed to predict failure in microstructures. Advances in maintenance and repair require specific design skills, access to targeted data sets, novel materials, and the ability to use all of that information to craft a qualified component part. Joining existing materials with new materials of novel composition and properties calls for control of interface integrity during this process.

Demonstration and Deployment

Utility companies place primary focus on their responsibility to provide a safe and reliable source of power to all sectors of the economy. Novel parts, components, systems, and fabrication techniques will require thorough testing and validation before utilities will accept them for use in their systems. For novel fabrication techniques, new standards and means of validation may also be required to preserve the intended cost and time benefits.

Testbeds

Existing coal-fired power plants that are underutilized or were recently decommissioned may be used as testbeds to evaluate new repair technologies and gain new insights on system and component repair or replacement needs. Methods are also needed to test the production of coal power system components at scale with control over production time and "critical" dimensions, bridging seamlessly from one scale to next.

Standards

Standards will be needed to verify data as well as the models that they help to generate. Working in partnership with NIST and setting up a combined database would support the development of needed standards. In all cases, the quality and fitness of data for specific uses must be made clear. As advanced manufacturing techniques enable a range of new materials and material fabrication technologies to support utility operations, standards and verification strategies could facilitate acceptance by utilities.

Automatic Qualification or Verification

For the near term, accelerated validation methodologies could help risk-averse utilities feel confident that any new materials or components made from those materials are safe and reliable for use in their systems (e.g., boilers, pressure vessels, and turbines). Improved components, including those designed for extreme environments, will only become available within the needed timeframe if their quality has been proven, industry accepts them, and rapid certification is available (see inset).

Novel techniques for the in-field robotic or additive fabrication of replacement parts will need to be thoroughly evaluated and proven to produce "qualified" materials. Even with the promise of reduced downtime, these parts will need to be readily available at low cost with assured interface integrity.

Born Qualified Parts: A multi-laboratory team is developing an exascale computing application to simulate additive manufacturing (AM) of "born-qualified" parts for critical systems. The simulator will allow the routine use of AM to build unique, qualifiable metal alloy parts across many industries relevant to DOE. Photo: Oak Ridge National Laboratory. www.additivemanufacturing.media/blog/post/how-exascale-computing-will-enable-born-qualified-am-parts

Next Steps

This report explores the potential for advanced manufacturing technologies to help meet OCCM objectives and identifies many broad opportunities for future research and analysis. New advanced manufacturing capabilities have already enlarged the realms of possibility for clean coal and carbon management and ignited the imaginations of U.S. researchers and technology developers. In addition, the novel applications of advanced manufacturing techniques described in this report present new avenues of research for the developers of advanced manufacturing technologies (e.g., materials and sensors that can withstand rapidly cycling temperatures and extreme environments; pre-qualified in-field repairs; and high-value markets for coal products).

DOE has embraced multidisciplinary approaches to problem solving for many decades, and the current pace at which our scientists develop ever more powerful tools and technologies underscores the need to continuously reach across the DOE programs to leverage new capabilities—maximizing the national benefits of research investment. Some of the opportunities identified in this report have already become the focus of FE-funded research activities, and a growing variety of advanced manufacturing techniques will help expedite progress in achieving OCCM objectives.

Appendix A: Workshop Agenda

Workshop on the Intersection of Advanced Manufacturing and Clean Coal and Carbon Capture Technologies

April 30, 2019

Ronald Reagan Building and International Trade Center
1300 Pennsylvania Ave NW
Washington, DC 20004

Background

Emerging Advanced Manufacturing technologies will create the coal plant of the future. These plants will respond to the need to provide secure, stable, and reliable power. To achieve this end, it is necessary to *transform* how coal technologies are designed and manufactured. Smart manufacturing will incorporate big data and information systems to provide the cornerstone for innovative and disruptive technologies to create coal-fired power plants capable of: *flexible* operations; using *next-gen* components to improve efficiency and reduce emissions; providing *resilient* power to Americans; and requiring smaller footprints compared to today's conventional utility-scale coal plants. They will truly be coal plants of the 21st century.

8:30– 9:00 AM	Registration Open
9:00–9:15 AM	**Welcome Remarks** (Angelos Kokkinos, Associate Deputy Assistant Secretary, Office of Clean Coal and Carbon Management, U.S. Department of Energy)
9:15—9:30 AM	**Opening Remarks** (Dr. Brian Anderson, Director, National Energy Technology Laboratory)
9:30-10:00 AM	**Keynote overview:** Future of advanced manufacturing by and beyond 2030 and synergies with novel coal technologies (Lalit Chordia, Founder & CEO, TharProcess)
10:00–11:15 AM	**Session 1 Lightning Round**: each non-DOE invitee gives 3-minute introduction outlining perspectives on advanced manufacturing techniques and their particular expertise. Comments relevant to applications for clean coal technologies are encouraged.
11:15 – 11:35 AM	Break
11:35 –12:50 PM	**Session 2 Breakouts:** Group break out group discussions. How DOE can better leverage advanced manufacturing to: (1) enable the advanced coal energy system of the future (meet in Hemisphere); (2) realize a competitive, resilient and flexible existing fleet, (meet in USEA Suite 550 Conference Room) and; (3) leverage new markets (meet in USEA Suite 550 Board Room)?
12:50– 1:50 PM	Lunch Break
1:50—3:05 PM	**Session 3 Breakouts:** (1) Manufacturing Materials for Harsh Operating Conditions (meet in Hemisphere); (2) Manufacturing Process Technologies

	(meet in USEA Suite 550 Conference Room); (3) Enabling Technologies and Systems (meet in USEA Suite 550 Board Room)
3:05 – 3:25 PM	Break
3:25 – 4:30 PM	**Session 4 Recommendations/Goals (meet back in Hemisphere)** (facilitated by Sarah Forbes, Office of Fossil Energy – US DOE & Sudarsan Rachuri, Advanced Manufacturing Office – US DOE)
4:30 – 5:00 PM	**Concluding Remarks** (facilitated by Jarad Daniels, Director, Office of Strategic Planning, Analysis and Engagement, Office of Clean Coal and Carbon Management – US DOE)

Appendix B: Attendee List

First Name	Last Name	Organization
Mark	Ackiewicz	U.S. Department of Energy
Roger	Aines	Lawrence Livermore National Laboratory
David	Alman	National Energy Technology Laboratory
Brian	Anderson	National Energy Technology Laboratory
Lallit	Chordia	Thar Process, Inc
Sydni	Credle	National Energy Technology Laboratory
Joe	Cresko	U.S. Department of Energy
Jarad	Daniels	U.S. Department of Energy
James	Ekmann	LTI
James	Ferguson	National Energy Technology Laboratory
Sarah	Forbes	U.S. Department of Energy
Janet	Gellici	National Coal Council
Rob	Gorham	NCDMM / America Makes
William	Grieco	RAPID Manufacturing Institute
John	Hutchinson	Electric Power Research Institute
Robert	Ivy	U.S. Department of Energy
Rachel	Jones	National Association of Manufacturers
Jai-woh	Kim	U.S. Department of Energy
Melissa	Klembara	U.S. Department of Energy
Angelos	Kokkinos	U.S. Department of Energy
Kenneth	Kort	U.S. Department of Energy
Alex	Krowka	United States Energy Association

First Name	Last Name	Organization
Anand	Kulkarni	Siemens Corporation
Vello	Kuuskraa	Advanced Resources International, Inc.
Robie	Lewis	U.S. Department of Energy
Yirong	Lin	The University of Texas at El Paso
Michelle	Littlefield	United States Energy Association
Haresh	Malkani	Clean Energy Smart Manufacturing Innovation Institute
Mahesh	Mani	Allegheny Science and Technology
Michael	Matuszewski	Aristosys LLC
Michael	McKittrick	U.S. Department of Energy
David	Miller	National Energy Technology Laboratory
KC	Morris	Office of Congressman Tom Reed
Kathryn	Peretti	U.S. Department of Energy
Will	Polen	United States Energy Association
Yarom	Polsky	Oak Ridge National Laboratory
Cynthia	Powell	Pacific Northwest National Laboratory
Robert M.	Purgert	The Energy Industries of Ohio
Sudarsan	Rachuri	U.S. Department of Energy
Adam	Rosenberg	House Committee on Science, Space, and Technology
John	Shingledecker	Electric Power Research Institute
Robert Kennedy	Smith	U.S. Department of Energy
Jeff	Summers	U.S. Department of Energy
Tao	Sun	Argonne National Laboratory
Xin	Sun	Oak Ridge National Laboratory

First Name	Last Name	Organization
Thomas	Tarka	U.S. Department of Energy
David	Teter	Los Alamos National Laboratory
Michael	Verti	Deloitte
Ryan	Wicker	The University of Texas at El Paso
Wei	Xiong	University of Pittsburgh

Appendix C: Advanced Manufacturing Institutes

The Department of Energy and other Federal, state, and private-sector entities are pursuing the continued improvement and application of advanced manufacturing techniques to shorten development times, lower costs, and produce components that are better suited to their intended use. Coal usage poses major technology and process challenges—from extractive processes to coal upgrading/use and responsible management of effluents and emissions. These challenges arise from both the scale and complexity of modern coal mining. These challenges vary with temperatures, pressures, and the presence of particulate matter. Further concerns include the complex by-products and slate of trace elements and components that often have significant impacts on health and the environment.

Advanced Manufacturing Office and Manufacturing USA

AMO's public-private R&D consortia or institutes bring together manufacturers, small businesses, universities, national laboratories, and state and local governments to pursue coordinated, early-stage R&D in areas of manufacturing that impact the energy industry. The consortia—while focused on distinct technology areas—work toward a common goal: To secure America's future through manufacturing innovation, education, and collaboration. Federal funding is the catalyst to bring stakeholders into shared spaces and address process and technological challenges that present a significant degree of scientific or technical uncertainty. Participants in R&D Consortia and Institutes gain access to collaborative communities, expertise, and the physical and virtual tools necessary to foster pre-competitive technology innovation.

Some of the institutes supported by AMO are part of Manufacturing USA, a network of regional institutes that each have a specialized technology focus. These institutes facilitate the transfer of innovative advanced materials, information, and process technologies to industry by enabling manufacturing scale-up. At the same time, the Institutes help prepare the next-generation workforce and foster development of the novel manufacturing technologies that make the United States a global leader in the manufacturing sector. A partial list is provided in Table C-1. Technologies being developed, improved, or integrated at the Institutes include additive manufacturing (including 3-D printing), roll-to-roll technologies, advanced and flexible electronics (which could enable sensors to be embedded in critical components with complex geometries), integrated computational materials engineering, process intensification (important to the capture and utilization of CO_2, including dilute streams), and development and characterization of materials for harsh environments.

Table C-1. Manufacturing USA Institutes

Institute	Location	Brief summary
Advanced Functional Fabrics of America (AFFOA)	Cambridge. MA	Enable a manufacturing-based revolution by transforming traditional fibers, yarns, and fabrics into highly sophisticated, integrated, and networked devices and systems.
AIM Photonics (American Institute for Manufacturing) Integrated Photonics	Rochester, NY	Accelerate the transition of integrated photonic solutions from innovation to manufacturing-ready deployment in systems. Photonic Integrated Circuits use light for applications that traditionally use electronics. The institute focuses on activities that target manufacturing readiness so that firms may more quickly transition to full-scale/volume operations.
America Makes	Youngstown, Ohio	Advance additive manufacturing technology and products to transform U.S. manufacturing sector and yield significant advancements to industry. America Makes is a national accelerator and the nation's leading collaborative partner for technology research, discovery, creation, and innovation in additive manufacturing and 3D printing.
Advanced Robotics for Manufacturing (ARM)	Pittsburgh, PA	Accelerate use of industrial robots and create and deploy robotic technology. Integrate diverse collection of industry practices and institutional knowledge across disciplines. Operational aims include versatile robotic systems capable of performing multiple tasks; rapid deployment and re-purposing of robots; collaborative robots; and safe, cybersecure, and cost-effective solutions.
Clean Energy Smart Manufacturing Innovation Institute (CESMII)	Los Angeles, CA	Research in and development of technologies and solutions to capture, share, and process, in real-time, increasing amounts of information available at manufacturing facilities. These technologies will enable dramatically improved process control and operation and realize benefits from advanced sensors; real-time big data analytics and control systems; and advanced high-fidelity modeling.
Institute for Advanced Composites Manufacturing Innovation (IACMI)	Knoxville, TN	Accelerate innovative research and development in the advanced composites field and validate manufacturing technologies that respond to private industry’s need for faster and more cost-, material-, and energy-efficient composite manufacturing, including recycling at the end of product life.

Institute	Location	Brief summary
Lightweight Innovations for Tomorrow (LIFT)	Detroit, MI	Develop and deploy advanced lightweight materials manufacturing technologies. Lightweight metal manufacturing provides the aerospace, automotive, shipping and defense industries with "light-weighting" solutions. Lightweight solutions increase fuel economy, reduce emissions, and use less material and fewer components. LIFT focuses on key metals manufacturing processes—melt processing, powder processing, thermo-mechanical processing, novel/agile processing, coatings, and joining and assembly—as well as Integrated Computational Materials Engineering (ICME).
The Digital Manufacturing Institute (MxD)	Chicago, IL	Encourages deployment of digital manufacturing and design technologies to enable factories to become more efficient and cost-competitive. Digital manufacturing and related design technologies connect different parts of the manufacturing life-cycle through data. MxD provides factories with the digital tools and expertise needed to build things more efficiently, more quickly, and at less cost.
NextFlex	San Jose, CA	Flexible hybrid electronics-enabled products are being used in human health and performance monitoring, structural health monitoring, (e.g. buildings and bridges), soft robotics, and antennas. Furthers U.S. development and adoption of flexible hybrid electronics that will revolutionize the way we live and work. Flexible hybrid electronics combine low-cost printed circuits with the processing power of thin semiconductors to create a new category of electronic devices that can stretch, bend, and flex to conform to surfaces.
National Institute for Innovation in Manufacturing Biopharmaceuticals	Newark, DE	Accelerates biopharmaceutical manufacturing innovation, to support the development of standards that enable more efficient and rapid manufacturing capabilities, and to educate and train a world-leading biopharmaceutical manufacturing workforce, fundamentally advancing U.S. competitiveness in this industry.
Power America	Raleigh, NC	Accelerate adoption of advanced semiconductor components made with silicon carbide and gallium nitride into a wide range of products and systems Develop advanced manufacturing processes for large-scale production of WBG semiconductors that will enable electronic

Institute	Location	Brief summary
		components to be smaller, faster, less expensive in use and more efficient than semiconductors made from silicon.
Rapid Advancement in Process Intensification Deployment (RAPID)	New York, NY	Focuses on new technologies that maximize processes at the molecular level to save energy with every chemical reaction. Develop breakthrough technologies to dramatically improve the energy efficiency of novel manufacturing processes and enable development of modular processes for chemical and commodity processing, intensified process fundamentals, and modeling and simulation.
Reducing EMbodied-energy And Decreasing Emissions (REMADE)	Rochester, NY	Focused on driving down cost of technologies essential to reuse, recycle and remanufacture materials such as metals, fibers, polymers and electronic waste. Innovations that could dramatically reduce the energy required to manufacture key materials and improve overall manufacturing energy efficiency through increased material reuse, recycling, and remanufacturing.

For more information: www.manufacturingusa.com/institutes