U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Advanced Manufacturing Office Multi-Year PROGRAM PLAN for Fiscal Years 2017 through 2021

DRAFT

Letter from the Director

December 2016

I am pleased to present the draft *Multi-Year Program Plan* for DOE's Advanced Manufacturing Office. The Advanced Manufacturing Office (AMO)—within the Department of Energy's Office of Energy Efficiency & Renewable Energy (EERE)—partners with manufacturers, not-for-profit entities, universities, national laboratories, and state and local governments to address energy related manufacturing challenges through research, development, and demonstration (RD&D).

The U.S. manufacturing sector uses approximately 25% of the nation's energy and energy is a significant cost in manufacturing. How we apply our diverse and abundant domestic energy resources to manufacturing can be a critical factor in the economic competitiveness, energy security and responsible environmental stewardship of the nation. Advancements in manufacturing impact the energy efficiency of products used throughout the economy. To drive manufacturing innovation and spur job creation, AMO supports the RD&D of new technologies with the potential to significantly improve energy efficiency in manufacturing. In addition, new technologies for manufacturing processes, information, and materials are critical to the efficient and competitive manufacturing of energy related products. Once developed, AMO drives wide-scale adoption and deployment of manufacturing technologies and energy management practices through support of voluntary industrial partnerships and training programs. AMO investments save the nation energy while reducing emissions, industrial waste, water usage, and the life-cycle energy consumption of manufactured products. With this work, the diverse energy resources of the nation can be harnessed as a strategic advantage and cutting-edge products can be most efficiently, productively and competitively manufactured here in the United States.

Technology innovation is central to advanced manufacturing. Our Multi-Year Program Plan (MYPP) provides an overview of the current state of energy use in manufacturing and analysis of opportunities for energy savings. The plan proposes technology goals and metrics for RD&D in areas with the potential to significantly improve manufacturing energy efficiency and minimize the life-cycle energy of manufactured products. The AMO team has focused on technology opportunities to strengthen our energy relevant advanced manufacturing capabilities and accelerate technical progress throughout the manufacturing sector. The resulting RD&D would be broadly applicable, but target advancements where technical uncertainty is too great for the private sector to support alone. By addressing the identified technology issues through merit-based RD&D, cost-effective solutions can help enable subsequent technology commercialization, adoption, and energy savings impacts nationwide.

Thank you for taking the time to read our MYPP. I'd like to thank all the participants and partners for helping AMO as we continue to strive to be a driver of innovation and partner for industry, small business, universities, national labs, and all the stakeholders we serve across the nation.

Dr. Mark Johnson
Director, Advanced Manufacturing Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy

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1.0 Executive Summary

This Multi-Year Program Plan (MYPP) for Fiscal Years 2017 through 2021 sets forth the mission, goals, and plan of the Advanced Manufacturing Office (AMO) within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE). The Office supports EERE's vision of a strong and prosperous America powered by clean, affordable, and secure energy. AMO is the only technology development office within the U.S. Government that is dedicated to improving the energy and material efficiency, productivity, and competitiveness of manufacturers across the industrial sector. Manufacturing accounts for 25% of total U.S. energy consumption at a cost of $130 billion. Reducing manufacturing energy use and costs can also have a significant impact on sustained competitiveness. In addition, manufacturing plays an essential role as a driver of overall economic growth, and manufactured products have a significant impact on energy use in every sector. A robust and competitive domestic manufacturing base is critical to national security because it ensures domestic supplies of key products of importance and assures secure and reliable energy resources for U.S. citizens. To maintain manufacturing competitiveness for future generations, the United States will need to remain a leader in the development of next-generation manufacturing technologies.

AMO brings together manufacturers, not-for-profit entities, research institutions, and institutes of higher education to identify challenges; catalyze innovations; and develop cutting-edge materials, process, and information technologies needed for an efficient and competitive domestic manufacturing sector. By targeting efficient manufacturing technologies, AMO seeks to drive energy productivity improvements in the U.S. manufacturing sector, efficiently utilize abundant and available domestic energy resources, and support the manufacture of clean energy products with benefits extending across the economy.

AMO pursues its goals through three subprogram approaches: individual Advanced Manufacturing Research and Development (R&D) Projects; pre-commercial Advanced Manufacturing R&D Consortia; and Industrial Technical Assistance. Given the diversity of the manufacturing sector, the Office uses a cross-cutting approach. AMO activities are designed to help bridge the gap from discovery to manufacturing so innovations important to sustained competitiveness make it into the market. Collaborative R&D is funded at various stages of technological progress and public-private partnerships leverage the technical expertise at the national laboratories and universities. These activities advance broadly applicable cross-cutting technologies for energy intensive and energy dependent manufacturing sectors; advance platform technologies that enable the manufacturing of products; establish partnerships to promote energy efficiency and technology innovation; and transfer knowledge through dissemination of tools and training.

This MYPP identifies the technology, outreach, and crosscutting activities the Office plans to focus on over the next five years. The technical focus areas in the plan align with the high-priority energy-related manufacturing topics identified in the 2015 DOE Quadrennial Technology Review (QTR). Technical targets are provided for each of the activity areas, along with a brief summary of why these activities are important to addressing the energy and competitiveness challenges facing the nation and U.S. manufacturing in particular.

This MYPP is intended for use as an operational guide to help AMO manage and coordinate its activities, as well as a resource to help communicate its priorities and opportunities to stakeholders and the public. The Manufacturing Overview section examines the context and market in which AMO operates, and discusses the importance of manufacturing and innovation. The Office Structure and Activities section presents the AMO subprograms and key activities. The Office Strategic Planning Approach presents the authorizing legislation and guidance documents; the AMO vision, mission, goals, and success indicators; analysis activities that support planning and decision making; and program and project evaluation activities. The Technology Research, Development and Demonstration (RD&D) Plan includes how AMO intends to contribute to the achievement of the goals and the ways in which AMO progress can be assessed.

Figure 1.1 shows the scope of the areas in the Technology RD&D Plan, including the connections between the fourteen advanced manufacturing technology areas (which coincide with the 2015 QTR Technology Assessment topics), emerging and crosscutting areas, and energy systems with manufacturing challenges. The Technology RD&D areas are presented in the three groups described below.

Advanced Manufacturing Technology Areas were selected because of their high potential to improve U.S. energy utilization economy-wide and reduce greenhouse gas emissions. Fourteen platform technology areas have been identified by DOE as having significant potential impacts, and where technology advancement and adoption can be accelerated by AMO efforts. These areas are listed in the order shown in Figure 1.1 (clockwise from the top) and all will benefit from materials, process, and information technology advances. These fourteen manufacturing technology areas were the focus of individual Technical Assessments topics in the 2015 QTR.

Emerging and Crosscutting Areas were selected because these RD&D areas have widespread impacts on manufacturing and the energy economy. The two emerging science and energy technology areas – clean water technologies and energy efficient advanced computing – impact all sectors of the energy economy, including manufacturing. The three crosscutting manufacturing focus areas are: industrial end-user technical assistance, workforce development, and communications and outreach.

Advanced Manufacturing for Energy Systems RD&D areas were selected because all sectors of the energy economy rely on manufactured goods. The energy economy sectors include electric power delivery, electric power generation, fuel production, buildings, and transportation. The 2015 QTR includes chapters on each of these energy economy sectors. The AMO MYPP identifies the specific manufacturing and materials challenges and opportunities within these sectors.

Figure 1.2 shows how AMO's vision, mission, and strategic goals support the DOE EERE Strategic Plan goals. AMO pursues its Office goals through the three subprograms.

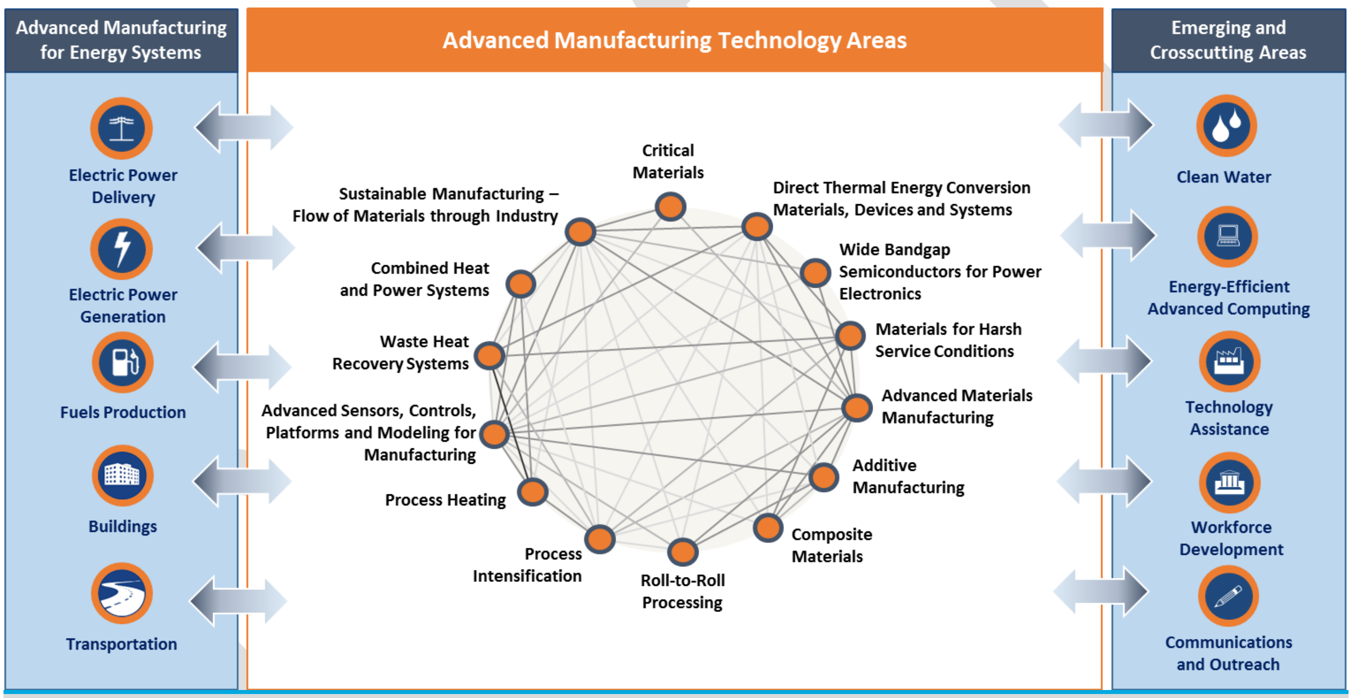

Figure 1.1 Diagram Showing Connections between the Fourteen Advanced Manufacturing Technology Areas (which coincide with the 2015 QTR Manufacturing Technology Assessment Topics), Energy Systems Influenced by Manufacturing, and Emerging and Crosscutting Areas.

EERE Strategic Plan Goals

- Improve the Energy Efficiency of Our Homes, Buildings, and Industries (#3)
- Stimulate the Growth of a Thriving Domestic Clean Energy Manufacturing Industry (#4)

AMO Vision and Mission

Vision: U.S. global leadership in sustainable and efficient manufacturing for a growing and competitive economy.

Mission: Catalyze research, development and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

AMO Strategic Goals

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

AMO Subprograms

R&D Consortia	R&D Projects	Technical Assistance

AMO Success Indicators

- Demonstrate selected advanced manufacturing technologies and deploy practices that increase the rate of energy intensity improvement from business as usual (~1% per year) to 2.5% per year.
- Develop advanced materials, manufacturing technologies, and end use products with the potential to reduce lifecycle energy impact by 50% by 2025 compared to the 2015 state-of-the-art.
- Establish partnerships resulting in 30,000 U.S. manufacturing facilities implementing AMO-recognized energy management products, practices and measures by 2025.
- Double supported technical education and training activities in advanced manufacturing made available for universities, community colleges, and high schools by 2025.

Figure 1.2 Strategic Framework of the Advanced Manufacturing Office

2.0 AMO Overview

The Advanced Manufacturing Office (AMO) supports EERE's vision of a strong and prosperous America powered by clean, affordable, and secure energy. Manufacturing plays an essential role as a driver of overall economic growth, and manufactured products have a significant impact on energy use in every sector. Opportunities abound to develop and deploy new manufacturing technologies to significantly improve U.S. energy efficiency. Reducing manufacturing energy use and costs can also have a significant impact on sustained competitiveness.

Through research, development, demonstration, and technical assistance activities, the AMO brings together manufacturers, not-for-profit entities, institutes of higher education, national laboratories, and state and local governments to develop and deploy cutting-edge manufacturing technologies. These technologies are critical to a more efficient and competitive U.S. manufacturing sector, for the competitive domestic manufacture of clean energy products, to efficiently use abundant and low-cost energy resources in manufacturing, and to support improved energy productivity across the entire U.S. economy.

A robust and competitive domestic manufacturing base is critical to national security because it ensures domestic supplies of key products of importance and assures secure and reliable energy resources for U.S. citizens. To maintain manufacturing competitiveness for future generations, the United States will need to remain a leader in the development of next-generation manufacturing technologies. In addition, many of the externalities of manufacturing, such as resource availability and carbon emissions, cannot be avoided by outsourcing the manufacture of products to another country. To remain competitive, the United States needs to demonstrate global leadership in the efficient manufacture of products, and capture the opportunity to export cutting-edge, clean energy technologies globally.

The AMO vision, mission, and goals are shown on the right. This section of AMO's Multi-Year Program Plan (MYPP) provides an overview of manufacturing and AMO's office structure, activities, and strategy.

AMO Vision, Mission, and Goals

Vision: U.S. global leadership in sustainable and efficient manufacturing for a growing and competitive economy.

Mission: Catalyze research, development and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

Goals:

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

2.1 Manufacturing Overview

The manufacturing sector[1] comprises establishments engaged in the mechanical, physical, or chemical transformation of raw materials, intermediate products, and components into final products, and the related technical support services, such as engineering, design and information technology. Production establishments in the manufacturing sector are often described as plants, factories or mills, and characteristically use machines and materials-handling equipment as well as process reactors wherein chemical and other physical transformations occur to convert feedstock materials to products. Manufacturing establishments transform raw materials that are outputs of agriculture, forestry, fishing, mining, or quarrying as well as intermediate products and/or co-products of other manufacturing establishments. The product of a manufacturing establishment may be finished in the sense that it is ready for utilization or consumption, or it may be semi-finished to become an input for an establishment engaged in further manufacturing. The connected set of establishments involved in moving materials and products from one facility to another facility for further manufacturing is a considered a supply chain.

U.S. Manufacturing in 2014

- 12% of U.S. gross domestic product.
- Directly employed 12 million people and generated millions of jobs in other sectors.
- Sold products valued at $5.9 trillion.
- Represented 17% of the world's manufacturing output.
- Supplied 51% of total U.S. exports.
- Accounted for 25% of U.S. energy consumption at a cost of $130 billion.

Manufactured goods are sold in a highly competitive global market and range from fundamental commodities such as metals and chemicals to sophisticated final-use products such as automobiles and appliances, along with energy-technology devices including solar photovoltaic (PV) modules, light-emitting diode (LED) lighting systems, and wind turbines.

In 2014, the U.S. manufacturing sector accounted for 12% of gross domestic product (GDP),[1] directly employed 12 million people,[2] and sold products valued at $5.9 trillion.[3] From an international perspective, the U.S. manufacturing sector represented 17%[4] of the world's manufacturing output, and supplied 51% of total U.S. exports.[5, 6]

In order to produce these goods, U.S. manufacturing firms used 24.3 quads of primary energy in 2014 (where a "quad" denotes one quadrillion (10^{15}) British thermal units (Btus)), or approximately one-quarter of U.S. total energy consumption.[7] This manufacturing energy includes nearly 8 quads of electrical energy generated by the electric power sector (about 2.6 quads of net electricity purchases by manufacturers, plus 5.2 quads of electricity generation and transmission losses attributable to manufacturers).[8] Total energy costs for manufacturing are estimated at approximately $130 billion in 2014.[9]

Definitions

Advanced Manufacturing: Making products with technology as a competitive difference.

Clean Energy Manufacturing: Manufacturing of clean energy products (renewable energy, sustainable transportation and energy efficiency technologies) and boosting U.S. manufacturing across the board by increasing energy productivity and efficiently using low-cost domestic fuels and feedstocks for manufacturing.

Energy Intensive Industries: The industries that use most of the energy consumed by the manufacturing sector. In the U.S., these industries account for almost 80%* of the sector's primary energy use and include petroleum refining, basic chemicals, iron and steel, pulp and paper, food, nonferrous metals (primarily aluminum), and nonmetallic minerals (primarily cement and glass).

Energy Dependent Industries: Those industries that have high manufacturing energy intensities but do not currently have a large sectoral footprint in the U.S.; for example, carbon fiber-reinforced polymer composites.

* U.S. Department of Energy, Manufacturing Energy and Carbon Footprints (2010 MECS), http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

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1 "Value Added by Industry as Percentage of Gross Domestic Product (2015)." U.S. Bureau of Economic Analysis. Release Date Nov. 3, 2016. Available at: http://www.bea.gov/industry/xls/io-annual/GDPbyInd_VA_1947-2015.xlsx.

2 "National Income and Product Accounts Tables – Section 6: Income and Employment History, Table 6.4D: Full-Time and Part-Time Employees by Industry (A)." U.S. Bureau of Economic Analysis. Last revised August 3, 2016. Available online at: http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=1&isuri=1.

3 "Census Bureau Releases 2014 Annual Survey of Manufactures Data." U.S. Census Bureau. Release Number CB15-TPS.108. Released Dec. 18, 2015, revised March 1, 2016. Available online at: http://www.census.gov/newsroom/press-releases/2015/cb15-tps108.html.

4 "GDP and its breakdown at current prices in US Dollars (2014)." United Nations Statistics Division. Available online at: http://unstats.un.org/unsd/snaama/dnlList.asp.

5 "U.S. International Trade in Goods and Services: March 2016." U.S. Bureau of Economic Analysis. CB 16-74 / BEA 16-23 / FT-900 (16-03). Released May 4, 2016. Available online at: http://www.census.gov/foreign-trade/Press-Release/2016pr/03/ft900.pdf.

6 "Exports, Imports, and Balance of Goods by Selected NAICS-Based Product Code, Not Seasonally Adjusted: December 2014." U.S. Bureau of Economic Analysis. Available online at: http://www.census.gov/foreign-trade/Press-Release/2014pr/12/exh1s.pdf.

7 The industrial sector is comprised of manufacturing and non-manufacturing industries; the non-manufacturing industries (mining, construction, and agriculture) consumed an additional 6.1 quads in 2014.

8 Estimated from the U.S. Energy Information Administration (EIA) 2014 Preliminary Manufacturing Energy Consumption Survey (MECS) data and EIA *Monthly Energy Review*. March 2015. Available online at: http://www.eia.gov/consumption/manufacturing/index.php.

9 Based on EIA industrial energy price data, 2010 MECS energy purchases data, and preliminary 2014 MECS energy consumption estimates. Estimate includes feedstock energy use, except for feedstocks converted into other energy products (e.g., transportation fuels).

Because manufacturing is highly connected with other sectors of the economy, manufacturing activities stimulate economic activity beyond the manufacturing sector itself. Recent reports have indicated that every $1.00 spent in the U.S. manufacturing sector generates between $1.33 and $1.81 in other services and production[10,11,12,13,14] – a multiplier higher than that of any other sector. Manufacturing also has a positive effect on overall employment, with manufacturing-related employment ranging from mining to warehousing, as well as engineering, financial, and legal services.[15] Advanced manufacturing technologies could have an even greater multiplier effect on employment than traditional manufacturing practices.[16] As such, manufacturing of products is an opportunity to leverage economic growth across the U.S. economy.

There are many factors that impede the development and adoption of advanced energy efficient technologies and practices in the manufacturing sector. The sub-sections below describe the complexities of energy use in manufacturing and the challenges associated with leveraging innovation and accelerating technological progress.

2.1.1 Energy Impacts from Manufactured Products

This section provides an overview of energy use in manufacturing and opportunities for energy savings. There are almost 300,000 manufacturing establishments in the United States that produce an enormous range of products.[17] There are significant opportunities to improve the energy efficiency and energy productivity and to reduce emissions within each manufacturing sector, particularly for the 120,000+ manufacturing establishments with more than 10 employees. Additionally, there are opportunities to advance and expand the manufacturing of clean energy technologies, which can reduce energy consumption and emissions in the United States and across the global market. To understand where the best opportunities exist for energy savings, AMO conducts analyses on the energy used in manufacturing processes to produce products and the total amount of energy associated with product use throughout its lifetime. Section 2.3.3 provides an overview of AMO's strategic analysis of opportunities.

Energy Use in Manufacturing and Opportunities for Savings

U.S. manufacturing is diverse. The majority of manufacturing energy use is concentrated in energy-intensive industries (refer to Definitions text box in section 2.1), such as chemicals and primary metals production, which collectively consume over three-quarters of the energy used in U.S. manufacturing. While downstream fabrication and assembly industries, such as automotive and aerospace, may not have high energy demands on site, these industries use many materials with high embodied energies – i.e., the cumulative amount of energy required considering all the energy expended during all lifecycle phases from raw material extraction, raw material processing, through materials manufacturing. Further, fast-growing industries (including clean energy manufacturing industries) may consume a greater proportion of manufacturing energy use as these industries evolve, considering the high market potential for these emerging products. This diversity inhibits a unified, sector-specific approach to improving energy efficiency in

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[10] Patrick Gallagher. "25 Years of Supporting U.S. Manufacturing." U.S. Department of Commerce blog. Dec. 27, 2013. Available online at: https://www.commerce.gov/news/blog/2013/12/25-years-supporting-us-manufacturing.

[11] "Manufacturing's Multiplier Effect is Stronger than Other Sectors'." Manufacturing Institute. Updated April 2014. Available online at: http://www.themanufacturinginstitute.org/Research/Facts-About-Manufacturing/Economy-and-Jobs/Multiplier/Multiplier.aspx.

[12] "Top 20 Facts about Manufacturing." National Association of Manufacturers (NAM). Available online at: http://www.nam.org/Newsroom/Top-20-Facts-About-Manufacturing/.

[13] Dan Meckstroth. "How Important is U.S. Manufacturing Today?" Manufacturers Alliance for Productivity and Innovation (MAPI). Posted September 13, 2016. Available online at: https://www.mapi.net/forecasts-data/how-important-us-manufacturing-today.

[14] Stephen Gold. "The Competitive Edge: Manufacturing's Multiplier Effect – It's Bigger Than You Think," by Stephen Gold, President and CEO, MAPI, IndustryWeek. Posted September 2, 2014. Available online at: http://www.industryweek.com/global-economy/competitive-edge-manufacturings-multiplier-effect-its-bigger-you-think.

[15] Thomas Kurfess. "Why Manufacturing Matters." The American Society of Mechanical Engineers (ASME). November 2013. Available online at: https://www.asme.org/engineering-topics/articles/manufacturing-processing/why-manufacturing-matters.

[16] David Danielson. "Clean Energy Manufacturing report examines global dynamics of energy manufacturing." Windpower Engineering & Development. Posted March 16, 2016. Available online at: http://www.windpowerengineering.com/featured/business-news-projects/clean-energy-manufacturing-report-examines-global-dynamics-energy-manufacturing/.

[17] "Manufacturing: Summary Series: General Summary: Industry Statistics for Subsectors and Industries by Employment Size: 2012." 2012 Economic Census of the United States. U.S. Census Bureau. Release date December 18, 2015. Available online at: http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ECN_2012_US_31SG2&prodType=table.

manufacturing and instead calls for a more cross-cutting technology oriented approach to research, development and demonstration applicable to energy efficiency and energy productivity in manufacturing.

Figure 2.1 shows energy use in manufacturing. The forms of energy used across the manufacturing sector are diverse, with no individual energy source comprising more than 33% of the supply.[18] This is in contrast to the transportation sector, for example, where petroleum accounts for more than 90% of primary energy consumption.[19] Within specific manufacturing operations, a wide array of technologies and processes are used to convert raw materials to finished products, often through long sequences of intermediate product-forms. Accordingly, the manufacturing sector draws on a diverse set of energy resources which often depends on the process and product manufactured. Steam and fuel energy are used in thermal processes such as melting, smelting, curing, and drying, while electricity is used to drive machines such as pumps, fans, compressors, and non-process related materials handling equipment (see Figure 2.9, a diagram of primary energy flows in the manufacturing sector). Manufacturing facilities also consume energy in nonprocess applications such as space heating and lighting (see footprint studies in section 2.3.3, Strategic Analysis of Opportunities, for further discussion). Additionally, manufacturers use certain fuels as feedstocks to produce plastics, refined fuels, asphalt, and other products. By utilizing abundant and low-cost domestic fuels, manufacturing firms are able to improve their competitiveness.

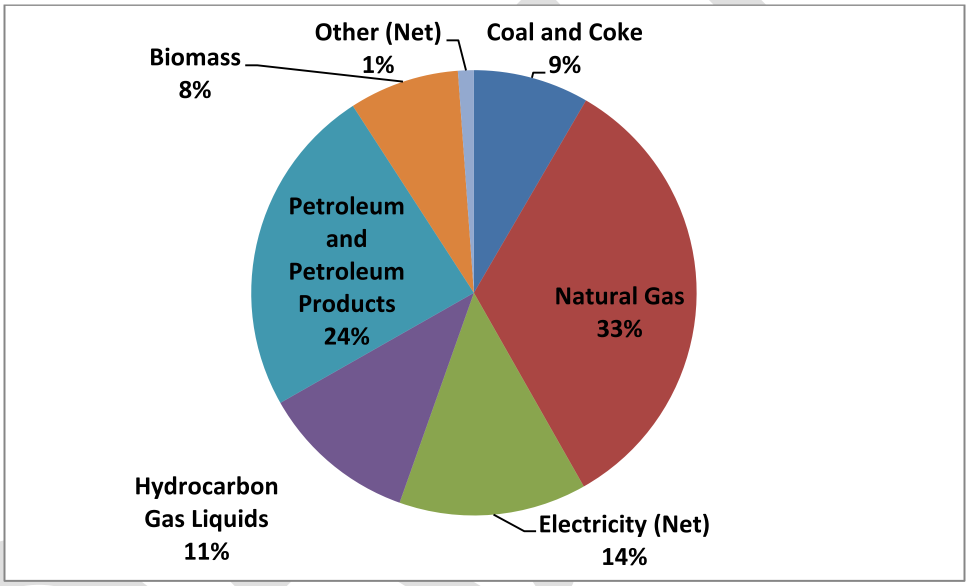

Figure 2.1 Diverse Energy Types Used by the U.S. Manufacturing Sector in 2014.[20]

Commensurate with its energy use, the manufacturing sector is also responsible for a substantial amount of greenhouse gas (GHG) emissions. The majority of manufacturing GHG emissions are carbon dioxide (CO_2) produced during combustion of fuels for heat and power. In addition, some facilities also generate significant GHGs in other processes.[21] These include non-combustion CO_2 emissions released in cement manufacturing and the emissions of other GHGs such as nitrous oxide, methane, and fluorinated gases. While produced in smaller quantities than CO_2, these other GHGs have significant environmental impacts because of their long lifetimes and high infrared absorption in the atmosphere.

[18] "Manufacturing Energy and Carbon Footprints (2010 MECS)" website at http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs, shows energy use for all of manufacturing as well as by manufacturing subsector. This website contains inks to 15 manufacturing sector carbon footprints as well as for all U.S. manufacturing in 2010.

[19] Lawrence Livermore National Laboratory 2015 Energy Flow Chart. Available online at: https://flowcharts.llnl.gov/.

[20] Supra 8. MECS 2014 Preliminary Estimates. EIA. Available online at: http://www.eia.gov/consumption/manufacturing/index.php.

[21] Detailed emissions data for reporting year 2014 is available from the U.S. Environmental Protection Agency (EPA's) Greenhouse Gas Reporting Program (GHGRP) website available at: https://www.epa.gov/ghgreporting/ghgrp-2014-reported-data. In addition, EPA's Facility Level Information on GreenHouse gases Tool (FLIGHT) provides facility-level data for large emitters. Available online at: https://ghgdata.epa.gov/.

Reductions in manufacturing energy use and GHG emissions can be attained through efficiency gains from improving and disseminating technologies and energy management approaches. Also, there are potential efficiency improvement opportunities from coordination between manufacturing facilities and across supply chains. Despite considerable efficiency gains and technology developments over the past 50 years, many industries continue to use far more energy than the theoretical minimum required for key processes (see bandwidth studies in section 2.3.3, Strategic Analysis of Opportunities, for further discussion). In addition to sector-specific opportunities for energy savings, advancements in cross-cutting process technologies used by energy-intensive and energy-dependent manufacturing industries, such as heating systems, steam systems and electrical power systems, can benefit nearly all sectors of manufacturing.

Lifecycle Impacts of Manufactured Products

Manufactured products reach all end-use sectors including all segments of the energy economy: energy production, energy delivery, and energy use. Examples of manufactured goods include steam and natural gas turbines used to generate electricity; the pipeline systems used to deliver natural gas to our homes and businesses; the solar and wind electricity generating systems used to supply renewable power; and the vehicles on our roads. Figure 2.2 shows that over 60% of the 98 quads of primary energy consumed economy-wide were wasted in 2014. Advanced manufacturing technologies could enable more effective utilization of this energy. The development and use of more efficient and competitive manufactured products throughout the economy, therefore, can lead to economy-wide energy and emissions reductions. The opportunity space for more efficient manufactured products includes improvements from manufacturing efficiency, as well as reduced energy use and emissions during product use throughout its lifetime. The lifecycle impacts of a product consider the natural resources needed to generate the raw materials; the energy needed to fabricate components and assemble the final product; the energy and emissions impacts associated with the lifetime of the product's use; and the impacts of recycling and/or disposing of the end-of-life (EOL) product. Another key consideration is ensuring responsible and effective stewardship of the environment during the entire product life cycle.

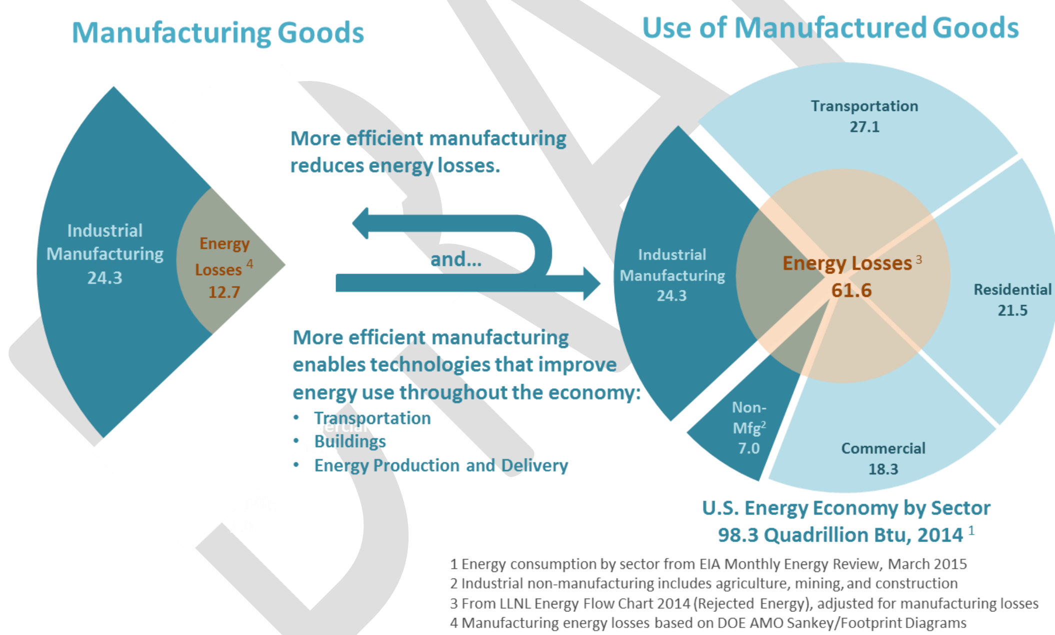

Figure 2.2 Opportunity Space for Energy Impacts from Manufacturing and the Use of Manufactured Goods

To determine the economy-wide impact of a manufactured good, net accounting of *overall* energy and emissions impacts must be considered. In some cases, energy-dependent products may result in greater energy consumption during manufacturing, but the energy associated with the product's use phase may be greatly reduced, resulting in an overall reduction in the life-cycle energy consumption. For example, carbon fiber composites are emerging as structural materials for lightweight, energy-efficient vehicles. Although more energy is required to manufacture a kilogram of carbon fibers than an equivalent quantity of steel, using carbon fiber technology for lightweighting with appropriate design and utilization of material can reduce total energy consumption in many cases because of fuel economy benefits realized during the vehicle use phase, particularly when the vehicle is used intensively.[22] Novel product design enabled by advanced manufacturing techniques can also reduce the product's impacts at EOL such as by improving capabilities for re-use, re-manufacturing, or recycling.

One challenge associated with deployment of clean energy products with life-cycle energy benefits is that the energy and environmental costs and benefits may be realized by different parties. In the carbon-fiber automotive component example, additional costs are assumed by the manufacturer during energy-intensive fabrication processes, while energy (and cost) savings occur in other sectors during the use, re-use, or recycling phases. In the absence of cost-parity with the incumbent technology, manufacturers would need to charge consumers a higher price for these products, and consumers would need to be willing to pay more upfront, with the expectation of recovering these costs during the use of the product.

Manufacturing Outlook and Energy Use Projections

The U.S. Energy Information Administration (EIA)'s *Annual Energy Outlook* (AEO) 2016 reference case projects that U.S. manufacturing output will grow significantly over the next 10 years, as shown in Table 2.1, but will slightly lag behind overall growth in U.S. GDP. Even though manufacturing energy intensity is expected to continue to decrease, energy consumption in manufacturing is expected to grow at a much higher rate than the economy as a whole.[23,24] In particular, the ongoing impact of the shale revolution contributes to a nearly 60% increase in projected output from the bulk chemicals industry between 2015 and 2025, and this industry accounts for well over half of the increase in manufacturing energy consumption during that period. However, the high level of energy intensity and growth in the bulk chemicals industry also masks the energy savings from energy efficiency improvements projected in other manufacturing industries during this period.

While the AEO is a valuable forecast, the projected data are subject to much uncertainty as events that shape energy markets cannot be anticipated. As a result, actual output and energy consumption in the future may be higher or lower than forecast. Over the longer term, improvements in energy productivity, or output per unit of energy, and the level of output will drive overall consumption of energy. For instance, a doubling of U.S. energy productivity, as advocated by the *Accelerate Energy Productivity 2030* partnership, would imply a 50% reduction in energy consumption assuming no change in output.[25] If economic output grew 40% during the productivity doubling period (similar to current AEO projections for GDP growth between 2015 and 2030), the result would only be a 30% reduction in total energy consumption from the original starting point. Key factors that impact overall changes in energy productivity include: (1) energy efficiency gains (or losses) due to technological or behavioral changes, and (2) structural changes in the mix of economic activity.

Table 2.1 Projected Growth for Salient U.S. Economic and Energy Statistics, 2015-2025

	2015-2025
U.S. Gross Domestic Product (GDP)	27.0%
Total U.S. Energy Consumption	5.0%
Manufacturing Value of Shipments	23.2%
Energy-Intensive Manufacturing	20.0%
Non-Energy-Intensive Manufacturing	24.7%
Manufacturing Primary Energy Consumption	17.9%

[22] S. Das, D. Graziano, V. K. K. Upadhyayula, E. Masanet, M. Riddle, and J. Cresko. "Vehicle lightweighting energy use impacts in U.S. light-duty vehicle fleet." *Sustainable Materials and Technologies* 8 (2016) 5-13.
[23] *Annual Energy Outlook 2016.* U.S. Energy Information Administration (EIA). DOE/EIA-0383 (2016). August 2016. Released September 15, 2016. Available online at: http://www.eia.gov/forecasts/aeo/. The full report is archived at http://www.eia.gov/outlooks/aeo/pdf/0383(2016).pdf.
[24] The AEO 2016 reference case projection cited is a business-as-usual trend estimate, given known technology and technological and demographic trends, and assumes that current laws and regulations are maintained.
[25] *Accelerate Energy Productivity 2030* website is available at: http://www.energy2030.org/. The roadmap documents are linked from the main page.

2.1.2 Innovation and Technology Development and Adoption

This section provides an overview of the drivers impacting innovation and technology development in manufacturing as well as the adoption of energy saving advanced technologies. Research to develop new materials, chemistries, and manufacturing processes that can significantly reduce manufacturing energy use is high-risk and typically beyond the risk threshold of the private sector. AMO works collaboratively with industrial end-users to understand the impact of potential advanced manufacturing technologies and their widespread adoption. Office activities, discussed in section 2.2, are designed to help bridge the gap from discovery to manufacturing innovation. AMO's technology RD&D plan presented in section 3 includes the highest priority areas for innovation and technology development to significantly impact manufacturing energy use and the lifecycle energy use of manufactured products.

Importance of Innovation Ecosystems

AMO partners with manufacturers, their suppliers, and interested stakeholders to invest in advanced manufacturing technologies and practices that strengthen U.S. manufacturing competitiveness. In order to develop new technologies in the United States, a healthy manufacturing base with critical strengths and capabilities is essential to transform innovative ideas into products.[26] Manufacturing is responsible for the vast majority of domestic research and development spending by U.S. companies, a key input into innovation.[27] Successive future rounds of innovation depend on the existence of a strong manufacturing base because much of the learning takes place as companies move their ideas beyond prototypes and demonstration through commercialization. For example, learning takes place as engineers and technicians at the factory work with the design engineers to find better solutions. During manufacturing, engineers are exposed to both the problems and the capabilities of existing technology, generating ideas both for improved processes and for applications of a given technology to new markets. Once component manufacturing is decoupled from design, there is a reduction in the latent knowledge of how things are made.

A strong manufacturing base for a technology positions companies to profit from manufacturing economies of scale. The economic importance of manufacturing is captured by Wright's Law, which describes how cumulative production in a given industry results in production efficiency improvement: as production increases cost tends to drop, although at different rates depending on the technology.[28] A recent clean energy manufacturing example is the reduction in price of solar PV modules. From 1980 – 2000, the primary cost reduction driver was technology improvements made possible by R&D investments. Since 2000, cost reductions at large PV module manufacturing plants have been driven by manufacturing economies of scale and are nearly equivalent to price declines resulting from R&D investments.[29]

Technological progress is widely acknowledged as one of the main drivers of economic growth but requires an atmosphere that fosters innovation. Recent studies analyzing manufacturing environments around the world found that successful manufacturing economies are comprised of regional ecosystems or hubs that foster innovation.[30,31,32] Businesses with complementary activities or resources co-locate around innovative hubs, increasing the flow of knowledge spillovers across firms and through the manufacturing supply chain, resulting in higher rates of growth and job creation. Innovation hubs bridge the gap between research and commercial application of advanced manufacturing technologies, accelerating products into the market. The infrastructure and supporting education and workforce training are built to sustain innovation in manufacturing, which is required to stay competitive in a global economy. AMO

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[26] R.M. Locke and R. Wellhausen, eds. *Report of the MIT Taskforce on Innovation and Production: A Preview of the MIT Production in the Innovation Economy Report*. MIT Press, Feb. 2013. Available online at: http://web.mit.edu/pie/news/PIE_Preview.pdf.

[27] S. Helper, T. Krueger, and H. Wial. *Why Does Manufacturing Matter? Which Manufacturing Matters? A Policy Framework*. Brookings Institution. Feb. 2012. Available online at: https://www.brookings.edu/wp-content/uploads/2016/06/0222_manufacturing_helper_krueger_wial.pdf.

[28] B. Nagy B., J.D. Farmer, Q.M. Bui, and J.E. Trancik. "Statistical Basis for Predicting Technological Progress." PLOS. Published February 28, 2013. Available online at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0052669.

[29] "Project Profile: Evaluating the Causes of Photovoltaics Cost Reduction: Why is PV Different?" EERE/DOE SunShot. Available online at: http://energy.gov/eere/sunshot/project-profile-evaluating-causes-photovoltaics-cost-reduction-why-pv-different.

[30] Supra 26. R.M. Locke and R. Wellhausen. *Report of the MIT Taskforce on Innovation and Production*. 2013.

[31] Supra 27. S. Helper, et al. *Why Does Manufacturing Matter? Which Manufacturing Matters? A Policy Framework*. 2012.

[32] *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing*. Executive Office of the President, President's Council of Advisors on Science and Technology (PCAST). Published July 2012. Available online at: https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf.

fosters innovative environments through public-private partnerships and leveraging the technical expertise at the national laboratories to address manufacturing challenges. Specific examples are provided in section 2.2 Office Structure and Activities.

Technology and Manufacturing Readiness Progression

AMO seeks to advance scientific innovations to overcome difficult manufacturing challenges and transition technologies, materials, and information into new manufacturing capabilities. The commercialization and adoption of technologies is subject to complex market dynamics. The Office works with stakeholders to identify opportunities to improve energy efficiency and performance and to accelerate technological progress.

AMO funds collaborative RD&D at various stages of technological progress typically from technology readiness levels (TRLs) 3 to 7. TRLs provide a systematic metric/measurement system to assess the maturity of a particular technology and enable a consistent comparison of maturity between different types of technology.[33] The TRLs span a scale from 1 to 9. The higher TRL numbers indicate the stage of development as a technology moves toward deployment, adoption, and use.

Manufacturing readiness levels (MRLs), initially developed by the Department of Defense,[34] is a numbering scale to identify the readiness of technologies to provide new manufacturing capabilities. MRLs have been adapted by DOE to assess the development of a technology's manufacturing base.[35] The MRL increases as the manufacturing capability transitions from laboratory prototype development through an initial low rate of production to full rate production. As shown in Table 2.2, manufacturing readiness and technology readiness are correlated; the MRL for a manufactured product cannot be higher than the TRL for the enabling technology. In other words, the product technology and product designs must be stable before the processes needed to manufacture the product can mature to the next level.

Converting cutting-edge, innovative research into commercially successful products is inherently risky. In the TRL model, risk decreases as a technology matures and progresses through each higher level.[36] Technologies at TRL 1-3 still require a basic level of research in order to gain more complete knowledge, and this research usually is not focused on a specific application. Once the focus of technology development is more applied, research is directed at advancing the state-of-the-art so that a new, innovative technology is available. Researchers define the problem they are trying to solve and establish goals and objectives, including performance parameters which serve to de-risk the technology for a particular application. The technology risk continues to decrease as the technology matures. For example, prototypes demonstrate the capabilities, functionality, performance, and quality required for a final product.

Investment Gaps Impacting Technology Development and Commercialization

The number of readiness levels, risk elements, and the complexities of technology development suggest the road between a discovery and innovation generated from basic research to a commercial product or process is long. Table 2.3 shows the typical innovation timeline in physical science R&D. It can take decades to develop technology and perhaps 5 – 10 years to develop a prototype, demonstrate its viability, and deploy into the market. Large companies may have the resources to fund each technology stage from technology development through prototyping and eventually product commercialization. Small and medium sized companies, however, usually have difficulty finding the needed resources to bridge the gap between technology development and manufacturing a viable commercial product.

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[33] *Manufacturing Readiness Level (MRL) Deskbook*. Prepared by the Office of the Secretary of Defense (OSD) Manufacturing Technology Program in collaboration with The Joint Service/Industry MRL Working Group. August 2015.

[34] "Manufacturing Readiness Level Definitions." Department of Defense (DoD). Available online at: http://www.dodmrl.com/MRL_Deffinitions_2010.pdf.

[35] D. Wheeler and M. Ulsh. *2010 Manufacturing Readiness Assessment Update to the 2008 Report for Fuel Cell Stacks and Systems for the Backup Power and Material Handling Equipment Market,* National Renewable Energy Laboratory, Technical Report NREL/TP-5600-53046. August 2012. Available online at: http://www.nrel.gov/docs/fy12osti/53046.pdf.

[36] Louis S. Wheatcraft. "Developing Requirements for Technology-Driven Products." Paper presented at the 15th Annual International Symposium of the International Council on Systems Engineering (INCOSE 2005), Rochester, NY, July 2005. Available online at: http://reqexperts.com/wp-content/uploads/2016/04/Rqmts-for-Technology-Driven-Products-Wheatcraft-INCOSE-012612.pdf.

Table 2.2 Technology and Manufacturing Readiness Level Definitions

Technology Readiness	Level	Manufacturing Readiness	Level
Basic principles observed and reported	TRL-1	Manufacturing feasibility assessed	MRL-1
Technology concept/ application formulated	TRL-2	Manufacturing concepts defined	MRL-2
Experimental critical function proof of concept	TRL-3	Manufacturing concepts developed	MRL-3
Technology validation in laboratory	TRL-4	Laboratory manufacturing process development	MRL-4
Technology validation in relevant environment	TRL-5	Manufacturing process development	MRL-5
Engineering, pilot scale validation	TRL-6	Critical manufacturing process prototyped	MRL-6
Full scale demonstration in relevant environment	TRL-7	Prototype manufacturing system	MRL-7
Actual system qualified and demonstrated	TRL-8	Manufacturing process maturity demonstration	MRL-8
Actual system operated at full-range conditions	TRL-9	Manufacturing process proven	MRL-9

Private sector resources are less available to develop and commercialize technologies that are based on fundamentally new materials, chemistries, and process innovations.[38] Developing these technologies requires significant capital, long development timelines, and they are often trying to compete in highly competitive commodity markets; markets that are strengthened by cheap energy prices. Figure 2.3 shows the capital requirements and typical investors as the risks associated with technology innovation progresses from research to development and commercial production. The "Technological Valley of Death" covers the stages between laboratory research and technological development. Technology developers must move beyond success in the laboratory and prove basic market viability. Investors are reluctant to fund these stages due to the high technical and market related risks and long development horizons. The "Commercialization Valley of Death" occurs when innovators seek to demonstrate commercial-scale technologies or manufacturing capabilities that require increasing amounts of funding. The third gap in funding is the large amounts of capital needed to scale-up to full-scale production. These funding gaps impede the development of innovative technologies that compete with established technologies.[39] AMO invests in high-risk research to bridge the "Technological Valley of Death".

Table 2.3 Physical Science Innovation Timeline[37]

Technology Stage	Timing
Theory	Decades
Fundamental Research	Decades
Technology Development	5-10 years
Proof of Concept	1-2 years
Prototype	6 months
Alpha Product	6-12 months
Qualification & Manufacturing	12 months
Product Extensions	2 years +

AMO collaborates with industrial end-users of advanced manufacturing technologies to understand the impact of a technology and the potential for broad technology adoption. Industry stakeholders have a unique and valuable understanding of how advanced technologies would affect a core process, the type of process modifications required for technology adoption, and the knowledge and expertise required to incorporate the technology into manufacturing processes.

[37] Table adapted by D. Graziano and M. Riddle from "Product development cycle time for business-to-business products" by A. Griffin. *Industrial Marketing Management*, 31(4), 291-304, July 2002. Adapted table presented at American Center for Life Cycle Assessment (ACLCA)'s LCA XVI Conference, Charleston, S.C., September 2016.

[38] B. Gaddy, V. Sivaram, and F. O'Sullivan. *Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation*. An MIT Energy Initiative Working Paper. July 2016. Available online at: http://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.

[39] J. Jenkins and S. Mansur. *Bridging the Clean Energy Valleys of Death: Helping American Entrepreneurs Meet the Nation's Energy Innovation Imperative*. Breakthrough Institute. Nov. 2011. Available online at: http://thebreakthrough.org/blog/Valleys_of_Death.pdf.

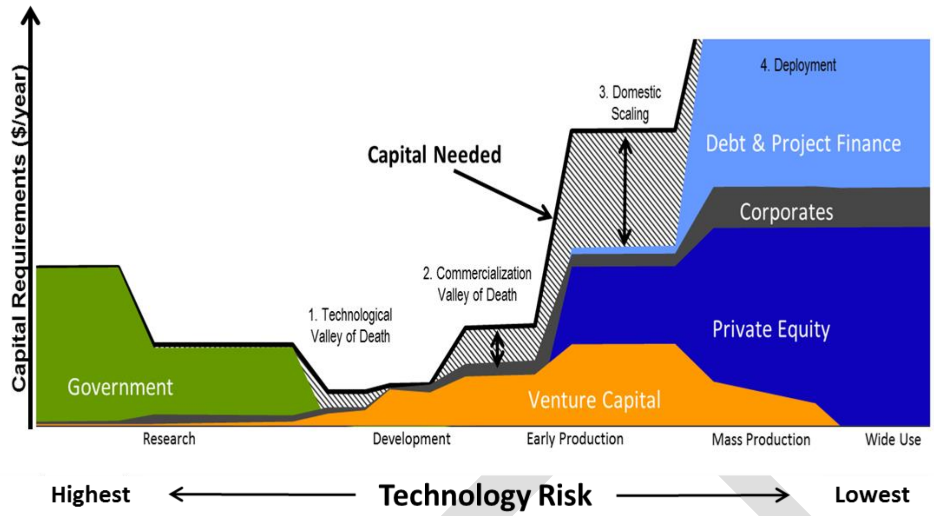


Figure 2.3 Gaps in Funding Associated with Technology Risk Impede Technological Progress.[40]

Barriers to Technology Adoption

The complexities of technology adoption are further documented in recent studies analyzing the potential reductions in industrial energy consumption that are possible if existing best practices and commercial technologies were implemented. These studies indicate that many manufacturing facilities could reduce energy use by 15% or more through improvement projects with payback periods of less than 3 years,[41] and as much as 32% by 2025.[42] However, the barriers that impede the adoption of advanced manufacturing technologies and practices in the market are numerous, including:

Economic and Financial Barriers

- *Internal competition for capital.* Manufacturers often have limited capital available for end-use efficiency projects and frequently require very short payback periods.
- *Corporate tax structures.* U.S. tax policies, such as depreciation periods, the treatment of energy bills, and other provisions can be a deterrent.
- *Split incentives.* Companies often split costs and benefits for energy efficiency projects between business units, which complicate decision-making.
- *Failure to recognize full value of efficiency.* Not considering non-energy or co-benefits of an end-use energy efficiency project weakens the business case.
- *Energy price trends.* Volatile energy prices can create uncertainty in investment returns, leading to delayed decisions on energy efficiency projects.

[40] Adapted from "Challenges and Opportunities for a Clean Technology Revolution: A Venture Capital Perspective" by V. Mehra. September 2011. Available online at: http://aleph.humanities.ucla.edu/2015/07/26/challenges-and-opportunities-for-a-clean-technology-revolution-a-venture-capital-perspective/.

[41] Data analysis uses information from the IAC database. Available online at: https://iac.university/.

[42] *Barriers to Industrial Energy Efficiency: Report to Congress.* U.S. Department of Energy (DOE). June 2015. Available online at: http://energy.gov/sites/prod/files/2015/06/f23/EXEC-2014-005846_6%20Report_signed_v2.pdf. This report examined barriers impeding the adoption of energy efficient technologies and practices in the industrial sector, and identified successful examples and opportunities to overcome these barriers. The report also included estimated economic benefits from a hypothetical federal energy efficiency grant program.

Regulatory Barriers

- *Utility business model.* The structure of utility cost recovery and lost revenue mechanisms can reduce a utility's interest in promoting industrial energy efficiency projects.
- *Environmental permitting.* Uncertainty, complexity, and costs associated with permitting processes such as New Source Review can deter facilities from moving projects forward.
- *Utility rates and interconnection.* Unfavorable rates or additional costs that can hinder installation of distributed generations such as combined heat and power (CHP) systems.

Informational Barriers

- *Adoption of systematic energy management system.* Some manufacturing plants lack information on the benefits of modern energy management systems and the locally-based resources to identify, implement and monitor the energy improvement activities that would result.
- *Awareness of incentives and risk.* Lack of knowledge of available Federal, state and utility incentives for end-use efficiency measures can lead to missed opportunities.
- *Metering and energy consumption data.* Lack of disaggregated energy consumption data and tools to evaluate such data, can prevent identification and evaluation of opportunities.

  In-house technical expertise. Lack of in-house technical expertise or the resources to hire outside staff for the development and operation of end-use efficiency projects can hinder deployment.

State and International Manufacturing Drivers

Revitalizing and reinvigorating U.S. manufacturing competitiveness is important at the state and local level for the economic development that it brings. Many states have developed programs designed to attract manufacturing to their area of the country. Competition for manufacturing also exists at the international level for the same reasons. Cooperation between nations is recognized as an opportunity to address energy use and associated emissions during manufacturing.

State and Local Environment

Most states have some form of economic development office, and are typically very interested in attracting manufacturing plants and the associated workforce for economic growth. States competing for manufacturing facilities can often lead to significant financial incentives for firms to locate in a particular state. For emerging manufacturing industries, being the leader in attracting initial facilities may be seen as a competitive advantage to attract future facilities. Many states also provide R&D tax credits for investors or manufacturing firms conducting research activities; and a few states have robust R&D program activities in the energy space, such as Iowa (Iowa Energy Center), California (California Energy Commission (CEC)) and New York (New York State Energy Research and Development Authority (NYSERDA)). Finally, many states also provide incentives for clean energy deployment through tax credits and other energy production related incentives, such as renewable portfolio standards.

International Environment

Internationally, governments are generally supportive of manufacturing, although trade disputes, currency fluctuations, and other competitiveness factors can make conditions challenging for individual domestic manufacturing firms. Manufacturing companies generally prefer to operate in countries with predictable and favorable regulatory and tax environments, and that provide resources that contribute to innovation.[43] For example, the Fraunhofer-Gesellschaft organization, consisting of 67 institutes and research units located throughout Germany, supports applied research across various technology domains relevant to manufacturing. More than 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Almost

[43] *Report to the President on Ensuring American Leadership in Advanced Manufacturing*. Executive Office of the President, PCAST. Published June 2011. Available online at: https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

30 percent of research revenue is contributed by the German federal and Länder governments in the form of base funding.[44]

2.2 Office Structure and Activities

AMO activities are designed to help bridge the gap from discovery to manufacturing innovation and address significant opportunities to save energy in manufacturing. These activities advance broadly applicable cross-cutting technologies for energy intensive and energy dependent manufacturing sectors; advance platform technologies that enable the manufacturing of products; establish partnerships to promote energy efficiency and technology innovation; and transfer knowledge through dissemination of tools and training.

Organizationally, AMO pursues its goals through the following three subprogram approaches:

- Advanced Manufacturing R&D Projects
- Advanced Manufacturing R&D Consortia
- Industrial Technical Assistance

To implement activities, AMO relies on its highly qualified scientific, engineering, and professional staff with diverse subject matter expertise. AMO staff partner with government scientists and engineers who are skilled in conducting research and conceptualizing innovations and industry stakeholders who are skilled in identifying and managing manufacturing risks. AMO leverages these collaborative research communities to develop and demonstrate targeted advanced manufacturing technologies through its R&D Projects and R&D Consortia subprograms. Through the Industrial Technical Assistance program, collaborative communities work to deploy energy efficient technologies and energy management practices that increase energy efficiency and reduce energy costs. All subprogram activities seek to bridge the technology development gap and capture private sector benefits from government investment in R&D (see Figure 2.4).[45] The AMO subprograms are discussed below.

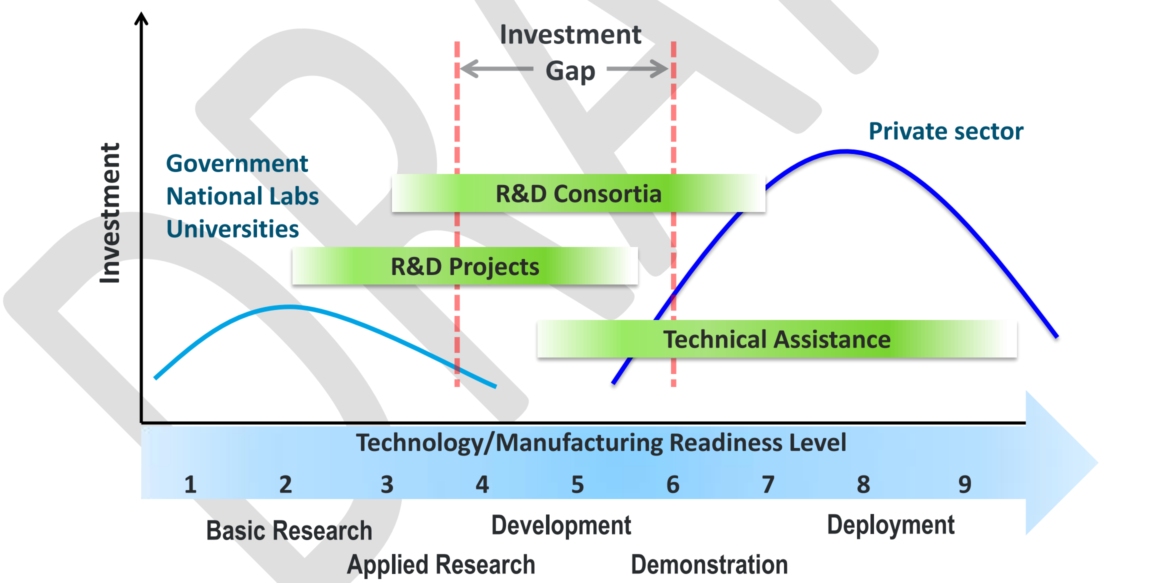


Figure 2.4 AMO Subprograms and their Role in Advancing and Deploying Manufacturing Technologies.

[44] "Facts and Figures." Fraunhofer – Gesellschaft. Available online at: https://www.fraunhofer.de/en/about-fraunhofer/profile/facts-and-figures.html.
[45] Charles Wessner. *Public/Private Partnerships for Innovation: Experiences and Perspectives from the U.S*. Presented at TIP Workshop on Public/Private Partnerships or Innovation. December 2001.

Advanced Manufacturing R&D Projects

The Advanced Manufacturing R&D Projects subprogram supports innovative advanced manufacturing applied research and development projects that focus on specific high-impact manufacturing technology and process challenges. The subprogram invests in foundational energy-related advanced manufacturing technologies that impact areas relevant to manufacturing processes (where energy costs are a determinant of competitive manufacturing) and broadly applicable platform technologies (the enabling base upon which other systems and applications can be developed). The competitively selected projects focus on developing next-generation manufacturing materials, information, and process technologies that improve energy efficiency in energy-intensive and energy dependent processes and facilitate the transition of emerging clean energy technologies to domestic production. Recent emphasis includes activities supporting high performance computing for manufacturing, small business and startup partnerships with DOE national laboratories, and atomically precise membranes and catalysts.

AMO also manages projects funded through the DOE-wide Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. These RD&D programs have specific funding mandates in Federal agencies with large extramural research budgets and are specifically tailored for the needs of small businesses. The projects are conducted by small technology firms and include Phase I projects that explore the feasibility of innovative concepts and Phase II projects with expanded RD&D efforts. Each year SBIR and STTR provide AMO with strategic opportunities to engage with the private sector to advance scientific discoveries and develop and commercialize manufacturing solutions. AMO suggests topics for funding consideration by the programs, participates in the competitive selection process, and assists with overseeing the projects awarded in relevant topic areas. Recently emphasized SBIR activities include atomically precise structures and devices for catalysis and high selectivity membranes, high performance conductors, manufacturing improvements for wide bandgap semiconductors, and novel low cost recovery methods for low temperature industrial waste heat.

The text box **"Leveraging National Laboratory Resources to Accelerate Innovation"** highlights examples of recent AMO initiatives to accelerate innovation in collaboration with the national laboratories.

Since the 1970s, over 300 AMO-supported RD&D projects have resulted in the development of a commercialized technology. By employing these technologies, manufacturers have saved considerable amounts of energy and money, and reduced emissions. Additionally, since 1991, 73 technologies have received an R&D 100 Award,[46] with 48 of those awarded after the year 2000. Over 500 patents have also been issued as a result of R&D projects.

[46] R&D 100 Awards is sponsored by R&D Magazine with selections by the R&D 100 Awards Committee to honor the 100 most innovative technologies and services newly introduced to the market by researchers from industry, academia, and government in a given year. Information is available online at: http://www.rdmag.com/article/2016/09/r-d-100-special-recognition-awards-finalists-announced.

Leveraging National Laboratory Resources to Accelerate Innovation

Advancing technologies for manufacturing readiness is a long and complex process. AMO and EERE provide unique opportunities for U.S. businesses to leverage the technical expertise at the national laboratories to help bring technologies to the market faster and gain a competitive advantage in the global economy. Lab-Industry activities established since 2015 include the following:

- **High Performance Computing for Manufacturing (HPC4Mfg) Program** – enables targeted collaborations between the national laboratories and the U.S. manufacturing industry that will serve to de-risk future investments. Under the program, selected projects apply modeling, simulation and data analysis to industrial products and processes to lower production costs and shorten the time to market by optimizing device designs, predicting device performance, and reducing the number of testing cycles in product development. The industry partner identifies the manufacturing challenge to ensure there is a direct commercial impact.
- **Technologist in Residence (TIR) Program** – streamlines engagement and increases collaborative research and development between national laboratories and private-sector companies. The program partners a senior technologist from a national laboratory with an industry professional from a manufacturing company or consortium of companies to better understand and tackle important problems and discover the lab capabilities that can best solve them.
- **Small Business Vouchers (SBV) Pilot** – connects small businesses with national laboratories to overcome the technical challenges inherent in bringing innovations to market.
- **Lab-Embedded Entrepreneurship Program (LEEP)** – provides an institutional home within the U.S. national laboratories for entrepreneurial scientists and engineers performing applied R&D with the express goal of launching a clean energy business. LEEP trains innovators to develop entrepreneurial acumen and skills, while introducing them to the ecosystem partners needed to facilitate commercial and investment opportunities. Three laboratories are currently acting as LEEP hosts, including:
  - Lawrence Berkeley National Laboratory (LBNL): Cyclotron Road
  - Argonne National Laboratory (ANL): Chain Reaction Innovations
  - Oak Ridge National Laboratory (ORNL): Innovation Crossroads
- **Technology Commercialization Fund (TCF)** – advances promising energy related technologies with commercial potential developed at the national laboratories and helps strengthen partnerships between the national laboratories and private sector companies that can deploy energy technologies to the marketplace. TCF funds will be used to match 50% non-federal funds from private sector partners.

Advanced Manufacturing R&D Consortia

The Advanced Manufacturing R&D Consortia subprogram helps the United States position itself as a world leader in strategic areas of manufacturing by bringing together manufacturers, suppliers, companies, institutes of higher education, national laboratories, and state and local governments in public-private R&D consortia.[47] These partnerships facilitate the transition of innovative advanced materials, information, and process technologies to industry by enabling manufacturing scale-up and helping to develop national capabilities that enable future global leadership in advanced manufacturing.

AMO has established the Critical Materials Hub, the ORNL Manufacturing Demonstration Facility, and three Institutes as part of the Manufacturing USA network: PowerAmerica, the Institute for Advanced Composites Manufacturing Innovation (IACMI), and the Clean Energy Smart Manufacturing Innovation Institute. Proposals have been solicited for Institutes in two additional topic areas: Modular Chemical Process Intensification Institute for Clean Energy Manufacturing and the Clean Energy Manufacturing Innovation Institute for Reducing EMbodied-energy And Decreasing Emissions (REMADE) in Materials Manufacturing. These manufacturing Institutes are public-private partnerships that have distinct technology focus areas but work towards a common goal: to secure America's future through manufacturing innovation, education, and collaboration. The technical challenges being addressed by AMO's R&D Consortia require targeted collaboration between industry stakeholders and research organizations. The subprogram has united experts in key areas of advanced manufacturing, thus taking a momentous first step to ensure sustained U.S. manufacturing competitiveness. The text box **R&D Consortia Approaches** describes the three different modes of R&D consortia.

AMO-supported R&D Consortia have resulted in 2 commercialized technologies, 11 R&D 100 Awards, 30 Industry Excellence Awards, over 50 publications, and numerous special projects with industry are underway.

[47] As authorized by the Energy Policy Act of 2005, P.L. 109-58, Section 989.

Brief descriptions of the R&D Consortia managed by AMO follow:

- **Critical Materials Hub** is working to diversify supply, develop substitutes, and improve reuse and recycling of rare earth metals and other materials that a crucial for clean energy technology deployment.
- **ORNL Manufacturing Demonstration Facility** helps industry adopt new manufacturing technologies to reduce life-cycle energy, lower production costs, and create new products and high-paying jobs.
- **PowerAmerica** is accelerating the adoption of advanced semiconductor components made with silicon carbide (SiC) and gallium nitride (GaN) into a wide range of products and systems.
- **Institute for Advanced Composites Manufacturing Innovation** (IACMI) is committed to accelerating development and adoption of cutting-edge manufacturing technologies for low-cost, energy-efficient manufacturing of advanced polymer composites for vehicles, wind turbines, and compressed gas storage.
- **Clean Energy Smart Manufacturing Innovation Institute** works to spur advances in smart sensors and digital process controls that can radically improve the efficiency of U.S. advanced manufacturing.
- **Modular Chemical Process Intensification Institute for Clean Energy Manufacturing** is focused on breakthrough technologies to dramatically improve energy efficiency of novel chemical manufacturing processes.
- **Clean Energy Manufacturing Innovation Institute for Reducing EMbodied-energy And Decreasing Emissions (REMADE) in Materials Manufacturing** will dramatically reduce life-cycle energy consumption through the development of technologies for reuse, recycling, and remanufacturing of materials.

R&D Consortia Approaches

AMO supports three “modes” of consortia: Advanced Manufacturing Innovation Institutes, Energy Innovation Hubs, and Manufacturing Demonstration Facilities. A description of each follows, including objectives for each consortium type.

Advanced Manufacturing Innovation Institutes

Each DOE Advanced Manufacturing Innovation Institute (MII) is designed to accelerate U.S. advanced manufacturing by *catalyzing the development of new technologies, national infrastructure, educational competencies, production processes, and products via shared contributions from the public and private sectors and institutes of higher education*.

With a focus on TRLs 4-7, MIIs provide shared facilities to local start-ups and small manufacturers to help them scale up new technologies, accelerate technology transfer to the marketplace, facilitate the adoption of innovation workforce skills at multiple levels, and strengthen business capabilities in large and small companies. Individual institutes serve as regional hubs in their areas, bridging the gap between applied research and product development with a focus in key technology areas that encourage investment and production in their region and across the United States. Institutes are expected to be self-sustaining and continue to serve the manufacturing community after an initial investment of government funds for start-up.

MIIs are nodes in the National Network for Manufacturing Innovation (NNMI), now known as Manufacturing USA. The network consists of multiple linked Institutes with common goals but unique technological concentrations. Each institute complements each other’s capabilities and benefits from shared approaches to matters such as intellectual property, contract research, and performance metrics.

Energy Innovation Hubs

Modeled after the strong scientific management characteristics of the Manhattan Project and AT&T Bell Laboratories, DOE Energy Innovation Hubs are *integrated research centers that combine basic and applied research with engineering to accelerate scientific discovery that addresses critical energy issues*.

Energy Innovation Hubs address:

- A high impact, energy related technology RD&D challenge which if addressed would have significant beneficial impact on society.
- A clear and meaningful technology challenge which spans basic research, applied research, development and demonstration (TRLs 1-7) in a comprehensive and inter-related way.
- Clear and meaningful technical challenges which are broad, requiring multidisciplinary approaches from disparate fields that would not otherwise be likely to collaborate on R&D.
- A need for a consortia approach combining multiple disciplines of researchers and experimental capabilities at institutes of higher education, national laboratories, not-for-profit institutions, for profit private sector firms, and governmental entities in order to develop and ultimately deploy the technology.
- A need for new shared resources to address the RD&D challenges, and likely sufficient industry support to transfer the resulting technology to market and continue support for shared resources following federal investment.

Manufacturing Demonstration Facility

A Manufacturing Demonstration Facility (MDF) is a *collaborative manufacturing community that shares a common RD&D infrastructure, thereby providing affordable access to advanced physical and virtual tools for rapidly demonstrating new manufacturing technologies and optimizing critical processes*.

Work conducted by MDF partners and users provides data that are used to reduce the technical risk associated with full commercialization of promising foundational manufacturing process and materials innovations. MDFs are organized to foster an open exchange of pre-competitive manufacturing best-practices and know-how – including design and processing tools, qualification and certification approaches, and fabrication costing methods – while still protecting a company's proprietary intellectual property. MDF staff include designers, manufacturing experts, and product evaluators to guide and train users. Technology developers may use a variety of collaboration instruments. MDFs may also host interns and guest workers from industry, academia, and government.

Industrial Technical Assistance

The Industrial Technical Assistance subprogram provides critical support to the deployment of advanced energy efficiency technologies and practices. The subprogram supports the deployment of cost-effective combined heat and power (CHP) technologies; provides resources to assist manufacturers in reducing their energy use intensity; promotes the adoption of energy management, including systems consistent with ISO 50001; and provides targeted energy efficiency, productivity, and waste/water use reduction technical assistance to small- and medium-sized manufacturers. Increased emphasis is being placed on establishing traineeships, quantification of energy savings and the establishment of energy management systems across all energy using sectors, including institutional, commercial and industrial with a focus on energy intensive manufacturing plants, campuses, supply chains and water and wastewater facilities. Notable accomplishments include:

- Industrial Assessment Centers (IACs), operating through 24 U.S. universities, provide energy assessments to often underserved small and medium sized manufacturers. The 17,421 IAC assessments provided have resulted in 61,147 implemented recommendations (and counting).[48] A third-party report estimates that roughly 54 trillion Btu gross energy savings, and an expanded energy-efficiency workforce with marketable skillsets, are attributable to IAC efforts.[49]
- The Better Plants program has formed 176 partnerships to date, including approximately 2,600 facilities, committed to a voluntary energy use reduction of 25% in 10 years. On average, partners in the Better Plants program have a higher rate of energy intensity improvement than the rest of the manufacturing industry.[50,51]
- The seven regional CHP Technical Assistance Partnerships (CHP TAPs) offered third-party technical assistance to manufacturers and other large energy consumers interested in pursuing CHP. More than 280 CHP projects are under development or online, with an estimated installed capacity of over 2GW.[52]
- Facilities implementing ISO 50001 and the Superior Energy Performance (SEP) program, on average, saw verified energy intensity improvement rates more than four times greater than the rates they experienced before SEP.[53]

Operational Program Support

In addition to the three subprograms, AMO staff support program operations in the following areas:

- Technical Project Management – providing project management support for AMO activities;
- Operations Management – providing staff management and program planning support for AMO activities;
- Budget Planning/Execution – including budget planning, execution, and financial tracking for AMO activities;
- Strategic Analysis and Data Management – including strategic analysis, program evaluation, and related activities; and
- Communications – providing awareness to overcome market barriers and accelerate technology deployment.

Overall, Office organization is designed to achieve the AMO mission and goals, operate efficiently within the DOE organization, and encourage dynamic staff interaction both within the office and across DOE offices and programs.

[48] Supra 41. IAC database. Available online at: https://iac.university/.

[49] *Saving Energy, Building Skills: Industrial Assessment Centers Impact*. SRI International. March 2015. Available online at: https://iac.university/technicalDocs/Industrial%20Assessment%20Centers%20Impacts%20SRI%20International.pdf.

[50] "Energy Consumption Trends in the Manufacturing Sector." MAPI blog. Posted April 16, 2013. Available online at: https://www.mapi.net/blog/2013/04/energy-consumption-trends-manufacturing-sector.

[51] Supra 8. MECS website. EIA. Available online at: http://www.eia.gov/consumption/manufacturing/index.php.

[52] U.S. DOE Combined Heat and Power (CHP) Installation Database including CHP TAPs monthly metrics reports. Data as of calendar year 2015. Calendar year 2016 data will be available in June 2017. Available online at: https://doe.icfwebservices.com/chpdb/.

[53] "Development of an Enhanced Payback Function for the Superior Energy Performance Program." Lawrence Berkeley National Laboratory. Report LBNL-190883. August 2015. Available online at: http://energy.gov/sites/prod/files/2015/10/f27/LBNL-190883.pdf.

Relationship to Other Federal Programs and Agencies

Coordination with other government programs and agencies involved in advanced manufacturing is necessary to avoid duplication of effort, leverage limited resources, optimize federal investment, and meet national energy, economic, and environmental goals. AMO coordinates with a broad range of federal programs, both within DOE and in other agencies, and gains knowledge and insights from subject matter experts across the Federal government.

Relationship with Other DOE Programs

Within DOE, AMO is the key program office that is focused on supporting the emergence of a thriving advanced energy efficient manufacturing industry. As shown in Figure 2.5, AMO works closely with other DOE programs to achieve crosscutting DOE goals. For example, AMO coordinates and collaborates, as needed, with the Office of Fossil Energy, the Office of Electricity Delivery and Energy Reliability (OE), the Office of Nuclear Energy, the Office of Science, and Advanced Research Projects Agency-Energy (ARPA-E).

AMO also collaborates with other EERE programs on individual projects and events (see Figure 2.5). For example, in areas of technology RD&D for power generation, the EERE Wind Program and AMO have jointly supported research applying additive manufacturing processes to create molds for the production of wind turbine blades. The processes currently used to manufacture utility-scale wind turbine blades – which can average over 150 feet in length – are complex, energy-intensive, and time-consuming. Also, AMO coordinates with the EERE Geothermal Technologies Office (GTO) in the area of water purification technology. Energy efficient clean water technologies are an emerging RD&D technology area for AMO. GTO conducts research on water purification technologies for use in geothermal applications.

Within the AMO Technology Assistance subprogram area, AMO collaborates with the EERE Building Technologies Office (BTO) to implement the Better Buildings, Better Plants program activities, including the annual Better Buildings, Better Plants Summit where partners and stakeholders exchange best practices and showcase energy solutions.

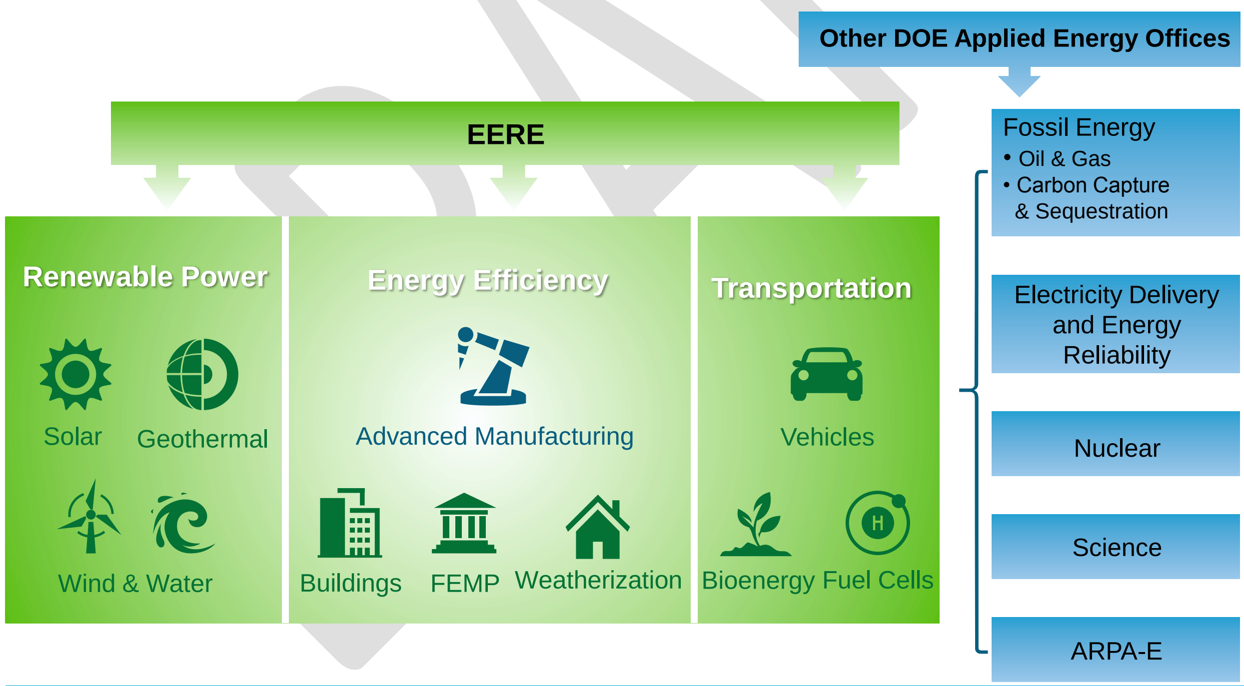


Figure 2.5 AMO Collaborates on RD&D with Multiple DOE Offices and Programs

Complementary Federal Programs and Collaborations

AMO coordinates advanced manufacturing activities with other Federal departments through DOE's representation on the National Science and Technology Council (NSTC) Subcommittee on Advanced Manufacturing. The NSTC is a Cabinet-level Council within the Executive Office of the President's Office of Science and Technology Policy (OSTP) and is the principal means through which the executive branch coordinates science and technology policy across the Federal R&D enterprise.

NSTC established an interagency working group to coordinate research activities in advanced manufacturing and created a Nationwide Network for Manufacturing Innovation (now known as Manufacturing USA) to scale up advanced manufacturing technologies and processes. Under the Revitalize American Manufacturing and Innovation Act of 2014, Congress authorized the Advanced Manufacturing National Program Office (AMNPO), which is hosted by the U.S. Department of Commerce's (DOC's) National Institute of Standards and Technology (NIST) and operates in partnership with DOE as well as the U.S. Department of Defense (DoD), NASA, the National Science Foundation (NSF), the U.S. Department of Education (ED), and the U.S. Department of Agriculture (USDA). AMNPO was authorized to hold "open-topic" competitions for manufacturing innovation institutes where topics of highest importance to industry could be proposed and it is responsible for operating the resulting Manufacturing USA network. Figure 2.6 lists the current and planned institutes of the Manufacturing USA network, including those managed by AMO for the DOE.

When a more formal collaboration is appropriate, Memorandums of Understanding (MOUs) between Federal entities are used to set out their respective coordinated roles. MOUs are also known as Memorandums of Agreement, Statements of Understanding, or Interagency Agreements. These instruments are used whenever there is an agreement to exchange information or coordinate programs to optimize the benefits from each party's efforts. For example, EERE has signed MOUs with NASA and NSF to clearly establish the organizational relationships, responsibilities and activities that comprise the parties' collaboration in the DOE institutes. AMO, as the EERE office managing the institutes, uses these agreements to guide collaborations with NSF and NASA with respect to established as well as future institutes.

AMO also works closely with NIST's Manufacturing Extension Partnership (MEP), a program of NIST. MEP has over 500 centers across the United States that provide technical assistance to small and mid-sized manufacturers, including help with process improvements, new green manufacturing technologies, and innovation strategies. Under the Manufacturing Impacts Through Energy and Commerce (MITEC) pilot program, DOE and DOC signed an MOU to facilitate collaboration between MEP Centers and DOE's national laboratories.[54] The purpose of MITEC is to increase access to the advanced energy innovation capabilities of the DOE national laboratories, spur U.S. manufacturing economic growth in select clean energy sectors, and multiply the tools and reach of the DOE national laboratories and MEP Centers to enhance competitiveness of small businesses through technical assistance, relationship building, and partnership opportunities. The MITEC pilot is a step toward linking innovation resources across the federal government and help states to develop strong, regional clean energy manufacturing and economic development clusters. Starting with four states (Georgia, Virginia, Ohio, and Michigan), DOE and DOC collaborate on a series of boot camps to bring expertise from national laboratory resources, MEP Centers and/or partners to targeted manufacturing small businesses. These boot camps will allow local small businesses to become aware of and tap into the vast resources of the national labs to boost their manufacturing competitiveness and grow their advanced energy manufacturing businesses.

[54] More information is available on the MITEC program is available online at: http://energy.gov/eere/cemi/manufacturing-impacts-through-energy-and-commerce-mitec.

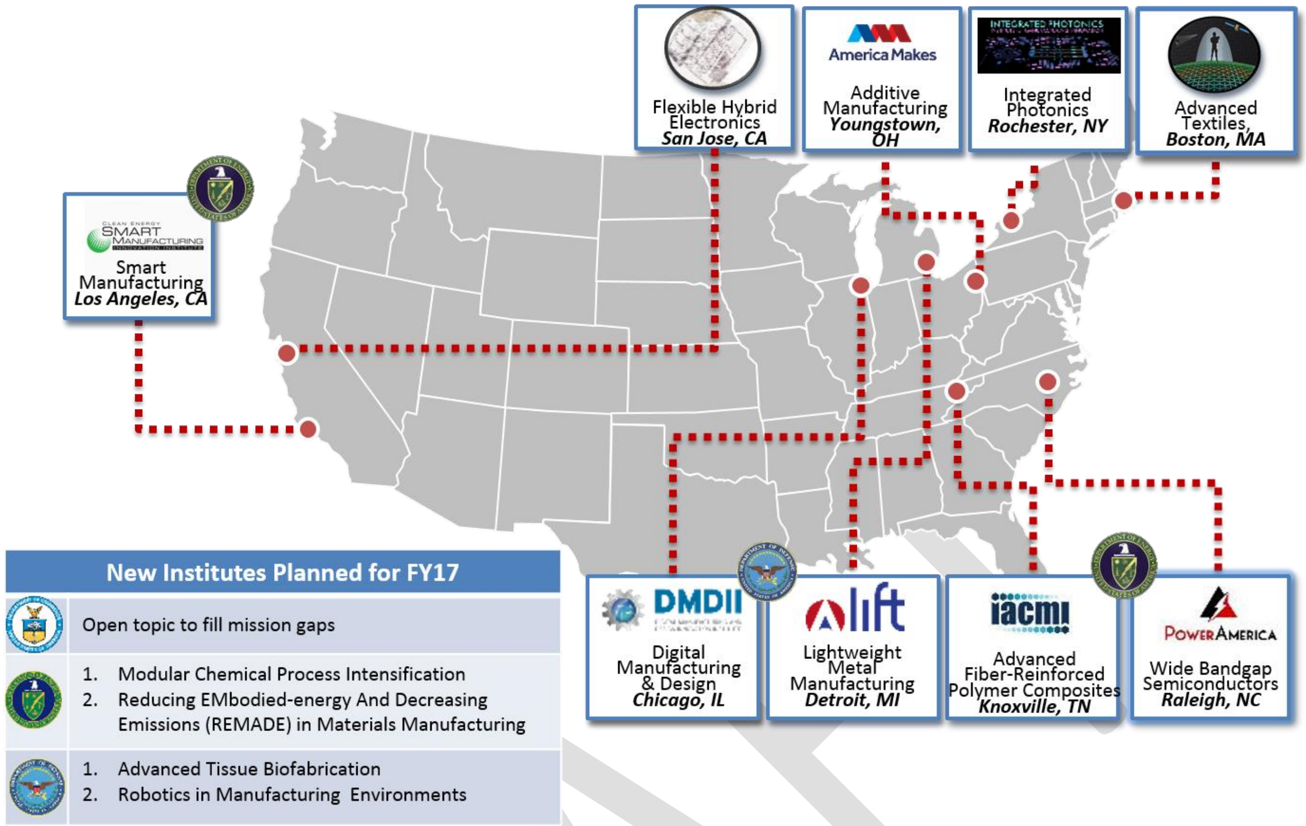


Figure 2.6 Manufacturing USA Network Status and 2017 Plans

The U.S. Environmental Protection Agency (EPA) also has several programs which impact manufacturing facilities. As a result, AMO collaborates with the EPA and the Department of Commerce to provide information and technical assistance to manufacturers. Through voluntary programs such as EPA's ENERGY STAR®, NIST's MEPs, and the DOE/AMOs Better Plants and ISO 50001 Ready programs, manufacturers pursue energy savings projects and energy management programs which result not only in energy savings, but often corresponding waste, water and cost savings. Reductions in energy, waste and greenhouse gas emissions gained through participation in these voluntary programs can help manufacturers meet state and Federal environmental regulations.

AMO also collaborates with Federal program offices and agencies to develop or comply with performance standards that impact advanced manufacturing materials and processes. The Smart Manufacturing institute will work closely with the NIST Cloud Computing Program to provide smart manufacturing software applications using cloud computing technologies, and standards for industrial control systems security and data analytics. AMO and NIST are working with industrial partners to develop procedures for verification, validation, and uncertainty quantification in modeling and computational simulation for advanced manufacturing under American Society of Mechanical Engineers (ASME) standards. The two entities also work together to advance smart grid interoperability standards, especially the Standard for Interconnecting Distributed Energy Resources and Microgrids with Electric Power Systems. These standards impact wide bandgap based power electronics developed to integrate renewable energy resources and microgrids to the grid.

Within EERE, AMO works with the Vehicle Technologies Offices (VTO) to ensure advanced materials for lightweighting transportation vehicles meet SAE International (formerly known as the Society of Automotive Engineers) Standards for aerospace/automotive/commercial vehicles and ASTM International standards when these materials are incorporated into transportation vehicle parts. These standards ensure the safety, quality, and effectiveness of parts and materials for dependable vehicle performance. VTO is also an important AMO partner in the area of electric drive systems application of wide bandgap semiconductor power devices. AMO also works closely with BTO to ensure advanced materials and processes for items such as packaged boilers and lighting meet appliance and equipment standards for energy conservation.

Solving persistent manufacturing challenges requires the expertise of scientists from different disciplines and continuous engagement of both end users and manufacturers. To facilitate the needed collaboration, AMO encourages the establishment of research partnerships to bring together expertise and facility resources across federal program offices, national laboratories and other research entities, including private industry. Such partnerships create unique research capabilities that can enable timely market entry of new technologies.

AMO collaborates with groups across the Federal Government when investigating whether the office should make RD&D investments in a specific technology. AMO hosts workshops to gather input on the future opportunities and technical challenges of advanced materials and technologies and invites experts from other federal entities to participate. Depending on the topic, federal technical experts from NSF, the Defense Advanced Research Projects Agency (DARPA), DoD research laboratories, DOE national laboratories, and other DOE offices including ARPA-E, Fossil Energy, OE, and others are encouraged to attend.

2.3 Office Strategic Planning Approach

This section of AMO MYPP for Fiscal Years 2017 through 2021 presents the strategic inputs that shaped the Office strategy and program approaches; the AMO vision, mission, goals, and success indicators; the strategic analysis activities that were used to identify opportunities and determine priorities; and program and project evaluation activities.

2.3.1 Foundational Authorities and Guidance

In developing this MYPP, AMO utilized relevant legislation, DOE and administrative guidance, key publications, and technical analysis as strategic inputs. These inputs form the guiding foundation for AMO's mission, vision, goals, activities, and general operations.

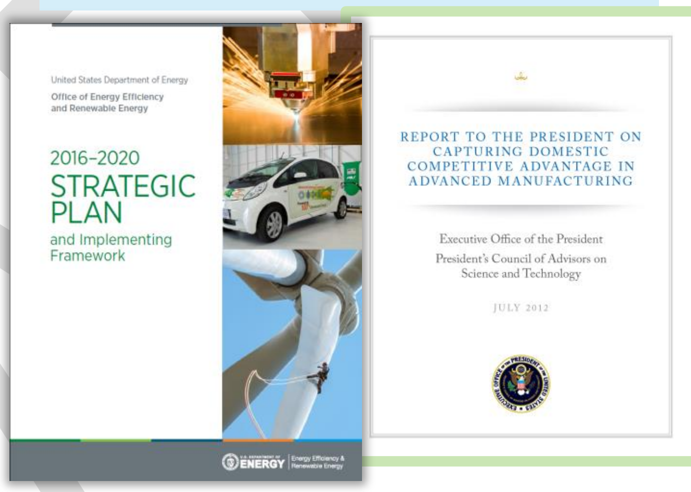
Key Strategic Inputs

- Energy Policy Act of 2005
- Energy Independence and Security Act of 2007
- DOE 2014-2018 Strategic Plan
- EERE 2016-2020 Strategic Plan
- 2015 Quadrennial Energy Review (QER)
- 2015 Quadrennial Technology Review (QTR)
- The Advanced Manufacturing Partnership (AMP)
- Advanced Manufacturing Partnership 2.0 (AMP2.0)

The Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 provide the most recent authorizations for AMO. An overview of this legislation's guidance on AMO is provided in the text box **"History and Major Legislative Authorities for Advanced Manufacturing in the DOE."**

The DOE 2014-2018 Strategic Plan states that DOE will support "prudent development, deployment, and efficient use of 'all of the above' energy resources that create new jobs and industries". Specifically related to AMO, the DOE Strategic Plan states,

"DOE will focus its investments in technologies and practices that can improve the competitiveness of U.S. manufacturing through increased energy productivity and increased manufacturing of clean energy products. Clean energy manufacturing institutes will provide a framework for innovation in advanced manufacturing of essential components and processes."[55]



In addition to the DOE Strategic Plan, the Office of Energy Efficiency and Renewable Energy (EERE) 2016-2020 Strategic Plan and Implementing Framework provides guidance regarding national leadership for the clean energy economy. AMO activities support two strategic goals within the EERE Strategic Plan:

- Improve the Energy Efficiency of Our Homes, Buildings, and Industries (#3).
- Stimulate the Growth of a Thriving Domestic Clean Energy Manufacturing Industry (#4).

AMO activities are aligned with the EERE Vision and Mission statements, shown in the text box at right.

EERE Vision:
A strong and prosperous America powered by clean, affordable, and secure energy

EERE Mission:
To create and sustain American leadership in the transition to a global clean energy economy

[55] *Strategic Plan 2014-2018.* U.S. Department of Energy. June 2014. Available online at: http://www.energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf.

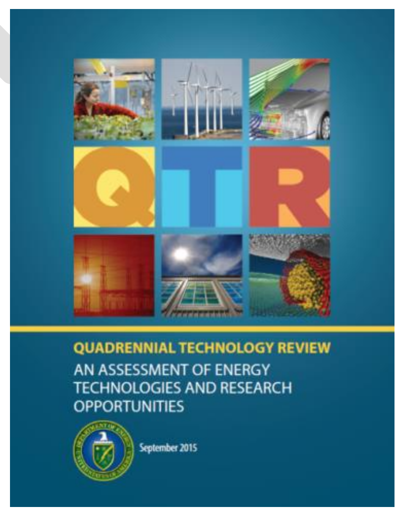
History and Major Legislative Authorities for Advanced Manufacturing in the DOE

AMO originated as the Industrial Energy Conservation Program in 1975, under the mandate of the Federal Nonnuclear Energy Research and Development Act of 1974. This Act directed that a comprehensive program be conducted to improve the efficiency of energy use in the industrial sector through RD&D of high-risk, innovative technologies. The program was incorporated into the DOE by the Department of Energy Organization Act of 1977 (P.L. 95-91), leading to the creation of the Office of Industrial Programs (OIP). Programs supported by OIP included both technology RD&D and technology assistance through university based partnerships.

After OIP's first major commercial success, catalytic distillation, the organization's experience in energy-efficiency RD&D continued to grow. As the international competitiveness of US industries was threatened in the 1980s, OIP's projects began to emphasize productivity, capital efficiency, and quality in addition to energy efficiency. Industrial waste reduction and pollution prevention also became critical elements of its RD&D portfolio, in order to support the continued competitiveness of industries adapting to comply with environmental regulations.

In 1990, OIP was reorganized into the Office of Industrial Technologies (OIT). Following enactment of the Energy Policy Act of 1992 (P.L. 102-486), OIT adopted a strategic approach of collaboration with energy intensive industries known as Industries of the Future to leverage investments for high priority, pre-competitive technologies along energy-intensive sector specific prioritization. In 2002, as part of a broader EERE reorganization, OIT was renamed the Industrial Technologies Program (ITP) and increased emphasis was placed on crosscutting technologies.

Both the Energy Policy Act of 2005 (P.L. 109-58) and the Energy Independence and Security Act of 2007 (P.L. 110-140) renewed the importance of federal support for RD&D related to manufacturing and industry, particularly relative to the importance of energy technology in maintaining a globally competitive U.S. manufacturing for clean energy products. In 2013, ITP was renamed the Advanced Manufacturing Office (AMO), expanding its focus to include platform technologies to enable diverse applications as well as cross-cutting technologies for the energy efficient and energy productive manufacturing of products for use throughout the U.S. economy.



AMO's decision-making is informed by a wide range of technical expertise and research. DOE authored two guiding publications: The Quadrennial Energy Review (2015 QER) and the Quadrennial Technology Review (2015 QTR). Released in April 2015, the first installment of the QER entitled "Energy Transmission, Storage, and Distribution Infrastructure" focused on the modernization of U.S. energy infrastructure. With an energy consumption of over 24 quads in 2014 alone, the manufacturing sector relies heavily on its ability to efficiently and effectively integrate with the energy infrastructure. In addition, the QER recommends "efforts to accelerate the development of high-quality energy and manufacturing curricula and apprenticeship programs."[56]

The 2015 QTR, released in September 2015, examined the most promising research, development, demonstration, and deployment opportunities across energy technologies to effectively address the nation's energy needs. In particular, chapter 6 of the 2015 QTR, *Innovating Clean Energy Technologies in Advanced Manufacturing*, focused specifically on energy-related innovations for advanced manufacturing, including the broader impacts of manufactured goods in the production, delivery and end-use of energy across the economy. This chapter examines the state-of-the-art and key energy opportunities in manufacturing. This chapter was supplemented by fourteen manufacturing-focused Technology Assessments on key topical areas. In addition, the 2015 QTR examines the key opportunities in other sectors of the energy economy (electric grid, electric power generation, fuels, transportation, and buildings), which are associated with their own manufacturing challenges. The 2015 QTR offers a valuable framework for identifying challenge areas and setting goals. Technical targets presented in section 3 are informed by the 2015 QTR framework.

The President's Council of Advisors on Science and Technology (PCAST), from the Obama Administration's Office of Science and Technology Policy, stated the importance of U.S. advanced manufacturing leadership in its June, 2011

[56] *Quadrennial Energy Review: First Installment: Transforming U.S. Energy Infrastructures in a Time of Rapid Change*. Available online at: http://energy.gov/epsa/downloads/quadrennial-energy-review-first-installment.

report *Ensuring Leadership in Advanced Manufacturing*. The report specified that a comparative advantage in manufacturing based upon cutting-edge technologies creates high-quality jobs, enables innovation by linking production and design, and benefits national security.[57] The Advanced Manufacturing Partnership (AMP), a plan to invest more than $500 million to jumpstart the process of revitalizing American manufacturing, was announced the same month. AMP engaged the DOE in "developing innovative energy-efficient manufacturing processes".[58]

The Advanced Manufacturing Partnership 2.0 (AMP2.0) Steering Committee was established in 2013 to build on AMP efforts.[59] AMP2.0 focuses on three pillars for investment: enabling innovation, securing the talent pipeline, and improving the business climate. AMO, through RD&D, technical assistance, and workforce development efforts, supports the pillars of innovation and securing the talent pipeline. In addition, based on recommendations by the AMP Steering Committee, AMP2.0 reaffirmed a commitment to expanding the National Network for Manufacturing Innovation (NNMI), now known as Manufacturing USA, through the establishment of institutes to bring together industry, academia, and national laboratories to develop transformative technologies.[60]

2.3.2 Strategic Elements

This section presents AMO's vision, mission, and goals which define the focus and direction of program activities. The Technology RD&D Plan, introduced here and presented in detail in section 3, describes how AMO intends to contribute to the achievement of the goals and the ways in which AMO intends to assess progress using AMO's success indicators.

Vision and Mission

AMO's vision and mission are provided below:

- **Vision**: U.S. global leadership in sustainable and efficient manufacturing for a growing and competitive economy.
- **Mission**: Catalyze research, development and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

Goals

The Office has identified four strategic performance goals in support of its mission:

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

Planning Areas

AMO's vision, mission, and goals guided the development of the MYPP Technology RD&D Plan, which is presented in section 3 of this MYPP. This plan charts a course to improve U.S. manufacturing energy efficiency and develop advanced manufacturing capabilities over the MYPP planning period and beyond. In selecting the RD&D areas in the

[57] Supra 43. *Report to the President on Ensuring American Leadership in Advanced Manufacturing.* PCAST. 2011.
[58] "President Obama Launches Advanced Manufacturing Partnership." Office of the President. The White House. Press Release. June 24, 2011. Available online at: https://www.whitehouse.gov/the-press-office/2011/06/24/president-obama-launches-advanced-manufacturing-partnership.
[59] "President Obama Launches Advanced Manufacturing Partnership Steering Committee '2.0'." Office of the President. The White House. September 26, 2013. Available online at: https://www.whitehouse.gov/the-press-office/2013/09/26/president-obama-launches-advanced-manufacturing-partnership-steering-com.
[60] Supra 32. *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing.* PCAST. 2012.

plan, AMO considered the potential energy and competitiveness impacts of AMO activities on the U.S. manufacturing sector and end-users of manufactured products across the economy. The opportunities identified in the DOE 2015 QTR were important determinants of AMO's priorities, especially the fourteen manufacturing-focused Technology Assessments on key topical areas presented in the supplement to the QTR. To support decision-making while developing this plan, AMO considered the important opportunities and challenges in each of the following:[61]

- Advanced manufacturing technologies and their impacts at unit operation and facility levels
- Lifecycle and supply chain impacts for advanced manufacturing, including environmental considerations
- Manufacturing technologies used in infrastructure across the energy economy
- Manufacturing challenges correlated to the energy economy, such as the water-energy-material nexus.

Figure 2.7 shows the scope of the technology RD&D areas covered in section 3. The RD&D areas are presented in three groups: Advanced Manufacturing Technology Areas; Emerging and Crosscutting Areas; and Advanced Manufacturing for Energy Systems. Figure 2.7 also shows the connections between the fourteen advanced manufacturing technology areas (which coincide with the 2015 QTR Technology Assessment topics), emerging and crosscutting areas, and energy systems with manufacturing challenges.

Success Indicators

The four success indicators are listed below. The success indicators can be used to show progress toward AMO's goals. Performance targets are provided for each of the technology RD&D areas presented in section 3. Each performance target supports one or more of the Office's success indicators and demonstrates progress compared to a 2015 baseline.

AMO's success indicators:

1. Demonstrate selected advanced manufacturing technologies and deploy practices that increase the rate of energy intensity[62] improvement from business as usual (~1 % per year) to 2.5% per year.
2. Develop advanced materials, manufacturing technologies, and end use products with the potential to reduce lifecycle energy impact by 50% by 2025 compared to the 2015 state-of-the-art.
3. Establish partnerships resulting in 30,000 U.S. manufacturing facilities implementing AMO-recognized energy management products, practices and measures by 2025.[63]
4. Double supported technical education and training activities in advanced manufacturing made available for universities, community colleges, and high schools by 2025.

Figure 2.8 shows how AMO's vision, mission, and strategic goals support the DOE EERE Strategic Plan goals. AMO pursues its Office goals through the three subprograms.

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[61] AMO analysis activities are described in more detail in section 2.3.3 of this MYPP. For example, AMO has developed methodologies and tools to assess impacts across all levels of manufacturing system integration (unit operation, facility, and supply chain).

[62] Energy intensity is energy consumed per unit of physical output.

[63] Supra 17. "Manufacturing Summary Series." 2012 Economic Census of the United States. The figure 30,000 is 25% of the 2012 U.S. Census estimate of manufacturing facilities with 10 or more employees.

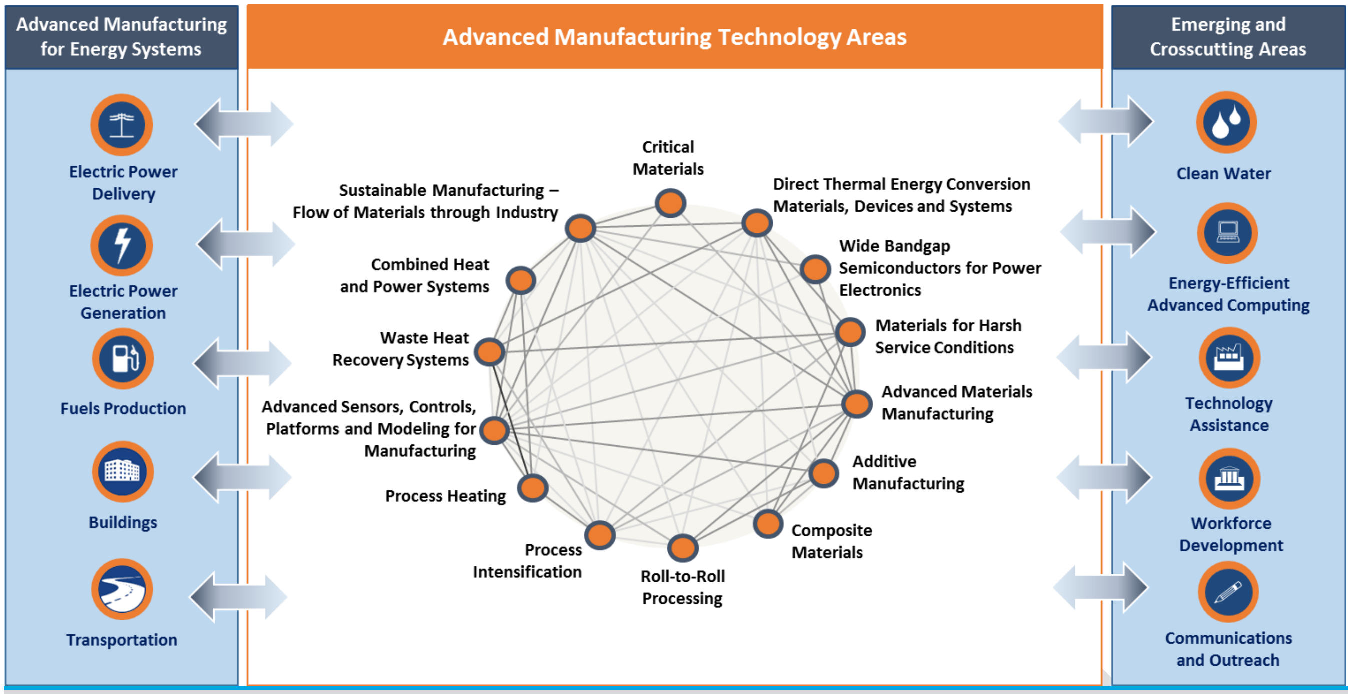

Figure 2.7 Diagram Showing Connections between the Fourteen Advanced Manufacturing Technology Areas (which coincide with the 2015 QTR Manufacturing Technology Assessment Topics), Energy Systems Influenced by Manufacturing, and Emerging and Crosscutting Areas.

EERE Strategic Plan Goals

- Improve the Energy Efficiency of Our Homes, Buildings, and Industries (#3)
- Stimulate the Growth of a Thriving Domestic Clean Energy Manufacturing Industry (#4)

AMO Vision and Mission

Vision: U.S. global leadership in sustainable and efficient manufacturing for a growing and competitive economy.

Mission: Catalyze research, development and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity.

AMO Strategic Goals

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

AMO Subprograms

R&D Consortia	R&D Projects	Technical Assistance

AMO Success Indicators

- Demonstrate selected advanced manufacturing technologies and deploy practices that increase the rate of energy intensity improvement from business as usual (~1% per year) to 2.5% per year.
- Develop advanced materials, manufacturing technologies, and end use products with the potential to reduce lifecycle energy impact by 50% by 2025 compared to the 2015 state-of-the-art.
- Establish partnerships resulting in 30,000 U.S. manufacturing facilities implementing AMO-recognized energy management products, practices and measures by 2025.
- Double supported technical education and training activities in advanced manufacturing made available for universities, community colleges, and high schools by 2025.

Figure 2.8 Strategic Framework of the Advanced Manufacturing Office

2.3.3 Strategic Analysis of Opportunities

AMO conducts rigorous analyses to support its decision-making and activities. These range from benchmarking studies to assessments of technology opportunities and their potential impacts. The results of AMO analysis are used to focus its research and technical assistance activities, and to inform the development of metrics and funding opportunity announcements.

AMO undertakes an integrated and coordinated approach to strategic analysis; efforts can be generally grouped into three main areas according to the analysis approach:

- **Advanced Manufacturing Technology Analysis:** the targeted analysis of manufacturing and industrial technologies to assess their energy impacts and identify energy saving opportunities at the unit operations and at the plant/facility levels.
- **Resource Efficiency & Supply Chain/Value Chain Analysis:** broad systems analyses such as lifecycle energy analyses of advanced manufacturing technologies and products to assess net impacts, including beyond the plant boundary. This also includes detailed techno-economic cost modeling of the manufacture of clean energy products, regional cost drivers, and factors impacting the supply chain/value chain. In addition, AMO conducts complex systems analyses that extend beyond traditional energy and environmental impact assessments to explore the flows of important non-energy resources in manufacturing. Specific analyses are currently focused on the water-energy-materials nexus.
- **Cross-Cutting Analysis:** benchmarking studies, sector-wide and cross-sectoral technology opportunity analyses, and the development of multi-use analysis methodologies and tools. AMO analysis tools are designed to track energy and material flows, examine manufacturing technology impacts on energy consumption and GHG emissions, and quantify opportunities.

The Role of Strategic Analysis

Objective: Provide independent, objective, and credible information to inform decision-making.

Planning and Focus

- Benchmark and analyze energy use
- Develop metrics
- Examine trends
- Identify opportunities

Execution

- Evaluate portfolio
- Inform selection of new initiatives

Results

- Determine energy savings and other impacts

A thorough analysis of some manufacturing technologies and their impacts on the industrial ecosystem may require concurrent analyses using several approaches. Representative AMO analysis activities are highlighted below. Analysis efforts are generally led by AMO technology managers who are subject matter experts in their technology area. Detailed reviews of AMO analysis efforts are available in presentations given at the 2016 AMO Peer Review meeting[64] and in reports on the AMO website's Energy Analysis webpage.[65]

Advanced Manufacturing Technology Analysis

Technology Assessments and Opportunity Analyses

AMO conducts analyses to evaluate the status, challenges, and opportunities for targeted manufacturing technologies. For example, AMO recently collaborated with the U.S. national laboratories to develop fourteen manufacturing-focused technology assessments for the 2015 QTR, as described in sections 2 and 3. These technology assessments included evaluations of current state-of-the-art performance for selected technologies and quantified the total estimated energy savings opportunities, supported by detailed calculations and results from the technical literature. Additional examples of AMO technology assessment activities include an energy opportunities analysis for electrotechnologies used in process heating; an examination of current performance and future trends in additive manufacturing based on a review of hundreds of machines and materials; and an analysis of efficiency opportunities and gaps for smart

[64] Three peer review presentations listed as Analysis Review are available on the AMO Peer Review, June 14-15, 2016 webpage at: http://energy.gov/eere/amo/downloads/amo-peer-review-june-14-15-2016.

[65] "Energy Analysis by Sector," AMO/EERE/U.S. DOE website. Available at: http://energy.gov/eere/amo/energy-analysis-sector.

manufacturing technologies. Technology assessments are essential for focusing funding and activities towards the most promising new technologies and practices. For example, data gathered in technology assessments are used to answer the EERE Core Questions (shown in the text box at right) to assess the merit of a proposed new activity prior to funding.

AMO conducts analysis to understand the market opportunities for emerging and state-of-the-art crosscutting technologies with significant energy savings potential in broad segments of manufacturing. For example, the U.S. *Waste Heat to Power Market Assessment* in March 2015 provided a comprehensive look at the industrial sources of high temperature and lower temperature waste heat across a wide variety of industrial sectors and processes, and highlights the immediate opportunity to provide substantial economic and environmental benefits.[66] In addition, the March 2016 study *Combined Heat and Power (CHP) Technical Potential in the United States* is a market analysis of opportunities in industrial facilities and commercial buildings for "topping cycle" CHP, waste heat to power CHP (WHP CHP), and district energy CHP. Data provided by CHP system size range, facility type, and state is in sufficient detail for stakeholders nationwide to consider CHP in strategic energy planning and energy efficiency program design.[67]

The 5 EERE Core Questions

1. **High Impact:** Is this a high impact problem?
2. **Additionality:** Will EERE funding make a large difference relative to what the private sector (or other funding entities) is already doing?
3. **Openness:** Have we made sure to focus on the broad problem we are trying to solve and be open to new ideas, new approaches, and new performers?
4. **Enduring U.S. Economic Benefit:** How will this EERE funding result in enduring economic benefit to the United States?
5. **Proper Role of Government:** Why is what we are doing a proper high-impact role of government versus something best left to the private sector to address on its own?

Resource Efficiency & Supply Chain / Value Chain Analysis

Lifecycle Energy Analyses

Traditional energy analysis methods tend to evaluate technologies narrowly, assessing impacts of a new product, material, and process only at the plant level (or on an industry sub-sector basis). Lifecycle energy (and energy-associated GHG emissions) analysis provides a more comprehensive assessment of the energy impacts by considering energy and resource use from all phases of a product's lifecycle (i.e., extraction of raw materials through end-of-life). AMO has been developing and utilizing consequential (i.e., prospective) lifecycle energy analysis techniques to holistically evaluate the net impacts of technologies such as additive manufacturing and wide bandgap semiconductors, which have far-reaching energy impacts beyond the manufacturing phase. Recent examples include an evaluation of materials and energy use associated with consumer electronics, and an analysis of the effects of carbon fiber recycling and precursor choice on the lifecycle energy impacts of carbon fiber composites in light-duty vehicles.

Techno-economic, Supply Chain / Value Chain, and Manufacturing Competitiveness Analyses

Advanced manufacturing technologies that save energy or other resources often must overcome substantial market hurdles before they are commercially adopted – particularly if the technology is associated with major capital investments, cost burden-shifting, or unclear value propositions for industry. Techno-economic, competitiveness, and supply chain analyses can help stakeholders understand these costs, barriers, and opportunities. For example, AMO funds analyses to examine critical factors driving manufacturer's strategic decisions, such as where to locate manufacturing plants. This type of analysis illuminates why certain countries or regions lead in production of specific technologies, and how or if these circumstances can be replicated elsewhere. Analyses can include global supply chain assessment and benchmarking, comparative cost analysis, analysis of the impact of qualitative factors, and sensitivity analysis. Specific examples of AMO-supported projects in this area include:

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[66] A. Elson, R. Tidball, and A. Hampson. *Waste Heat to Power Market Assessment*. Prepared by ICF International for Oak Ridge National Laboratory. March 2015. Available online at: http://info.ornl.gov/sites/publications/Files/Pub52953.pdf.

[67] *Combined Heat and Power (CHP) Technical Potential in the United States*. U.S. DOE. Report DOE/EE-1328. March 2016. Available online at: http://www.energy.gov/sites/prod/files/2016/04/f30/CHP%20Technical%20Potential%20Study%203-31-2016%20Final.pdf.

- An examination of the challenges for deployment of additive manufacturing technologies in different manufacturing sectors.
- Development of a U.S recycling cost model for rare earth elements to explore the economic viability of recycling these materials.
- An analysis of the carbon fiber composites value chain, including the impacts of manufacturing location and precursor type on carbon fiber competitiveness.
- A cost analysis of silicon-carbide-based medium voltage industrial motor drives and an exploration of new potential markets for wide bandgap devices through a supply chain analysis.

Some AMO analysis activities are conducted by or in collaboration with the Clean Energy Manufacturing Analysis Center (CEMAC),[68] which AMO helped to establish. CEMAC provides objective analysis and up-to-date data on global clean energy manufacturing. Analyses evaluate where key technologies are made, where they are used, and offer insights as to why markets are as they are. Using detailed bottom-up cost analysis, CEMAC examines the dynamics and health of the entire supply chains for clean energy technologies, and from that, gains insights to help policymakers, industry, and investors better understand the global market for clean energy technologies.

Water-Energy-Materials Nexus Analyses

With wide-reaching impacts on global ecology and national security, water efficiency has emerged as an increasingly important metric for environmentally responsible manufacturing. Further, because water and energy systems are tightly linked, reductions in water use can often reduce energy use (and vice versa). DOE's 2014 water-energy nexus report[69] identified water treatment technologies (desalination and wastewater treatment) as a cross-cutting focus area for DOE. The desalination bandwidth study underway now (see "Energy Bandwidth Studies" earlier in this section) will be a valuable benchmarking reference for technologies and opportunities in this area. Specific water- and energy-intensive manufacturing industries identified in the water-energy nexus report include forest products, food and beverage, chemicals, and petroleum refining. These and other manufacturing industries could benefit from enhanced water management strategies and technologies.

AMO's water-related analysis activities include a large-scale water data mining effort, which will identify gaps in data availability and quality at the state, county, and facility levels; a study focused on cataloguing and analyzing industrial water use in the Great Lakes region; and an ongoing study examining water re-use, water criticality in manufacturing, and barriers to greater adoption of water meters at manufacturing facilities.

[68] Clean Energy Manufacturing Analysis Center (CEMAC) website at: http://www.manufacturingcleanenergy.org/.

[69] *The Water-Energy Nexus: Challenges and Opportunities*. Water-Energy Tech Team. U.S. DOE. July 2014. Full report available from: http://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities.

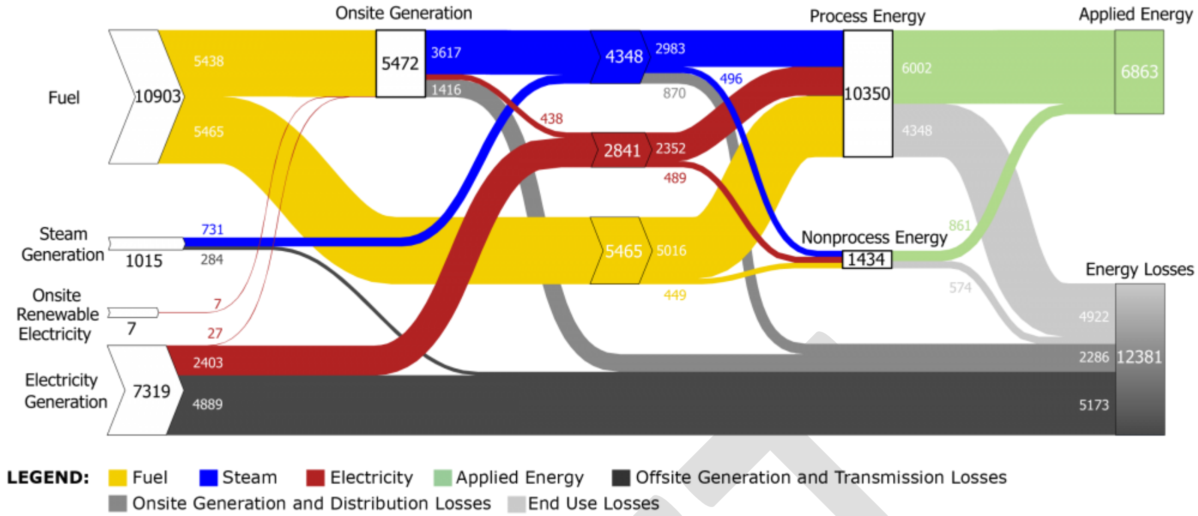

Figure 2.9 Sankey Diagram of Primary Energy Flow in the U.S. Manufacturing Sector in 2010 (TBtu; Feedstock Energy Excluded).[70]

Crosscutting Analysis

Footprint Studies

Identifying the sources and end uses of energy helps to pinpoint the areas of highest energy intensity, and characterize the unique energy needs of individual industries. An example of an analytical tool that helps AMO to benchmark and assess manufacturing energy use is the "Energy Footprint" analysis. Energy Footprints map the flow of energy within individual U.S. manufacturing industries and for manufacturing overall. The most recent Energy Footprints are based on data from the 2010 EIA Manufacturing Energy Consumption Survey (MECS), the most recent data available.[71] A high-level Energy Footprint for all manufacturing in the form of a Sankey diagram is shown in Figure 2.9; similar diagrams are available for 16 individual manufacturing subsectors.

On the supply side, Energy Footprints provide details on the energy purchased from utilities (electricity and fossil fuels), energy generated onsite, and excess energy transferred to the local grid. On the demand side, the Footprints illustrate where and how energy is used within a typical plant, from central boilers to motors. Most importantly, the Footprints identify where energy is lost due to inefficiencies, both inside and outside the plant boundary. Considerable energy is lost, for example, in steam and power generation systems, as well as in the pipe and transmission lines that carry energy to final use equipment. MECS data span entire industries, and thus represent average energy use and average process efficiencies. Actual energy patterns in individual plants vary according to site.

Energy Bandwidth Studies

Energy bandwidth studies provide an effective tool to gather and analyze energy data in a specific manufacturing area, including the current typical energy use, the potential for improvement if state-of-the-art technologies were deployed, and the potential for future energy savings if next-generation technologies under development were realized. The difference between these ranges are termed "energy bandwidths," and results can be visually compared to determine, at a glance, which manufacturing industries, processes, and sub-processes are the most energy intensive and which offer the greatest savings opportunities from technology advancements. Data can also feed into other analytical studies to understand the contribution of the manufacturing phase of the product to the net lifecycle energy impacts of end-use products. Determination or estimation of the total energy used in a manufacturing process, or a profile of energy consumed in the various steps in the manufacturing process, provide useful information. However, knowing the actual

[70] Supra 8. MECS 2010 data. MECS website. EIA. Available online at: http://www.eia.gov/consumption/manufacturing/index.php.
[71] Ibid

amount of energy consumed is not the same as knowing the amount of energy that could ultimately be reduced at any step of the process. Estimating the amount of energy that could be reduced by a combination of technologies, best practices, or other operational changes, is the type of information needed to inform planning.

Bandwidth analyses have been recently completed for the four industries depicted in Figure 2.10. This U.S. energy bandwidth study shows energy savings potential for chemicals, petroleum refining, pulp and paper, and iron and steel. The current opportunity bands represent energy savings that could be achieved by deploying the most energy-efficient commercial technologies available worldwide. The R&D opportunity bands represent the potential savings that could be attained through successful deployment of applied R&D technologies under development worldwide. In addition to this study, draft bandwidth reports were recently completed to analyze manufacturing energy use for a series of lightweight materials, including carbon fiber reinforced polymer composites, glass fiber reinforced polymer composites, aluminum, advanced high-strength steel (AHSS), magnesium, and titanium.[72] These bandwidth reports are currently being peer reviewed. New analyses are underway to develop bandwidth studies for manufacturing of food and beverage, cement, glass, plastics and rubber products, and for water desalination.

Analysis Methodology and Tools Development

AMO develops and maintains a portfolio of quantitative analysis tools, many of which were developed in collaboration with researchers at DOE national laboratories, Manufacturing Demonstration Facilities (MDFs), and other external stakeholders. Examples of AMO tools in use or under development include:

- *LIGHTEn-UP tool:* a tool that can be used to explore the cross-sectoral energy and greenhouse gas emissions impacts of implementing next-generation technologies, utilizing a lifecycle approach.
- *MFI tool:* a tool that can be used to examine how materials move through industrial supply chains and to explore the effects of advanced technologies on energy, carbon, and resource use.
- *Additive Manufacturing Energy Impacts Tool:* a calculator that provides a consistent methodology to assess and compare the life-cycle energy impacts of a component produced via conventional and additive manufacturing techniques.
- *Market Penetration Calculator:* a tool for systematically projecting future market penetration of manufacturing technologies for prospective life-cycle analyses.
- *Plant Water Profiler:* a user-friendly platform that manufacturers can use to understand and track their water use and to identify savings opportunities.
- *Carbon Fiber Reinforced Polymer Energy Estimator:* a tool that manufacturers can use to evaluate the embodied energy of a carbon fiber reinforced polymer product, based on their customized manufacturing pathway and process steps.
- *Guide to Energy Management and QEST Tools:* These tools provide guidance on how to put an energy management system (EnMS) in place that is compliant with the ISO 500001 International Energy Management Standard. The tools include a regression-based methodology to calculate and report energy savings that supports the overall EnMS.
- *Energy System Optimization Tools.* This suite of software assists plant and facility personnel in understanding the major energy using systems within their facilities and provides outputs that support efforts to optimize energy use. These major system area tools cover compressed air, motor, pump and fan systems on the electrical side and steam and process heating systems on the thermal side.

[72] Bandwidth reports are available from "Energy Analysis by Sector" website at: http://energy.gov/eere/amo/energy-analysis-sector.

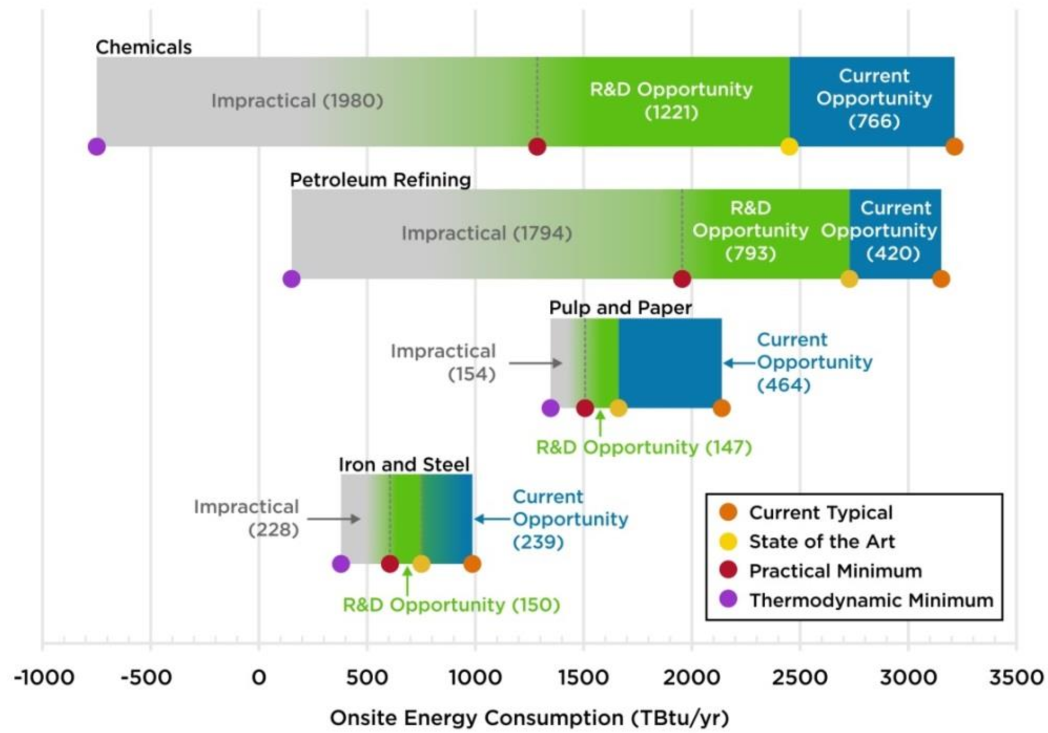

Figure 2.10 U.S. Energy Bandwidth Study Results Show Energy Savings Potential for Four Manufacturing Industries: Chemicals, Petroleum Refining, Pulp and Paper, and Iron and Steel.

2.3.4 Selection and Evaluation

Within AMO subprogram areas, funded projects and awards are selected through an open and competitive proposal process and after a thorough technical merit-based review of all submissions by technology experts from industry, academia and government. To assess progress, the Office's evaluation activities include performance monitoring, as well as program and project evaluation. These activities provide the means to measure relevant outputs and outcomes that aid the Office in evaluating its decisions, goals, and approaches; and to track the actual progress being made. By design, the assessment processes provide input from other government agencies, stakeholders, and independent experts on effectiveness and progress towards Office mission and goals.

Application and Selection Process

AMO provides financial and other support to stimulate the applied research, development and deployment of advanced manufacturing technologies. Funding Opportunity Announcements (FOAs) are used to solicit applications in specific program areas, and projects and awards are selected based on an objective technical merit review process. The competitive application process may include multiple phases such as a concept paper submission prior to development of a full application, and a process to reply to reviewer comments before final selections. AMO performs multiple levels of review of submitted applications, including initial eligibility and thorough technical reviews. This fair, open and merit-based process is used to select the best public sector investments and comply with EPAct 2005 requirements. Specific evaluation criteria are used to rate each proposal. The merit-based selection criteria may emphasize the scientific and technical merit of the approach, potential energy and economic impacts, quality of the work plan, capabilities and resources of the applicant team, and other criteria specific to the FOA. Rigorous technical reviews of eligible submissions are conducted by reviewers that are experts in the subject matter of the FOA. These reviews may include obtaining input and expertise from individuals within DOE or from industry and academia. Using the input from the technical experts, the DOE Technology Manager formulates a selection recommendation. The Selection Official considers the recommendation, along with other considerations such as program policy factors and funds available, in determining which applications to select. The outcome after successful award negotiations is usually a grant or cooperative agreement.

Peer Reviews

AMO uses an external peer review process to assess the performance of activities, as well as of the Office as a whole. The Office implements the peer review process through a combination of technology area peer reviews, individual consortia peer reviews, and an overall Office peer review. Guidance for performing peer review activities is provided by the EERE Peer Review Guide.

The emphasis of the Office peer review is on the portfolio as a whole to determine whether or not it is balanced, organized, strategically focused, impactful and performing appropriately. In contrast, the emphasis of the technology area reviews is on the activities that comprise the respective portfolios and whether or not those activities are performing appropriately and contributing to technology area goals.

The program peer reviews evaluate the contributions of each activity toward the overall Office goals, as well as the management and effectiveness of the Office. The review is led by an independent committee that selects independent experts to review the Office and its portfolio of activities. The results of the review provide feedback on the performance of the Office and its portfolio, identifying opportunities for improved Office management, as well as gaps or imbalances that need to be addressed. By addressing this feedback, the Office will continue to stay focused on the highest priorities.

The technology area peer reviews are conducted with the following objectives:

- Review and evaluate RD&D accomplishments and future plans of projects in each portfolio; follow the process guidelines of the EERE Peer Review Guide; and incorporate the project evaluation criteria used in the Office Stage-Gate Management Process.
- Provide an opportunity for participants to learn about and provide feedback on the projects in that portfolio; use this feedback to help shape future efforts so that the highest priority work is identified and addressed.
- Foster interactions among industry, universities, and national laboratories conducting the RD&D, thereby facilitating technology transfer.

Technical experts from industry, academia, and government are selected as reviewers based on their experience in various aspects of advanced manufacturing technologies under review. The reviewers score and provide qualitative comments on RD&D based on the presentations given at the meeting and the background information provided. The reviewers are asked to identify specific strengths and weaknesses.

The Office analyzes all of the information gathered at Office review meetings and develops appropriate responses to the findings. This information is documented and published in a review report that is made available to the public through the Office website.

Project Management and Evaluation

RD&D projects are continuously managed through the EERE Active Project Management program. The Office regularly conducts internal project-level technical reviews, and projects are assessed quarterly. RD&D projects are subject to the Office Stage-Gate Management Process and annual comprehensive project reviews. Guidance, training, and tools in project management are provided to Office staff by the EERE Project Management Coordination Office.

Technology Tracking

AMO has assessed the progress of the technologies supported by its research programs for more than 30 years. AMO managers have long recognized the importance of developing accurate data on the impacts of the programs. Such data are essential for assessing AMO's past performance and can help guide the direction of future research activities.

Energy savings associated with specific technologies are estimated by Pacific Northwest National Laboratory (PNNL) through data tracking and management. When a technology's full-scale commercial unit is operational in a commercial setting, the technology is considered commercially successful and is placed on the active tracking list. When a commercially successful technology unit has been in operation for about ten years, the unit is considered a mature technology and typically is no longer actively tracked. The active tracking process involves collecting technical and market data on each commercially successful technology, including details on the following:

- Number of units sold, installed, and operating in the United States and abroad (including size and location);
- Units decommissioned since the previous year;
- Energy saved;
- Environmental benefits;
- Improvements in quality and productivity achieved;
- Any other impacts, such as employment and effects on health and safety; and
- Marketing issues and barriers.

Information on technologies is gathered through direct contact with either the technology's vendors or end users. These contacts provide the data needed to calculate the technology's unit energy savings, as well as the number of operating units. Therefore, unit energy savings are calculated in a unique way for each technology. Technology manufacturers or end users usually provide unit energy savings or at least enough data for a typical unit energy savings to be calculated. The total number of operating units is equal to the number of units installed minus the number of units decommissioned or classified as mature in a given year. This information is usually determined from sales data or end-user input. Operating units and unit energy savings can then be used to calculate total annual energy savings for the technology.

The cumulative energy savings measure includes the accumulated energy saved for all units actively tracked. These energy savings include the earlier savings from now mature and decommissioned units. Once cumulative energy savings have been determined, long-term impacts on the environment are calculated by estimating the associated reduction of air pollutants. This calculation is based on the type of fuel saved and the pollutants typically associated with combustion of that fuel and uses assumed average emission factors.

Program benefits documented by PNNL are conservative estimates based on technology users' and developers' testimonies. These estimates do not include derivative effects resulting from new technologies that spin off of AMO technologies or the secondary benefits of the energy and cost savings accrued in industries and applications downstream of the new technologies. Therefore, actual benefits are likely to be higher than the numbers reported here. The benefits-tracking process provides a wealth of information on the program's successes.

Technology Assistance Evaluation

End user technical assistance activities are evaluated periodically to determine how the programs are meeting established objectives. Examples of these evaluations include the following:

- The Industrial Assessment Center (IAC) Impacts Study evaluated the impact of activities at small- and medium-sized manufacturers that receive energy audits to identify opportunities to improve productivity, reduce waste, and save energy. Each year, about 300 engineering students at university-based IACs receive hands-on training while paired with faculty to deliver audits. The study conducted by SRI International calculated the energy saved by manufacturers from implemented IAC recommendations; calculated the effect of sales and employment of program participation; measured the impacts on IAC alumni skills; and measured the impacts on the energy efficiency workforce.[73]
- The Better Buildings, Better Plants Progress Update is an annual assessment of program activities. Since 2009, DOE has partnered with manufacturers and water utilities to seek out and capture these energy efficiency opportunities. Partners set a specific goal, typically to reduce energy intensity by 25% within 10 years across their U.S. operations. DOE provides all Better Plants partners with technical assistance to achieve their goals and national recognition for their leadership. The metrics include number of partner facilities; cumulative energy savings and cost savings among a growing number of partner companies; average annual energy-intensity improvement rate; and percent of U.S. manufacturing energy footprint impacted.[74]

[73] Supra 51. *Saving Energy, Building Skills: Industrial Assessment Centers Impact.* SRI International. 2015.
[74] "Better Plants Progress Update, Fall 2016. Better Plants, U.S. DOE. Available online at: https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/2016%20Better%20Plants%20Progress%20Update.pdf.

Program Plan Updates

Technological and societal changes are continuous, and they have both direct and indirect impacts on the manufacturing sector. MYPPs are living documents and are anticipated to be updated on a regular basis. Results from Office portfolio peer reviews, merit reviews and other types of evaluations also inform the MYPP process, helping to determine whether investments are working according to plan or are in need of improvements, and whether they are leading to impactful energy, economic, environmental, and energy security benefits.

The level of revision to this MYPP in the future may depend on the rate of technology advancements and market changes, revisions to Departmental goals, progress toward goals, and other factors that affect the landscape in which the Office operates. Thanks to AMO's active and forward-looking analytical and evaluation efforts, AMO will be well-positioned to make adjustments to its plans and activities in order to maximize effectiveness in the evolving manufacturing landscape.

3.0 Technology Research, Development and Demonstration Plan

The technology RD&D plan addresses the key energy opportunities in the manufacturing sector to realize AMO's goals. The technology RD&D areas, along with the primary objective of each, are shown in Table 3.1 This section of the Multi-Year Program Plan (MYPP) provides specific plans for each RD&D area. The RD&D areas are presented in the three groups introduced below. AMO focuses on technical areas that directly align with the 2015 QTR. The connections between the advanced manufacturing technology areas (which coincide with the 2015 QTR), emerging and crosscutting areas, and energy systems are shown in section 2, in Figure 2.7.

> **Section 3.1 Advanced Manufacturing Technology Areas:** This section covers fourteen technology areas: critical materials; direct thermal energy conversion; wide bandgap semiconductors for power electronics; materials for harsh service conditions; advanced materials manufacturing; additive manufacturing; composite materials; roll-to-roll processing; process intensification; process heating; advanced sensors, controls, platforms, and modeling for manufacturing; waste heat recovery; combined heat and power; and sustainable manufacturing. These areas are listed in the order shown in Figure 2.7 (clockwise from the top).
>
> The fourteen manufacturing technologies were identified as DOE focus areas during the 2015 QTR development process because of their high potential to improve energy utilization in the United States and the potential of AMO efforts to accelerate technology advancement and adoption. The energy benefits come from efficiency increases in manufacturing processes and unit operations; new materials and process technologies; the optimization of manufacturing supply chains through material substitution and distributed production, for example; and the use of advanced manufacturing processes to produce clean energy products, including energy impacts from all phases of the product's lifecycle.
>
> **Section 3.2 Emerging and Crosscutting Areas:** This section includes two emerging science and energy technology areas as well as three crosscutting manufacturing areas. The two emerging science and energy technology areas – clean water technologies and energy efficient advanced computing – impact all sectors of the energy economy, including manufacturing. The three crosscutting manufacturing focus areas are: industrial end-user technical assistance, workforce development, and communications and outreach.
>
> **Section 3.3 Advanced Manufacturing for Energy Systems:** Manufacturing is strongly linked to other sectors of the energy economy, as identified in the 2015 QTR. This section describes how AMO's work supports and intersects with DOE activities in the five other sectors of the energy economy: electric power delivery, electric power generation, fuel production, buildings, and transportation. The 2015 QTR includes chapters that cover the specific manufacturing challenges of these sectors. The energy benefits come from the adoption of the new technology and products enabled by manufacturing advancements; new materials; and cost-effective production of emerging energy technologies, relative to existing approaches available in the market.

For each RD&D area in section 3.1, 3.2, and 3.3, the following are provided: an overview of the technical area, the manufacturing objective, challenges and barriers, targeted impacts, and AMO approach. All of the RD&D areas in sections 3.1 and 3.2 have unique, AMO-specific performance targets. Examples of current and planned activities are included to show the breadth of projects and technical assistance activities. The technical targets tables in section 3.3 indicate which of the AMO-specific performance targets included in sections 3.1 and 3.2 support DOE's activities in the other energy sectors.

Each performance target in a table supports one or more of AMO's success indicators. The four success indicators (initially presented in section 2.3.2) are listed in Table 3.2 along with the two-letter abbreviation symbol used in the tables appearing throughout this section. The success indicators can be used to show progress toward the AMO goals (see section 2.3.2). Each target demonstrates progress compared to the 2015 baseline. The current status (2016) is determined by comparing the 2015 baseline and progress to date. Because of the technical difficulty of overcoming the challenges and barriers, targets may have end dates that extend beyond the MYPP planning period.

The technical targets tables also indicate if there are any current AMO activities under way for each target. The options listed in the key of these tables refer to an activity area in an AMO subprogram (discussed in Section 2.3). The table key lists these options: 'CST = Funded Institute or Hub,' which indicates activities that are part of the Advanced Manufacturing R&D Consortia subprogram; 'R&D = Funded R&D Project,' which indicates activities that are part of the Advanced Manufacturing R&D Projects subprogram; and 'PRA = Practices,' which indicates activities that are part of the Industrial Technical Assistance subprogram. 'SBIR = Funded SBIR Project,' which is also listed as an option, refers to projects AMO manages that are funded through the DOE-wide Small Business Innovation Research (SBIR) Program.

Table 3.1 AMO RD&D Areas and Objectives

RD&D Area	Objective
Advanced Manufacturing Technology Areas	
Critical Materials	Advance technology solutions that enable the increased and consistent availability of materials essential to clean energy applications by diversifying the supply, developing cost effective substitutes, and improving reuse and recycling of critical and near-critical materials.
Direct Thermal Energy Conversion Materials, Devices, and Systems	Advance technologies that improve materials, devices, and systems that directly convert energy from one form to another (e.g., waste heat to electricity), in order to realize lifecycle energy efficiency benefits on an economically effective basis.
Wide Bandgap Semiconductors for Power Electronics	Advance economically viable wide bandgap semiconductor materials and devices, technologies and applications that result in improvements in energy efficiency, enable cost-efficient integration of power systems and accelerate the adoption of clean energy technologies.
Materials for Harsh Service Conditions	Advance technologies that increase the durability and reduce the cost of materials and components operating in harsh and extreme environments (e.g., high temperature, corrosive, hydrogen, and radiation) to enable technologies that lower energy use and greenhouse gas emissions.
Advanced Materials Manufacturing	Advance technologies that accelerate the research, development, and demonstration of new materials, on a path towards integration of these materials into applications for cost effective, advanced clean energy technologies.
Additive Manufacturing	Advance additive manufacturing technologies that (1) increase the reliability at which parts can be produced at specifications required by industry, (2) increase the range of high-performing materials and processes, and (3) advance characterization and modeling techniques for qualification and certification of parts, in order to reduce lifecycle energy use and costs and enable more innovative products compared to conventional manufacturing methods.
Composite Materials	Advance composite material production technologies that (1) reduce embodied energy and greenhouse gas (GHG) emissions and (2) reduce cost of composites to be competitive with current materials and manufacturing methods, to enable widespread use of composite materials in clean energy applications.
Roll-to-Roll Processing	Advance technologies to reduce cost, increase precision, and enable in-line quality control and defect detection, resulting in expanded use of roll-to-roll processing to produce clean energy technologies.
Process Intensification	Advance technologies that significantly improve industrial process productivity and energy efficiency through optimized molecular level kinetics, thermodynamics, and heat and mass transfer.
Process Heating	Advance cost effective technologies for process heating that improve the properties of manufactured products, and develop alternative, low thermal budget technologies that reduce the energy requirements of materials processing.
Smart Manufacturing: Advanced Sensors, Controls, Platforms, and Models for Manufacturing	Advance the development of sensors, controls, platforms and modeling technologies that are interoperable, secure, and able to function under the harsh conditions specific to certain manufacturing facilities, while also making these systems less expensive to deploy than incumbent technologies, in order to aggressively reduce the energy intensity of complex processes through data-driven prediction, control, optimization, and artificial intelligence.
Waste Heat Recovery Systems	Advance technologies for waste heat recovery systems that enable the cost-effective capture and use of energy from industrial waste heat in order to reduce overall energy demands of manufacturing facilities.

RD&D Area	Objective
Combined Heat and Power Systems	Advance technologies and develop deployment strategies that accelerate the adoption of combined heat and power through streamlined installation processes; operating improvements; increased flexibility of fuel use; and reduced cost, greenhouse gas emissions, and perceived customer risk.
Sustainable Manufacturing	Advance technologies and tools to improve resource efficiency in the manufacturing industries, including recycling and reuse, and lower the lifecycle cost and cross-sectoral energy impacts of manufactured products.
Emerging and Crosscutting Areas	
Clean Water Technologies	Advance technologies to improve the processing and production of water from a variety of water sources – surface, ground, brackish, sea, produced (such as those from oil and gas extraction) and highly saline extracted (resulting from CO_2 injection) – at the same economic, energy, and environmental impact as currently supplied water.
Energy Efficient Advanced Computing	Advance energy-efficient, cost-effective, and reproducible materials and manufacturing technologies to extend computational power beyond Moore's Law.
Industrial End-User Technical Assistance	Provide technical assistance to industrial energy users to optimize energy use, reduce emissions, establish energy management systems, and increase productivity.
Workforce Development	Provide educational resources for primary, high school, community college, and university students as well as mentoring and on-the-job training opportunities in order to increase the number of qualified technical employees in advanced manufacturing at all levels.
Communications and Outreach	Provide information on energy technology resources and solutions for manufacturing, build networks of technical experts, and generate awareness of AMO and its activities.
Advanced Manufacturing for Energy Systems	
Advanced Manufacturing to Enable Modernization of Electric Power Systems	Advance manufacturing technologies and innovative materials to support grid modernization efforts, including the successful integration of conventional and renewable energy resources, storage, and energy efficient central and distributed power generation in a safe, reliable, and cost-effective manner.
Advanced Manufacturing for Clean Electric Power Generation	Advance technologies to improve the cost and performance of electric power technologies through development of advanced capabilities in materials and manufacturing.
Advanced Materials and Manufacturing Processes for Clean Fuels	Advance technologies that improve materials and associated manufacturing processes for economical fuel resource extraction, production, distribution, and storage for three primary fuel pathways – biomass, hydrogen, and oil and natural gas.
Advanced Manufacturing to Increase Efficiency in Building Systems and Technologies	Advance cost effective manufacturing technologies, systems management, and information technologies to improve building energy efficiency, environmental footprint, and resiliency.
Advanced Manufacturing for Clean Transportation Systems	Advance materials and manufacturing technologies to reduce vehicle weight and improve vehicle efficiency and range at a cost comparable to conventional vehicles.

Table 3.2 Symbols Used to Map Performance Targets to Success Indicators

Symbol	Success Indicator
EI	Demonstrate selected advanced manufacturing technologies and deploy practices that increase the rate of **energy intensity** improvement from business as usual (~1 % per year) to 2.5% per year.
LC	Develop advanced materials, manufacturing technologies, and targeted end use products with the potential to reduce **lifecycle energy impact** by 50% by 2025 compared to the 2015 state-of-the-art.
EM	Establish partnerships resulting in 30,000 U.S. manufacturing facilities implementing AMO-recognized **energy management** products, practices and measures by 2025.
TE	Double supported **technical education** and training activities in advanced manufacturing made available for universities, community colleges, and high schools by 2025.

3.1 Advanced Manufacturing Technology Areas

3.1.1 Critical Materials

Objective:

Advance technology solutions that enable the increased and consistent availability of materials essential to clean energy applications by diversifying the supply, developing cost effective substitutes, and improving reuse and recycling of critical and near-critical materials.

Challenges and Barriers:

- **Supply diversity**: reliance on sole (or nearly sole) suppliers and politically unstable regions for key energy materials.
- **Lack of material substitutes**: need for viable material- or system-level substitutions to reduce the dependence of energy technologies on particular critical materials.
- **Cost and regulatory barriers for new mines**: inability to quickly commission new mines, which works against efforts to diversify supply.
- **Utilization of co-produced rare earths**: challenges in making full use of abundant, co-produced rare earth elements (such as cerium) in practical applications.
- **Separations challenges**: technical difficulty and inefficiency of certain separations processes used to extract rare earth metals.
- **Recycling and reuse**: uncertain market and collection logistics for recovering critical materials.

Overview of Technical Area

Certain materials provide unique and essential properties for clean energy technologies, such as magnetic, catalytic, and luminescent chemical and physical properties. When the supply of one of these materials is at risk, it becomes a "critical" material. The concept of criticality is dynamic, meaning that a material that is critical today may not be critical in five years (or vice versa) due to shifts in demand, increased substitutes, or a diversified supply. The critical materials currently being addressed by AMO are those identified by the 2011 DOE Critical Materials Strategy[75] and include five rare-earth elements (REEs): neodymium, dysprosium, europium, terbium and yttrium. DOE also identified two non-rare-earth elements – lithium and tellurium – as "near-critical" materials; these materials play a key role in energy storage and battery technologies, such as hybrid and electric vehicles and photovoltaic thin films. In the coming years, other materials that are needed for manufacturing clean energy technologies, such as tungsten and bismuth, may be analyzed as potential critical materials. Reliable supply chains of materials critical to clean energy technologies are essential to supporting innovation in U.S. manufacturing and enhancing U.S. energy security.

AMO coordinates with programs across DOE, as well as with other federal organizations, to support technology development and analysis related to critical materials. The AMO-supported Critical Materials Institute (CMI) is an interdisciplinary consortium that is seeking technology solutions in the area of critical materials processing, manufacture, substitution and use. In addition, DOE is a co-chair of NTSC's Subcommittee on Critical and Strategic Minerals Supply Chains. AMO participates on the Subcommittee to examine wide-ranging issues including market risk, critical materials in emerging high-growth industries, and opportunities for long-term benefit through innovation; this Subcommittee is working to develop a coordinated, cross-government critical materials agenda. The NTSC recently released an early warning screening methodology to help indicate what materials are at risk of becoming critical based on their supply chain.[76] Within DOE, GTO supports technology development to recover minerals (e.g., lithium and REEs) from geothermal brines. The Office of Fossil Energy is investigating the viability of recovering rare earth elements from coal and coal byproducts. The R&D efforts within these offices strengthen DOE's approach to diversifying supplies of critical materials while complementing the efforts being supported by AMO.

For further discussion of the applications, challenges, and opportunities for critical materials from an energy perspective, see the *2015 QTR Technology Assessment 6F: Critical Materials* (the link to this assessment is provided below under "Related Resources" to Section 3.1.1).

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[75] 2011 Critical Materials Strategy website at: http://energy.gov/node/349057. This site includes a link to the full 196-page DOE report.

[76] *Assessment of Critical Minerals: Screening Methodology and Initial Application*. Subcommittee on Critical and Strategic Mineral Supply Chains of the Committee on Environment, Natural Resources, and Sustainability of the National Science and Technology Council (NSTC). March 2016. Available online at: https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf.

Targeted Impacts

Primary focus applications for AMO include critical material use in wind, electric vehicles, as well as energy-efficient lighting.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.3. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 1.1: Develop processing technologies for neodymium and other critical materials needed to meet U.S. clean energy deployment goals.

Neodymium is a critical material used in permanent magnets in wind turbines and electric vehicle applications. A secure supply of neodymium is important to fully leverage the economy-wide energy savings and environmental benefits from these technologies. One approach to diversifying the supply of neodymium is to develop new, more efficient routes for chemical processing of concentrated mixtures of REEs obtained from mining into separated purified rare earth oxides, including ores from non-REE mining such as phosphate ores. New techniques are needed that will address the fundamental similarity of the REEs, making possible more efficient and environmentally friendly separations with minimal consumption of chemicals and energy. Domestic capabilities may be enabled in the future by improving the economics of solvent extractant and other separation schemes through new technologies. The following are examples of specific activities towards achieving this target:

- Develop enhanced beneficiation, leaching, and extraction technologies to separate rare earth elements from phosphate processing streams that would be capable of meeting 50% of 2011 U.S. neodymium demand[77].
- Develop a new or improved technology for beneficiation of rare earth ores, improving recovery from 60% to 75%.
- Develop processes or extractants to improve adjacent lanthanide separation factors to enable a 33% reduction in separation, operation, and capital costs compared to current typical technology.
- Demonstrate a new material or process employing cerium with the potential to increase use of this metal by 20% compared to 2011 demand (the peak demand in recent years). Increased cerium demand would enhance the overall economics of rare earth mines, allowing for increased cost effective production of needed materials for clean energy technologies.

Target 1.2: Develop a new phosphor that requires one-tenth critical rare earth elements compared to current fluorescent lamp phosphors.

REE-based fluorescent phosphors typically include lanthanum, cerium, europium, terbium, and yttrium. These materials are key to energy efficient lighting applications – especially florescent lamps, but also compact florescent bulbs and light-emitting diode (LED) lighting. These energy efficient lighting technologies consume much less energy during use than traditional incandescent light bulbs, and they can therefore provide lifecycle energy savings. The REEs used in phosphors are of limited supply in the U.S. Furthermore, REEs for phosphor applications must be extremely pure (99.999%) to achieve precise color characteristics, necessitating costly purification steps during their manufacture. In addition, typical material development and replacement cycles are 20 years, although a materials genome approach linking advanced theory, computation, accelerated testing, and expert knowledge may shorten this cycle. The following are examples of specific activities towards achieving this target:

- Develop a new green phosphor that reduces the terbium content by 90% and eliminates lanthanum.
- Develop a new red phosphor which eliminates both europium and yttrium.
- Assess the feasibility of utilizing these newly developed phosphors for commercial lighting by evaluating chemical issues related to slurry compatibility and improving fabrication procedures.

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[77] U.S. neodymium demand in 2010 was approximately 500 metric tons as indicated by rare earth oxide demand for magnets. Source: *2015 OTR, Technology Assessment 6F: Critical Materials*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6F-Critical-Materials.pdf.

Critical Materials Institute (CMI)

The Critical Materials Institute (CMI), an Energy Innovation Hub established in 2013 and led by Ames Laboratory, is a sustained, multidisciplinary effort to develop solutions across the materials lifecycle as well as reduce the impact of supply chain disruptions and price fluctuations associated with these valuable resources. By bringing together scientists and engineers from diverse disciplines, the CMI is addressing challenges in critical materials, including mineral processing, manufacture, substitution, efficient use, and end-of-life recycling; integrating scientific research, engineering innovation, manufacturing and process improvements; and developing a holistic solution to the materials challenges facing the nation. It includes expertise from four national laboratories, seven universities, and ten industry partners to minimize materials criticality as an impediment to the commercialization of clean energy technologies.
Within its first five years, CMI will develop at least one technology adopted by U.S. companies in each of three areas:

1. Diversify and expand production – (i) design separations agents to improve production efficiency, reduce costs, minimiz environmental impact and thus enhance the commercial viability of new rare-earth mines, (ii) develop transformative a environmentally benign technologies that make domestic manufacturing of rare-earth metals, alloys, and other produc possible, and (iii) design new chemical extractants that will transform the recovery of lithium from highly concentrated brines.
2. Reduce wastes – (i) improve the efficiency with which rare earths are utilized in manufacturing, and (ii) enhance efficient reuse and recyclin of manufacturing wastes and materials in discarded household products.
3. Develop substitutes – invent and qualify new materials for use in existing products, and redesign products to accommodate new materials.

Target 1.3: Develop substitute materials for rare earth permanent magnets that exhibit properties similar to current magnets, but contain one-tenth rare earth/critical materials compared to 2015 state-of-the-art materials.

Permanent magnets are dependent on REE materials to enable the conversion of energy between mechanical and electrical forms – an integral property to the functionality of the lightweight, high-power generators and motors found in wind turbines and electric vehicles. Growing deployment of these clean energy technologies is contributing to rising demand for these REEs, but availability is complicated by a lack of supply diversity in the supply chains. Substitute materials can help reduce the dependence of a clean energy technology on a particular material. New materials with similar functionality to the critical REE materials can be pursued as drop-in replacements. Alternatively, new manufacturing routes can be used to develop substitute permanent magnets that require much less REE material. Lastly, alternative system-level designs are being explored to reduce the overall use of critical materials. The following are examples of specific activities towards achieving this target:

- Develop a substitute permanent magnet that exhibits properties similar to current neodymium-iron-boron magnets but contains 50% less critical rare earth materials than 2015 typical technology.
- Fabricate functionally graded magnets with at least comparable energy density relative to 2015 typical technology.
- Identify ferro-magnetic materials with minimal REE which exhibit a Curie temperature > 400 Kelvin (K), a magnetic susceptibility >1 mega-ampere per meter (MA/m), and magneto-crystalline anisotropy >3 megajoules per cubic meter (MJ/m^3).

Target 1.4: Recover and recycle materials from end-of-life (EOL) products and manufacturing waste to increase domestic availability of critical materials for clean energy technologies by 20%.

Recovering and recycling products containing REEs is another avenue to reduce the material criticality of REEs. Currently less than 1% of EOL products containing REEs are recycled. Computer hard drives used in data centers are one potential recycling stream source for neodymium that can be used for NdFeB permanent magnets[78] critical for wind

[78] This is referred to as a neodymium magnet and it consists of an alloy of neodymium (Nd), iron (Fe), and boron (B).

and electric vehicle applications. While some hard drives are recycled for their steel and aluminum content, less than 1% of magnets contained within consumer products are recycled, in part because the drives are shredded and the parts containing REEs are lost in the scrap. Approximately one-third of the hard drive population is replaced annually. Challenges for recycling rare earth permanent magnets from end-of-life hard drives include: locating and extracting the magnets in a cost-effective manner (such devices are not currently designed for disassembly), separating REEs from within the components (varied compositions and impurity levels may alter the recycling process), and the re-insertion of recycled materials back into the supply chain. The following are examples of specific activities towards achieving this target:

- Develop a process to disassemble and recover the rare-earth magnet within a hard disk drive, with processing time < one second (1 s) per hard drive.
- Develop electro-recycling and pyro-processing technologies that involve cell design and limited oxidation of scrap materials for recovery of selected critical materials from consumer products with potentially upgraded partially oxidized materials.
- Demonstrate dispersion-free supported liquid membrane solvent extraction for the separation, concentration, and recovery of critical REEs from EOL magnets.

Table 3.3 Technical Targets for Technical Area 1: Critical Materials

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	**Progress to Date**[79]	
1.1	Develop processing technologies for neodymium and other critical materials needed to meet U.S. clean energy deployment goals.	2025	CST	No Nd is currently produced in the U.S.	6 patent applications	LC
1.2	Develop a new phosphor that requires one-tenth critical rare earth elements compared to current fluorescent lamp phosphors.	2020	CST	Phosphors consume 250 REE tonnes/year, including europium, terbium, yttrium and lanthanum	1 patent application submitted	LC
1.3	Develop substitute materials for rare earth permanent magnets that exhibit properties similar to current magnets, but contain one-tenth rare earth/critical materials compared to 2015 state-of-the-art materials.	2025	CST	Typical REE magnets contain~25% Nd (by mass) with a typical energy product range of 25-50 MGOe[80]	1 patent application submitted	LC
1.4	Recover and recycle materials from end-of-life (EOL) products and manufacturing waste to increase domestic availability of critical materials for clean energy technologies by 20%.	2025	CST	<1% of EOL REE are recycled	7 patent applications submitted, 1 licensed technology	LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6F: Critical Materials*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6F-Critical-Materials.pdf.
- Critical Materials Strategy, U.S Department of Energy, 2010. Available online at: http://energy.gov/node/206101.
- Critical Materials Strategy, U.S. Department of Energy, 2011. Available online at: http://energy.gov/node/349057.
- CMI website at: https://cmi.ameslab.gov.

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[79] Information on patents and invention disclosures are available online at: http://cmi.ameslab.gov/research/cmi-invention-disclosures.

[80] MGOe is an abbreviation for mega-gauss oersteds and represents the stored energy in a magnet where 1 mega-gauss oersted (MGOe) equals 7.96 kJ/m^3.

3.1.2 Direct Thermal Energy Conversion Materials, Devices, and Systems

Objective:

Advance technologies that improve materials, devices, and systems that directly convert energy from one form to another (e.g., waste heat to electricity), in order to realize lifecycle energy efficiency benefits on an economically effective basis.

Challenges and Barriers:

- **Figure of merit of materials:** direct energy conversion materials tend to have low efficiencies and properties that restrict how and where they can be used.
- **Cost of materials:** direct conversion materials remain too expensive in order to compete directly with conventional energy sources.
- **Manufacturing challenges**: current labor-intensive methods are costly and limit production.
- **System-level challenges:** systems have design and material needs (e.g., heat exchanger design, powerful ferromagnetic materials) that limit the ability to leverage direct conversion properties and be able to compete with established technologies.

Overview of Technical Area

Direct energy conversion materials, devices, and systems convert energy from one form to another without intermediate steps. For thermal energy applications, direct thermal energy conversion (DTEC) technologies are in various stages of maturity, and include phase-change, caloric, thermo-acoustic-piezoelectric, thermionic, thermophotovoltaic, and thermoelectric material systems. Thermoelectric systems, the most mature DTEC technology, can be used to convert heat to electric energy and vice versa. Thermoelectric generators are used from seat warmers and coolers in luxury automobiles to powering NASA's Voyager series and Galileo space probes. Because DTEC systems rely on the properties of solid state materials, DTEC systems could in principle be smaller, more reliable, quieter, and more energy efficient than current technologies, but so far, DTEC systems have seen limited market penetration.

Converting waste heat to electrical power is a promising application for DTEC materials. For example, the industrial manufacturing sector provides a vast opportunity for waste heat recovery as 20 – 50 % of the energy consumed is ultimately lost in hot fluid waste heat streams. Combined Heat and Power (CHP) systems, described further in section 3.1.13, can attain 75% overall efficiency, a substantial improvement over non-collocated schemes which typically achieve an overall efficiency of about 50%. DTEC materials could make CHP systems even more efficient. However, high labor input, low energy conversion efficiency, and system integration and reliability issues make DTEC materials expensive. New material systems are needed to improve efficiencies, and advanced manufacturing approaches such as wafer-based or additive manufacturing and increased automation have tremendous potential to reduce costs even with current DTEC materials.

Caloric material heat pumps for industrial refrigeration face similar challenges. Caloric materials change temperature when exposed to magnetic fields (magnetocaloric), electric field (electrocaloric), or stress fields (elastocaloric). They can be used for space heating and cooling, which use over 20% of U.S. electricity. Just like thermoelectrics, caloric materials can increase energy efficiency, given that vapor-compression heat pumps are approaching their efficiency limit and their most effective refrigerants have high global warming potential.

Increasing the adoption of thermoelectric generation, caloric material cooling, and other DTEC systems can have a sizable impact in U.S. energy consumption and greenhouse gas emissions, but high installed costs hinder adoption. R&D in DTEC manufacturing scale-up and materials is needed for these systems to reach cost parity with conventional technologies.

For further discussion of the applications, challenges, and opportunities for DTEC from an energy perspective, see the *2015 QTR Technology Assessment 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems* (the link to this assessment is provided below under "Related Resources" to Section 3.1.2). For a general discussion of waste heat recovery opportunities, see also *2015 QTR Technology Assessment 6M: Waste Heat Recovery*, the link to which is provided in Section 3.1.12.

Targeted Impacts

The key focus applications for AMO are waste heat-to-power and industrial refrigeration. Success in these areas will likely have cross-cutting benefits in vehicles and in residential and commercial cooling as well.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.4. The rationale for including each target, and AMO's approach to overcoming the key challenges and barriers, are described in this section.

Target 2.1: Develop direct thermal energy conversion systems with energy efficiencies greater than 30%

Single DTEC thermoelectric modules for generating electricity have been demonstrated at 10% efficiency in the laboratory.[81] Cascading modules can theoretically increase the efficiency of the entire system,[82] but in practice overall efficiency is significantly reduced owing to incompatibility between material properties. There are promising new materials that overcome compatibility issues, but the technologies are immature and currently have lower efficiencies and reliability, and higher cost than established materials.

Target 2.2: Demonstrate systems for industrial refrigeration with energy efficiency greater than 30% over vapor-compression systems

System level studies on solid-state caloric material refrigeration show energy efficiency improvements as much as 30% over vapor-compression systems.[83] Solid state refrigeration approaches have significant systems advantages since they have fewer moving parts and no compressor. Vapor compression also faces challenges with flammability, toxicity, and regulatory refrigerant phase-out. Active regeneration and cascading techniques can be used to expand the temperature difference and heat pumping capacity of caloric material systems. Systems level innovations on heat exchanger designs and efficient solid-liquid heat conduction pathways will further boost efficiencies.

Target 2.3: Develop waste heat recovery direct thermal energy conversion systems with modeled deployment cost of less than $1/W

It is estimated that the cost of installed heat recovery DTEC systems will need to reach $1 per watt (W)[84] in order to compete with industrial electricity price of $0.068 per kilowatt-hour (kWh).[85] Paths to achieving the cost target include developing lower-cost DTEC materials, new manufacturing methods, and automated methods of assembly. DTEC systems operating with high temperature heat sources (500°C or more) are more efficient and therefore more cost effective. Current systems are estimated to cost about $4.48/W with a 500°C source and $19.02 with a 250°C source.[86]

Target 2.4: Bring heat pump direct energy conversion systems to cost parity with conventional commercial technologies

Thermoelectric materials account for up to 80% of the cost of such systems. Elastocaloric materials cost $2000/kg today and need to reach $50 per kilogram (kg) to achieve cost parity with current heat pumping technology.[87] Technologies such as powder injection molding can lower the cost of elastocaloric materials. In magnetocaloric

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[81] W. Liu, H.S. Kim; S. Chen; Q. Jie; B. Lv; M. Yao; Z. Ren; C. P. Opeil; S. Wilson; C-W. Chu; and Z. Ren. "n-type thermoelectric material $Mg_2Sn_{0.75}Ge_{0.25}$ for high power generation." *Proceedings of the National Academy of Sciences*, 112 (11), pp. 3269–3274. March 2015. Available online at: http://www.pnas.org/content/112/11/3269.full.pdf.

[82] R. Venkatsubramanian. "Recent Device Developments with Advanced Bulk Thermoelectric Materials." Presented at the 3rd DOE Thermoelectrics Applications Workshop, March 21, 2012. Available online at: http://energy.gov/sites/prod/files/2014/03/f10/venkatasubramanian.pdf.

[83] J. Cui, Y. Wu, J. Muehlbauer, Y. Hwang, R. Radermacher, S. Fackler, M. Wuttig, and I. Takeuchi. "Demonstration of high efficiency elastocaloric cooling with large ΔT using NiTi wires." *Applied Physics Letters* 101: 073904. August 17, 2012. Available online at: http://mse.umd.edu/sites/default/files/documents/faculty/takechui/151.pdf.

[84] A $1 per watt DTEC-based system with a five-year life, discount rate of 7%, capacity factor of 75%, and maintenance and operating costs of $0.20 per watt.

[85] "Electricity Data Browser." Data for 2013. EIA. Available online at: http://www.eia.gov/electricity/data/browser/.

[86] Data source: *2015 QTR Technology Assessment 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6G-Direct-Thermal-Energy-Conversion-Materials-Devices-and-Systems.pdf. Cost analysis is based cost model in "Material and manufacturing cost considerations for thermoelectrics" by S. Leblanc, S. K. Yee, M. L. Scullin, C. Dames, and K. E. Goodson. *Renewable and Sustainable Energy Reviews* 32, pp. 313-327. 2014. Available online at: http://www.leblanclab.com/uploads/2/6/4/3/26439896/material_and_manufacturing_cost_considerations_for_thermoelectrics_leblancyee.pdf.

[87] Supra 85. J. Cui, et al. 2012.

refrigeration systems, the magnet is the largest fraction of the cost.[88] The cost of magnetocaloric refrigeration systems can be lowered by substituting rare and expensive elements, and by engineering materials with shorter heat treatments, and rapid solidification and post-processing. Large scale production of the magnets will call for replacing certain rare earth elements with others and using transition elements such as manganese (Mn) and iron (Fe) (section 3.1.1 on *Critical Materials* discusses targets on replacing REEs in materials). The current state of electrocaloric materials and the benefits of adopting them are similar to magneto- and elastocaloric materials.

Target 2.5: Develop caloric materials, integrated devices, and systems that require applied field strengths 30-50% lower than 2015 baselines

Currently, caloric materials have not lived up to their promise because of lack of affordable materials that exhibit strong enough caloric effect (CE) to make them economically competitive. Magnetocaloric materials change up to 12°C with magnetic fields of 10 to 50 kilo-oersteds (kOe); they need to require lower field strengths and have 5 times the caloric effect of current materials. Elastocaloric materials need to work with one-half of current stress fields to reach commercial viability. Improvements of existing materials and discovery of new ones, possibly that respond to multiple types of fields (e.g., electric, magnetic, stress) at the same time would be impactful. Potential applications include: thermal management of electronics and batteries, jet-fuel chilling, gas separation (hydrogen sulfide (H_2S) and CO_2 from low-Btu natural gas), and gas liquefaction.

Table 3.4 Technical Targets for Technical Area 2: Direct Thermal Energy Conversion Materials, Devices, and Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016) 2015 Baseline	Current Status (2016) Progress to Date	SI
2.1	Develop direct thermal energy conversion systems with energy efficiencies greater than 30%.	2025	NCA	For thermoelectrics:[89] • R&D (2-stage cascaded, T_h=500°C)[90]: 11% • Commercial (T_h=230°C)[91]: 4.5%	NCA	EI, LC
2.2	Demonstrate systems for industrial refrigeration with energy efficiency greater than 30% over vapor-compression systems.	2025	R&D	• Vapor compression: systems can operate at 60% of the Carnot theoretical efficiency	Research ongoing	LC
2.3	Develop waste heat recovery direct thermal energy conversion systems with modeled deployment cost of less than $1/W.	2025	NCA	For thermoelectrics:[92,93] • Half-Heusler, T_h=500°C: $4.48/W • Chalcogenide, T_h=500°C: $5.06/W • Silicide, T_h=500C: $5.56/W • Skutterudite, T_h=250°C: $19.02/W • Chalcogenide, T_h=250°C: $11.92/W	NCA	EI, LC

[88] R. Bjørk, C. R. H. Bahl, and K. K. Nielsen. "The lifetime cost of a magnetic refrigerator." *International Journal of Refrigeration* 63, pp. 48-62. 2016. Available online at: https://arxiv.org/pdf/1605.02524v1.pdf.

[89] While any technology solution that can reach the target is of interest, these baselines reflect thermoelectric technologies, which were explored in detail in *2015 QTR Technology Assessment 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems*.

[90] Supra 84. R. Venkatsubramanian. 3rd DOE Thermoelectrics Applications Workshop. 2012.

[91] "HZ-14 Thermoelectric Module." Hi-Z Technology, Inc. Available online at: http://hi-z.com/wp-content/uploads/2016/08/HZ-14-data-sheet.pdf.

[92] MGOe is an abbreviation for mega-gauss oersteds and represents the stored energy in a magnet where 1 mega-gauss oersted (MGOe) equals 7.96 kJ/m^3.

[93] Supra 88. *2015 QTR Technology Assessment 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems*. Cost model based on S. Leblanc, et al. 2014.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
2.4	Bring heat pump direct energy conversion systems to cost parity with conventional commercial technologies.	2025	R&D	• Magnetocaloric material (Gd):[94,95] $20/kg • REE magnet:[96,97] $40/kg • Electrocaloric material $BaTiO_3$:[98] $50/kg	Research ongoing	LC
2.5	Develop caloric materials, integrated devices, and systems that require applied field strengths 30-50 % lower than 2015 baselines.	2025	R&D	• Magnetocalorics: magnetic field strengths typically 1 – 5 Tesla • Electrocalorics: 15 – 120 megavolts per meter (MV/m) • Elastocalorics: 0.1 – 0.6 gigapascals (GPa)	Research ongoing	LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6G-Direct-Thermal-Energy-Conversion-Materials-Devices-and-Systems.pdf.
- Caloric Materials Consortium (Caloricool), part of the Energy Materials Network website at: https://www.caloricool.org/.

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[94] R. Bjørk, A. Smith, C.R.H. Bahl, and N. Pryds. "Determining the minimum mass and cost of a magnetic refrigerator." *International Journal of Refrigeration* 34 (8), pp. 1805-1816. 2011. Available online at: http://orbit.dtu.dk/files/100219325/Determining_the_minimum_mass_and_cost_of_a_magnetic_refrigerator.pdf.

[95] Supra 90. R. Bjørk, et al. "The lifetime cost of a magnetic refrigerator." 2016.

[96] Supra 96. R. Bjørk, et al. "Determining the minimum mass and cost of a magnetic refrigerator." 2011.

[97] Supra 90, R. Bjørk, et al. "The lifetime cost of a magnetic refrigerator." 2016.

[98] Y. Bai, G.-P. Zheng, K. Ding, L. Qiao, S.-Q. Shi, and D. Guo. "The giant electrocaloric effect and high effective cooling power near room temperature for $BaTiO_3$ thick film." *Journal of Applied Physics* 110 (9). Nov. 2011.

3.1.3 Wide Bandgap Semiconductors for Power Electronics

Objective:
Advance economically viable wide bandgap semiconductor materials and devices, technologies and applications that result in improvements in energy efficiency, enable cost-efficient integration of power systems and accelerate the adoption of clean energy technologies.

Overview of Technical Area

Wide bandgap (WBG) semiconductor materials can enable device operation at higher frequencies, temperatures, and voltages compared to devices based on conventional silicon-based semiconductors. A semiconductor material is generally considered WBG if its bandgap is larger than 2 electron volts (eV), substantially higher than silicon's bandgap of 1.1 eV. Examples of WBG materials include silicon carbide (SiC) with a bandgap of 3.3 eV and gallium nitride (GaN) with a bandgap of 3.4 eV. Next-generation, energy-efficient power electronics and motor-driven systems will benefit from the development of improved WBG semiconductors, which are expected to reduce their cost, increase operating voltage, and increase power efficiency. As a case in point: WBG semiconductors are expected to accelerate the motorization of large compressors prevalent in the chemical, oil, and gas industries, which could improve system-wide efficiencies and reduce fugitive methane emissions. The higher voltage capabilities, switching frequencies, and junction temperatures of WBG devices will enable the integration of medium voltage (MV) class motors with WBG-based variable frequency drives (VFDs).

VFDs improve electrical motor efficiencies and can lead to significant energy savings in the manufacturing sector. WBG semiconductor devices can play an important role in the modernization of the electrical grid and enable high-penetration of distributed energy generation. WBG-based solid state transformers, fault current limiters, high-voltage direct current, and power flow controllers can reduce transmission and distribution losses, optimize power delivery, protect critical assets, and enhance the electrical network resilience.[99]

For further discussion of the applications, challenges, and opportunities for WBG semiconductors from an energy perspective, see the *2015 QTR Technology Assessment 6N: Wide Bandgap Semiconductors for Power Electronics* (the link to this assessment is provided below under "Related Resources" to Section 3.1.3).

Challenges and Barriers:

- **Cost of substrates and epitaxial materials:** small production volumes and high manufacturing costs result in high costs.
- **Interface challenges:** high lattice strains at GaN/Si interfaces caused by the coefficient of thermal expansion mismatch (for example) leads to lattice defects, which decrease performance.
- **Device reliability:** variability in threshold voltages and low device reliability (perceived or actual) compared to silicon-based technologies; long term reliability data unavailable for wide bandgap devices.
- **Growth of high quality nucleation layers:** challenging nucleation and growth of WBG materials because of tradeoffs between growth rate and quality, and because of interfacial charges.
- **Power limitations for GaN devices:** novel device architectures (such as vertical architectures) in order to raise the operating voltage of GaN devices to >600V.

Targeted Impacts

WBG semiconductors comprise a platform technology with energy saving opportunities in all energy segments. In manufacturing as well as commercial and residential building settings, WBG semiconductors can be used in electric motor variable frequency drives (VFDs), as rectifiers used in consumer electronics and data centers, in elevator power electronics, and as circuit breakers. In energy generation and distribution WBG are useful in DC-AC inverters that tie solar and wind energy to the grid, transformers to provide enhanced capabilities in high-voltage grid substations, and grid-level energy storage converter systems. In transportation, WBG semiconductors have uses in regenerative power brakes and motor drives for hybrid-electric and all-electric road and rail vehicles, and in aircraft and ships for generating and managing electric power.

AMO is focusing its efforts on SiC and GaN devices, which are currently the most promising WBG material systems in the power electronics industry (and the most technologically mature). GaN-on-silicon is suitable for power electronics

[99] *Controlling the Flow: Next-Generation Power Electronics Systems for Tomorrow's Electric Grid*. Office of Electricity Delivery and Energy Reliability (OE) / U.S. DOE. December 2015. Available online at: http://energy.gov/sites/prod/files/2016/06/f32/GIGA%20Project%20Summary.pdf.

applications of <600 V and <10 kW, such as DC-DC converters, power supplies, micro and string photovoltaic inverters, and SiC can be used for higher power systems, in the range of 600 V to 15 kV and 10 kW to 10 MW.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.5. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 3.1: Reduce volume and weight of targeted power electronic systems by 50% with respect to their silicon-based equivalent.

The use of WBG semiconductors in power electronics can result in significant levels of energy reduction as well as enabling substantial decreases in the weight and volume of the drive electronics compared to Si-based semiconductors. The higher switching frequencies of WBG devices allow smaller inductors and capacitors to be used in power circuits. Inductance and capacitance scale with the frequency, i.e., a 10x increase in frequency produces a 10x decrease in the required capacitance and inductance. This can result in an enormous decrease in weight and volume as well as cost. For example, one estimate stated that the heat sink size for the variable speed drive of a 10 horsepower (hp) industrial electric motor could be reduced by 66% if WBG-based power electronics were used.[100] In addition, higher operating frequency can result in less acoustic noise in motor drive applications.[101] The following are examples of specific activities towards achieving this target:

- Develop SiC and GaN power electronics with volume and weight requirements that meet or exceed silicon power electronics and are cost competitive.
- Develop power microwave WBG devices suitable for high efficiency process heating applications (see Section 3.1.10 Process Heating).
- Develop programs that train technicians and engineers on how to design and manufacture WBG devices that take full advantage of WBG's performance
- Identify and promote specific applications where using WBG devices offer significant value over silicon devices

Target 3.2: Increase the efficiency of targeted power electronic systems by 2-3% (a reduction in losses of 28% or above) with respect to their silicon-based equivalents.

Increasing the efficiency of power electronics is imperative to reducing energy consumption. At a system level, the use of WBG devices can significantly reduce cooling requirements. For example, reducing the size of heat sinks, radiators, pumps, and piping can result in cost savings from materials manufacturing and ancillary power savings that translate to higher system-level efficiency. Significant energy efficiencies can be realized in commercial electronics and power supply circuits. The annual U.S. shipped stock of laptops and netbooks, a total of 36.7 million units, have an average active mode efficiency of 87% and 404 gigawatt-hours (GWh) of total annual consumption.[102,103] Deploying GaN high-electron-mobility transistors (HEMTs) to laptop power adapters could increase power efficiency by 3%. Power conversion activities inside an average data center account for 10.4% of the energy consumed in the average data center.[104] Switching from Si based devices to WBG based devices could increase conversion efficiency to as much as

[100] Hull, B. "SiC Power Devices – Fundamentals, MOSFETs and High Voltage Devices." In The 1st IEEE Workshop on Wide Bandgap Power Devices and Applications. Columbus, Ohio. 2013.
[101] Eden, R. *The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors – 2013 Edition (Vol. 9790).* IHS. Wellingborough. 2013.
[102] *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Battery Chargers and External Power Supplies*. BTO/EERE/DOE. Prepared by Navigant Consulting, Inc., D&R International, Ltd., and LLNL. March 2012. Available online at: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/bceps_nopr_tsd.pdf.
[103] Das, S. and West, D. Oak Ridge National Laboratory (ORNL). Unpublished analysis. 2012.
[104] *Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431*. ENERGY STAR Program. U.S. EPA. Published August 2, 2007. Available online at: https://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Datacenter_Report_Congress_Final1.pdf.

98%.[105] This means that data centers could see an 8.3% reduction in energy use thanks to WBG power electronics. These types of applications require very high production volumes of power electronics; such volumes will, in turn, lead to lower cost per device and thus favor broad adoption. The following are examples of specific activities towards achieving this target:

- Developing SiC and GaN power electronics components and devices capable of efficiencies that exceed silicon power electronics by 3%;
- Achieving a production volume of 10,000 WBG wafers per year through innovative foundry models and manufacturing innovations; and
- Producing full SiC-based inverters that are commercially competitive in automotive applications by 2025.

PowerAmerica: The Next Generation Power Electronics National Manufacturing Innovation Institute

The mission of PowerAmerica, established in 2014, is to develop advanced manufacturing processes that will enable large-scale production WBG semiconductors, which allow electronic components to be smaller, faster and more efficient than semiconductors made from silicon. WBG semiconductor technology has the potential to reshape the American energy economy by increasing efficiency in everything that uses a semiconductor, from industrial motors and household appliances to military satellites. PowerAmerica is led by North Carolina State University.

Target 3.3: Demonstrate a 3x improvement in the reliability (failures reduced to one-third over 10 years) of targeted electrical devices produced at high volumes over their silicon-based equivalent.

Material quality still remains an area for improvement. SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) are the most prominent WBG switching device used today but they are limited by MOS interface quality issues. Problems with the interface can lead to variability in threshold voltages and lower reliability. This reduces the adoption of SiC junction gate field-effect transistors (JFETs) and bipolar junction transistors (BJTs) over SiC MOSFETs, the latter being preferable devices. Fundamental reliability research at the device level needs to be performed as well as new packaging methods that allow WBG devices to operate at their full potential. The only commercial WBG power devices with more than ten years' market performance are SiC Schottky diodes. As such, they are the only devices with proven reliability at the scale required for high-end applications. Large scale adoption will not occur until cost-effective devices are demonstrated with lifetime reliability that exceeds ten years in demanding applications. The following are examples of specific activities towards achieving this target:

- Commission an 8-inch SiC wafer fabrication facility to improve yield of large devices and reduce wafer edge related defects;
- Conduct applied research to improve the reliability of SiC/SiO_2 interface;
- Develop better GaN/dielectric interface to improve the reliability of GaN power devices;
- Develop new methods for growing bulk and low-defect density GaN substrates; and
- Produce a 1.2 kV SiC MOSFET at high volume with a cost of $0.10/A.

Target 3.4: Increase the efficiency of targeted electric machines by 2-3% (a reduction in losses of 28 - 75%).

Motors and generators are critical in industrial applications, driving equipment such as fans, pumps, compressors, and conveyer systems. In order to design electric machines (i.e., integrated drive systems) with higher efficiency, it is important to study the electric losses occurring in them. Losses in a rotating electric machine such as a DC generator or

[105] L.M. Tolbert, T.J. King, B. Ozpineci, J.B. Campbell, G. Muralidharan, D.T. Rizy, A.S. Sabau, H. Zhang, W. Zhang, Y. Xu, H.F. Huq, and H. Liu. *"Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications."* ORNL/TM-2005/230. December 2005. Available online at: http://web.ornl.gov/~webworks/cppr/y2001/rpt/124182.pdf.

DC motor can be caused by losses in armature and field windings, brush contact, hysteresis, eddy current, mechanical, and friction.[106] For over 100 years, mechanical commutation was the only practical way of switching the direction of the current flow; however, the availability of high power semiconductors has made electronic commutation possible.[107] A specific example of activity towards this target is:

- Develop a 1 megawatt (MW) electric motor, operating at 15,000 revolutions per minute (rpm), driven by a WBG based, medium voltage, variable speed drive, with a minimum efficiency of 93%.

Next Generation Electric Machines

AMO's Next Generation Electric Machines (NGEM) effort is driving technology advancements in power electronics and enabling materials to improve a wide array of electric machines. Electric machines include electric motors and the associated drive-control systems used in motor-driven systems and generators, as well as non-rotating equipment such as transformers used on the grid. A key target area for NGEM is a new generation of energy efficient, high power density, high speed, integrated medium voltage (MV) drive systems for a wide variety of industrial applications. Improvements to a wide range of electric machines can be realized through the application of key enabling technologies, such as wide bandgap devices, advanced magnetic materials, improved insulation materials, aggressive cooling techniques, high speed bearing designs, and improved conductors or superconducting materials.

The aim of AMO's R&D is to reduce the motor size and drive systems by up to 50 percent and cut energy waste by as much as 30 percent. The new motor-driven systems can be used in the chemical and petroleum refining industries, natural gas infrastructure, electric propulsions systems for transportation, and general industry compressor applications like HVAC systems, refrigeration, and wastewater pumps. These application areas represent a significant number of motor installations, a large amount of electrical energy consumption, and significant opportunities for U.S. technology and manufacturing competitiveness.

Table 3.5 Technical Targets for Technical Area 3: Wide Bandgap Semiconductors

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
3.1	Reduce volume and weight of targeted power electronic systems by 50% with respect to their silicon-based equivalents.	2020	CST, R&D	Current equivalent silicon devices represent the baseline (i.e., 100%)	50% reduction in volume in 3 out of 8 devices under development[108]	EI, EM
3.2	Increase the efficiency of targeted power electronic systems by 2-3% (a reduction in losses of 28% or above) with respect to their silicon-based equivalents.	2020	CST, SBIR	93 - 96%, depending of the device[109]	Efficiency increase of 2-3% demonstrated for 4 devices and 5 more on track to meeting the goal[110]	EI, LC

[106] Kiran Daware. "Losses in a DC Generator and DC Motor." ElectricalEasy.com. Accessed July 13, 2016 at: http://www.electricaleasy.com/2014/01/losses-in-dc-machine.html.

[107] "Electrical Machines - Electric Drives (Fundamentals)." Electropedia. Accessed July 14, 2016 at: http://www.mpoweruk.com/machines.htm

[108] The devices are an electric vehicle fast charger and two different photovoltaic systems' DC-AC inverters.

[109] *Premium Efficiency Motor Selection and Application Guide: A Handbook for Industry.* AMO/EERE/U.S. DOE. Report DOE/GO-102014-4107. February 2014. Available online at: http://www.energy.gov/sites/prod/files/2014/04/f15/amo_motors_handbook_web.pdf.

[110] The devices that met the goal are an electric vehicle fast charger and three different photovoltaic DC-AC inverters. Additionally, there are projects on track to deliver 3 more DC-AC inverters, two electric vehicle inverters and one heavy-duty electric vehicle inverter.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
3.3	Demonstrate a factor of 3 improvement in the reliability (failures reduced to one-third over 10 years) of targeted electrical devices produced at high volumes over their silicon-based equivalent.	2020	CST, SBIR	Si MOSFETs: 30 failures/10^9 hours[111, 112, 113, 114]	Research ongoing	LC
3.4	Increase the efficiency of targeted electric machines by 2-3% (a reduction in losses of 28 – 75%).	2020	R&D	93-98%[115]	Research ongoing	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review Technology Assessment 6N: Wide Bandgap Semiconductors for Power Electronics*. Available online at: http://energy.gov/sites/prod/files/2016/02/f29/QTR2015-6N-Wide-Bandgap-Semiconductors-for-Power-Electronics.pdf.
- Next Generation Power Electronics Manufacturing Innovation Institute (PowerAmerica) website at: https://www.poweramericainstitute.org/.
- "Wide Bandgap Semiconductors to Increase the Energy Efficiency and Reliability of Power Electronics" website at: http://energy.gov/eere/amo/power-america.

[111] Jeffrey B. Casady. "SiC Power Devices and Modules Maturing Rapidly." *Power Electronics Europe: Issue 1*. 2013. Available online at: http://www.power-mag.com/pdf/feature_pdf/1361891494_Cree_Cover_Story_Layout_1.pdf.
[112] "Power products commercial roadmap for SiC from 2012 – 2020." Cree Power. HMW Direct-Drive Motor Workshop. 2014
[113] "Industrial Readiness of SiC Power Devices." GE Global Research. CFES 2015 Annual Conference.
[114] Conversations with Anant Agarwald. September 28, 2016.
[115] Supra 111. *Premium Efficiency Motor Selection and Application Guide*. U.S. DOE. 2014.

3.1.4 Materials for Harsh Service Conditions

Overview of Technical Area

In harsh service environments, unusually intense values of environmental and/or operational variables, such as temperature; pressure; mechanical load; radiation; chemical-, electrical-, or magnetic potential; or time variations of such variables drive or accelerate key failure modes of a product, device, or component. The actual values (or their temporal variations) that define a condition as "harsh" are relative but can be a defining condition which acts as a barrier for a transformative change in a manufacturing process or product that could result in significant savings in energy, CO_2 or cost. It should also be noted that development of improved materials for harsh service conditions is an enabler for other technology areas rather than an area by itself. Future trends – such as the increased introduction of clean energy, electrification, and increased H_2 usage – will present challenges with regards to materials and structures at harsh conditions. For example, maintaining stability under high chemical potentials or high temperatures is critical for energy storage devices (e.g., batteries) and for lightweighting applications (e.g., multi-material joints). Conceptual solutions based on materials discovery may exist in many cases but these are often too expensive or impractical to implement from a manufacturing point of view. Fundamental materials solutions are needed to overcome barriers caused by harsh condition and enable the cost-effective manufacturing of parts and structures based on these materials.

Harsh service environments (and the associated materials durability challenges) are common across multiple applications and sectors. All thermal power systems (coal, natural gas, nuclear, geothermal, solar thermal electric, and waste incineration) involve subjecting materials in turbines, boilers, and heat exchangers to high temperatures, often in combination with aggressive chemical environments and mechanical loads. In many sectors of manufacturing, tools, dies, rolls, and molds share such conditions. Cyclical variations in chemistry would also pose a challenge, such as in pipes that can transport natural gas and hydrogen in the same line. Extreme mechanical loads encountered by parts of machinery, such as gears and bearings, may also constitute harsh conditions. Extreme chemical potential gradients (chemical variation across interfaces/surfaces) can be encountered in multi-material structures, including multi-material systems used for lightweighting. Stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits will require new materials and new processing solutions.

For further discussion of the applications, challenges, and opportunities for materials in harsh environments from an energy perspective, see the *2015 QTR Technology Assessment 6H: Materials for Harsh Service Conditions* (the link to this assessment is provided below under "Related Resources" to Section 3.1.4).

Objective:
Advance technologies that increase the durability and reduce the cost of materials and components operating in harsh and extreme environments (e.g., high temperature, corrosive, hydrogen, and radiation) to enable technologies that lower energy use and greenhouse gas emissions.

Challenges and Barriers:

- **Manufacturing**: Conceptual solutions for materials exist for virtually any harsh condition, but the pathway to manufacture them cost effectively does not. Cost-effective manufacturing includes production of materials and assembly of parts which requires integration of materials in structures (joining, coating, sealing, lubrication, etc.) and consideration of the supply chain (e.g., raw material flexibility and recycling or reprocessing after end of use).
- **Fundamental understanding of extreme and complex conditions:** Material degradation ranging from gradual performance loss to catastrophic failure can result from a complex combination of conditions which is difficult to replicate experimentally or predict computationally. Current barriers include lack of in-situ characterization technologies; poor understanding of time dependence of reactions and transformations under non-steady state conditions; lack of predictive capability in a multi-scale environment; and a lack of data and informatics for integrated computational materials engineering.
- **Materials discovery**: Accelerated materials discovery is needed to meet the demands for future power systems. Surfaces and interfaces are the first line of defense against chemical attack, tribological and contact mechanical loads, and thermal resistance. Bulk structures need to be resilient against temperature, creep, un-desired phase changes, and other micro-structural changes.
- **Flexible and clean energy**: The future will inevitably present challenges to materials when a variety of clean power sources play an important role in the grid. Beyond power generation, electrification, CO_2 reduction, and fuel flexibility will require machines and tools operating under new types of harsh conditions.

Targeted Impacts

Focus areas for AMO include (but are not limited to) the developmentof materials that can withstand high temperatures, often in combination with other harsh conditions such as chemically-reactive environments or mechanical loads.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.6. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 4.1: Accelerate by 50% the ability to predict a material's response (microstructure and properties) to a change in conditions

Harsh operating conditions often constitute a complex juxtaposition of a number of extreme conditions, and the design and availability of advanced experimental facilities is key, including *in situ* metrology tools that accurately simulate harsh conditions. Capabilities for multi-scale predictive modeling of micro-structural evolution are also key, and need to go beyond steady-state isothermal conditions in order to capture the effects of transient history and cyclic conditions. To enhance predictive capabilities, novel accelerated test procedures are needed, as is improved access to the wide variety of specialized tests currently available. Predictive models are needed to describe microstructural evolution and property changes at a level of detail beyond existing phenomenological models, many of which are based on steady state and do not consider transient behaviors. Advanced models will also require multi-scale coupling between microstructural evolution and temporal variations in thermal conditions, mechanical loads, and environmental variations.

Target 4.2: Accelerate the process of materials discovery by 50% to improve performance in selected applications or materials classes.

It can take 10-20 years or more for a new material to advance from initial discovery through commercialization.[116] For emerging applications, the development of a new material is often the critical barrier for implementing a more efficient manufacturing process or power plant. Often, the timeline for new materials development exceeds the window of opportunity for new technology development, forcing developers to select known existing materials that may not have all of the desired attributes for their particular application. Accelerating the materials development timeline will require the use of modeling at various scales to identify potential material solutions. A particular challenge will be the development and availability of high-throughput characterization and testing techniques that could be used for screening materials. The research is often application-specific to meet the challenges of emerging mega-trends such as increasing clean energy and electrification.

For example, considering that fossil-fuel-burning power plants will continue to be the predominant source of electricity for the nation for years to come, there is a need to make fossil plants more efficient. Gas and steam turbine power plants could achieve higher efficiencies if they operated at higher inlet temperatures. By raising the hot-side temperature from 1200°F to 1300°F, the efficiency of a Carnot cycle heat engine would increase almost 2%. However, operating temperatures are constrained by the thermal and chemical stability of existing turbine alloys and coatings at high temperatures and pressures. Advanced materials are needed to achieve the temperature and pressure increases required for higher-efficiency turbine operation. Representative examples of activity towards this target include:

- Develop materials for high temperature and pressure steam turbine operation to enable a 100°F increase in service temperature compared to current typical technology and at cost parity.
- Develop a natural gas rod packing seal with a minimum 25% improvement in wear life compared to conventional fluoropolymer-based (e.g., Teflon™) component materials.
- Develop an advanced material seal for natural gas applications that reduces gas emissions by 50% while increasing seal lifetime in natural gas compressors by a factor greater than 2.

[116] Source: *2015 QTR Technology Assessment 6B: Advanced Materials Manufacturing.* This is available online at: http://energy.gov/sites/prod/files/2016/04/f30/QTR2015-6B-Advanced-Materials-Manufacturing.pdf.

Target 4.3: Achieve performance-based cost parity for the manufacture of alternate materials and parts for use in harsh service conditions.

Alternative material solutions could provide the critical material flexibility needed for national security, as well as unique properties not provided by conventional materials in many applications. Achieving cost parity in an alternative material system could include higher cost alloys with better performance as well as lower cost alloys that can achieve the same performance. Materials need to be produced and integrated into structures (joined, coated, lubricated) informed by challenges in supply chain (processing tools, raw materials flexibility, recyclability etc.). This is an opportunity (and challenge) to engage with a network of industries to identify the most rapid way of developing a manufacturing process for a material or part with better performance. Conversely, an opportunity also exists to reduce the manufacturing cost for a currently used material or part. Representative examples of activity towards this target include:

- Develop tailored powders for additive manufacturing for use in high-temperature, high-pressure, high-value applications such as power generation turbine blades.
- Develop manufacturing pathways to extend the temperature operating range of iron-based alloys by 100°F or more for use in heat exchangers as a replacement for nickel-based alloys.
- Develop coatings, surface treatments, and tailored surface layers that provide 50% improvement in wear resistance as indicated by a lower coefficient of friction and a reduction in erosive loss of material, compared to selected baseline components.

Table 3.6 Technical Targets for Technical Area 4: Materials for Harsh Service Conditions

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
4.1	Accelerate by 50% the ability to predict a material's response (microstructure and properties) to a change in conditions.	2025	NCA	Analysis needed	NCA	LC
4.2	Accelerate the process of materials discovery by 50% to improve performance in selected applications or materials classes.	2025	NCA	Analysis needed	NCA	LC
4.3	Achieve performance-based cost parity for the manufacture of alternate materials and parts for use in harsh service conditions.	2025	NCA	Analysis needed	NCA	LC

***Key:** CST = Funded Institute or Hub; PRA = Practices; R&D = Funded R&D Project; NCA = No Current Activity; SBIR = Funded SBIR Project

Related Resources

- *2015 Quadrennial Technology Review (QTR) Technology Assessment 6H: Materials for Harsh Service Environments.* Available online at: http://energy.gov/sites/prod/files/2016/02/f29/QTR2015-6H-Materials-for-Harsh-Service-Conditions.pdf.
- U.S. DOE Workshop: *Materials for Harsh Service Conditions*, November 19-20, 2015. Presentations available online: http://energy.gov/eere/amo/downloads/workshop-materials-harsh-service-conditions-november-19-20-2015.

- S.U. Nimbalkar, et al. *Technologies and Materials for Recovering Waste Heat in Harsh Environments*. Oak Ridge National Laboratory Report No. ORNL/TM-2014/619. December 15, 2014. Available online at: http://info.ornl.gov/sites/publications/files/Pub52939.pdf.
- *The Materials Genome Initiative (MGI)*. Available online at: https://www.mgi.gov/.
- U.S. DOE Office of Science, *Basic Research Needs for Materials Under Extreme Environments*. Report of the Basic Energy Sciences Workshop on Materials under Extreme Environments, June 11-13, 2007. Available online at: http://science.energy.gov/~/media/bes/pdf/reports/files/muee_rpt.pdf.

3.1.5 Advanced Materials Manufacturing

Overview of Technical Area

Advanced Materials Manufacturing (AMM) refers to the research, development, and demonstration of new materials with desirable properties for use in energy saving applications. Current AMO activity in this area focuses on accelerating the development of specific, promising materials – such as stronger, lighter steel, and materials with improved thermal and/or electrical conductivity. Looking ahead, improving the materials research and production process itself represents a major opportunity space with wide-ranging benefits. Conventional materials development, based largely on labor-intensive iterations of synthesizing and testing materials, can take 10-20 years from initial discovery to commercialization of a new material. An advanced system of computational, experimental, and data tools could be employed to research and validate new materials at a significantly accelerated rate. This acceleration of the materials development cycle has vast potential to enable lifecycle energy savings and more efficient clean energy technologies. Lightweight materials that improve vehicle fuel economy, energy conversion materials that improve potential for waste heat recovery, and advanced photovoltaic materials that produce electricity from sunlight exemplify the range of potential benefits across the entire manufacturing supply chain.

AMM can leverage advanced tools to accelerate materials development, including:

- Physics-based process simulations;
- Computational materials engineering to predict microstructural evolution;
- Econometric models;
- Enhanced modeling and simulation technologies, employing high performance computing (HPC), to enable predictive design at a rapid pace and with high accuracy;
- High-throughput experimental processes and validation technologies; and
- Innovative data management and validated analytics.

Collective advances such as these are poised to revolutionize the materials manufacturing process. For further discussion of the applications, challenges, and opportunities for advanced materials and their manufacturing from an energy perspective, see the *2015 QTR Technology Assessment 6B: Advanced Materials Manufacturing* (the link to this assessment is provided below under “Related Resources” to Section 3.1.5).

Objective:
Advance technologies that accelerate the research, development, and demonstration of new materials, on a path towards integration of these materials into applications for cost effective, advanced clean energy technologies.

Challenges and Barriers:

- **Time to develop new materials**: long discovery-to-market timeframe involved in the development of new materials.
- **Detailed knowledge of processing conditions**: the proprietary nature and equipment-unique nature of the production processing conditions can mean that the physics of the processes as well as the detailed boundary conditions may not be known in order to develop comprehensive multi-physics models.
- **Predictive theory and modeling**: high cost and long development times for models with the required predictive capabilities.
- **Experimentation and model validation**: lack of capabilities for the synthesis, characterization, manufacturing scale-up, and performance validation of new materials; lack of in situ metrology and real-time process control.
- **Uncertainty in models**: difficulties in quantifying model uncertainties, which can propagate through linked models or computations.
- **Uncertainty in physical systems**: stochastic nature of point flaws can initiate global material failure.
- **Data volume**: large volumes of data; extensive challenges in digital data management, e.g., for material databases.
- **Demonstrations**: high costs and time requirements of building full-scale demonstration systems.

Targeted Impacts

Focus applications for AMO include materials for use in additive manufacturing, lightweight structural applications, low resistance conductor materials and novel low cost soft magnetic materials to reduce weight, size and losses in transformers, wide bandgap semiconductors, waste heat recovery systems, catalysts, and highly selective membranes with atomically precise pores for water purification, fuel cells, and industrial separation processes.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.7. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 5.1: Develop lightweight metals for light duty vehicles at a strength/weight ratio of at least 200 megapascals (MPa) / grams per cubic centimeter (g/cm^3) at an added cost of no more than $7/kg of weight saved.[117]

Stronger, lighter materials can result in significant lifecycle energy savings through lightweighting and performance advantages in automobiles, buildings, aviation, and machinery. Specifically, research is underway to validate material properties and reduce production costs of a promising variety of steel. The following are examples of specific activities towards achieving this target:

- Produce a coil of advanced high strength steel with a minimum tensile strength of 1200 MPa and minimum elongation of 15%.
- Produce a coil of advanced high strength steel with a minimum tensile strength of 1500 MPa, achieving a continuous processing rate of 8 feet per minute.
- Develop cold formable advanced high strength steel with a minimum tensile strength of 1800 MPa and a > 30% cost and weight reduction over conventionally produced steels.

Target 5.2: Develop scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity.

Materials with improved thermal or electrical conductivity could save energy in manufacturing processes and product use through a variety of applications. For instance, metals with higher electrical conductivity could reduce the amount of electrical materials necessary in certain devices, resulting in lifecycle energy savings through lightweighting in automotive and aerospace applications. Metals with improved thermal conductivity could increase heat exchanger efficiency. These are just two examples of a wide range of lifecycle energy savings that would be made possible by materials with improved conductivity properties, in the manufacturing space and beyond. Recently, significant conductivity improvements in metals such as copper, iron, and aluminum have been achieved through the infusion of carbon nanoparticles into the material. Opportunity spaces exist to apply a similar process to significantly increase the conductivity of numerous alloys. Manufacturing processes are being developed concurrently to ensure materials with improved thermal and electrical conductivity are available for clean energy applications.

- Develop a high-conductivity copper with a 50% higher thermal conductivity and 10% higher electrical conductivity than conventional copper.
- Develop a high-conductivity aluminum with a 50% higher thermal conductivity and 10% higher electrical conductivity than conventional aluminum
- Produce winding metals with a validated 33% reduction in electrical losses compared to conventional conductor materials

Target 5.3: Develop new and advance existing in situ modeling and simulation tools capable of predicting material behavior (e.g., tensile strength, hardness, fatigue strength, corrosion, and toughness) as microstructure evolves during materials processing.

Advanced models and computational tools are needed to link together and expand existing modeling and simulation tools in order to accelerate the materials development process. Integrated computational materials engineering (ICME) is one approach to accomplishing this task of integrating material information and analysis systems. Predicting how material behavior is affected by processing steps, microstructure, size, thermal history, and many other characteristics is incredibly complex. Progress towards more holistic modeling systems could significantly speed up the material design process and aid in predictive design, rather than trial and error. In addition, HPC can be leveraged to rapidly

[117] M. Zaluzec and W. Joost. Materials Technical Team Presentation to National Research Council Committee on Review of the U.S. DRIVE Partners. June 2016.

analyze thousands of possible materials before experimentation occurs. The ability to quickly design and optimize materials with desirable properties for use in clean energy applications can enable and accelerate realization of lifecycle energy savings and energy efficiency improvements. The following are examples of specific activities towards achieving this target:

- Conduct projects through the High Performance Computing for Manufacturing (HPC4Mfg) Program focused on materials modeling and prediction to address manufacturing challenges.
- Using an ICME approach, build capability to predict forged alloy structural properties (for example, aluminum – lithium) as a result of the material processing parameters.
- Develop multi-physics models to provide experimentally validated process maps for tailoring microstructure to achieve desired performance for laser powder-bed fusion additive manufacturing.
- Develop data tools and data analytics for use in materials manufacturing.

Target 5.4: Develop new process technologies that can provide production quantities of commercial-scale atomically precise products.

Atomically precise manufacturing refers to the concept of producing macro-scale material components in which individual atoms are positioned exactly relative to other atoms, without impurities or other defects. Defects and inclusions in conventional materials result in substantially inferior properties than what is theoretically possible. For instance, the theoretical strength of most materials is about ten times the strength of the same materials as applied in commercial practice. New advances in material design and manufacturing could result in materials that approach these theoretical strength levels; these materials could be applied to reduce weight and create lifecycle energy savings in automotive and other applications. Other application areas for atomically precise manufacturing include the creation of separation membranes which could greatly reduce the energy intensity of water desalination, or atomically precise catalysts which could greatly reduce the energy required for chemical reactions. The following are examples of specific activities towards achieving this target:

- Develop a new class of separation membrane materials (which achieve thicknesses below 10 nanometers (nm), incorporate molecular pores for 100% selectivity, are atomically flat, and are strongly cross-linked) to increase permeance by 10X over state-of-the-art polymer membranes.
- Develop a new class of atomically precise catalysts for 10,000x improvements in catalytic activity compared to state-of-the-art catalysts, with energy consumption less than 25% over the theoretical limits.
- Develop a sustained program to design and construct nanosystems for automated, programmable, atomically precise manufacturing using positional assembly (“molecular additive manufacturing”).
- Develop molecular additive manufacturing technologies able to produce materials near their theoretical strength (10X above state-of-the-art) for transportation applications (e.g., lightweight structural metals).

Table 3.7 Technical Targets for Technical Area 5: Advanced Materials Manufacturing

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
5.1	Develop lightweight metals for light duty vehicles at a strength/weight ratio of at least 200 MPa/(g/cm^3) at an added cost of no more than $7/kg of weight saved.	2025	R&D, SBIR	153 MPa/(g/cm^3) Cost/Weight: Analysis needed	**Flash Bainite 1500:** 191 MPa/(g/cm^3) [118] Cost/Weight: Analysis needed	LC
5.2	Develop scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity.	2025	R&D	**Thermal:** [119] Cu: 385 W/m K Al: 205 W/m K Fe: 79.5 W/m K **Electrical:** Cu: 100% IACS[120] Al: 61% IACS Fe: 17% IACS	**Thermal:** Research ongoing **Electrical:** Cu Covetics: 133% IACS[121]	EI, LC
5.3	Develop new and advance existing *in situ* modeling and simulation tools capable of predicting material behavior (e.g., tensile strength, hardness, fatigue strength, corrosion, and toughness) as microstructure evolves during materials processing.	2025	R&D	Analysis needed	Not available	LC
5.4	Develop new process technologies that can provide production quantities of commercial-scale atomically precise products.	2030	SBIR	Analysis needed	Research ongoing	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6B: Advanced Materials Manufacturing.* Available online at:http://energy.gov/sites/prod/files/2016/04/f30/QTR2015-6B-Advanced-Materials-Manufacturing.pdf.
- Argonne National Laboratory, Covetic Materials, AMO Program Review Meeting May 28-29, 2015. Available online at: http://energy.gov/sites/prod/files/2015/06/f23/P4-Balu_Covetic%20Materials_AMO%20RD%20Program%20Review_2015_0.pdf.

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118 "Flash Bainite" ultimate tensile strength information available at: http://www.flashbainite.com/products/flash-tubing.html; "Flash Bainite" cost estimate information available at http://www.flashbainite.com/about/cost.html.

119 Table of Thermal Conductivity. Available online at: http://webcache.googleusercontent.com/search?q=cache:http://hyperphysics.phy-astr.gsu.edu/hbase/tables/thrcn.html.

120 International Annealed Copper Standard (IACS) is a unit of electrical conductivity for metals and alloys relative to a standard annealed copper conductor. The conductivity of annealed copper is defined to be 100% IACS.

121 U. Balachandran. "High Performance Electrical and Thermal Conductors." Argonne National Laboratory, Presentation at the 2016 AMO Program Review, June 14 -15, 2016. Available online at: http://www.energy.gov/sites/prod/files/2016/07/f33/R1a%20-%20High%20Performance%20Electrical%20and%20Thermal%20Conductors%20ANL%202016_compliant_0.pdf.

3.1.6 Additive Manufacturing

Overview of Technical Area

Additive manufacturing (AM) involves the deposition of materials layer-by-layer or point-by-point to fabricate complex components directly from computer-aided design models,[122] in contrast to conventional subtractive manufacturing methods that involve the removal of material from a starting work piece. These new techniques, while still evolving, are projected to exert a profound impact on manufacturing. They can give industry new design flexibility, reduce lifecycle energy use, and shorten time to market.[123] For further discussion of the applications, challenges, and opportunities for additive manufacturing from an energy perspective, see the *2015 QTR Technology Assessment 6A: Additive Manufacturing* (the link to this assessment is provided below under "Related Resources" to Section 3.1.6).

Objective:
Advance additive manufacturing technologies that (1) increase the reliability at which parts can be produced at specifications required by industry, (2) increase the range of high-performing materials and processes, and (3) advance characterization and modeling techniques for qualification and certification of parts, in order to reduce lifecycle energy use and costs and enable more innovative products compared to conventional manufacturing methods.

Challenges and Barriers:

- **Process control:** feedback control systems and metrics to improve precision, reliability, and quality.
- **Tolerances:** micron-scale accuracy.
- **Surface finishes:** finishes to achieve desired tribological and aesthetic properties.
- **Processing speed:** high-throughput additive processing methods to compete with conventional techniques.
- **Scalability:** capabilities for large-volume production, both in size and number of parts produced.
- **Materials compatibility:** new metal and polymer materials formulated for additive manufacturing, providing application-specific properties such as flexibility, conductivity and transparency.
- **Modeling:** physics-based models to understand the fundamentals of additive processes, especially for multi-material and multi-phase systems and interfaces.
- **Validation and demonstration:** established material properties for additive manufacturing materials and qualification of manufactured components.

Targeted Impacts

Focus applications for AMO range from small components to large structures in the transportation, energy production, manufacturing, and buildings sectors. In manufacturing this includes tools and molds that can achieve greater productivity at the facility level, and enable distributed manufacturing that can improve supply chain efficiency. AMO also collaborates with federal programs supporting aerospace and defense applications in order to advance the technology.

AMO Approach

AMO invests in collaborative R&D technology projects that advance fundamental additive manufacturing unit operations to enable broader uptake by industry and encourage uptake of additive technologies through R&D consortia. Technical targets for this activity area with current status are summarized in Table 3.8. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 6.1: Demonstrate AM components whose physical properties and cost/value outperform selected conventionally produced parts by 20%.

AM parts often cost twice as much as conventionally manufactured parts and have lower structural performance.[124] Most materials currently used in additive processes have composition and properties optimized for traditional manufacturing such as casting and forging. Unlike conventional manufacturing processes, AM techniques enable selective thermal processing, which can reduce process heating energy requirements, and spatially-dependent modification of the texture or microstructure within a component, which can increase performance. To fully leverage these benefits, AM specific

[122] Oak Ridge National Laboratory Manufacturing Demonstration Facility: Strategic Plan 2016 – 2021.
[123] "Wohlers Report 2014 – 3D Printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress Report." Wohlers Associates, 2014.
[124] Douglas S. Thomas and Stanley W. Gilbert. *Costs and Cost Effectiveness of Additive Manufacturing*. NIST Special Publication 1176. December 2014. Available online at: http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf.

chemistries in polymers, ceramics, and metals must be matched with tailored process controls. Optimized fiber orientation (in polymer, metal, or ceramic composites) or tailored grain structure, size, shape, and orientation (in metals) could lead to improved mechanical design based on microstructural engineering. Implementing these concepts reliably will require not only new material development, but also improvements in process science, characterization and metrology techniques, and controls specific to AM processes. For example, actions that can help achieve this target include the following:

- Develop polymer AM materials designed for composite tooling and autoclave survivability.
- Develop a nickel superalloy suitable for land-based gas turbine applications with high temperature stability to enable higher efficiency than current conventional production allows.
- Develop bio-derived reinforced polymers that can replace traditional, energy and emissions intensive materials such as 6000-series aluminum alloys.
- Develop new aluminum alloys designed for AM with mechanical properties appropriate for lightweight automotive and aircraft applications.
- Develop a suite of computational tools that enable optimized designs based on microstructure control.

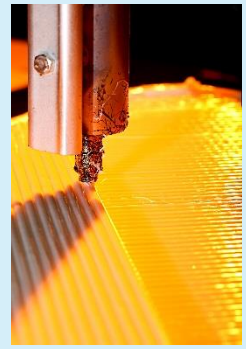
Target 6.2: Develop rapid qualification methodologies that reduce certification cost to 25% of the total component cost.

Few AM components are currently being used in production environments due to the challenges and costs associated with the certification and qualification of components. DOE study found that cost of certification can limit application even when production is cost-effective.[125] To overcome this barrier, the AM industry needs a material- and technology-agnostic framework to collect, analyze, and interpret process and performance data to advance the understanding of AM. These advances could save time and energy in AM processing by improving reliability and yield, while enabling higher-performance components with lower overall lifecycle energy impacts. For example, actions that can help achieve this target include the following:

- Demonstrate rapid qualification methodologies for melt processing of polymers and metallic alloys with automatic defect detection and process evaluation from in-situ process metrology.
- Extend qualification tools to incorporate the characterization data emerging from coordinate measurement, nondestructive tomography, and optical, electron, and other microscopy/spectroscopy characterization techniques.
- Incorporate machine learning and data mining to enable computationally efficient data analytics and visualization of multiple spatial-temporal datasets including in-situ thermal and optical measurements, design and build files, machine logs, and ex-situ characterization of residual stress and distortion.
- Integrate physics-based computational modeling with qualification tools to augment and extend certification capabilities for complex geometries.

[125] S. Nimbalkar, K. Visconti, and J. Cresko. "Life Cycle Energy Assessment Methodology and Additive Manufacturing Energy Impacts Assessment Tool." Presented at the American Center for Life Cycle Assessment Conference, San Francisco, CA, October 2014.

Manufacturing Demonstration Facility



The Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL) is DOE's first research facility established to provide industry with affordable and convenient access to infrastructure, tools, and expertise to facilitate rapid adoption of advanced manufacturing technologies. The mission of the MDF is to develop and aid the deployment of additive manufacturing (AM) and composite technologies within U.S. small-, medium-, and large-scale industries for clean energy applications. Goals of the MDF include:

- Improved Performance Characteristics of AM Components;
- Qualification and Certification of AM Components for Intended End Use;
- AM Systems Optimized to Achieve Mainstream Manufacturing Applications; and
- Comprehensive Understanding of AM Process Capabilities and Limits.

The MDF is supported and managed by DOE's Advanced Manufacturing Office, which is also a member of the America Makes Government Advisory Board. America Makes is the NNMI dedicated to additive manufacturing, with the U.S. Department of Defense leading Federal involvement.

- Deploy rapid qualification tools to collaborating organizations in order to test the characterization frameworks on a wide variety of processes and materials while generating additional data for model calibration and validation.
- Develop accelerated long-term testing procedures for qualifying AM materials and AM-built components

Target 6.3: Develop next-generation AM systems that deliver consistently reliable parts with predictable properties to six standard deviations ("six-sigma") for specific applications.

AM systems are limited by the costs of materials, rates of fabrication, reliability of processes, integration with other processes, and limitations in layer-by-layer deposition. Next generation systems must incorporate controls, hardware, feedstock condition, and software to develop new machines with high deposition rates, large build volumes, and improved properties while also performing more reliably than existing systems. Reliability is necessary for commercial viability of AM products that can provide lifecycle energy benefits, and it can also increase material efficiency in the manufacturing sector by reducing waste and scrap. For example, actions that can help achieve this target include the following:

- Demonstrate macroscale defect-free manufacturing of both multi-material and metal parts that exceed 1000 pounds (lbs.).
- Demonstrate full closed loop control with error detection and quality assurance and quality control (QA/QC) on large-scale additive manufacturing systems.
- Achieve six sigma process reliability on AM systems through a combination of defect detection and adaptive process controls that respond locally to build conditions.
- Develop the tool path generation software and kinematic system capable of 5-axis AM without the need for support structures and with variable nozzle size for surface finish.
- Develop and demonstrate a large-scale hybrid AM system capable of 5-axis manufacturing of multiple materials (polymer, carbon fiber, ceramic, and metal).

Table 3.8 Technical Targets for Technical Area 6: Additive Manufacturing

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
6.1	Demonstrate AM components whose physical properties and cost/value outperform selected conventionally produced parts by 20%.	2025	CST	Components belonging to 7 niche supply chain scenarios[126]	Research ongoing	EI, LC
6.2	Develop rapid qualification methodologies that reduce certification cost to 25% of the total component cost.	2025	CST	50%[127]	Research ongoing	EI, LC
6.3	Develop next-generation AM systems that deliver consistently reliable parts with predictable properties to six standard deviations ("six-sigma") for specific applications.	2025	CST	Best-in-class AM technology delivers reliability on the order of one-sigma, e.g., 68% success rate.	Research ongoing	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6A: Additive Manufacturing*. Available online at: http://energy.gov/sites/prod/files/2015/11/f27/QTR2015-6A-Additive%20Manufacturing.pdf.
- Manufacturing Demonstration Facility website: http://web.ornl.gov/sci/manufacturing/mdf/.
- America Makes website: https://www.americamakes.us/index.php.

[126] Zack Simkin and Anna Wang. "Cost-Benefit Analyses." *Wohlers Report 2015: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report*. Ed. Terry, T. Wohlers and Tim Caffrey. Wohlers Associates, 2015. Available online at: http://senvol.com/wp-content/uploads/2015/05/Senvol_2015-Wohlers-Report.pdf.

[127] Christopher Holshouser, Clint Newell, Sid Palas, Chad Duty, Lonnie Love, Vlastimil Kunc, Randall Lind, Peter Lloyd, John Rowe, Ryan Dehoff, William Peter, and Craig Blue. "Out of bounds additive manufacturing." *Advanced Materials & Processes:171(3).* March 2013. Available online at: http://web.ornl.gov/sci/manufacturing/docs/AM&P_March%202013_cvr_w-articles.pdf.

3.1.7 Composite Materials

Objective:
Advance composite material production technologies that (1) reduce embodied energy and greenhouse gas (GHG) emissions and (2) reduce cost of composites to be competitive with current materials and manufacturing methods, to enable widespread use of composite materials in clean energy applications.

Overview of Technical Area

Lightweight, high-strength, and high-stiffness composite materials have been identified as an important cross-cutting technology in U.S. manufacturing. These materials have the potential to improve the energy efficiency of the transportation sector, enable more efficient power generation, improve the storage and transport of low-carbon fuels, and improve manufacturing processes.[128] In order to reach this potential, advanced manufacturing techniques are required that will enable an expansion of cost-competitive production of composite materials at commercial volumes. For further discussion of the applications, challenges, and opportunities for composite materials from an energy perspective, see the *2015 QTR Technology Assessment 6E: Composite Materials* (the link to this assessment is provided below under "Related Resources" to Section 3.1.7).

Targeted Impacts

Targeted markets are high volume carbon, glass and emerging fiber composite manufacturing with end use applications including lightweight vehicles, compressed gas storage, wind turbine blades, and industrial applications (such as high temperature insulation and membranes). Composites are a cross cutting technology that can benefit lightweighting of structural and non-structural components in a range of transportation applications, including automobiles, rail cars, and aircraft. Composites enable fuel storage for low carbon hydrogen and compressed natural gas in stationary applications. Power generation from renewable sources such as wind, hydropower, and solar can benefit from lightweight composite materials.

Challenges and Barriers:

- **Material costs**: high raw material costs, particularly for fiber precursors.
- **Scalability**: lack of generally applicable, high-production-volume manufacturing methods for composite materials and components.
- **Production speeds**: long cycle times and low throughputs for composite part manufacturing, including joining techniques.
- **Manufacturing energy intensity**: high raw material embodied energy and manufacturing energy requirements, reducing some of the energy advantages of lightweighting.
- **Recyclability**: difficulty in separating fiber reinforcements from cured thermoset matrix materials; inferior mechanical properties in recycled materials compared to virgin products; immature infrastructure for collecting and re-using composite materials at end-of-life.
- **Validation and In-line diagnostics:** lack of standard performance validation techniques for crashworthiness and other safety-critical applications; lack of low cost high speed in-line diagnostics for quality control to minimize defects in materials and components.
- **Prognostics:** lack of established design protocols and reliable end-to-end predictive modeling techniques for composite materials and components.

AMO Approach

AMO activities in composite materials are expected to drive progress towards the objective. To assess progress, technical targets for this activity area with current status are summarized in Table 3.9. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 7.1: Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.

The substitution of composite materials for traditional structural materials such as steel has the potential to provide lifecycle energy savings in many applications – for example, the use of lightweight composites in vehicles can provide fuel savings during vehicles' use. However, material cost is a major barrier to the use of composite materials in many industrial or high volume commercial applications.

[128] *Materials: Foundation for the Clean Energy Age.* The Minerals, Metals, and Materials Society (TMS). Sponsored by AMO/U.S. DOE and contracted through ORNL. In cooperation with ASM International and The Energy Materials Initiative. Available online at: http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf.

Key raw materials used in composites manufacturing – such as carbon fiber precursors – are specialty, non-commodity products made by relatively few manufacturers globally. Additionally, labor costs can also be high since composite parts are often manufactured through manual lay-up processes. Scale of production and production speed is also a barrier related to cost, as discussed in Target 7.2. For example, actions that can help achieve this target include the following:

- Develop an automotive-grade carbon fiber (minimum 25 megapounds per square inch (msi) stiffness and 250 kilopounds per square inch (ksi) tensile strength) at pilot scale with >10% projected cost reduction at full scale based on modeled results compared to 2015 baseline.
- Optimize material usage through improved design to reduce cost and use of low scrap processes

Target 7.2: Develop composite molding manufacturing process with <1.5 minutes part-to-part cycle time for a structural component with surface area >0.5 square meters (m^2)

Scalability and production speed are additional challenges for composite materials. Typical manufacturing processes do not meet the cycle time and production throughput requirements of high volume industries like automotive for structural applications. The long cycle times for composites can be partially attributed to the extended curing times for thermoset resins used in many composites, and partially attributed to the need for manual operations such as hand lay-up or sub-optimal automation. Stacking, alignment, cutting, and kitting of the preform fabrics that create a preformed part are critical steps in assuring quality components and are still ongoing challenges in manufacturing at high speed. These long cycle times are a barrier to commercial viability of lightweight composites in high volume industries, where they could provide lifecycle energy benefits. For example, actions that can help achieve this target include the following:

- Develop composite component fabrication technologies that do not rely on hand lay-up, thereby reducing cycle time on large composite structures by 50% compared to 2015 typical technologies.
- Develop automated molding processes for thermoset and thermoplastic polymer systems with a cycle time of less than 90 seconds at laboratory scale.

Target 7.3: Develop manufacturing technologies that reduce the embodied energy and production-associated greenhouse gas (GHG) emissions of carbon fiber reinforced polymer (CFRP) by 75% compared to 2015 typical technology.

From an energy perspective, the high embodied energy of composite materials can severely restrict the lifecycle energy benefits of these materials, since the fuel energy savings from the use of lightweight materials must offset the production energy before net energy savings can begin to accumulate. Carbon fibers, for example, are produced from a high-embodied-energy precursor material, and the conversion process is also energy intensive as a result of extensive process heating operations required to oxidize and carbonize the precursor fibers using today's technologies. More energy efficient manufacturing processes for carbon fiber conversion could enhance the lifecycle energy benefits of these materials. Optimization of material usage within the design of components is also an area of opportunity. High scrap rates also contribute to the high-energy content of a final component, and material efficiency improvements represent another key opportunity area. For example, actions that can help achieve this target include the following:

- Demonstrate a low-waste textile preforming process optimizing material use and reducing embodied energy of the component.
- Develop a low-cost manufacturing process for carbon fibers utilizing Joule heating of polyacrylonitrile (PAN) or carbon nanotube precursors, and demonstrating potential to reduce energy consumption by 25%.
- Demonstrate an induction-based, out-of-autoclave forming and curing process for carbon fiber reinforced composites suitable for aerospace applications that yields energy savings of at least 25% compared to 2015 typical technologies.
- Develop a process for composite manufacturing using new, lower-energy carbon fibers resulting in an embodied energy reduction of at least 50% as an intermediate target.

Institute for Advanced Composites Manufacturing Innovation (IACMI)

The Institute for Advanced Composites Manufacturing Innovation (IACMI), launched in 2015, is the fifth Institute in the Manufacturing USA network. Researchers at IACMI are working to develop lower-cost, higher-speed, and more-efficient manufacturing and recycling processes for advanced composite materials. IACMI research, development, and demonstration projects are performed through industrial partnerships under five technology focus areas:

- Composite Materials and Processes;
- Compressed Gas Storage;
- Design, Modeling, and Simulation;
- Vehicles; and
- Wind Turbines.

Overarching goals of IACMI include lowering the overall manufacturing costs of advanced composites by 50%, reducing their energy intensity by 75%, and increasing composites recyclability to at least 95% by 2025. IACMI is supported by the Advanced Manufacturing Office under a cost-share model.

Target 7.4: Demonstrate technologies at a pilot scale that recycle or reuse >95% of fiber reinforced polymer composites into useful components with projected cost and quality competitive with virgin materials.

Recycling is a key strategy to increase material efficiency in the supply chain, as recycling extends the use of a given quantity of raw material and reduces the amount of material going to landfills. However, composite materials pose unique recycling challenges as a result of their heterogeneity and lack of an established recycling/reuse infrastructure. In cured thermoset composite systems (such as epoxy-based composites), separation of the reinforcement material from the matrix is particularly difficult. Recycling technologies (such as pyrolysis and mechanical grinding) typically degrade the fiber properties, and the recycled fibers must be used in less demanding applications compared to the virgin product. Thermoplastic composites can be recycled more readily (generally by remelting and remolding directly), but these materials represent a relatively small portion of the composites market. In addition, a recycling infrastructure is needed for collection and re-use of end-of-life products and to accommodate use of recycled materials in product design and manufacturing. Use of recycled materials with a lower embodied energy content to replace virgin material can also contribute to Target 7.3 (reducing the overall embodied energy of final components). For example, actions that can help achieve this target include the following:

- Determine the business case(s) for reuse of carbon fibers in selected application areas.
- Evaluate feasibility of a thermoplastic-based (recyclable) carbon fiber composite system for pultruded spar caps for wind turbine blades.
- Incorporate recovered end-of-life carbon fibers (at least 50% of original material) into a prototype part as an intermediate target.

Target 7.5 (Stretch Goal): Develop fiber-reinforced polymer composites with projected cost and embodied energy parity with 2015 typical glass fiber composites and with performance of carbon fiber composites.

Glass and carbon fibers are both widely used as reinforcements in composite materials, each having their own advantages: glass fibers are relatively low-cost and have low embodied energy, while carbon fibers offer higher strength and stiffness. Novel and emerging reinforcement materials may offer their own unique advantages. For example, natural fibers could provide major energy and environmental benefits, particularly if they could match the performance of carbon fibers or the cost of glass fibers with a lower embodied energy content. Additional opportunities may include clean-sheet redesigns of composite products to take advantage of their unique properties, including optimizations of fiber ratios and fiber positioning to maximize mechanical properties where strength or stiffness are needed most. These optimized composite products could provide lifecycle energy benefits, for example by enabling a lower product weight (and corresponding fuel savings) in transportation applications. For example, actions that can help achieve this target include the following:

- Establish processing capabilities for bio-based or natural fibers with (1) ash content below 500 parts per million (ppm), (2) room temperature thermal conductivity below 0.35 W/m-K, and (3) flexural strength greater than 1 MPa.
- Complete analysis to identify remaining technical challenges and opportunities in the composites space.

Table 3.9 Technical Targets for Technical Area 7: Composite Materials

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline[129]	Progress to Date	
7.1	Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.	2025	CST, R&D	Auto: $55-$78 per kg[130] Wind: $16 per kg[131] Press. Vess: $36 per kg[132]	Auto: Research ongoing Wind: Research ongoing Press. Vess: Research ongoing	EI, LC
7.2	Develop composite molding manufacturing process with <1.5-minute part-to-part cycle time for a structural component with surface area $>0.5m^2$.	2020	CST	3.5 - 9.0 minutes depending on component and process[133]	Research ongoing	EI, LC
7.3	Develop manufacturing technologies that reduce the embodied energy and production-associated GHG emissions of carbon fiber reinforced polymer (CFRP) by 75% compared to 2015 typical technology.	2025	CST, R&D, SBIR	Auto: 94-1409 MJ/kg[134] Wind: 131 MJ/kg[134] Press. Vess: 2247 MJ/kg[134]	Auto: Research ongoing Wind: Research ongoing Press. Vess: Research ongoing	EI, LC
7.4	Demonstrate technologies at pilot scale that recycle or reuse >95% of fiber reinforced polymer composites into useful components with projected cost and quality competitive with virgin materials.	2025	CST	Analysis needed	Research ongoing	EI, LC
7.5	Stretch Goal: Develop fiber reinforced polymer composites with projected cost and embodied energy parity with 2015 typical glass fiber composites and with performance of carbon fiber composites.	2025	CST, R&D	**Cost:** Auto: $25 - $78 per kg of part weight Wind: $16 per kg of part weight Press. Vess.: $35 per kg of part weight **Embodied Energy:** Auto: 94-1410 MJ per kg of part weight Wind: 131 MJ per kg of part weight Press. Vess.: 773 MJ per kg of part weight	Research ongoing	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review Technology Assessment 6E: Composite Materials.* Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6E-Composite-Materials.pdf.

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[129] Modeled baseline cost.

[130] Price range and embodied energy range corresponds to injection overmolding of doors with glass fiber reinforced composites at the low end and increasing all the way up to the top of the range for compression molding of inner hood with carbon fiber composites.

[131] Based on vacuum assisted resin transfer molding of a 61.5m spar cap.

[132] Wet filament winding of high strength, high modulus carbon fiber for 70MPa Type IV H2 pressure vessel, energy estimate includes energy content of HDPE liner, PU dome protection and Aluminum boss.

[133] Brocious, D. "An Integrated Approach to Achieving Widespread Adoption of CFRP in Automotive." Presented at Carbon Fiber 2016, Scottsdale, Ariz., November 9-11, 2016.

[134] Brocious, D., Das, S., Visconti, K., Deo, R. "IACMI Baseline Cost and Energy Metrics." Presentation prepared by IACMI to be Presented at the Members Meeting, Denver, February 1-2, 2017.

- Institute for Advanced Composites Manufacturing Innovation (IACMI) website at: http://iacmi.org/.
- Oak Ridge National Laboratory Manufacturing Demonstration Facility: Carbon Fiber Composites website at: http://web.ornl.gov/sci/manufacturing/research/carbon-fiber/.
- Carbon Fiber Technology Facility (CFTF) website at: https://www.ornl.gov/content/carbon-fiber-technology-facility.

3.1.8 Roll-to-Roll Processing

Overview of Technical Area

Roll-to-roll (R2R) processing is a low-cost, high throughput technique for continuous two-dimensional (2-D) deposition of materials over large areas onto moving webs, carriers, or other substrates. Known also as web processing and reel-to-reel processing, R2R creates products on a roll of flexible plastic, glass, ceramic, composite, or metal foil. R2R enables low-cost production of complex-functional, large surface area devices needed for many clean energy applications and many R2R products cannot be produced using other known techniques. For further discussion of the applications, challenges, and opportunities for R2R processing from an energy perspective, see the *2015 QTR Technology Assessment 6K: Roll-to-Roll Processing* (the link to this assessment is provided below under "Related Resources" to Section 3.1.8).

Objective:
Advance technologies to reduce cost, increase precision, and enable in-line quality control and defect detection, resulting in expanded use of roll-to-roll processing to produce clean energy technologies.

Challenges and Barriers:

- **Continuous processing**: need for low-temperature, continuous processing on flexible substrates, including nontraditional substrates such as stretchable plastics and textiles.
- **Registration and alignment challenges**: lack of reliable, high-speed registration and alignment techniques, particularly for multilayer devices.
- **Scalability**: need for high-throughput and large-area printing/deposition techniques compatible with a wide range of materials, inks, and substrates.
- **Materials compatibility**: need for development of novel aqueous ink and substrate materials compatible with roll-to-roll processing techniques for application-specific properties.
- **Defects in flexible electronics**: defects can cause open and short circuits, leading to device failure; defect avoidance and detection challenging for continuous roll-to-roll processes.
- **Stoichiometry control and bath depletion in electroplating systems**: poor control of stoichiometry in continuous, high-speed coating systems, resulting in non-uniformities and oxidation issues.
- **Availability of materials data**: lack of databases populated with material properties and fabrication process parameters to enable effective modeling and simulation.

Targeted Impacts

R2R processing has applications in the following technology areas:

- **Flexible and integrated hybrid electronics** for solar panels, printed electronics, displays, heater assemblies, thin film batteries, multilayer capacitors and piezoelectrics, smart labels (e.g., radio frequency identification tags and antennas), and thin and thick film detectors and sensors
- **Separation membranes,** such as indoor air quality and dehumidification membranes, gas separation membranes for natural gas processing, hydrogen processing and CO2 capture, forward-osmosis capacitive polarization membranes for water processing, and membranes for fuel cells for both polymer and solid oxide fuel cell (SOFC) electrolytes and conductors.
- **Photovoltaics** for flexible organic and inorganic solar cells, power provision (especially lighting) for buildings, and battery charging.
- **Selective barrier materials** with the ability to control water, air, or temperature for use in applications such as insulating but transparent window films (reflectives, thermochromics and electrochromics), vapor barriers to protect structural components from moisture and prevent corrosion, and composite materials used to increase the performance of structural membranes.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.10. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 8.1: Develop technologies to reduce the cost per manufactured throughput of continuous R2R manufacturing processes for selected products by 50% concurrent with a 10X production capacity increase compared to 2015 typical technology.

This high-value R2R manufacturing target will focus on technologies and methods to improve yields and reduce costs by developing advanced approaches for deposition and processing, precision patterning processes, ever-smaller and finer size scale such as high-resolution in-line metrology techniques, and embodied thermal energy minimization and enhanced cooling. New technologies will be identified that will lead to less energy intensive manufacturing and facilitate scale-up due to reduced factory capital costs. These improved, low-cost R2R technologies could be instrumental to realizing benefits from technologies such as advanced energy-efficient desalination membranes for freshwater production and other membranes related to water production. Challenges to meeting this target include inadequate deposition processes and equipment (process models, nanoscale printing, drying, and new materials for low temperatures), lack of scalability and flexibility of new manufacturing processes, development of new materials and substrates, lack of understanding of the fundamental chemistry and material properties, development of a real-time capability to identify defects with inline monitoring and control, inability to print a vertically interconnected multi-layer material, lack of collaboration and accessibility to demonstration facilities, and high costs for developing new materials applicable to R2R processes. Representative examples of activities towards the target include:

- Increasing throughput of R2R processes by 5 times for batteries (to 50 square feet per minute (50 ft^2/min)) and capacitors and 10 times for printed electronics and the manufacture of other substrates and membranes used in support of these products.
- Developing resolution capabilities to enable registration and alignment that will detect, align, and co-deposit multiple layers of coatings and print < 1 micron (1 µm) features using continuous process scalable for commercial production.
- Developing scalable and reliable R2R processes for solution deposition of ultra-thin (<10 nm) films for active and passive materials.
- Develop in-line multilayer (<1 micron) coating technology on thin films (5 – 10 microns) with yields greater than 95%.

Target 8.2: Develop in-line instrumentation tools that will evaluate the quality of single and multi-layer materials in-process with respect to final product performance and functionality against performance specifications at a 100% level.

Commercial enterprises that incorporate R2R manufacturing processes must detect, control, and otherwise eliminate potential quality issues within products. Technology development to enable higher resolution and increased data capture/processing rates is needed to enhance inspection for mechanical defects, such as pinholes, cracks, and inter-layer delamination and voids, and measurement of electrical properties such as resistance. All data would be integrated into process control and feedback systems; technologies would help correlate defects to performance. Development of in-line quality control would increase productivity, output, and overall product and material quality. The key R&D challenges include attaining uniform thickness and detecting the existence of point defects. Ultimately, processes would use sensing technologies that can assess and map 100% of the material with feedback control. Representative examples of activities towards the target include:

- Developing in-line quality control technologies and methodologies for real-time identification of defects and expected product properties “in-use/application” during continuous processing at all size-scales with a focus on the “micro” and “nano” scale traces, lines, and devices, i.e., <1 µm at 300 ft./min for R2R processing in air and <10 nm at 20 ft./min for vacuum processing.
- Developing technologies to increase the measurement frequency of surface rheology without significant cost increases with a goal of a 10-nanometer in-line profilometry at a production rate of 100,000 square millimeters per minute (100,000 mm^2/min).

Table 3.10 Technical Targets for Technical Area 8: Roll to Roll Processing

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
8.1	Develop technologies to reduce the cost per manufactured throughput of continuous R2R manufacturing processes for selected products by 50% concurrent with a 10X production capacity increase compared to 2015 typical technology.	2025	NCA	Battery Cost: $503/kWh Production: 0.9m2/min PV Cost: $0.65/W - $0.70/W Production: TBD Membranes (Water De-salination) Cost: TBD Production: TBD OLEDs Cost: $1850/m2 Production: 0.03m2/min	NCA	EI
8.2	Develop in-line instrumentation tools that will evaluate the quality of single and multi-layer materials in-process with respect to final product performance and functionality against performance specifications at a 100% level.	2025	NCA	Analysis needed[135]	NCA	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6K: Roll-to-Roll Processing.* Available online at*:* http://energy.gov/sites/prod/files/2016/02/f30/QTR2015-6K-Roll-to-Roll-Processing.pdf.
- Advanced Manufacturing Office: High Value Roll-to-Roll Manufacturing Workshop Summary Report. Available online at: http://energy.gov/sites/prod/files/2016/08/f33/AMO_R2R%20Workshop%20Report%20Final.pdf.
- Review of Defense Display Research Programs website at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.2499&rep=rep1&type=pdf.
- Developing roll to roll manufacturing processes for flexible CIGS photovoltaics website at: http://www.uk-cpi.com/case-studies/developing-roll-to-roll-manufacturing-processes-for-flexible-cigs-photovoltaics/.
- High Value R2R Technology White Paper, US DOE EERE AMO, HV R2R Technology Team, May 2014

[135] Defect modeling which reflects expected performance is on-going for battery materials. Initial efforts from laboratory environment remain to be scaled up.

- “Nanofabrication Technologies for Roll-to-Roll Processing.” Report from the NIST-NNN Workshop, September 27 - 28, 2011. Edited by Jeffrey D. Morse. Available online at: http://www.internano.org/r2rworkshop/wp-content/blogs.dir/4/2012/10/Workshop-Report_Nanofabrication-Technologies-for-R2R_Final.pdf.

3.1.9 Process Intensification

Overview of Technology Area

Process intensification (PI) targets dramatic improvements in manufacturing and processing of chemical products by rethinking existing process designs and operation schemes into ones that are more precise and efficient. PI frequently involves combining separate unit operations (such as reaction and separation) into a single piece of equipment, resulting in a more efficient, cleaner, and more economical manufacturing process. PI optimizes and improves process performance by focusing on molecular level kinetics, thermodynamics, and heat and mass transfer, helping to reduce the number of discrete equipment needed, lower facility footprints, reduce energy consumption, minimize process complexity, and reduce cost and risk in chemical manufacturing.

Next generation PI technologies will support the development of new processes to enable innovative business models and provide new opportunities to manufacture better products while efficiently utilizing abundant domestic energy resources. PI technologies supplement the implementation of related manufacturing applications, including just-in-time and distributed manufacturing, as well as modularization for scale-up and improved construction and integration. For further discussion of the applications, challenges, and opportunities for process intensification from an energy perspective, see the *2015 QTR Technology Assessment 6J: Process Intensification* (the link to this assessment is provided below under "Related Resources" to Section 3.1.9).

Objective:
Advance technologies that significantly improve industrial process productivity and energy efficiency through optimized molecular level kinetics, thermodynamics, and heat and mass transfer.

Challenges and Barriers:

- **Equipment capital costs**: high possible expenditures for replacing equipment.
- **Multifunctional systems**: few degrees of freedom for integrated systems control compared to single-purpose process equipment.
- **High selectivity separations**: lack of sufficiently selective low-energy separation agents (e.g., membranes and molecular sieves) to replace energy-intensive distillation and evaporation.
- **High throughput separations**: lack of separation methods with sufficient throughput (flux, loading capacity, etc.) to meet economic viability.
- **Alternative energy**: lack of cost effective technical pathways relative to existing sources for processes using alternative energy (e.g., ultrasound and microwave).
- **Modeling and simulation**: lack of integrated predictive tools at multiple scales to better understand molecular level interactions.

Targeted Impacts

The main focus for AMO effort is in chemicals and fuel (petroleum and biomass based) manufacturing, given the large energy consumption of these sectors. However, applications for PI technologies crosscut other energy-intensive industries such as metals manufacturing; forest products manufacturing; oil and gas production, capture, conversion, and spill remediation; food and beverage manufacturing; and other related industries.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.11.The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section. Advanced modeling and simulation at various scales and use of high performance computing will be key as well in the development of PI technologies.

Target 9.1: Develop process intensification technologies with an order of magnitude energy intensity (kJ/kg) improvement relative to 2015 typical technology.

The chemicals industry is the second-largest energy consuming industry in U.S. manufacturing (after petroleum refining). In 2010, 11 chemicals (which have significant opportunities for energy savings via implementation of PI technologies) accounted for 43% of chemicals industry onsite energy consumption.[136] Many PI technologies are still in

[136] *2015 QTR, Chapter 6, Technology Assessment 6J: Process Intensification.* Available online at: http://energy.gov/sites/prod/files/2015/11/f27/QTR2015-6J-Process-Intensification.pdf.

the early stages of technology readiness, and development and demonstration of these technologies can help to increase their potential for near- and long-term energy use reduction across the chemical and other industries. An example of a specific action that can help achieve this target is:

- Demonstrate process intensification technology at pilot-scale with >20% energy intensity (kJ/kg) improvement relative to 2015 typical technology.

Target 9.2: Develop modular process intensification technologies that double energy productivity (economic output per unit energy input).

Traditional manufacturing typically involves large, centralized facilities. PI offers a way to develop smaller, modular equipment, which has the potential to reduce waste, energy use, and capital and operating costs, while increasing product yields compared to existing state-of-the-art processes. New PI technologies need to overcome process conditions and barriers to entry to be effective such as high temperatures or corrosive environments that can lead to fouling of membranes, degradation of catalysts, and the lack of predictive design tools for new processes and equipment must be considered and overcome. An example of a specific action that can help achieve this target is:

- Demonstrate at pilot scale at least one modular chemical process that has a 10x reduced capacity cost ($ / (kg per day)) with improved energy intensity (kJ/kg) and 20% lower emissions and/or 20% lower environmental waste (kg waste / kg product) relative to commercial state-of-the-art technology.

Modular Chemical Process Intensification Institute for Clean Energy Manufacturing

In May 2016, the Energy Department issued a funding opportunity announcement for a Clean Energy Manufacturing Innovation Institute for Modular Chemical Process Intensification as a part of the broader Manufacturing USA network. The Institute will focus on breakthrough technologies to dramatically improve the energy efficiency of novel manufacturing processes and enable development of modular processes. The Institute's proposed research, development, and demonstration projects will be performed through industrial partnerships under five technology focus areas to impact multiple industries:

- Methods, tools, technical know-how, and equipment for modular intensified chemical processes;
- Development and test-bed demonstration of intensified integrated process modules;
- Module manufacturing applied research, development, and demonstration;
- Applied research, development, and knowledge dissemination of cross-cutting PI technologies; and
- Development of open-architecture, open-standard, and open-source (when possible) software and design tools.

Target 9.3: Develop modular process intensification technologies with capital and operating cost parity relative to 2015 state of the art for selected existing processes.

An overarching goal is to apply PI methods to develop smaller, modular equipment, which, as noted above, can reduce waste, energy use, and capital and operating costs when compared to the state-of-the art technology. Many of these modular solutions have higher costs than typical centralized chemical production methods. As noted by a 2007 European PI roadmap, overall cost competitiveness is a major focus for innovation of PI technologies, but specialty chemical and pharmaceutical manufacturers may value selectivity, yield, and processing time over cost reductions.[137] Reducing the cost of modular PI processes may help to increase the adoption by both large and small producers. For example, actions that can help achieve this target include the following:

- Develop tools and technologies to reduce the cost to deploy modular chemical process intensification in selected existing processes by 50%.
- Develop modular technologies that will convert natural gas from remote and stranded sources to liquid fuels or chemicals at conversion rates >40%.

Target 9.4: Develop technologies that optimize catalyst conversion rates, selectivity, activity, and stability and enable at least 20% improvement in energy intensity compared to 2015 state-of-the-art technology.

[137] Creative Energy. *European Roadmap for Process Intensification*. 2007. Available online at: http://efce.info/efce_media/-p-531.pdf?rewrite_engine=id.

PI technologies often involve the combination of reactors and separators into one combined hybrid unit. In these hybrid systems, catalysts determine the efficiency, yield, and selectivity that can be achieved in chemical conversions. Thus, enhancements in catalysis research are integral to PI.[138] Improved catalysts for use in PI reactor-separation systems will allow for higher conversion rates of chemical inputs, increasing product outputs and improving overall energy intensity. For example, actions that can help achieve this target include the following:

- Develop selective active site catalysts to handle diverse feedstock streams to produce only the class of products desired at conversion rates >40%.
- Develop methane direct activation catalysts that will convert natural gas from remote and stranded sources to liquid fuels or chemicals at conversion rates >40%.
- Develop oxygen-air separation catalysts that will produce a 99% pure oxygen stream at a 50% reduction in capital cost compared to 2015 state-of-the-art technologies.
- Develop water splitting catalysts that will produce hydrogen at a 50% reduction in capital costs compared to 2015 state-of-the-art technologies.

Table 3.11 Technical Targets for Technical Area 9: Process Intensification

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
9.1	Develop process intensification technologies with an order of magnitude energy intensity (kJ/kg) improvement relative to 2015 typical technology.	2030	CST	Process specific. Analysis needed.	Not available	EI
9.2	Develop modular process intensification technologies that double energy productivity (economic output per unit energy input).	2030	CST	Process specific. Analysis needed.	Not available	EI
9.3	Develop modular process intensification technologies with capital and operating cost parity relative to 2015 state of the art for selected existing processes.	2030	CST	Process specific. Analysis needed.	Not available	EI
9.4	Develop technologies that optimize catalyst conversion rates, selectivity, activity, and stability and enable at least 20% improvement in energy intensity compared to 2015 state-of-the-art technology.	2030	CST, R&D, SBIR	Process specific. Analysis needed.[139]	Research ongoing	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6J: Process Intensification*. Available online at: http://energy.gov/sites/prod/files/2015/11/f27/QTR2015-6J-Process-Intensification.pdf.
- AMO Process Intensification Workshop – September 29 – 30, 2015. Workshop proceedings and summary report available online at: http://energy.gov/eere/amo/downloads/process-intensification-workshop-september-29-30-2015.

[138] *2015 QTR, Chapter 6, Technology Assessment 6B: Advanced Materials Manufacturing*. Available online at: http://www.energy.gov/sites/prod/files/2016/04/f30/QTR2015-6B-Advanced-Materials-Manufacturing.pdf.

[139] Catalytic conversion rates are calculated and then that information is used to calculate energy savings. Higher conversion rates imply lower energy consumption.

- "Energy Department Announces American Institute of Chemical Engineers to Lead New Manufacturing USA Institute." U.S. DOE/EERE. December 9, 2016. Available online at: http://energy.gov/eere/amo/articles/energy-department-announces-american-institute-chemical-engineers-lead-new.

3.1.10 Process Heating

Overview of Technology Area

Process heating operations supply thermal energy needed to transform materials into a wide variety of commodities and end-use consumer products. Over 7 quads of manufacturing energy use annually are related to processes heating (70% of all process energy use), with approximately 36% of that energy lost as waste heat, accounting for over 2,500 TBtu annually.[140] Energy for process heating equipment (e.g., furnaces, heat exchangers, evaporators, kilns, and dryers) can be provided by electricity, steam, and fuels such as natural gas, coal, biomass, and fuel oils.

Advances in process heating technologies can lower manufacturing energy and emissions and associated costs, and also enable the manufacture of improved materials, technologies, and products. For further discussion of the applications, challenges, and opportunities for process heating from an energy perspective, see the *2015 QTR Technology Assessment 6I: Process Heating* (the link to this assessment is provided below under "Related Resources" to Section 3.1.10).

Targeted Impacts

Key opportunity industries include the petroleum refining, chemicals, forest products, iron and steel, and food and beverage manufacturing industries, which collectively account for more than 80% of all process heating energy use in U.S. manufacturing. However, because process heating operations and systems are used throughout manufacturing, improvements would benefit a wide range of industries. In addition, advanced thermal (especially low-thermal and non-thermal alternative) technologies can enable the manufacture of new/improved materials and products not amenable to traditional process heating unit operations.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.12. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 10.1: Develop low-thermal-budget manufacturing technologies that reduce energy intensity (energy consumed per unit of physical output) by at least 50% compared to 2015 typical technology.

While incremental technology advances have improved process heating efficiency, there have been no recent significant, pervasive breakthroughs adopted by industry to reduce energy intensity. Waste heat losses, which can occur at walls, doors, openings, and through venting, are a major consideration in process heating, especially for higher-temperature systems such as in steelmaking and glass melting. Low-thermal-budget and selective heating techniques such as microwave, ultraviolet, and other electromagnetic processing methods, which deliver energy directly where it is needed rather than heating the environment, increase the

Objective:
Advance cost effective technologies for process heating that improve the properties of manufactured products, and develop alternative, low thermal budget technologies that reduce the energy requirements of materials processing.

Challenges and Barriers:

- **Equipment inventory:** Lack of comprehensive and detailed understanding of the demographics (e.g., age, state, utilization capacity) of process heating equipment in the U.S.
- **Electrotechnologies**: currently very limited (<5%) use of electric and hybrid-electric systems for heating, curing, drying, and other operations to take advantage of selective and/or volumetric heating energy benefits.
- **Multi-physics modeling and design tools**: lack of models to optimize energy use and heat transfer in high-temperature applications, including hybrid systems.
- **Sensors and controls**: lack of reliable, robust, and affordable sensors and process controls for use in high-temperature and corrosive environments.
- **Retrofittable technologies**: lack of strategies for integrating new furnace technologies into existing systems to improve performance without major interruptions.
- **Fuel flexibility**: poor compatibility of most process heating systems with a variety of input fuels, including fuel blends and low-heat-value fuels such as waste products.
- **Combustion processes**: lack of understanding of fundamental processes (e.g., turbulent mixing, flue gas stream characteristics, conversion of fuels in catalytic combustion systems).
- **Emissions**: challenges in controlling greenhouse gas and fine particle emissions especially under diverse or varying process conditions.

[140] Supra 18. "Manufacturing Energy and Carbon Footprints (2010 MECS)." AMO/EERE/DOE. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

proportion of useful heat energy delivered to the product, reducing the occurrence of waste heat. In addition, the capability of radiative heat transfer to selectively heat certain materials or product parts can also enable materials transformations and manufacturing operations not attainable by traditional conductive/convective methods. For example, actions that can help achieve this target include the following:

- Evaluate the current breakdown - by application and equipment - of the seven quads of U.S. energy use in process heating, to estimate the energy savings potential and identify technologies with the potential to provide a >50% energy intensity improvement.
- Develop low-thermal-budget electromagnetic (EM) energy sources to improve upon and/or replace current thermal-based heating/drying/curing processes.
- Develop advanced materials characterization techniques and multi-physics modeling related to advanced process heating methods and associated manufacturing platforms (sensors/models/controls) to enable in-situ, noncontact materials measurement for automatic process control.

Target 10.2: Develop advanced process heating unit operations that provide improved properties, quality, and/or product value at cost parity to conventional techniques.

While improving the efficiency of process heating systems will have energy, emissions, and cost saving benefits, other benefits can be realized including improved product properties, quality, and/or value. For example, actions that can help achieve this target include the following:

- Develop hybrid process heating systems that combine energy sources and/or heating principles to optimize energy performance and increase overall thermal efficiency. Optimizing the heat transfer mechanisms in these hybrid systems can significantly reduce energy consumption and increase speed/throughput while also improving product quality.
- Develop electrotechnologies, such as non-ionizing radiation sources including microwave, radio frequency, and induction heating systems, that can offer greater efficiency and enable the manufacture of improved or novel products due to attributes such as selective and volumetric heating. Other electrotechnologies, such as ionizing radiation sources including electron beam and ultra-violet, can directly or indirectly photo-initiate chemical reactions at or near room temperature, enabling desired transformations such as polymerization with significantly reduced energy use.
- Develop furnaces/ovens utilizing high-efficiency high power wide bandgap (WBG) microwave semiconductor devices instead of bulky inefficient magnetrons. Multiple miniaturized microwave sources can direct energy resulting in much more selective or uniform heating, depending on desired configuration.

Table 3.12 Technical Targets for Technical Area 10: Process Heating

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
10.1	Develop low-thermal-budget manufacturing technologies that reduce energy intensity (energy consumed per unit of physical output) by at least 50% compared to 2015 typical technology.	2025	NCA	Analysis needed	NCA	EI
10.2	Develop advanced process heating unit operations that provide improved properties, quality, and/or product value at cost parity to conventional techniques.	2025	NCA	Analysis needed	NCA	LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6I: Process Heating*. Available online at: http://energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf.
- AMO Process Heating Systems website: http://energy.gov/eere/amo/process-heating-systems.
- AMO PHAST tool available online at: http://energy.gov/eere/amo/articles/process-heating-assessment-and-survey-tool.

3.1.11 Smart Manufacturing: Advanced Sensors, Controls, Platforms and Modeling for Manufacturing (ASCPMM)

Overview of Technical Area

Objective:
Advance the development of sensors, controls, platforms and modeling technologies that are interoperable, secure, and able to function under the harsh conditions specific to certain manufacturing facilities, while also making these systems less expensive to deploy than incumbent technologies, in order to aggressively reduce the energy intensity of complex processes through data-driven prediction, control, optimization, and artificial intelligence.

Challenges and Barriers:

- **Value proposition:** reduction of costly infrastructure and staffing/training needed to implement smart manufacturing technologies.
- **Compatibility with existing operations and business structure:** avoidance of interruption of continuous production processes for implementation of sensor and IT technologies.
- **Technical limitations in sensing and control:** instrumentation that can operate reliably and noninvasively in harsh industrial environments.
- **Hardware and software lock-in issues:** forwards and backwards compatible control equipment and software to mitigate retrofitting challenges.
- **Cybersecurity and risk:** resilience to cyberattacks that pose risks to IT-dependent operations.

Applications of advanced networked data and information technologies for manufacturing, referred to here as smart manufacturing or 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. Smart manufacturing will be driven by three main opportunities: 1) Process and operational effectiveness and optimization, 2) digital to physical and physical to digital transformation, and 3) data intelligence and fact based decision making. ASCPMM technologies enable the extensive application of data for the optimization of enterprises and multi-company supply chain ecosystems. Data from advanced sensor systems form the basis for process control applications, decision work flows, and enterprise and supply chain optimization. ASCPMM optimizes manufacturing processes while minimizing excess production at each manufacturing step.[141] A networked, open-architecture, open-access, and open-application data platform combined with "plug-and-play" capabilities enables integration and customization across ASCPMM technologies while ensuring that a standard of performance is met at a low implementation cost. One report projects that, by 2025, factories that adopt ASCPMM technologies could realize energy savings of 10 – 20% and potentially generate an economic impact between $1.2 and $3.7 trillion per year.[142]

Energy management is a critical aspect of smart manufacturing. Many manufacturing facilities have some form of energy management system, such as ISO 50001-2011, which provides a standard process to incorporate energy considerations and energy management into daily operations to improve their energy performance.[143] The DOE Superior Energy Performance (SEP) Program, which is a measurement and verification protocol built upon the ISO 50001 standard, has demonstrated across eleven manufacturing plants an average energy performance improvement of twelve percent compared to business-as-usual within eighteen months of SEP implementation. While such continual process improvement protocols are effective frameworks for managing energy in manufacturing, there is now a need for physical and computational platforms for cost-effectively implementing energy management in real-time across manufacturing processes, facilities, enterprises and supply-chains. For further discussion of the applications, challenges, and opportunities for ASCPMM, see the *2015 QTR Technology Assessment 6C: Advanced Sensors, Controls, Platforms and Modeling for Manufacturing* (the link to this assessment is provided below under "Related Resources" to Section 3.1.11).

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141 Rogers, E. "The Energy Savings Potential of Smart Manufacturing." Research Report IE 1403. Washington, D.C., American Council for an Energy-Efficient Economy. June 2014. Available online at: http://aceee.org/node/3078?id=5205.

142 McKinsey Global Institute. "The Internet of Things: Mapping the Value Beyond the Hype." McKinsey & Company. 2015. Available online at: http://www.mckinsey.com/business-functions/business-technology/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world.

143 ISO 50001 Standard. Available online at: http://www.iso.org/iso/home/standards/management-standards/iso50001.htm.

Targeted Impacts

AMO is especially interested in applying smart manufacturing technologies to energy intensive and energy dependent industries. However, smart manufacturing technologies are expected to be broadly applicable across all sectors as a tool for enhancing productivity, minimizing waste, and enhancing global competitiveness.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.13. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 11.1: Develop advanced sensors, controls, platforms, and models for targeted applications that reduce energy intensity (energy consumed per unit of physical output) by 15% compared to 2015 typical technology.

Advanced sensors are needed throughout manufacturing to withstand harsh operating environments while meeting certain requirements such as packaging for survivability, accuracy, low power consumption, connectivity, and low installation and maintenance cost. New methods are also needed to design and build platform infrastructures that integrate computing and communication capabilities together with the sensing and actuation functions of components. Open-architecture, open-standard, and open-source (when possible) software and communication platforms can enable the needed plug-and-play connectivity to ease integration and customization across components, different manufacturing requirements, and the latest information technology (IT) hardware and standards. The advanced production planning, coordination, and control enabled by the use of these platforms leads to manufacturing energy intensity improvement.

Clean Energy Smart Manufacturing Innovation Institute

The Clean Energy Smart Manufacturing Innovation Institute (CESMII), selected in 2016, is the ninth manufacturing hub in the Manufacturing USA network. The focus of this Institute is the research, development, and widespread industrial adoption of technologies and solutions that can capture, share, and process in real-time the increasing amounts of information available at manufacturing facilities. These technologies are expected to enable dramatically improved process control and operation, and enable benefits such as improved energy efficiency, equipment reliability, productivity gains, as well as related improvements in safety, quality, and yield in manufacturing processes. The CESMII will focus on the following technology areas:

- Advanced Sensors;
- Real-Time Data Analytics and Control Systems;
- Standardized Open Software and Communication Platforms;
- Advanced High Fidelity Modeling; and
- First-of-Kind Application Toolkits for Smart Manufacturing Deployment.

Target 11.2: Reduce the cost of deploying Smart Manufacturing systems (advanced sensors, controls, platforms, and models) in existing processes by 50% compared to 2015 typical technology.

Investments in process control and IT are often viewed as optional and noncritical. The development of real-time data-driven software applications for control, decision making, and/or optimization can be difficult and expensive without understanding the value of data as an asset. There is a critical need for RD&D to enable affordable access to cutting-edge physical and virtual tools, develop expertise to reduce the cost and risk of commercialization, address technical challenges of scale-up, and provide data for business case development Adoption of cost effective technologies and solutions that capture, share, and process the increasing amounts of information in real-time improves data management and can be used to monitor, control and ultimately reduce lifecycle energy impact in many sectors of the economy .

Table 3.13 Technical Targets for Technical Area 11: Smart Manufacturing - ASCPMM

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
11.1	Develop advanced sensors, controls, platforms, and models for targeted applications that reduce energy intensity (energy consumed per unit of physical output) by 15% compared to 2015 typical technology.	2025	CST	Analysis needed	Not available	EI
11.2	Reduce the cost of deploying Smart Manufacturing systems (advanced sensors, controls, platforms, and models) in existing processes by 50% compared to 2015 typical technology.	2025	CST	Analysis needed	Not available	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6C: Advanced Sensors, Controls, Platforms and Modeling for Manufacturing.* Available online at: http://energy.gov/sites/prod/files/2015/11/f27/QTR2015-6C-Advanced-Sensors-Controls-Platforms-and-Modeling-for-Manufacturing.pdf.
- "Unlocking the Potential of the Internet of Things," McKinsey Global Institute. Available online at: http://www.mckinsey.com/business-functions/business-technology/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world.

3.1.12 Waste Heat Recovery Systems

Overview of Technical Area

Waste heat recovery offers significant potential to increase industrial efficiency; approximately 2,500 TBtu/year waste heat remains unrecovered from industrial manufacturing operations.[144] This heat is distributed within a broad temperature range, varying from <450°F to as high as 3000°F. Waste heat is generated from a variety of industrial systems throughout a manufacturing plant. The largest sources of waste heat for most industries are exhaust and flue gases and heated air from heating systems such as high-temperature gases from burners in process heating; lower temperature gases from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. Waste heat is also discharged in the form of hot surfaces, steam leaks, and boiler blow-down water.[145]

Redirected waste heat can serve a number of useful purposes in an industrial facility, including combustion air preheating, boiler feedwater preheating, load preheating, power generation, steam generation, space heating, and water preheating. There are, however, practical limits – both technical and economic – with respect to the recovery potential of waste heat. Factors impacting the feasibility of waste heat recovery options include heat quantity, heat temperature, composition of the waste heat source (e.g., contamination in the flue gas), and logistical constraints such as operating schedules and availability.[146] For further discussion of the applications, challenges, and opportunities for waste heat recovery from an energy perspective, see *the 2015 QTR Technology Assessment 6M: Waste Heat Recovery* (the link to this assessment is provided below under "Related Resources" to Section 3.1.12).

Opportunities for waste heat to power are also covered in the *Combined Heat and Power* Technology Assessment and the *Direct Thermal Energy Conversion* Technology Assessment.

Objective:
Advance technologies for waste heat recovery systems that enable the cost-effective capture and use of energy from industrial waste heat in order to reduce overall energy demands of manufacturing facilities.

Challenges and Barriers:

- **Cleanliness of waste heat streams:** fouling and interference with heat exchange as a result of moisture, particulates, and chemical contamination in waste stream.
- **Lack of end use for waste heat:** certain waste heat streams may have no viable end use within the facility, especially for low-temperature and contaminated gases.
- **Low temperature waste heat:** non-viable recovery for lower temperature (low quality) waste heat streams from cost and energy efficiency standpoints.
- **Ultra-high-temperature waste heat:** special materials required for ultra-high-temperature applications; material and equipment design critical.
- **System maintenance challenges:** lack of cleaning systems to allow on-line or automatic removal of contaminant materials on heat transfer surfaces.
- **Materials availability:** need for low-cost materials compatible with corrosive, high-temperature conditions.
- **Equipment size:** large system footprints make retrofitting challenging in space-constrained facilities.

Targeted Impacts

The most energy-intensive industries provide the greatest potential for waste heat recovery. Sectors with significant waste heat recovery potential include aluminum, cement, chemicals, coatings, food, glass, iron and steel, petroleum refining, and paper industries.[147] Other waste heat recovery applications include advanced heat exchangers for lower temperature waste heat recovery in applications such as building heating and cooling.

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144 Supra 8. MECS website. EIA. Available online at: http://www.eia.gov/consumption/manufacturing/index.php.
145 *2015 QTR: Chapter 6, Technology Assessment 6M: Waste Heat Recovery*. Available online at: http://energy.gov/sites/prod/files/2016/02/f30/QTR2015-6M-Waste-Heat-Recovery.pdf.
146 *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. Industrial Technology Programs, U.S. DOE. Prepared by BCS Incorporated. 2008. Available online at: https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf.
147 *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities.* ORNL. 2014. Available online at: http://info.ornl.gov/sites/publications/files/Pub52987.pdf.

AMO Approach

The primary technical targets for this activity area with current status is summarized in Table 3.14. The rationale for these targets, and AMO's approach for overcoming the key challenges and barriers, are described in this section. Note that AMO's approach for waste heat recovery systems targets the capture of waste heat, and presumes that waste heat is first minimized by other means, e.g., process heating efficiency improvements (see the 2015 QTR Technology Assessment on *Process Heating*). Technologies for direct thermal energy conversion (covered in section 3.1.2) and CHP (covered in section 3.1.13) are interconnected with the waste heat recovery technologies covered in this section.

Target 12.1: Develop enabling technologies for low maintenance, high reliability recovery systems for industrial waste heat streams, and reduce payback period by at least 30% compared to existing systems in various temperature ranges.

Improvements in current waste heat recovery technologies could enable increased deployment in industrial facilities. Industrial users demand equipment lifetimes of several years, low maintenance and cleaning requirements, and consistent and reliable performance. Furthermore, finding adequate space for a heat recovery system can be challenging. In addition, some waste heat streams contain contaminants, necessitating the development of new waste heat recovery system designs and materials. For example, actions that can help achieve this target include the following:

- Develop anti-fouling technologies to remove contaminants from waste heat streams or mitigate build-up of debris on heat exchanger surfaces.
- Develop system designs with smaller footprints that allow installation as a retrofit in applications with limited space in plants.
- Develop low cost, reliable pre-treatment technologies for waste heat recovery systems to remove contaminants from hot input streams (e.g., flue gas).

Target 12.2: Develop material and system advancements to enable greater recovery from high-temperature (>650°C) and heavily contaminated industrial waste heat streams, and cost-effectively utilize 30% of available waste heat in this temperature range.

High temperature (>650°C) waste heat streams represent concentrated sources and a considerable portion of the waste heat from manufacturing operations; a particular problem is when streams contain particles, combustibles and other contaminants which make it difficult to use conventional systems. For these waste heat streams, materials are needed that can withstand high-temperature gases that may be contaminated with particulate matter or corrosive chemicals. For example, actions that can help achieve this target include the following:

- Develop advanced materials that can withstand high temperatures and chemical reactions with the waste heat source and the cyclic nature of waste heat in terms of mass flow rates, temperature, or composition.
- Develop secondary heat recovery systems, which are compatible with the existing equipment, to supplement and enhance the performance of the primary systems.
- Develop new designs and concepts to clean (remove) particulates from high-temperature gases.

Target 12.3: Develop innovative, cost-effective systems to recover heat from low-temperature (<230°C) waste heat sources and successfully utilize 20% of available waste heat in this temperature range.

Low temperature (<230°C) waste heat streams represent the largest proportion of waste heat from manufacturing operations. Though waste heat in this temperature range is lower quality, it is present in sufficiently large magnitudes that its work potential exceeds that of other waste heat sources. For these waste heat streams, low heat transfer rates and large recovery equipment footprints are major barriers. Recovering heat from these streams can be achieved via processes such as condensation of water vapor in flue gases and hence present issues related to formation of acidic components leading to corrosion of commonly used metallic components. For example, actions that can help achieve this target include the following:

- Develop innovative heat transfer methods and heat exchanger geometries to reduce equipment size.
- Develop high-efficiency, liquid-gas heat exchangers for low-temperature flue gases or exhaust air from dryers.

- Develop advanced heat pumps (e.g., adsorption/desorption and chemical looping reactions).
- Develop dry coolers for cooling liquids that reduce or eliminate water use in heat exchangers.

Table 3.14 Technical Targets for Technical Area 12: Waste Heat Recovery Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
12.1	Develop enabling technologies for low maintenance, high reliability recovery systems for industrial waste heat streams, and reduce payback period by at least 30% compared to existing systems in various temperature ranges.	2030	R&D (SBIR)	2015 typical payback periods estimated between 3.0 and 22.3 years, depending on industry[148]	Same as baseline	EI, EM
12.2	Develop material and system advancements to enable greater recovery from high-temperature (>650°C) and heavily contaminated industrial waste heat streams, and cost-effectively utilize 30% of available waste heat in this temperature range.	2030	NCA	Analysis needed	NCA	EI, EM
12.3	Develop innovative, cost-effective systems to recover heat from low-temperature (<230°C) waste heat sources and successfully utilize 20% of available waste heat in this temperature range.	2030	NCA	Analysis needed	NCA	EI, EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6M: Waste Heat Recovery*. Available online at: http://energy.gov/sites/prod/files/2016/02/f30/QTR2015-6M-Waste-Heat-Recovery.pdf.
- *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. Available online at http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf.
- *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities*: http://info.ornl.gov/sites/publications/files/Pub52987.pdf.
- CHP Technical Assistance Partnerships (CHP TAPs) website at: http://www.energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps.

[148] Supra 68. A. Elson, et al. *Waste Heat to Power Market Assessment*. Prepared by ICF International for ORNL. 2015.

3.1.13 Combined Heat and Power (CHP) Systems

Objective:
Advance technologies and develop deployment strategies that accelerate the adoption of combined heat and power through streamlined installation processes; operating improvements; increased flexibility of fuel use; and reduced cost, greenhouse gas emissions, and perceived customer risk.

Overview of Technical Area

Combined heat and power (CHP) is the concurrent production of electricity or mechanical power and useful thermal energy (for heating, cooling, and/or process uses) from a single energy input. CHP technologies provide manufacturing facilities, federal and other government facilities, commercial buildings, institutional facilities, and communities with ways to reduce energy costs and emissions while also providing more resilient and reliable electric power and thermal energy. There are two types of CHP, which depend on the sequencing of usage cycles. With topping cycle CHP, engines, turbines, microturbines, or fuel cells first generate electricity from an input fuel (typically natural gas) and then the waste heat is used for heating, cooling, and/or process use. Bottoming cycle CHP, often referred to as waste heat to power, occurs when the waste heat from an industrial process or another source (such as a boiler) is used to drive an electricity generator, frequently a steam turbine or organic Rankine cycle.[149] AMO's CHP programs include R&D and deployment services for all forms of combined heat and power.

The overall efficiency of a CHP system can be calculated by dividing the total usable energy output (both electrical and thermal) by the total energy content of fuel inputs to the system. To maximize operations, today's CHP systems are generally designed to meet the thermal demand of the energy user, though looking forward efforts to better match electric demands are projected to be a new role for CHP. CHP systems can achieve energy efficiencies of 75% or more compared to separate production of heat and power, which collectively averages about 50% system efficiency.[150] For further discussion of the applications, challenges, and opportunities for CHP systems from an energy perspective, see the *2015 QTR Technology Assessment 6D: Combined Heat and Power Systems* (the link to this assessment is provided below under "Related Resources" to Section 3.1.13) or visit *energy.gov/chp*.

Targeted Impacts

CHP systems can be used in a range of settings and power levels, and are currently commercially available in sizes generally ranging from 50 kW to more than 20 MW. Markets for CHP transcend all the sectors of our economy including manufacturing facilities (e.g., chemicals, petroleum refineries, food, paper, and primary metals); institutional facilities (e.g., colleges and universities, retirement homes, research institutions, and government buildings); commercial buildings (e.g., hotels, airports, and office buildings); district energy systems (e.g., campuses, urban centers, and military bases); residential buildings (e.g., multifamily housing); and critical infrastructure (e.g., hospitals, wastewater and solid waste facilities, and emergency services

Challenges and Barriers:

- **Cost and complexity of installation and operation**: capital investments can often be cost prohibitive, particularly in a rapidly changing policy and economic environment.
- **Reliability, availability, maintainability, and durability:** need for improved performance characteristics verification for CHP systems.
- **System packaging:** need for pre-packaged CHP solutions that harmonize multiple components and can be easily selected and installed.
- **Scalability**: need for higher-efficiency CHP systems in the 1-5 MW size range.
- **Fuel flexibility**: lack of versatility to use a variety of input fuels, including renewable fuels.
- **High power-to-heat ratios:** lack of high P/H ratios to enable broader adoption in end-use sectors.
- **Materials challenges:** lack of economical materials that can operate at higher temperatures and resist corrosion.
- **Combined-cycle integration:** need for balance of power distribution between cycles and optimization of internal mass and heat flows.
- **Hybrid CHP-renewable energy:** need for commercially proven and available hybrid CHP-renewable energy systems.
- **Regulatory barriers:** inconsistent interconnection requirements and standards; need to quantify CHP's full energy and non-energy value of CHP in utility procurement and resource planning and incentives, and accurately apportion rates based on cost of service; unfavorable standby rates.

[149] *QTR 2015: Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing Technology Assessments*. Available online at: http://www.energy.gov/under-secretary-science-and-energy/downloads/chapter-6-innovating-clean-energy-technologies-advanced.
[150] Ibid

facilities).[151] For more specific information on the technical potential for CHP in the U.S., by state and market sector, visit *energy.gov/chp-potential*.

AMO Approach

Technical targets for this activity area with current status are summarized Table 3.15. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 13.1: Achieve a ten-fold cumulative increase in direct CHP technical support activities to potential commercial, institutional, and industrial end-users.

CHP generates electricity and captures energy that would normally be lost in power generation, transmission, and distribution and uses it to provide heating, cooling and other thermal energy at or near the site, making CHP 75-80% efficient at using fuel versus 45-50% of traditional grid power and on-site boiler/furnace. While CHP has been around for decades, there are significant economic, regulatory, and informational barriers that are difficult for end-users focused on their core business to overcome.[152] Among the hurdles are competition with core business for capital investments versus operating expenditures; lack of low-cost financing; uncertain tax codes and accounting practices; extensive utility regulations and practices with uncertain and often confusing interconnection standards and utility rates such as standby rates; and inconsistent and confusing local zoning codes and environmental, health, and safety requirements. To help overcome the barriers and support the installation of CHP across the United States, there is a need for increased market opportunity assessments, education and awareness about the benefits of CHP, and technical assistance to promote and transform the market for CHP systems.[153] Leaders in the deployment of CHP systems – including utilities, regions, cities, and states – should be recognized as role models and resources for other organizations. Changes are also occurring in the utility and grid operator space, where utilities and the grid operators are becoming supportive of policies that promote CHP and, in some cases, are leading to utility construction and operation of CHP for grid and end user usage. Representative examples of activity towards this target include:

- Develop resources that lead to a doubling of the installation of cost effective CHP systems (with >75% efficiency at higher heating value (HHV)) that are fueled with renewable and opportunity fuels.
- Support the doubling of utilities that own or incentivize CHP as part of their business model.
- Introduce over 75% of high-technical-potential commercial/industrial markets to CHP opportunities, including waste heat to power.
- Conduct CHP assessments for at least 50% of target markets with most significant CHP technical potential.
- Develop online resources for site self-assessment for CHP and waste heat to power potential.
- Work with at least 5 CHP developers in highlighting the opportunities with hybrid CHP-renewable systems.
- Establish 100 partnerships with cities, states and utilities to encourage the use of CHP.

Target 13.2: Advance the development of cost-effective CHP systems that are responsive to site demands as well as grid requirements.

Traditional business models and regulations linking cost recovery and utility revenue to electricity sales create uncertainty in utility value proposition for CHP systems in some markets. Since most facilities remain connected to the grid and rely on the utility for supplemental power needs beyond their self-generation capacity – as well as for standby and back-up service during outages or planned maintenance – utility tariff structures and standby rates impact the economics of on-site generation. Utilities and independent system operators (ISOs) can help minimize customer costs through ratemaking strategies that better reflect how CHP is utilizing the utility's services, such as offering a self-supply option for reserves, offering daily or monthly as-used demand charges, and allowing customer-generators to buy all of their backup power at market price.[154] Cost-effective, efficient CHP systems that have standardized

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[151] Ibid

[152] Supra 42. *Barriers to Industrial Energy Efficiency: Report to Congress.* U.S. DOE. 2015.

[153] Supra 69. *Combined Heat and Power (CHP) Technical Potential in the United States*. U.S. DOE. Report DOE/EE-1328. 2016.

interconnection ability with verifiable performance and can be easily integrated onto the grid will aid in these efforts. Representative examples of activities towards this target include:

- Develop cost-effective 1-20 MW CHP systems capable of automatically providing reliable capacity response and other ancillary market support to the electrical grid (with >75% efficiency at HHV).
- Develop cost-effective CHP systems that are flexible with respect to site energy requirements (thermal to electrical demand ratio)
- Develop cost-effective solutions for CHP systems that can provide rapid, frequent, and energy-efficient start-ups and shutdowns in both warm and cold conditions (as defined by the number of hours of system downtime), to enable improved grid responsiveness. Coupling responsive CHP systems with grid interface technology (for two-way transactional energy flow)[155] could provide robust distributed resilience.

Target 13.3: Develop cost effective, high power-to-heat (P/H) ratio CHP systems with >65% electric generation efficiency, >75% system efficiency (HHV), and P/H greater than or equal to one (>= 1)

Thermally driven CHP systems are generally sized to supply 100% of a facility's thermal demand (with a low P/H ratio, typically below 0.75) and are currently cost-effective in many markets and applications. However, there remains a significant unserved market with smaller thermal demand relative to electrical in the industrial, commercial/institutional, and residential sectors. It is estimated that a P/H ratio of up to 1.5 is potentially achievable,[156] which could expand the uptake of this type of distributed generation technology in those locations where electrical demand is the driving force. Energy and cost savings opportunities could be realized in these applications by increasing P/H while maintaining the high system efficiencies that thermally sized CHP systems enjoy. Increasing P/H without loss of efficiency would require the development of ultra-high-efficiency electrical generation technologies along with improved thermal recovery.

Target 13.4: Support a 20% reduction in installed cost of commercially available, packaged (<10 MW) CHP systems (while maintaining >75% system efficiency at HHV).

CHP systems have traditionally been individually designed and engineered to meet specific requirements, thus requiring extensive time and cost. In addition, when treated as a unique solution, CHP is often viewed as a risky investment due to lack of operating data needed by financers and project developers. A solution to these concerns in the commercial and manufacturing sectors (<10 MW systems) is the development of pre-packaged CHP systems that include standardized engineering design and verified performance data. Designed to increase deployment of CHP in key commercial and manufacturing markets that are underdeveloped due to a variety of barriers that increase the perceived risks to both end-users and CHP system vendors, this option would be quicker to install, easier to finance, and have greater operating certainty, thus reducing the risk of new technology. In addition, packaged systems could be scoped and purchased for multiple sites with similar performance (hotels, hospitals, schools) leading to economies of scale in purchasing as well as consistency in operations and maintenance needs. For example, actions that can help achieve this target include the following:

- Increase the installation of standardized, packaged CHP systems from qualified vendors based on the value of shorter decision and project delivery times, lower hurdle rates, and better customer protection for end-users.
- Develop web-based catalog ("eCatalog") of pre-qualified DOE-recognized packaged systems that meet DOE technical specifications and have warranties and service agreements to ensure performance to design; and robust market engagement programs targeted to reduce total project costs and installation times for CHP systems in the eMarket by 20%.
- Develop a screening protocol for qualifying systems for inclusion in the eCatalog of DOE-recognized, packaged CHP systems based on technical viability and performance as documented in the technical specification requirements.

[155] See also section 3.3.1: Advanced Manufacturing to Enable Modernization of Electric Power Systems.

[156] *2015 QTR, Chapter 6, Technology Assessment 6D: Combined Heat and Power Systems*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6D-Combined-Heat-and-Power-Systems.pdf.

- Support the development of a robust packaged CHP system eCatalog with at least 25 vendor allies and over 100 pre-qualified, DOE-recognized packaged CHP systems with service agreements to be used in multiple markets that lead to economies of scale and speed of deployment that show a decrease of cost and time in the installation of packaged systems nationwide.
- Recruit and promote at least 15 states, communities, or utilities to establish an eMarket in their jurisdiction by using the eCatalog for program design and launching robust market engagement strategies to support the packaged CHP system program.

Table 3.15 Technical Targets for Technical Area 13: Combined Heat and Power Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI**
				2015 Baseline	Progress to Date	
13.1	Achieve a ten-fold cumulative increase in direct CHP technical support activities to potential commercial, institutional, and industrial end-users.	2030	PRA	400 activities[157, 158]	650 activities[161, 158]	EI, EM
13.2	Advance the development of cost-effective CHP systems that are responsive to site demands as well as grid requirements.	2030	NCA	Analysis needed	NCA	EI
13.3	Develop cost effective, high power-to-heat (P/H) ratio CHP systems with >65% electric generation efficiency, >75% system efficiency (HHV), and P/H >= 1.	2025	NCA	Analysis needed	NCA	EI
13.4	Support a 20% reduction in installed cost of commercially available, packaged (<10 MW) CHP systems (while maintaining >75% system efficiency at HHV).	2025	PRA	Varies by size, technology and function. Typically, between $1,800/kW and $10,000/kW installed cost based on technology, system size, and installation complexity.[159]	Not available	EM

***Key:** CST = Funded Institute or Hub; PRA = Practices; R&D = Funded R&D Project; NCA = No Current Activity; SBIR = Funded SBIR Project

Related Resources

- *2015 Quadrennial Technology Review (2015 QTR) Technology Assessment 6D: Combined Heat and Power Systems*. Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6D-Combined-Heat-and-Power-Systems.pdf.

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[157] Claudia Tighe. "CHP Deployment Program: AMO Technical Assistance Overview." Better Buildings Program, U.S DOE. Available online at: http://energy.gov/sites/prod/files/2014/06/f17/CHP%20Deployment%20Program.pdf.

[158] Supra 54. DOE Combined Heat and Power Installation Database and CHP TAPs monthly metrics (which are included in quarterly financial assistance reports). Available online at https://doe.icfwebservices.com/chpdb/.

[159] Combined Heat and Power Technology Fact Sheet Series," U.S. DOE. July 2016. Available online at: http://www.energy.gov/chp-technologies.

- Combined Heat and Power R&D website at: http://energy.gov/eere/amo/combined-heat-and-power.
- CHP Deployment information available at: http://www.energy.gov/eere/amo/chp-deployment.

3.1.14 Sustainable Manufacturing

Overview of Technical Area

Sustainable manufacturing[160] encompasses a wide range of systems issues, including energy intensity, carbon intensity, and use intensity. Manufacturing systems have traditionally been designed based on a linear model, starting with raw materials extracted from nature and ending at disposal in a landfill at the end of the product's useful life. However, analyzing the supply chain and material flow through a product's entire lifecycle can help to identify energy, material, and water savings opportunities throughout the greater U.S. economy, including the production and delivery of energy and energy use within the industrial, transportation, and buildings sectors. Lifecycle assessments (LCAs) are already being used by industry to better inform where process improvements can reduce waste, increase efficiency, reduce toxins, and save costs of manufactured products across their lifecycles. Pursuing strategies to optimize designs for recyclability and increase efficiency of material use will reduce the material use intensity of supply chains and in turn provide additional opportunities for energy efficiency. For further discussion of the applications, challenges, and opportunities for sustainable manufacturing from an energy perspective, see the 2015 *QTR Technology Assessment 6L: Sustainable Manufacturing/Flow of Materials through Industry* (the link to this assessment is provided below under "Related Resources" to Section 3.1.14).

Objective:
Advance technologies and tools to improve resource efficiency in the manufacturing industries, including recycling and reuse, and lower the lifecycle cost and cross-sectoral energy impacts of manufactured products.

Challenges and Barriers:

- **Minor metals recycling:** economic barriers for recycling metals occurring in low concentration, embedded in complex products, and those that are low-value (which may not justify recovery costs).
- **Inefficient industry material flow tracking:** lack of efficient methods to track and trace materials through full product lifecycle to optimize materials use, including associated data management and analytics.
- **Product yields and in-plant scrap:** lower product yields due to material loss during processing are barriers to materials efficiency.
- **Recycling mentality:** lack of support for incorporating recycling/re-use into product designs to increase materials reclamation rates.
- **Security of materials supply chains:** Efficiency of materials utilization through the supply chain is also dependent on politically unstable regions for certain materials.
- **Distributed manufacturing:** lack of on-demand manufacturing methods of parts close to the point of need which would minimize transportation-related inefficiencies.

Targeted Impacts

While sustainable manufacturing is a broad topic, technology focus areas include alternative material feedstocks, end-of-life management (e.g., recycling), material-water-energy relationships, sustainable product design, and waste utilization and reduction.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.16. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

[160] Numerous definitions for sustainable manufacturing are in use; all are concerned with the environmentally responsible production and use of manufactured goods. The U.S. Department of Commerce defines sustainable manufacturing as "the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers." See http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp. EPA defines sustainable manufacturing as "the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources." For more information, see: http://www.epa.gov/sustainablemanufacturing/glossary.htm. The Organization for Economic Co-operation and Development defines it as "managing operations in an environmentally and socially responsible manner." For additional information, see: http://www.oecd.org/innovation/green/toolkit/aboutsustainablemanufacturingandthetoolkit.htm.

Target 14.1: Develop material reuse, recycling, remanufacturing, and/or reprocessing technologies that enable an absolute increase in recycling rate[161] by 30%[162] of select energy-intensive materials and 25% improvement in embodied-energy efficiency.

While reducing the initial demand of a certain material is an important strategy to reduce waste and save energy, utilizing pre- and post-consumer scrap is less energy intensive than using virgin materials (in most cases). One example is aluminum manufacturing – it takes 88% less energy to manufacture secondary aluminum ingot compared to primary aluminum ingot[163]. However, in order to be able to increase secondary aluminum manufacturing rates, there is a need for R&D technology improvement in the metals separations processes to easily and cost effectively recover metals at the required quality levels. Technology approaches include development of recycle friendly alloys, product engineering and design for reuse, and automated methods to sort and separately manage mixed alloys. Similar challenges exist for many other types of materials, especially heterogeneous materials like composites.

Target 14.2: Develop tools and technologies to reduce the cost of using recycled feedstocks in existing processes to cost parity (including energy) with primary feedstocks.

The utilization of recycled feedstocks for a number of select materials, such as metal, fibers, and polymers, requires much less energy than producing virgin materials. However, it is often costly and complex to identify and separate the secondary material, resulting in contamination issues in the recycled feedstock. Technologies that enable use of recycled materials with costs that are equivalent to or less than non-recycled primary feedstocks are needed. Examples of technologies include low-cost physical separation, detection and identification; waste-stream recovery; and contaminant removal processes. Cost- and performance-effective recycling contributes to sustainable manufacturing's goals of lowering net energy consumption of secondary material production and associated emissions.

Target 14.3: Develop technologies and targeted end use products that have the potential to improve material efficiency compared to 2015 state-of-the-art, resulting in 10x reduction in primary material feedstock and 20% lower GHG emissions.

Reducing the amount of material required for manufacturing and processing can result in net energy and other resource savings – whether direct (realized at the manufacturing facility), indirect (realized elsewhere in the supply chain), or both. An example of this concept is additive manufacturing, which in some applications can have a higher energy intensity compared to conventional manufacturing, but can provide multiple benefits through the product lifecycle, including reduced material demand, rapid production, and manufacturability of complex or novel product designs. Third-party, independently verified accounting of resource and material use is an effective corporate strategy to assess, document and communicate the effectiveness of materials utilization. The efficiency of technologies and manufacturing processes directly impact materials use. Inefficient material production and manufacturing processes result in excess in-plant scrap and represent opportunities to improve material use intensity. Further, product designs that do not consider end-of-life and materials/product recycle/reuse/remanufacturing (i.e., design for disassembly and/or reuse) reduce the likelihood that materials will be reused and inhibit a shift towards a more efficient circular economy. Some industries, such as the garment, aluminum, and steel industries, use post-consumer scrap (at significantly differing recycle rates) and have already taken steps to reduce manufacturing scrap by implementing materials efficiency technologies or by reusing in-plant scrap and post-consumer scrap; however, there is still a large untapped potential to reduce energy consumption by optimizing materials flows in product manufacturing and throughout the supply chain.

Target 14.4: Develop technologies and targeted end use products that have the potential to reduce water intensity compared to 2015 state-of-the-art.

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[161] Absolute recycling rate relates to within the manufacturing system.

[162] The processing and mining of energy-intensive materials consumes more than 8 quads annually, of which up to 50% (4 quads) is estimated to be landfilled within one year of production. Internal analysis shows that by increasing the recycling rate of key material classes by 30% and improving the energy efficiency of secondary feedstock processing by 30%, energy savings of up to 1.6 quads can be achieved.

[163] *Bandwidth Study on Energy Use and Potential Energy Saving Opportunity in the Manufacturing of Lightweight Materials: Aluminum*. Prepared by Energetics Incorporated for NREL and AMO/EERE/U.S. DOE. March 2016. Available online at: http://energy.gov/sites/prod/files/2016/04/f30/Aluminum%20Report.pdf.

Just like energy, water is a resource and is tracked as a part of the lifecycle inventory. The increasing focus on water scarcity due to drought impacts in the western U.S. and stressed aquifers from over-withdrawals underscores the pressing need to consider the connections between water and energy, and how LCA can help inform energy decisions by taking water impacts into account. A group of manufacturers through the Better Buildings Water Savings Initiative are seeking ways to incorporate more efficient and sustainable water use in their operations to reduce water intensity of their facilities' operations and create impacts for the broader stakeholder community. The development of specific technologies and targeted end use products to reduce water intensity of manufacturing processes and products can increase and augment these foundational impacts.

Clean Energy Manufacturing Innovation Institute for Reducing EMbodied-energy and Decreasing Emissions (REMADE) in Materials Manufacturing

In June 2016, the Energy Department issued a funding opportunity announcement for a Clean Energy Manufacturing Innovation Institute for Reducing Embodied-energy And Decreasing Emissions (REMADE) in Materials Manufacturing as a part of the broader Manufacturing USA network. The Institute will focus on improving technologies and processes to achieve cost parity of recycled and waste materials with primary feedstocks, while improving material efficiency in manufacturing processes. The Institute's proposed research, development, and demonstration projects would be performed through industrial partnerships under technology focus areas that may include, but are not limited to:

- Information collection, standardization, and design tools for tracking materials, reducing waste, and predicting how a process will work with secondary feedstocks or reused materials
- Rapid end-of-life and waste material gathering, identification, and sorting
- Separation of mixed materials
- Removal of trace contaminants
- Robust and cost-effective reprocessing and disposal methods
- Efficient material use during manufacturing
- Waste stream separation and recovery
- End-of-life (EOL) material reuse
- Design of products for reuse/disassembly at EOL

Table 3.16 Technical Targets for Technical Area 14: Sustainable Manufacturing

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
14.1	Develop material reuse, recycling, remanufacturing, and/or reprocessing technologies that enable an absolute increase in recycling rate[164] by 30% of select energy-intensive materials and 25% improvement in embodied-energy efficiency.	2025	CST	Material dependent; analysis needed	Not available	LC
14.2	Develop tools and technologies to reduce the cost of using recycled feedstocks in existing processes to cost parity (including energy) with primary feedstocks.	2025	CST	Process dependent; analysis needed	Not available	LC

[164] Absolute recycling rate relates to within the manufacturing system.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
14.3	Develop technologies and targeted end use products that have the potential to improve material efficiency compared to 2015 state-of-the-art, resulting in 10x reduction in primary material feedstock and 20% lower GHG emissions.	2025	CST	Technology dependent; analysis needed	Not available	LC
14.4	Develop technologies and targeted end use products that have the potential to reduce water intensity compared to 2015 state-of-the-art.	2025	R&D, PRA	Technology dependent; analysis needed	Not available	LC, EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- 2015 Quadrennial Technology Review Technology Assessment 6L: *Sustainable Manufacturing*, http://energy.gov/sites/prod/files/2016/05/f31/QTR2015-6L-Sustainable-Manufacturing.pdf
- Clean Energy Manufacturing Innovation Institute for Reducing EMbodied-energy And Decreasing Emissions (REMADE) in Materials Manufacturing, Funding Opportunity Announcement (FOA) Number: DE-FOA-0001594, https://eere-exchange.energy.gov/FileContent.aspx?FileID=2351e7e9-9271-44da-aa29-5d8201ae5e9b

3.2 Emerging and Crosscutting Areas

3.2.1 Clean Water Technologies

Overview of Crosscut Area

Water scarcity, variability, and uncertainty are becoming more prominent, potentially leading to vulnerabilities in the U.S. energy infrastructure which depends on water for energy production and electricity generation, as noted in DOE's *Water-Energy Nexus* report.[165] The intertwined nature of water and energy are notable; thermo-electric cooling in power plants is the largest consumer of water and the extraction of oil and gas is accompanied with significant consumption of water. Sustainable water management requires the consideration of water sources beyond fresh surface water, which accounts for only a few percent of available water. Vast amounts of untapped water resources could be utilized if key technical challenges are addressed, including processing and purifying water in a low cost and energy-efficient manner. The potential impacts of using untapped water resources would reach far beyond the energy sector since water stress is growing global challenge in light of population growth, industrialization, and climate change.

Source waters include surface, ground, brackish, sea, produced (such as those from oil and gas extraction), and highly saline extracted (resulting from CO_2 injection). In addition, there is waste water from industrial and municipal use. Purifying water from a given source for a specified need requires energy. Given the diversity of water needs and respective requirements, there are multiple shared technical challenges that need to be addressed to produce clean water at the energy requirements, cost, and carbon footprint comparable to today's fresh water purification technologies:

- **Fundamental materials discovery** is needed for various components including membranes, pipes, tanks and pumps. For example, membranes with high rejection rate that do not foul or clog are needed. Additional material needs are for pipe, tank and pump materials that do not corrode and can withstand higher pressures and offer lower friction. Molecular modeling and additive manufacturing may be tools employed for materials discovery.
- **Better components** are needed (membranes, pumps, evaporators, heat exchangers etc.) that can operate more efficiently, without interruptions, and dynamically adapt to changing conditions (salinity, bio-organisms, pH, temperature, etc.). Multi-scale models to simulate processes need to be developed to predict performance and optimize design, ultimately leading to cost effective component manufacturing processes.

Objective:

Advance technologies to improve the processing and production of water from a variety of water sources – surface, ground, brackish, sea, produced (such as those from oil and gas extraction) and highly saline extracted (resulting from CO_2 injection) – at the same economic, energy, and environmental impact as currently supplied water.

Challenges and Barriers:

- **Contaminants:** water sources contain contaminants that may vary widely in type and quantity, even within a given water source, making a single solution hard to achieve
- **Energy intensity:** water purification is energy intensive with the intensity increasing with contamination concentration
- **Carbon neutral water purification:** to reduce CO_2 emissions beyond what is achieved by reducing the energy consumption, water purification systems need to be integrated with renewable or waste energy sources
- **Cost of water:** market penetration of new technologies varies geographically because of uneven water costs in different parts of the country due to acquisitions of water rights and other factors
- **Limited suppliers:** need more domestic suppliers of large scale-water purification systems to manufacture critical components and parts
- **Pipe materials and pumps:** need materials than can withstand high pressures, salts, and bio-fouling
- **Membranes:** need membranes that can remove a wide array of impurities while enabling high throughput of recovered water as well as membranes with embedded sensor technology to monitor when membrane systems need to be flushed
- **Integrating complete water systems:** entire systems (intake, purification technology, power supply) need to be integrated to enable optimal performance
- **Public sector risk aversion:** many water and wastewater systems are owned by public entities, which are often reluctant to invest in new efficient technologies that are seen as unproven

[165] Supra 71. *The Water-Energy Nexus: Challenges and Opportunities*. U.S. DOE. 2014.

- **Unit operation optimization** to lower the energy/economic impact of water transport, purification, treatment, waste recovery, and dynamic adaptation. This requires design optimization at the level where components are integrated with one another in a unit operation such as intake, filtration, and desalination. Furthermore, the value of chemicals or embedded chemical energy from waste/residuals from each operation need to be identified and extracted.
- **System integration, control and dynamics** to enable optimal system-wide performance (intake, purification, power supply). Water purification can be optimized as a through process utilizing tools akin to those being developed for manufacturing processes in the Smart Manufacturing Technology area (see section 3.1.11). Sensing and measuring water flow, temperature, pressure, and contaminant levels at various processing stages will be required. Data collection and analysis will be required for thorough process model development for feedback and enabling of dynamic adjustments for process optimization. While smart manufacturing concepts are of value to any high throughput process there are several critical challenges for water purification: (1) Designs and development for integration of water purification systems with renewable energy sources, and addressing challenges related to maintenance costs, variable power, and direction coupling without going through the grid; (2) co-location of water production with other industries in order to optimize aspects such as energy recovery, water intake, and waste usage; and (3) challenges with regards to changes in water flow or contaminant level (salt intrusion or bio-contaminant level increase due to global warming) need to be managed.

Targeted Impacts

AMO will focus on producing water in various U.S. geographic areas for three primary uses –agricultural, industrial and municipal fresh water. The aforementioned technical challenges will be addressed in each application but the emphasis may vary depending on the scale of the production facility, source of water, contamination, and target usage.

AMO Approach

An overall target for advancing clean water manufacturing technologies is to reduce the overall lifecycle energy impact for clean water production by 50%. However, the impact will vary depending on the source water used. Technical targets for this activity area with current status are summarized in Table 3.17. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers are described in this section.

Target 15.1: Provide water at <500 milligrams per liter (mg/l) total dissolved solids (TDS) at a cost of maximum $0.10/m^3$, 0.5 kWh/m^3, 0.2 lbs. CO_2/m^3 for water from brackish sources.

Brackish water from estuaries and aquifers typically have 0 – 3% salinity and require both desalination and pre-treatment. Brackish aquifers exist throughout the nation and could provide water for potable and agricultural needs for the nation's heart land. Unlike large scale coastal sea-water desalination plants, plants for brackish sources will need to be affordable, smaller, and modular. The modular nature of the plants is expected to be more conducive to coupling to renewable power. Since the salt concentrations are significantly lower than sea water, the energy and cost targets are more aggressive. Since brackish sources cover a vast region of the inland, challenges related to modularity of plants and water transport to users need to be addressed. Opportunities related to plant design, location, and maintenance need to be investigated as well as the potential for using renewable power sources. The target of $0.10/$m^3$ is aimed at providing water for potable as well as agricultural needs. The target for CO_2 is expected to be achieved partly through reduction in energy consumption for purification but more importantly through the use of renewable and waste energy sources in place of electricity derived from fossil energy.

Target 15.2: Provide water at <500 mg/l TDS at a cost of $0.50/$m^3$, 1 kWh/$m^3$, 1 lb. CO_2/m^3 for water from salt water.

Seawater salinity values are 3 – 5% and currently rely on large-scale energy intensive desalination facilities. The energy consumption goal of 1 kWh/m^3 is targeted for desalination of seawater. The current cost of potable freshwater varies from place to place; for example, in California the cost ranges from $0.40/$m^3$ to $0.80/$m^3$. A high-level economic goal of $0.50/$m^3$ for new technologies is targeted to achieve pipe parity for potable freshwater. The CO_2 target is expected to be met through reduction in energy consumption for purification and partly through the colocation with other industries to enable combined water intake and use of waste energy sources to offset the use of electricity derived from fossil energy. Coastal desalination plants with high throughput of seawater would be expected to be less conducive for coupling to renewable power because such plants often serve cities with larger populations and thus require a high and consistent energy supply. Much of the opportunity for technical innovation is materials discovery for membranes, including designing membrane structures and properties, and multi-scale modeling of the membrane performance. Breakthrough materials and process technology innovation in pretreatment systems are also needed. These systems are long-lived assets, so they must be built of low-cost and degradation resistant materials to match the expected lifetime of municipal water plants.

Target 15.3: Provide purified water from produced water sources for industrial use at processing costs below $1/m^3$, 1 kWh/m^3, and 1 lb. CO_2/m^3 to eliminate the need for well re-injection.

Produced waters, typically from oil and gas extraction, have typically lower salinity values than seawater (<5%) and contain other contaminants such as hydrocarbons that may vary depending on source. Re-injection costs have been reported to be greater than \$15.00/m^3 implying that there is considerable market opportunity for lower cost water treatment and processing technologies to generate a useful water supply from an otherwise costly waste stream. The \$1/m^3 cost target is higher than the target for seawater, owing to the need to separate hydrocarbons and other contaminants. The targeted energy savings and reduction in CO_2 is similar to that of sea water purification.

Target 15.4: Provide purified water from extracted water sources for industrial use at processing costs below \$1/m^3, 15 kWh/m^3, and 15 lbs. CO_2/m^3 to eliminate the need for well re-injection.

Extracted waters from CO_2 injection typically have a total dissolved solids content that is 2 to 4 times higher than seawater, beyond the level at which reverse osmosis can cost effectively function. Consequently, when purifying these waters, desalination alone through evaporation and/or crystallizers, will require >40 kWh/m^3. The properties and constituents will depend on the source of the injected CO_2. The targets for purification technologies for these waters are thus set more conservatively since entirely new technologies for desalination may need to be developed since energy efficient RO membranes do not function under these conditions. The applicability of coupling to waste energy sources from power plants would be relevant for lowering the carbon footprint, since the injected CO_2 would emanate from power plants and industries.

Target 15.5: Research, develop and demonstrate advanced manufacturing technologies with potential to reduce cost for equipment and parts for water processing by 50%

Capital cost is a major hindrance for building new water purification plants. AMO is targeting a 50% manufacturing cost reduction of materials ranging from alloys for pipes and pumps to filters and membranes. The technical breakthroughs are expected to be realized through implementation of technologies developed in other AMO technology areas such as roll to roll processing, smart manufacturing, and advanced materials manufacturing.

Target 15.6: Reduce net energy consumption of waste water treatment by 50% in 10 years

Organic wastewater treatment poses a different set of challenges than inorganic sources. A paradigm shift is underway in the municipal wastewater treatment community. Faced with the exorbitant cost of replacing a large portion of its water treatment infrastructure, now close to 100 years old in some cases, the wastewater industry has begun to view its treatment facilities as a form of integrated biorefineries. In this new paradigm, wastewater is seen as a resource for producing clean drinking water, combined heat and power, and nutrient streams. There is also increasing recognition of the potential for co-digestion of food and other organic wastes as a strategy for enhanced energy recovery. A coalition of DOE offices, other federal agencies including EPA, NSF, and USDA, and external stakeholders has recognized this opportunity and collaborated in convening a series of workshops over the last 2 years, the results of which directly inform this target. The target will be achieved through an accumulation of advances in a number of sub-targets[166] which include: reduction in electricity consumption for aeration by 50-100%, and reduction in capital cost by at least 50% at pilot and demonstration scales, particularly for plants with capacity of 5 million gallons per day (MGD).

[166] *Waste-to-Energy Workshop Summary*. Sponsored by the Bioenergy Technologies Office (BETO) / U.S. DOE. Report prepared by Energetics Inc. June 2015. Available online at: http://www.energy.gov/sites/prod/files/2015/08/f25/beto_wte_workshop_report.pdf.

Table 3.17 Technical Targets for Emerging Technical Area 15: Clean Water Technologies

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
15.1	Provide water at <500 mg/l TDS at a cost of maximum $0.10/m^3, 0.5 kWh/m^3, and 0.2 lb. CO_2/m^3 for water from brackish sources.	2030	SBIR	$ 0.50/m^3	Research ongoing	LC
15.2	Provide water at <500 mg/l TDS at a cost of $0.50/m^3, 1 kWh/m^3, and 1lb CO_2/m^3 for water from salt water.	2030	NCA	$ 2.00/m^3	NCA	LC
15.3	Provide purified water from produced water sources for industrial use at processing costs below $1/m^3, 1 kWh/m^3, and 1 lb. CO^2/m^3 to eliminate the need for well re-injection.	2030	NCA	$ 15.00/m^3	NCA	LC
15.4	Provide purified water from extracted water sources for industrial use at processing costs below $1/m^3, 15 kWh/m^3, and 15 lbs. CO_2/m^3 to eliminate the need for well re-injection.	2030	NCA	$30.00/m^3	NCA	LC
15.5	Research, develop and demonstrate advanced manufacturing technologies with potential to reduce cost for equipment and parts for water processing by 50%.	2030	NCA	Capital costs vary depending on size of facility but processing equipment and parts are reported to constitute approximately 50% of the capital costs[167]	NCA	FC
15.6	Reduce net energy consumption of waste water treatment by 50% in 10 years.	2025	NCA	0.4[168] kWh/m^3	NCA	LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[167] Numbers noted as average energy usage among facilities in *Energy-Positive Water Resource Recovery Workshop Report*. Prepared by Energetics Inc., for NSF, U.S. DOE, and EPA interagency working group. Workshop held Arlington, Va., April 28 – 29, 2015. Report available online at: https://www.energy.gov/sites/prod/files/2016/01/f28/epwrr_workshop_report.pdf.
[168] Ibid

3.2.2 Energy Efficient Advanced Computing

Objective:
Advance energy-efficient, cost-effective, and reproducible materials and manufacturing technologies to extend computational power beyond Moore's Law.

Challenges and Barriers:

Energy consumption of system: energy efficiencies must enable the entire system to operate within affordable power budgets when run at targeted computational rates

Novel materials development: disruptive materials and technologies are needed, such as carbon nanotube based transistors and other nanoscale devices, since the minimum effective size of CMOS circuitry is approaching

Synergistic innovations: simultaneous innovations in materials, devices, and system architectures are also required to achieve beyond exascale computing capability

Overview of Crosscut Area

Continual advances in computing capabilities are necessary to address critical problems in manufacturing as well as environmental, climate, and security challenges. Information technology (IT) represents the fastest growing consumer of energy in the U.S. Cisco Systems, a major internet infrastructure manufacturer, reports[169] that data center traffic is projected to have a compound annual growth rate (CAGR) of 23% from 2013-18, with similar increases in computing needs expected for personal and portable devices as well. The scaling down in the size of complementary metal-oxide-semiconductor (CMOS) devices has increased the energy efficiency, storage capacity, and lowered the cost of integrated circuits consistently since the 1970s; the pace of the scaling is known as Moore's Law[170]. Even with these improvements, energy demand from the growth in IT is expected to grow from 91 billion kWh in 2013 to 252 billion kWh in 2018.[171]

CMOS device dimensions are expected to reach their physical limit within a decade, bringing about the end of Moore's Law. This will either limit growth in computing power or increase IT energy use to unsustainable levels. In order to continue the growth in computing power, basic and applied research is needed to accelerate the development of energy-efficient IT beyond the scaling limit of CMOS technology as well as maintaining a semiconductor manufacturing base in the U.S. There are three approaches to tackle the challenges posed by the end of Moore's Law:

1. **Materials and devices:** The materials and devices focus area will explore, identify, model, and demonstrate new materials and devices for ultra-efficient computing. Examples include low voltage transistor concepts such as the tunnel field-effect transistor[172] (TFET), and energy efficient memory such as optical non-volatile photonic storage[173] and spin transfer torque random access memory[174].
2. **Manufacturing:** The manufacturing focus area will leverage DOE expertise in nano-manufacturing methods, including extreme ultraviolet lithography, heterogeneous integration of advanced photonics and wide bandgap devices, and three-dimensional (3-D) stacking of integrated circuits to research, develop and deploy appropriate manufacturing technologies for devices from the first thrust. Current microfabrication tools were, by and large, designed for planar, silicon-based devices. Integrated circuits that use alternative materials required investments in microfabrication methods.
3. **Systems:** The systems focus area will apply DOE expertise in advanced computing to exploit new device and materials enabled by the first two thrusts to build computing systems and components.

[169] Cisco Global Cloud Index, 2013–2018.
[170] Moore's Law is an observation – not an actual scientific law – that the number of transistors on a central processing unit (CPU) would double roughly every two years thereby doubling overall processing power for computers.
[171] N. Bin Mohd Nor and M. H. Bin Selamat. "Green Data Center Frameworks and Guidelines Review." *Intl. J. Computer Information Systems and Industrial Management App.*, 7, pp. 94-105. 2015. Available online at: http://www.mirlabs.org/ijcisim/regular_papers_2015/IJCISIM_10.pdf.
[172] A.C. Seabaugh and Q. Zhang. "Low-voltage tunnel transistors for beyond CMOS logic." *Proceedings of the IEEE*, 98(12), pp. 2095 – 2110. December 12, 2010. Available online at: http://ee.sharif.edu/~sarvari/25290/2010-Seabaugh.pdf.
[173] C. Rios, M. Stegmaier, P. Hosseini, D. Wang, T. Scherer, C. D. Wright, H. Bhaskaran, and W. H.P. Pernice. "Integrated all-photonic non-volatile multi-level memory." *Nature Photonics:* 9, pp. 725-732. September 21, 2015.
[174] T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich. "Antiferromagnetic spintronics." *Nature Nanotechnology*, 11, pp. 231-241. March 3, 2016. The arXiv electronic preprint of the article is available online at: https://arxiv.org/pdf/1509.05296v1.pdf.

Accelerating the development of energy-efficient IT will enable low-power computing and low-cost smart grid, building electronics, and next-generation sensors and electronics for a broad swath of industries. Technology advances are needed in a number of areas in order to extend computation capabilities beyond the end of Moore's Law. Research on manufacturability to transition to high volume manufacturing is needed in order to achieve broad societal impact. For further discussion of the challenges and opportunities for energy efficient advanced computing, visit the Exascale Initiative website.[175]

Targeted Impacts

The main focus areas for AMO are semiconductor materials and semiconductor device fabrication technologies that extend computation and storage capabilities beyond what is achievable with today's silicon technology, while enabling low-power computing.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.18. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in the section.

Target 16.1: Develop and demonstrate technologies that will enable 10x improvement in computing energy efficiency over 2015 state of the art by 2025

Thermal-power challenges and increasingly expensive energy demands pose serious threats to the rate of increase of processor performance.[176] Device technology and computer architecture are both rapidly maturing to their engineering limit of performance as set by current manufacturing technology. Meeting the goals of the Exascale Initiative requires processing power (measured in giga-operations per second (GOPS)) to be 10x more energy efficient than the 2015 state of the art. Research and development of new semiconductor technologies is needed that will leverage fundamental scientific understanding of relevant quantum-scale phenomena. A variety of new materials are needed, including materials exhibiting desirable phase transitions which can be gated at temperatures well above room temperature, materials exhibiting orders of magnitude faster switching speeds for memory and logic devices, and materials with improved spin-filtering characteristics for random access memory devices. Co-design of devices and circuits is essential to the optimization of energy efficiency computing and some important research issues can only be fully addressed by considering devices, circuits, architecture, and applications as a whole. Circuits and architectures must also address issues such as device-to-device variation, sensitivity to noise, power supply variations, and other environmental factors, and the effects of aging and wear on new devices and material systems.

Target 16.2: Develop and demonstrate manufacturing technologies that expand the limits of three-dimensional integrated circuits

One way of extending processing power growth beyond the end of Moore's Law is by bringing common-place planar integrated circuits into the third dimensions. This can be achieved by stacking multiple dies, successively adding layers of logic circuit on a single substrate, fabricating out-of-plane circuits, and other methods. Some of these methods are already being adopted. 3-D integrated circuits present a number of manufacturing and integration challenges that limit their indefinite expansion, such as cooling, electrical interference, and built-in stress in the materials deposited.

Target 16.3: Develop and demonstrate processors at 100x higher processing speeds than 2015 commercial processors.

Another way of extracting more computing power from current processor designs is by increasing clock speeds. However, heat dissipation in silicon at clock speeds greater than a few gigahertz (GHz) limits the speed of current processors. Short term gains in clock speed can be had by cooling processors using more aggressive methods than current air-based cooling, such as cryogenic, evaporative, and liquid cooling directly on the chip die. These methods,

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[175] The Exascale Initiative and its Path Forward plan is available at http://www.exascaleinitiative.org/pathforward. See also "Looking Beyond CMOS Technology for Future HPC" Workshop at http://beyondcmos.ornl.gov/.
[176] *Report to the National Science Foundation on The Workshop for Energy Efficient Computing*. Arlington, Va., April 14 – 15, 2015. Available online (for downloading) at: https://www.src.org/nri/energy-efficient-computing-workshop.pdf.

while known and explored for a long time, have remained technically impractical or economically unfeasible for mass adoption.

Long term advances in processor clock speeds may be had by using semiconductor materials other than silicon. Certain materials, such as indium gallium arsenide (InGaAs) and silicon germanium (SiGe), as well as single-walled carbon nanotubes (SWNTs) have higher charge carrier mobilities than silicon, which means they can potentially perform the same function as CMOS processors but at higher speeds and lower power consumption. Some of the challenges are that these materials have a large and unfavorable disparity between electron and hole mobility, lack native oxides, or behave physically and chemically different from silicon. These materials rely on technologies, such as metalorganic chemical vapor deposition and hybrid vapor-phase epitaxy, which are less mature than conventional silicon microfabrication methods. Therefore, there is a need to improve microfabrication technologies for candidate materials and also to identify and evaluate promising new materials.

Target 16.4: Develop and demonstrate optoelectronic interconnects with a chip footprint one-tenth of 2015 technology

The latency of communication between processing units and memory banks have been identified as a challenge for ultra-fast computing. One way to reduce latency is to rely on optical communication between components. There are a number of challenges with interfacing the optical and the electrical circuit, such as packaging. Furthermore, current optoelectronic components, such as lasers and photodiodes, are relatively big. Therefore, converting the optical signals into electrical signal, and vice versa, with a component density high enough to be a viable solution for the massive number of interconnects that exascale computers will require is still an unresolved challenge. Recent advances[177] show promise, but these solutions are yet to be transitioned to manufacturing.

Target 16.5 Develop and demonstrate a one square micron (1 μm^2) atomically precise circuit

Imperfections in the silicon lattice and inaccuracies and spatial variations in the etching and deposition of CMOS microfabrication put engineering limits to device dimensions that are short of the ultimate limit of the components. Manufacturing computing devices with absolute atomic precision is a path increase computing efficiency in the short term and perhaps the only path in the long term. In the short term, improving feature precision of components to the atomic level would push manufacturing capabilities to the ultimate performance limit of current architectures. In the longer term, molecular computing technologies can shrink the size of functional components by an order of magnitude over the idealized shape of current components, as well as enable massive parallel processing and other capabilities beyond the reach of current commercial computers. Activities that would further this target include

- Improvements of current microfabrication tools and development of new microfabrication technologies with superior capabilities compared to current microfabrication methods
- Development of manufacturing methods for molecular computing that are scalable to commercial production volume and costs

Target 16.6: Develop and demonstrate manufacturing methods for computing spintronics devices

Spin-based computing holds tremendous promise as the basis for future generation computing machines, especially those beyond the exascale (those capable of performing one million trillion operations per second), which are expected to be demonstrated sometime in the next decade. Current spin-based processing devices are yet to transition from the lab to applied systems. This is in part due to the immaturity in microfabrication methods and component architecture of such devices. Transitioning spintronics devices from the lab to the manufacturing floor, and eventually bring them to per-operation parity with silicon devices, is needed in order to realize their promise.

[177] H. Subbaraman, X. Xu, A. Hosseini, X. Zhang, Y. Zhang, D. Kwong, and R.T. Chen. "Recent advances in silicon-based passive and active optical interconnects." *Optics Express*, 23(3), pp. 2487 – 2510. February 9, 2015. A preprint version is available online at: http://chen-server.mer.utexas.edu/2015/oe-23-3-2487.pdf.

Target 16.7: Develop and demonstrate basic neuromorphic integrated circuits with a footprint one-tenth of 2015 technology

The calculator-like Von Neumann architecture (physical layout) of today's microprocessors and computers creates a bottleneck, or limitation, in the rate of transfer of data between external memory, (and/or internal microprocessor cache memory), and the control and arithmetic/logic units in the microprocessor or CPU. Essentially, these architectures operate sequentially on data fetched from memory. However, the human brain processes data in a fundamentally different way. The computational power of neural circuits is unparalleled when it comes to certain tasks (such as pattern recognition) and offer order-of-magnitude increases in energy efficiency over transistor-based logic. The human brain consumes a mere 20 W of power in its exascale processing (performs 10^{18} operations per second), while most experts agree an exascale computer, as envisioned today, will probably consume around 20 MW. Most electrical circuits built to mimic neurons rely on traditional electronic components and thus are ultimately unable to fulfill the promise in terms of speed and circuit density. Recent advances in logical components whose operation mechanisms are starting to resemble neural circuits[178] make neuromorphic electronic devices within practical grasp. These technologies rely on materials and microfabrication methods that are immature and face manufacturing barriers for their commercial manufacture and deployment.

Table 3.18 Technical Targets for Emerging Technical Area 16: Advanced Energy Efficient Computing

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
16.1	Develop and demonstrate technologies that will enable 10x improvement in computing energy efficiency over 2015 state of the art by 2025	2025	NCA	5 GOPS/W	NCA	EI, LC
16.2	Develop and demonstrate manufacturing technologies that expand the limits of three-dimensional integrated circuits	2025	NCA	Analysis needed	NCA	EI, LC
16.3	Develop and demonstrate processors at 100x higher processing speeds than 2015 commercial processors	2025	NCA	3 GHz clock speed	NCA	EI, LC
16.4	Develop and demonstrate optoelectronic interconnects with a chip footprint one-tenth of 2015 technology	2025	NCA	Analysis needed	NCA	EI, LC
16.5	Develop and demonstrate a 1 μm^2 atomically precise circuit	2025	NCA	50 nm^2 atomically precise circuit[179]	NCA	EI, LC
16.6	Develop and demonstrate manufacturing methods for computing spintronics devices	2025	NCA	Analysis needed	NCA	EI, LC
16.7	Develop and demonstrate basic neuromorphic integrated circuits with a footprint one-tenth of 2015 technology	2025	NCA	Analysis needed	NCA	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[178] Z. Wang, S. Joshi, S. E. Savel'ev, H. Jiang, R. Midya, P. Lin, M. Hu, N. Ge, J.P. Strachan, Z. Li, Q. Wu, M. Barnell, G-L. Li, H. L. Xin, R. S. Williams, Q. Xia and J. J. Yang. "Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing." *Nature Materials*. 2016. Available online at: http://www.nature.com/nmat/journal/vaop/ncurrent/full/nmat4756.html.

[179] J. C. Ellenbogen and J. C. Love, "Architectures for molecular electronic computers: Logic structures and an adder designed from molecular electronic diodes." Proceedings of the IEEE 88 (3). March 3, 2000. Abstract and full article (for purchase) available online at: http://ieeexplore.ieee.org/abstract/document/838115/.

3.2.3 Industrial End User Technical Assistance

Overview of Crosscut Area

In the manufacturing sector, significant cost savings are available through cost-effective investment in energy efficiency, such as the adoption of energy management practices and advanced technologies. These energy and cost savings contribute to competitiveness and reduce the embodied energy in manufactured products. A host of market and non-market barriers, as described in the sidebar, often prevent industrial companies from investing in greater energy efficiency.

AMO addresses these barriers and provides critical support needed to help U.S. manufacturers across diverse supply chains accelerate the deployment of advanced energy efficiency technologies and practices. Technical assistance activities aim to reduce manufacturing energy intensity; demonstrate the viability of new approaches and technologies; and reduce waste and water use.

Manufacturers can implement a broad range of technologies and practices to increase energy and cost savings. Technology examples include advanced electric motor systems and drives including fans and pumps, high efficiency boilers, waste heat recovery, energy-efficient lamps and lighting controls, modernization or replacement of process equipment, improved process performance through the use of sensors and controls, and combined heat and power (CHP). Examples of energy management practices include (1) strategic energy management (SEM), which entails the identification and quantification of energy savings from operational opportunities; and (2) systematic energy management systems (EnMS), which consists of long-term, persistent approaches (such as the ISO 50001 International Energy Management Standard) that drive continual improvements. While many facilities and energy managers already manage energy on an ad hoc basis, systemic tools, training, and processes can lead to greater consistency and adoption of energy efficient technologies, processes, and practices. The Technical Assistance program works with AMO's R&D programs to ensure that new and emerging technologies and processes are incorporated in the portfolio of energy saving equipment, processes, and tools available to industry.

Objective:
Provide technical assistance to industrial energy users to optimize energy use, reduce emissions, establish energy management systems, and increase productivity.

Challenges and Barriers:

Awareness and corporate priorities
- Competing corporate polices and structures
- Lack of awareness of cost-effective opportunities to save energy
- Lack of technical expertise and staff time to implement improvements
- Project uncertainty (real and perceived) and risk of disrupting production

Economic barriers
- Competition for capital and emphasis on quick return on investment (ROI); energy can be a small part of operating costs
- Non-energy benefits are often not captured in energy assessments and ROI calculations
- Lack of financing incentives and market drivers for investments
- Unclear value proposition

Technical issues
- Slow capital technology/equipment turn over/retirement time
- Lack of widespread and effective implementation of energy management standards and energy-saving protocols
- Aging workforce and projected need for new highly trained staff to manage energy

Regulatory issues
- Uncertain future carbon policies; no current national policy driver for efficiency
- Permitting, interconnection, and tariff/fee issues that prevent or inhibit combined heat and power installations

Targeted Impacts

End user technical assistance activities focus on manufacturers at the corporate and facility-level as well as state and utility stakeholders with programs impacting energy use in manufacturing. Assistance is also provided to commercial, institutional, and water/wastewater treatment facilities with similar operations.

AMO Approach

Technical targets for this activity area, along with current status, are summarized in Table 3.19. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are also described in this section.

Target 17.1 Quadruple the number of technology assistance partners who successfully achieve their established program goals and targets; annually or consistent with the established program goal period.

Equipping manufacturers with decision support software tools, training, and information resources is an effective way to support facilities of all sizes in identifying, analyzing, and implementing energy savings opportunities at the corporate and plant-level. For example, existing technical resources provide step-by-step ways to help manufacturers track energy use, identify areas of improvement, improve the efficiency of specific systems and equipment, monitor progress, and improve overall efficiency and productivity.

Energy productivity can also be increased by providing direct technical support to partner facilities. For example, energy system subject matter experts can be used to provide advice, training, or guidance to partner facilities; and university-based engineering faculty and engineering students can be leveraged to provide energy audits and assessments to manufacturers. AMO coordinates with regional energy efficiency organizations, state energy offices, and electric, natural gas, and water utilities to maximize the savings potential for the small- and medium-sized clients.

Representative examples of actions that can help achieve this target include the following:

- Modernize the DOE energy system software tool suite and associated training resources and make 100% of these resources accessible online and in an 'open source' environment.
- Launch an e-Learning center with resources for beginner through advanced energy efficiency practitioners.
- Enhance energy system resources that reduce industry-wide barriers to advancing state-of-the art technologies including financial risks, lack of performance standards, and a general lack of knowledge.
- Demonstrate advanced manufacturing technologies in 100 Better Plants facilities.
- Facilitate 20 engineer “swaps” annually among AMO partners.
- Double the number of small and medium sized firms currently served by AMO annually.
- Double the number of AMO state, local, and national partners, including the Manufacturing Extension Partnerships (MEPs), utilities, and state economic development offices

Target 17.2: Expand AMO partner commitments to 25% of large energy user footprint.

AMO has a long history of supporting its industrial partner companies in setting and achieving energy savings and energy intensity commitments. AMO provides DOE recognition and technical assistance; its partners provide energy use data and take actions to achieve their goals. This approach raises the public profile of partner companies, brings recognition to the energy champions, and raises corporate awareness of the value of energy optimization. Technical assistance activities can help individual manufacturers select the appropriate data collection methodology and report energy intensity reduction; demonstrate the viability of improved energy management approaches; and pursue targets for energy efficiency, productivity, waste reduction, and water use. AMO also encourages key stakeholders with direct relationships with manufacturers, such as gas and electric utilities, public utility commissions, and state and local energy programs, to communicate the value of AMO partnerships. This value proposition goes beyond energy management, and includes technical assistance on water use and re-use, waste reduction, and supply chain strategies. Representative examples of actions that can help achieve this target include the following:

- Increase outreach to large energy users, with the goal of expanding the Better Plants program to include more than 300 partners
- Expand Better Plants program with a focus on supply chain companies
- Double the number of AMO partnerships that include water use and re-use, cyber security, and waste reduction
- Educate public utility commissions (PUCs), state energy offices, air and economic organizations, and utilities with the goal of encouraging 30 states and/or utilities to adopt strategic energy management in new or enhanced programs for large energy users

Target 17.3: Catalyze a 3x increase in the number of ISO 50001 certified or conformant facilities.

SEM is a proven way for any energy using facility (including manufacturers, commercial, and institutional) to achieve greater energy savings with more persistent savings over time. Adopting a comprehensive energy management system

(EnMS) such as the ISO 50001 International Energy Management Standard, helps a facility in establishing formal policies and procedures to systematically track, analyze, and improve energy efficiency which becomes part of corporate 'culture'. Studies have shown that energy savings from EnMs range from 2% to greater than 10% per year, depending on the facility and the rigor of the EnMS instituted. The greatest savings have been realized by AMO partners that were conformant to ISO 50001. When those partners compared their savings from ISO 50001 facilities to non-ISO 50001 facilities, the ISO 50001 achieved close to double the savings.[180] The ISO 50001 certification of facilities is valuable recognition of the company's sustainability commitment and also recognizes the energy team for implementing an energy management system and/or achieving a validated amount of energy savings. Finally, conformance with ISO 50001 will align the United States with other countries that are implementing ISO 50001 as a climate change mitigation strategy and support multinational companies that seek to create more sustainable facilities across the globe. Representative examples of actions that can help achieve this target include the following:

- Develop processes and recognition for facilities to meet the requirements of ISO 50001 and become "ready" to certify.
- Develop means to quantify energy savings from strategic energy management that includes robust, industry-consistent measurement and verification protocols.
- Develop an energy management tool (Guide to Energy Management (GEM) Tool) to assist utility programs or for direct use by end-users that allows the tool users to meet the requirements of ISO 50001 and become ready to certify.
- Engage 15 or more states in adopting state plans or PUC guidance to utility programs that utilize AMO's GEM Tool or the ISO 50001 Energy Management Standard and Superior Energy Performance (SEP) Program as options for industrial opt-out, self-direct, or to directly meet state goals or potential regulatory requirements.
- Support at least 1000 Better Plants or Industrial Assessment Center (IAC) clients to become ISO 50001 ready by 2025
- Recognize 1000 or more U.S. industrial, commercial, institutional and water/wastewater facilities for achieving ISO 50001 ready through use of the GEM Tool or SEP certification.

Better Buildings, Better Plants

The U.S. Department of Energy's Better Buildings, Better Plants Program engages leading manufacturers and industrial-scale energy-using organizations in demonstrating their commitment to improving energy performance by signing a voluntary pledge to reduce their energy intensity by 25% over a ten-year period.

Better Plants Partners benefit from DOE technical support and are able to implement cost-effective energy efficiency improvements that save energy and improve competitiveness. To date, Better Plants Partners consists of close to 180 industrial companies, representing about 2,400 facilities and 11.4% of the total U.S. manufacturing energy footprint as well as several water and wastewater treatment organizations. Collectively they have reported savings of about 457 TBtus and $2.4 billion cumulatively in energy costs. These companies are showing that good energy management practices are good for business and good for the environment.

Better Plants
U.S. DEPARTMENT OF ENERGY

[180] "3M and Schneider Electric Implement ISO 50001 and Superior Energy Performance and Escalate Energy Savings." EERE/DOE. June 9, 2016. Available online at: http://energy.gov/eere/amo/articles/3m-and-schneider-electric-implement-iso-50001-and-superior-energy-performance-and.

Table 3.19 Technical Targets for Crosscutting Area 17: Industrial End User Technical Assistance

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
17 .1	Quadruple the number of technology assistance partners who successfully achieve their established program goals and targets; annually or consistent with the established program goal period	2025	PRA	35 partners successfully achieved program goals[181]	Activity ongoing	EI, EM
17.2	Expand AMO partner commitments to 25% of large energy user footprint.	2025	PRA	11.4% of total manufacturing foot print[182]	Activity ongoing	EI, EM
17.3	Catalyze a factor of 3 increase in the number of ISO 50001 certified or conformant facilities.	2025	PRA	4,000 facilities[183]	Activity ongoing	EI, EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Related Resources

- Barriers to industrial Energy Efficiency, Report to Congress, June 2015

[181] Supra 76. "Progress Update: Fall 2016." Better Plants. U.S. DOE.

[182] Ibid

[183] Hilton certified approximately 3,900 U.S. hotels to ISO 50001. For more information, see: "Hilton Worldwide Unveils Upgrades to Corporate Responsibility Reporting Across Its Global Portfolio." Press Release. Oct. 22, 2015. Available online at: http://news.hiltonworldwide.com/index.cfm/news/hilton-worldwide-unveils-upgrades-to-corporate-responsibility-reporting-across-its-global-portfolio-. There are approximately 100 additional ISO 50001 certifications in the United States (estimate based on three sources: Reinhard Peglau of the German Federal Environment Agency, ISO Survey 2015 (http://www.iso.org/iso/iso-survey), and DOE Superior Energy Performance website (http://energy.gov/eere/amo/certified-facilities).

3.2.4 Workforce Development

Objective:
Provide educational resources for primary, high school, community college, and university students as well as mentoring and on-the-job training opportunities in order to increase the number of qualified technical employees in advanced manufacturing at all levels.

Challenges and Barriers:

- **Skill gap:** insufficient quantity of workers with the skills needed to fill manufacturing jobs
- **Image gap:** the outdated perception of manufacturing work as dark, dirty and dangerous
- **Awareness gap:** potential employees are not aware of manufacturing jobs and training opportunities
- **Demographics:** aging workforce nearing retirement age and the loss of their knowledge
- **Job security:** concerns of manufacturing jobs being outsourced to foreign competitors[2]
- **Training development process:** long timeframe for establishing new accredited technical degrees, skill certifications, and other workforce capacity building efforts
- **Time delay:** lag between initiation of workforce development efforts and actual expansion of workforce

Overview of Crosscut Area

A prosperous manufacturing sector requires workers with a wide range of technical skills, including in-plant production, manufacturing energy management and analysis, R&D, and information technology. In the plant, specific skills are required to optimally operate industry-specific processes optimally. Additional specific skills are required to operate facility-wide systems equipment and data-driven platforms that are more broadly used across manufacturing. One of the keys to the competitiveness of American manufacturing will be a technical workforce knowledgeable about these operations and possessing the ability to optimize them to reduce costs and minimize waste. Researching and developing the next generation of competitive and efficient advanced manufacturing technologies requires a workforce of engineers, researchers, and innovators with experience in relevant academic and manufacturing fields. In turn, a growing number of technically skilled production workers will be needed to fill the new jobs created by the implementation and operation of these emerging advanced manufacturing technologies.

Manufacturers are currently facing a significant skill gap because of retirement of trained workers and a lack of workers trained in the latest technologies and energy management skillsets for a 21st Century manufacturing space. Skilled workers with diverse areas of expertise are needed, ranging from the technician level to bachelor and graduate level. While the skill set required varies depending on the specific advanced manufacturing technology deployed it will include math, science, engineering, materials, computer, and data collection and analysis.[184] Despite ample demand for workers, manufacturers are unable to find the talent capable of filling many open positions. In addition, workforce development efforts often lag behind the actual needs of employers. For example, it takes a long time to establish new accredited degrees for some positions required of the technical workforce. Of the 3.4 million job openings projected to be added by U.S. manufacturers between 2015 and 2025, over 2 million are expected to go unfilled.[1] This lack of sufficient workforce could inhibit industry growth and deter domestic manufacturing. Workforce development efforts – including revitalizing manufacturing's image, expanding training programs, and spreading awareness of those training programs – will be essential to enabling U.S. job growth in advanced manufacturing. The Advanced Manufacturing Partnership 2.0 (AMO2.0), created to revitalize the manufacturing sector, recognized the challenges posed by workforce gaps and identified opportunities to address solutions through collaboration between government, companies, academia, and labor organizations. AMO activities are part of this national effort to address workforce challenges in manufacturing.

Targeted Impacts

Focus applications for AMO include developing skillsets in energy management and in emerging areas specific to AMO Manufacturing Innovation Institute (MII) consortia, including composite materials, wide bandgap electronics, smart manufacturing, sustainable manufacturing, and chemical process intensification.

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[184] *The skills gap in U.S. manufacturing: 2015 and beyond*. Deloitte and Manufacturing Institute. Available online at: http://www.themanufacturinginstitute.org/~/media/827DBC76533942679A15EF7067A704CD.ashx.

AMO Approach

Technical targets for this activity area with current status are summarized in Table 3.20. The rationale for including each target, and AMO's approach for overcoming the key challenges and barriers, are described in this section.

Target 18.1 Develop or advance 15 workforce curricula focused on manufacturing energy systems and advanced technologies.

Training curricula needs to be relevant to advanced manufacturing technologies and practices in use and be easy to access, contain self-paced learning, and develop a worker's skill set and value. Curricula must also be updated and maintained to incorporate new skills and knowledge needed to support new and emerging advanced manufacturing technologies. Systematic energy management processes and systems are needed that are robust and transferrable across facilities worldwide (e.g., training on the implementation of the ISO 50001 international standard for energy management). Certification of professionals with proven expertise and who have passed exams relevant to specific industries is needed to establish credibility and create a market for individuals with this expertise. Representative examples of actions that can help achieve this target include the following:

- Through the Industrial Assessment Centers, lead the establishment of a Bachelor of Science (B.S.) in energy efficiency engineering at 50 universities.
- Convert AMO energy system tools for pumps, fans, compressed air, steam, and process heating to open-source platform, and develop companion tool training.
- Expand AMO's In-Plant Trainings offered to Better Plants partners for energy systems and energy management.
- Develop Certified Practitioner exam-based certifications for specific energy systems (e.g., compressed air, steam, process heating, pumping) in addition to existing Energy Management Systems certification (CP EnMS).

Target 18.2: Train at least 3,000 individuals per year in advanced manufacturing technologies and solutions, including energy management practices.

As advanced manufacturing technologies, materials, and processes are developed and deployed, the new attributes required to perform the jobs these advances will create need to be identified and integrated into educational pathways in K-12 schools, community and technical colleges, and universities. These competencies also need to be incorporated into efforts to increase the skills of the incumbent manufacturing workforce. Inviting manufacturing facility staff to participate in online training, webinars, peer-exchange calls, meetings, in-person training, and industry workshops and conferences is a way to enhance manufacturing expertise and help individuals learn how to operate plants more efficiently. Hands-on training activities focused on energy management and other clean energy practices can also help manufacturing facilities decrease energy costs and reduce greenhouse gas emissions. Establishing internships and training opportunities that bring together leading practitioners in emerging technologies with science and engineering students seeking hands-on experience is another way to develop a high quality advanced manufacturing workforce. The following are representative examples of activities towards achieving this target:

- Train at least 50 educators per year in advanced manufacturing technologies for clean energy, including energy management practices.

Industrial Assessment Centers

Industrial Assessment Centers (IACs) utilize university-based engineering faculty and engineering students to provide energy efficiency and waste reduction assessments for small- and medium-sized manufacturers. In the process, the Centers play an integral role in workforce development. Students participating in their school's IAC learn valuable energy efficiency skills and gain hands-on experience applying these skills in the real world – expanding their knowledge of industrial process systems, plant systems, industrial information technology, energy management systems, wastewater systems, and energy management practices. Ultimately, this training expands the pipeline of energy efficiency engineers.

- Provide advanced manufacturing and energy management training to 400 engineering students per year at ABET (Accreditation Board for Engineering and Technology) accredited universities.
- Train 500 individuals per year in manufacturing energy system optimization and energy management online and in classroom.

Table 3.20 Technical Targets for Crosscutting Area 18: Workforce Development

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
18.1	Develop or advance 15 workforce curricula focused on manufacturing energy systems and advanced technologies.	2030	PRA, CST	7 curricula	8 curricula [185]	TE
18.2	Train at least 3,000 individuals per year in advanced manufacturing technologies and solutions, including energy management practices.	2025	PRA, CST	941/year[186]	1080/year	TE

***Key:** CST = Funded Institute or Hub; PRA = Practices; R&D = Funded R&D Project; NCA = No Current Activity; SBIR = Funded SBIR Project

Related Resources

- The Skills Gap in U.S. Manufacturing 2015 and Beyond, Deloitte and Manufacturing Institute skills gap study.
- Overwhelming Support, U.S. Public Opinions on the Manufacturing Industry, Deloitte and the Manufacturing Institute public opinion study.
- Minding the Manufacturing Gender Gap, How Manufacturers Can Get Their Fair Share of Talented Women, Deloitte, the Manufacturing Institute, and the APICS Supply Chain Council gender gap study.
- Report to the President on Ensuring American Leadership in Advanced Manufacturing, June 2011.
- Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing, July 2012.
- Report to the President Accelerating U.S. Advanced Manufacturing, October 2014.
- https://iac.university/technicalDocs/Industrial%20Assessment%20Centers%20Impacts%20SRI%20International.pdf
- Industrial Assessment Center website: https://iac.university/ and http://energy.gov/eere/amo/industrial-assessment-centers-iacs.

[185] IACs: One new In-Plant Training (INPLT) in 2016; PowerAmerica: 7 WBG courses developed by 2015; no additional courses in 2016.
[186] IACs: 300 students trained annually. IACMI: completed Workforce Needs Assessment; no students trained. PowerAmerica: 641 trained in 2015, 780 trained in 2016.

3.2.5 Communications and Outreach

Objective:
Provide information on energy technology resources and solutions for manufacturing, build networks of technical experts, and generate awareness of AMO and its activities.

Communications and Outreach Planning:
At the completion of the MYPP in FY17, AMO plans to develop a robust communications and outreach plan that will include key messages, strategies, tactics, deliverables, and a timeline of events.

Overview of Crosscut Area

AMO is a lead government agency responsible for improving energy efficiency in manufacturing. The office partners with all levels of government, industry, small business, universities, National Laboratories, states, utilities, and other stakeholders to develop and deploy technologies and practices.

AMO Approach

At the highest level, AMO conducts communications and outreach activities to accomplish the following:

- Provide energy technology resources and solutions for manufacturing
- Build networks of technical experts to develop and deploy foundational technologies
- Expand the use of proven technologies and energy management practices to achieve near-term savings
- Generate awareness of AMO and its activities.

Targeted Impacts

Implementing this strategy requires clear communication to a variety of external and internal audiences. Unlike other EERE programs, AMO must convey the opportunities and value of energy efficiency improvements in diverse technical areas and applications relevant to different manufacturers. In addition, AMO must engage diverse audiences to also include professional organizations, the media, and the general public. AMO's communications and outreach strategy focuses on four key elements to achieve Program goals.

Communications Products – The AMO Weekly Announcement is sent by e-blast to the AMO listserv each week to provide notices of upcoming opportunities and activities as well as reports on funding awards and progress. EERE and the White House may also issue press releases on AMO-funded opportunities and awards. AMO maintains an up-to-date website with targeted publications, blogs, and press releases to promote awareness of AMO products and services (including current R&D projects and facilities) and to make the business case for energy efficiency (including fact sheets, infographics, success stories, case studies, webinars, presentations, videos, and innovative web-based products). Activity areas may conduct outreach to a sub-set of stakeholders and send e-blasts to a targeted listserv. AMO also develops custom content and uses electronic and print media, including social media platforms, to reach small and large audiences.

Research, Development, Commercialization, and Deployment Activities – AMO emphasizes various communication and outreach activities throughout the R&D cycle – from technology assessments, planning, solicitation development, and project selection. External efforts to support these activities often include the following:

- ***Technology Workshops*** – AMO plans and facilitates workshops to the public to solicit guidance on technology gaps and opportunities.
- ***Request for Information*** (RFI) – To obtain additional information on a technology opportunity, AMO may issue a RFI to collect written information in response to key questions in order to identify current capabilities and needs in the market.
- ***Webinars*** – In order to assist stakeholders, AMO may provide webinars on funding opportunities, technical assistance where appropriate, and other subjects of potential interest.
- ***Events*** – At the annual AMO Peer Review, the Office conducts a review of its activities in a public meeting. Activity areas may host summits to share technical and management solutions and publicize achievements.

Strategic events are held in conjunction with professional organizations and other stakeholders to pursue specific objectives. AMO staff make presentations at various events, and participate in community and EERE-led activities, to build partnerships and publicize programs, opportunities, and accomplishments. Members of AMO senior leadership are often invited to sit on panels, participate in forums, and present keynote addresses at prominent industry, partner-led, or government events.

Partnerships – Public-private partnerships are essential in delivering our products and services to such a large and diverse economic sector. Targeted communication and outreach activities are conducted to address the following:

- ***Regional, State, and Local Partnerships*** – AMO's MIIs are developing and deploying foundational technologies to serve specific regions and the nation. Throughout the United States, AMO partners with diverse state, utility, university, National Laboratory, and other stakeholders to cooperatively seek energy intensity reductions in manufacturing.
- ***Stakeholder Development*** – To greatly expand our outreach and effectiveness, AMO partners with organizations affiliated with large subsets of industry. AMO encourages companies to elevate energy efficiency as a priority and deploy new energy-efficient technologies.
- ***Voluntary Agreements, Certification, and Recognition Programs*** – AMO develops and implements initiatives with partners to address market failures and accelerate a reduction in manufacturing energy intensity. AMO conducts marketing campaigns to promote the initiatives and encourages corporate and facility-level participation. AMO recognizes accomplishments and energy savings.

Target 19.1: Increase social media outreach of AMO and its activities

The use of web-based communication tools such as Facebook, Twitter, You Tube, LinkedIn, Twitter and Instagram has changed the way individuals and large organizations communicate. DOE/EERE have an array of social media tools of which AMO can use to provide up-to-date, timely information about AMO initiatives, resources, funding and partnership opportunities, and events to reach a large number of stakeholders. By increasing social media outreach efforts, AMO can expand its connectedness to stakeholders by providing a platform for two-way communication with stakeholders, share more targeted content through various formats including videos, live streaming events, and infographics, and increase its social network on a global level.

Target 19.2: Enhance the usability of the AMO Website annually

The AMO website serves as the main hub to provide energy technology resources and solutions for manufacturing. AMO has plans to refresh the site design to make it even easier to use and more intuitive with greater access to resources and tools that meet users' needs regarding content, organization, navigation, and graphics.

Table 3.21 Technical Targets for Crosscutting Area 19: Communications and Outreach

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
19.1	Increase social media outreach of AMO and its activities.	2020	PRA, CST, R&D	Social media metrics were not tracked in 2015	Total reach since July 2016 is 718,126[187]	EI, LC, EM, TE
19.2	Enhance the usability of the AMO Website annually.	2020	PRA, CST, R&D	638,695 pageviews	827,547 pageviews	EI, LC, EM, TE

***Key:** CST = Funded Institute or Hub; PRA = Practices; R&D = Funded R&D Project; NCA = No Current Activity; SBIR = Funded SBIR Project

[187] Reach is the total number of people touched across all social media platforms, which includes clicks, shares, tweets, re-tweets, etc.

3.3 Advanced Manufacturing for Energy Systems

3.3.1 Advanced Manufacturing to Enable Modernization of Electric Power Systems

Objective:
Advance manufacturing technologies and innovative materials to support grid modernization efforts, including the successful integration of conventional and renewable energy resources, storage, and energy efficient central and distributed power generation in a safe, reliable, and cost-effective manner.

Challenges and Barriers:

- **Supply side diversification:** aging low-efficiency generation capacity is replaced by a mix of central stations and distributed generation, powered by both fossil fuels and renewable resources.
- **Demand side diversification:** rapidly growing use of distributed generation and interactive control systems in buildings, industrial equipment, and consumer goods.
- **Need for "smart" technologies:** the grid performance expectations and end-user engagement have increased, resulting in demand for more complex systems and technologies.
- **More control points:** grid operations are moving from directing systems with a limited number of control points at central stations to potentially millions of highly interactive distributed control points.
- **Demand growth and increased reliance on electricity:** critical services and other aspects of society are becoming more digital and automated, resulting in continued growth in electricity consumption and causing power disruptions to have greater consequences.
- **Size and cost of required investments:** the nation's electric grid is massive with much capital invested in it; the scale and cost of modernizing the system are significant.

Overview of Technical Area

The U.S. electric power system is the centerpiece of the nation's energy economy. However, the design and operation of today's grid is being challenged to meet the evolving security, cost, and environmental needs of a low-carbon, digital economy. Shifts are occurring on the supply side (e.g., increased adoption of renewable resources and shift from coal to natural gas for baseload) and demand side (e.g., growing use of demand side management and new business models based on data and information that can inform consumers' energy-use decisions). Accompanying these changes is the growing adoption of digital communications and control systems (i.e., smart grid technologies) to improve performance and engage consumers – and optimize the balance between supply and demand.

Additionally, grid operations are moving from a handful of control points at central stations to vast network of highly interactive distributed control points. As such, the existing power grid is confronted with new requirements as it attempts to perform in ways for which it was not designed. Meanwhile, the nation's reliance on a dependable, efficient, and resilient power grid is rising.

DOE has undertaken a Grid Modernization Initiative (GMI) that has identified six key technical areas where progress and developments are needed to modernize the grid:[188]

- Devices and Integrated Systems Testing
- Sensing and Measurements
- System Operations, Power Flow, and Control
- Design and Planning Tools
- Security and Resilience
- Institutional Support

A modernized electric power system will need to dynamically optimize distributed resources, rapidly detect and mitigate disturbances, engage millions (if not billions) of intelligent devices, integrate diverse generation sources (including renewables), integrate demand response and energy-efficiency resources, enable consumers to manage their electricity use and participate in markets, and provide strong protection against physical and cyber risks. For further discussion of the applications, challenges, and opportunities related to the grid infrastructure, see the 2015 QTR Technology Review, Chapter 3: *Enabling Modernization of the Electric Power System*.

[188] *Grid Modernization Multi-Year Program Plan (MYPP).* U.S. Department of Energy. November 2015. Full report is linked at: http://energy.gov/downloads/grid-modernization-multi-year-program-plan-mypp.

Targeted Impacts

AMO supports DOE goals[189] for grid modernization, particularly those established for developing advanced power electronics, energy storage systems, smart grid devices, and grid infrastructure, which include:

1. *Develop power electronics-based converters for renewable, distributed energy, and energy storage systems that can provide grid services and self-optimize around the market and energy environment.*
2. *Decrease the system costs of deployed grid-scale, energy storage system to under $300/kWh by establishing grid-scale storage systems' metrics for safety, reliability and performance, and through new energy storage technologies development.*
3. *Enable buildings, large building loads (e.g., heating, ventilation, and air conditioning (HVAC) systems and refrigeration systems), and EV charging systems to: (1) diagnose if they are functioning properly, (2) forecast their energy needs over the next day or several days, (3) characterize their available flexibility, and (4) have embedded control and decision-making tools to provide capacity, energy, and ancillary services to the electrical grid and other valuable services to system owners.*
4. *Develop innovative grid infrastructure technologies and components that improve electrical grid efficiency and reliability by 10 percent.*
5. *Develop low cost, multi-purpose sensors for electric grid components to monitor real-time health status, stress accumulation leading to component loss of life, and real time loading that takes local environmental conditions into account.*

AMO research includes advanced materials for more efficient and reliable energy use, advanced technologies for control and monitoring of equipment, power electronics to support bi-directional energy flows, new manufacturing approaches to produce the required materials and technologies, and improved combined heat and power (CHP) systems for distributed generation. More extensive research and development activities in support of grid modernization is conducted by DOE's Office of Electricity Delivery and Energy Reliability (OE).

AMO has a long history of RD&D and technical assistance activities on distributed generation technologies, including CHP systems. Since these dispatchable distributed generation technologies can be precisely controlled and are available at any time during the day or night, they can augment intermittent renewable energy resources. AMO is now exploring what additional functionality and characteristics are needed from dispatchable distributed generation technologies so that these systems can play a larger role in supporting the electric grid. For example, faster generator response times, increased generator efficiency at partial load, and low cost telemetry for small generators are areas that merit additional research and development.[190] In the future these distributed assets may play a larger role on the electric grid by selling energy into wholesale markets or providing ancillary services such as frequency regulation.

AMO Approach

AMO activities are focused in three overarching areas: (1) advanced materials and manufacturing technologies for grid applications and products, (2) next generation electric machines and other advanced power electronic devices, and (3) efficient and clean distributed generation and grid services.

Advanced materials and manufacturing technologies for grid applications and products

Grid applications will benefit from materials that can withstand extreme and harsh service conditions such as high-temperature and/or high-frequency.

A major focus is on the development of wide bandgap (WBG) semiconductor materials, which are suitable for use in next generation electric machines and many other power electronic systems, such as solid state transformers and power flow controllers. One example of the use of WBG is for power electronics in CHP systems; WBG semiconductors could enable smaller power conversion units within packaged CHP, decrease waste heat, and further increase the

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[189] Ibid

[190] *Workshop Summary Report: R&D for Dispatchable Distributed Energy Resources at Manufacturing Sites*. U.S. DOE. April 2015. Report available online from: http://energy.gov/eere/amo/downloads/rd-dispatchable-distributed-energy-resources-manufacturing-sites-workshop-summary.

overall system efficiency as well as providing a more robust interface with the grid. Additionally, improvements in other materials important for power electronics systems such as multilayer ceramic capacitors, polymer film capacitors, glass capacitors, and inductors (potentially including inductors with amorphous or nanocomposite magnetic cores) can enable devices that can take full advantage of WBG properties.

AMO also targets low resistance conductor materials, materials for advanced batteries and other energy storage devices, novel low-cost soft magnetic materials for transformers, materials that can withstand extreme and harsh service conditions, and advanced lightweight composites for energy infrastructure (which also have important applications for lightweighting in transportation). Among AMO-supported new manufacturing technologies are additive manufacturing approaches to improve material properties for power sector applications as well as roll-to-roll manufacturing for batteries and other energy storage devices.

Several AMO targets that directly contribute to work in this area are shown in Table 3.22 below.

Table 3.22 Selected AMO Targets for Advanced Materials and Manufacturing Technologies for Electric Power Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
3.3	Demonstrate a factor of 3 improvement in the reliability (failures reduced to one-third over 10 years) of targeted electrical devices produced at high volumes over their silicon-based equivalent.	2020	CST, SBIR	SiC MOSFETs: 10 failures/10^9 hours[191, 192, 193]	Research ongoing	LC
5.2	Develop scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity.	2025	R&D	**Thermal:** [194] Cu: 385 W/m K Al: 205 W/m K Fe: 79.5 W/m K **Electrical:** Cu: 100% IACS[195] Al: 61% IACS Fe: 17% IACS	**Thermal:** Research ongoing **Electrical:** Cu Covetics: 133% IACS[196]	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Next generation electric machines and other advanced power electronic devices

AMO supports the development of many new technologies and devices that facilitate clean energy technology integration with the modern grid, such as advanced sensor systems (which have applications in power flow monitoring); inverters (which have applications in renewable energy production, storage, and dispatch); power electronics for next generation electric machines (which have applications in electrical transformation, fault current limiting, and power flow control); and power electronics for electric vehicle supply equipment (i.e., chargers and related equipment).

For example, grid-tied inverters or power converters are used to integrate power generators with the grid and can provide power factor control to help stabilize the grid. Wide bandgap (WBG)-enabled devices can allow for higher temperature and higher voltage operation compared to their conventional silicon-based counterparts, and can provide improvements in efficiency. The advantages of WBG devices are particularly relevant for renewable resource

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[191] Supra 113. J.B. Casady. "SiC Power Devices and Modules Maturing Rapidly." *Power Electronics Europe: Issue 1*. 2013.
[192] Supra 114. "Power products commercial roadmap for SiC from 2012 – 2020." Cree Power. 2014.
[193] Supra 115. "Industrial Readiness of SiC Power Devices." GE Global Research. CFES 2015 Annual Conference.
[194] Supra 121: Table of Thermal Conductivity.
[195] Supra 122: IACS definition.
[196] Supra 123: U. Balachandran. "High Performance Electrical and Thermal Conductors." AMO Program Review 2016.

integration; for example, WBG-based devices operating at 3 kilohertz (kHz) switching speed are enabling significant performance enhancements in inverters in wind power and solar photovoltaic systems. AMO has improved these devices by reducing the volume and weight of several photovoltaic converters in addition to improving their efficiency. Advances in SiC-enabled inverters can support other grid power electronic systems such as solid state transformers and high-voltage direct current (HVDC) converters.

Several AMO targets that directly contribute to work in this area are shown in Table 3.23 below.

Table 3.23 Selected AMO Targets for Next Generation Electric Machines and Other Advanced Power Electronic Devices for Electric Power Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI**
				2015 Baseline	Progress to Date	
3.1	Reduce volume and weight of targeted power electronic systems by 50% with respect to their silicon-based equivalents.	2020	CST, R&D	Current equivalent silicon devices represent the baseline (i.e., 100%)	50% reduction in volume in 3 out of 8 devices under development[197]	EI, EM
3.2	Increase the efficiency of targeted power electronic systems by 2-3% (a reduction in losses of 28% or above) with respect to their silicon-based equivalents.	2020	CST, SBIR	93 - 96%, depending of the device[198]	Efficiency increase of 2-3% demonstrated for 4 devices and 5 more on track to meeting the goal[199]	EI, LC
3.4	Increase the efficiency of targeted electric machines by 2-3% (a reduction in losses of 28 - 75%).	2020	R&D	93-98%[200]	Research ongoing	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Efficient and clean distributed generation and grid services

Smart grid technologies could help balance generation with demand, shift generation dispatch toward those with lower environmental impacts, manage the control of evolving storage technologies, and increase overall grid efficiency. WBG-enabled power electronic inverters could enable increased deployment of distributed generation through more seamless interconnection with the grid and by providing smoother, more consistent waveforms.

AMO supports development of advanced metering devices; control systems for interoperable and transactional demand response of industrial loads; integrated cybersecurity of manufacturing systems; and modeling and simulation for dynamic operational efficiency of industrial processes. AMO also seeks to improve the cost and efficiency of CHP systems by developing small packaged systems, high-value applications with attractive end-user economics, and increasing waste heat to power thermal efficiency.

AMO targets that directly contribute to work in this area are shown in Table 3.24 below.

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197 The devices are an electric vehicle fast charger and two different photovoltaic systems' DC-AC inverters.

198 Supra 111. *Premium Efficiency Motor Selection and Application Guide: A Handbook for Industry.* AMO/EERE/U.S. DOE. 2014.

199 The devices that met the goal are an electric vehicle fast charger and three different photovoltaic DC-AC inverters. Additionally, there are projects on track to deliver 3 more DC-AC inverters, two electric vehicle inverters and one heavy-duty electric vehicle inverter.

200 Supra 111. *Premium Efficiency Motor Selection and Application Guide: A Handbook for Industry.* AMO/EERE/U.S. DOE. 2014.

Table 3.24 Selected AMO Targets for Efficient and Clean Distributed Generation and Grid Services

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI**
				2015 Baseline	Progress to Date	
11.2	Reduce the cost of deploying Smart Manufacturing systems (advanced sensors, controls, platforms, and models) in existing processes by 50% compared to 2015 typical technology.	2025	CST	Analysis needed	Not available	EI
13.2	Advance the development of cost-effective CHP systems that are responsive to site demands as well as grid requirements.	2030	NCA	Analysis needed	NCA	EI
13.4	Support a 20% reduction in installed cost of commercially available, packaged (<10 MW) CHP systems (while maintaining >75% system efficiency at HHV).	2025	PRA	Varies by size, technology and function. Typically, between $1,800/kW and $10,000/kW installed cost based on technology, system size, and installation complexity.[201]	Not available	EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[201] Supra 161. "Combined Heat and Power Technology Fact Sheet Series," U.S. DOE. 2016.

3.3.2 Advanced Manufacturing for Clean Electric Power Generation

Overview of Technical Area

The current portfolio of technologies for electricity production includes a combination of reliable but aging base-load generation, evolving renewable resources, new natural gas plants, and new and pending nuclear and clean coal facilities. As the industry evolves to meet growing electrification and domestic demand, challenges arise in optimizing the electric power system, minimizing risks, and maintaining reasonable cost. Future developments will likely include a mix of three broad categories: (1) fossil-based generation with carbon capture and storage (CCS), (2) nuclear energy, and (3) renewables, such as solar and wind. Technologies that enable higher efficiencies and effective GHG and environmental pollution control are an essential complement to this evolving generation mix. Similarly, crosscutting concepts – such as supercritical carbon dioxide Brayton cycles – could, if broadly applied, impact efficiency, emissions, and water consumption. While supporting aggressive emission reductions, the traditional market drivers such as reliability, safety, and low cost must be maintained and enhanced.

For further discussion of the applications, challenges, and opportunities related to electric power technologies, see the 2015 QTR Technology Review, Chapter 4: *Advancing Clean Electric Power Technologies and the accompanying technology assessments*. For AMO activities applicable to other grid modernization technologies, including energy storage systems, see section 3.3.1 Advanced Manufacturing to Enable Modernization of Electric Power Systems.

Objective:
Advance technologies to improve the cost and performance of electric power technologies through development of advanced capabilities in materials and manufacturing.

Challenges and Barriers:

- **Integration with the grid:** the modern grid is evolving from a relatively static system into a dynamic and evolving interactive system with two-way flow of electricity and information.
- **New technology uncertainty:** the future potential and viability of emerging new generation technologies is uncertain, making it challenging to determine which technologies to support.
- **Meeting all needs of the grid:** a balanced power grid needs baseload, intermediate, and peaking resources; the new evolving generation mix needs to meet these grid requirements.
- **Policy uncertainty:** policy environment has a significant impact on the economic viability of different generation technologies; policy uncertainty discourages investment.
- **Environmental constraints:** while increasing electricity demand necessitates expansion of generating capacity, environmental constraints – including water, GHGs, and other air pollutants – impact the viability and desirability of different generating technologies.

Targeted Impacts

AMO supports DOE goals for significant improvements in cost and performance of electric power generation technologies. These goals include:

1. *Reduce the total installed cost of utility-scale solar energy systems to $0.06/kWh by 2020 and to $0.03/kWh by 2030.*[202]
2. *Reduce the total installed cost of land-based utility-scale wind power to $0.057/kWh by 2020 and $0.042/kWh by 2030 and that of off-shore wind to $0.167/kWh by 2020 and $0.10/kWh by 2030.*[203]
3. *Lower the levelized cost of electricity from newly developed conventional geothermal systems to $0.06/kWh by 2020 and by 2030 for enhanced geothermal systems.*[204]
4. *Invigorate hydropower industry innovation, identify or enable opportunities, and solve challenges in the U.S. to support the goal of expanding the contribution of hydropower and pumped storage hydropower in non-powered dams, undeveloped streams, and pumped storage.*[205]

[202] SunShot Initiative Mission website at: http://energy.gov/eere/sunshot/sunshot-initiative-mission.
[203] *Wind Vision: A New Era for Wind Power in the United States.* EERE/U.S. DOE. DOE/GO-102015-4557. March 2015. Report available online at: http://www.energy.gov/eere/wind/maps/wind-vision.
[204] *Department of Energy FY 2017 Congressional Budget Request*. U.S. DOE. DOE/CF-0121 Vol. 3. See p. 166. Available online at: http://www.energy.gov/sites/prod/files/2016/02/f29/FY2017BudgetVolume3_2.pdf.

5. *Demonstrate component improvements that will allow an increase in wave energy conversion system power-to-weight ratio (PWR) of 100% (baseline for wave is 0.25 kW/ton).*[206]
6. *Advance fuel cell technologies for transportation, stationary, and early market applications. (Note that the focus of clean electric power generation is stationary fuel cell technologies)*
    a. *Develop distributed generation and micro-CHP fuel cell systems (5 kW) operating on natural gas that achieve 45% electrical efficiency and 60,000-hour durability at an equipment cost of $1,500/kW by 2020.*
    b. *Develop medium-scale CHP systems (100 kW – 3 MW) by 2020 that achieve 50% electrical efficiency, 90% CHP efficiency and 80,000-hour durability at a cost of $1,500/kW for operation on natural gas and $2,100/kW when configured for operation on biogas.*[207]
7. *Advanced Energy System with CO_2 capture at no more than $40 per tonne of CO_2 captured ready for demonstration by 2020 and less than $40 per tonne of CO_2 captured ready for demonstration by 2030.*[208]
8. *Develop Advanced Nuclear Reactor Technologies focused on high value research for long term concepts, R&D needs of promising mid-range (2030) concepts, and development of technologies that benefit multiple reactor concepts and stimulation of new ideas for transformational future concepts.*[209]

AMO contributes to these high-level goals through RD&D focused on developing advanced next generation materials and innovative process manufacturing approaches to improve the efficiency of power generation, reduce the lifecycle energy impacts, and ensure U.S. competitiveness in the global market.

AMO Approach

AMO activities are focused in three areas: (1) developing advanced materials needed for efficient power generation; (2) developing next generation manufacturing processes and technologies for electric power generation, and (3) developing advanced technologies to improve the lifecycle energy efficiency of clean electric power generation and strengthen a wide breadth of domestic industries.

Develop advanced materials for clean and domestic electric power generation

Many of the electric power generation systems operate in extreme environments and would benefit from AMO research in materials for harsh service conditions. Power from renewable sources (solar, hydroelectric, or wind) when coupled with the grid will provide variable power and this needs to be supplemented through fossil sources, which will in turn need to operate variably. Frequent cycling of fossil-fueled generators may lead to accelerated component wear and performance degradation compared to steady-state operation.[210] Material performance under such conditions is not well established. The goal will be to develop a reliable system to function with 50% solar or 50% wind energy supplemented by fossil fuels. The thermal and chemical environments experienced by components will vary in a manner where, for example, protection against oxidation cannot be ensured with current predictive capabilities.

Research is underway to develop phase stable materials as well as tailored powders for additive manufacturing for use in high-temperature, high-pressure, high-value applications such as power generation turbine blades. Advanced

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205 "Water Power Technologies FY 2017 Budget at-a-Glance." EERE/U.S. DOE. Available online at: http://energy.gov/sites/prod/files/2016/03/f30/At_A_GLANCE%20%28WATER%29.pdf. For a more complete assessment of technology needs refer to: *Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source.* U.S. Department of Energy. October 2016. Available online at: http://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-Full-Report-10212016.pdf.

206 Ibid

207 *Fuel Cell Technologies Office Multi-Year Research, Development and Demonstration Plan: Section 3.4 Fuel Cells.* Fuel Cell Technologies Office (FCTO) / U.S. DOE. 2016 Fuel Cells Section. Available online at: http://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf.

208 Supra 206, *Department of Energy FY 2017 Congressional Budget Request*, p. 623 of FY2017 Budget Volume 3_2.

209 Supra 206, *Department of Energy FY 2017 Congressional Budget Request*, p. 639 of FY2017 Budget Volume 3_2.

210 D. Lew, G. Brinkman, N. Kumar, P. Besuner, D. Agan, and S. Lefton. "Impacts of wind and solar on fossil-fueled generators." *Proceedings of IEEE Power and Energy Society General Meeting*, San Diego, July 22-26, 2012. NREL Paper No. NREL/CP-5500-53504. Available online at: http://www.nrel.gov/docs/fy12osti/53504.pdf.

structural and functional materials also have the potential to lower the cost and improve the performance of power generation systems, especially fossil-based systems. Enhanced geothermal systems could benefit greatly from advanced materials that could be used to develop tools able to withstand higher temperature and pressure environments for long periods of operation. Advanced materials that can withstand extreme environments are also needed in concentrated solar power systems as well as supercritical CO_2 Brayton cycle systems for nuclear power. Power generation would also benefit from AMO research on covetic nanomaterials with improved thermal conductivity. These materials would enable more efficient heat exchangers which are key components in power generation.

Corrosive and biofouling environments are a challenge for marine, hydrokinetic, and hydropower generation technologies. Power generation from these sources would benefit from future research in the clean water technologies program that will develop materials and coatings that can withstand corrosive environments with high levels of bio-contaminants.

AMO has a long history of supporting advancements in membranes and catalysts and is currently researching advanced technologies to develop membranes and catalysts that are highly selective. Membranes with high selectivity for CO_2 will enable energy efficient capture of CO_2 from power generation that can then be stored or used for value added production. Highly selective, atomically precise technologies will enable thinner membranes and catalysts with lower precious metal loadings for more efficient fuel cells.

Advanced composite materials that meet strength and weight performance targets are being developed for all types of wind turbine components and tooling to support the demand for clean and domestic wind energy. AMO is also developing substitute materials for rare earth permanent magnets found in wind turbine motors, reducing the dependence of wind turbine motors on rare earth elements and increasing domestic content of the motors.

AMO targets that directly contribute to work in this area include advanced materials for heat exchangers and advanced process technologies for atomically precise membranes and catalysts, as shown in Table 3.25. A number of other targets may also contribute, either directly or indirectly, and may be found in sections 3.1.1 Critical Materials; 3.1.6 Additive Manufacturing; 3.1.7 Composite Materials; and 3.2.1 Clean Water Technologies.

Table 3.25 Selected AMO Targets for Advanced Materials for Clean Electric Power Generation

	Target	**Fiscal Year**	**Current AMO Activity***	**Current Status (2016)**		**SI**
				2015 Baseline	**Progress to Date**	
5.2	Develop scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity.	2025	R&D	**Thermal:** [211] Cu: 385 W/m K Al: 205 W/m K Fe: 79.5 W/m K	**Thermal:** Research ongoing	EI, LC
5.4	Develop new process technologies that can provide production quantities of commercial-scale atomically precise products.	2030	SBIR	Analysis needed	Research ongoing	EI, LC
7.1	Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.	2025	CST, R&D	Wind: $16 per kg[212]	Wind: Research ongoing	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[211] Supra 121: Table of Thermal Conductivity.

[212] Based on vacuum assisted resin transfer molding of a 61.5m spar cap.

Develop next generation manufacturing process and technologies for clean electric power generation

AMO is currently supporting many technologies with applications in clean electric power generation. For example, wide bandgap semiconductor technologies are under development to improve the performance of power inverters for integration of renewable resources into the electric grid, as discussed in section 3.3.1. AMO is also supporting efforts to improve processing and extraction techniques for neodymium, a critical material used in the permanent magnets of most wind turbines, and to identify substitute materials that could reduce or avoid the use of rare earth elements in permanent magnets altogether.

Composite materials are highly relevant to wind power generation, as glass-fiber-reinforced and carbon-fiber-reinforced polymers are both widely used in wind turbine components. Lightweight structures with very high strength and stiffness are essential to the design of an energy-efficient wind turbine, but cost and manufacturing challenges still cause major challenges in this industry. AMO-supported activities in advanced composites aim to address many of these challenges through manufacturing and materials development advances, which will directly benefit the power generation sector. Roll-to-roll (R2R) manufacturing technologies to produce flexible solar panels could reduce the levelized cost of electricity for solar energy, and R2R could also be used to produce reflective optical films for concentrated solar power and membranes for fuel cell applications. These technologies could strengthen our competitiveness in solar PV module manufacturing as discussed in section 3.1.2.

Advanced sensors for power generation must withstand harsh conditions including high temperature, vibrations, and reducing/oxidizing environments, and must be durable, reliable, and low-maintenance. Manufacturing facilities also often require advanced sensor systems that stand up to harsh conditions, and sensors developed for Smart Manufacturing applications could potentially benefit power generation systems as well (or vice versa). AMO is also supporting the development of controls that will allow plug-and-play connectivity to ease integration and customization across components enabling efficiency improvements. These advancements could enable robust monitoring and real-time optimization of fully integrated, highly efficient power-generations systems which could also produce a more concentrated stream of CO_2 for more efficient carbon capture. Advanced manufacturing to modularize these systems (a process intensification concept) will be key to reducing the cost and increasing the performance of future carbon capture systems. Process intensification modularization techniques could also be leveraged to develop new hydropower capacity by developing modular, standardized designs that would be cost-effective and also easy to deploy. Additive manufacturing using composite materials could be used to manufacture drivetrain components that are lighter, stronger, and more corrosion-resistant for hydropower generation.

Several AMO targets that directly contribute to work in this area are shown in Table 3.26. A number of other targets may also contribute, either directly or indirectly, and may be found in sections 3.1.3 Wide Bandgap (WBG) Semiconductors; 3.1.4 Materials for Harsh Service Conditions; 3.1.6 Additive Manufacturing; and 3.1.11 Smart Manufacturing.

Table 3.26 Selected AMO Targets for Next Generation Manufacturing and Process Technologies for Clean Electric Power Generation

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
1.1	Develop processing technologies for neodymium and other critical materials needed to meet U.S. clean energy deployment goals	2025	CST	No Nd is currently produced in the U.S.	6 patent applications	LC
1.3	Develop substitute materials for rare earth permanent magnets that exhibit properties similar to current magnets, but contain one-tenth rare earth/critical materials compared to 2015 state-of-the-art materials	2025	CST	Typical REE magnets contain~25% Nd (by mass) with a typical energy product range of 25-50 MGOe[213]	1 patent application submitted	LC

[213] MGOe is an abbreviation for mega-gauss oersteds and represents the stored energy in a magnet where 1 mega-gauss oersted (MGOe) equals 7.96 kJ/m^3.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
7.1	Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.	2025	CST, R&D	Auto: $55-$78 per kg[214] Wind: $16 per kg[215] Press. Vess: $36 per kg[216]	Auto: Research ongoing Wind: Research ongoing Press. Vess: Research ongoing	EI, LC
7.5	Stretch Goal: Develop fiber reinforced polymer composites with projected cost and embodied energy parity with 2015 typical glass fiber composites and with performance of carbon fiber composites.	2025	CST, R&D	**Cost:** Auto: $25 - $78 per kg of part weight Wind: $16 per kg of part weight Press. Vess.: $35 per kg of part weight **Embodied Energy:** Auto: 94-1410 MJ per kg of part weight Wind: 131 MJ per kg of part weight Press. Vess.: 773 MJ per kg of part weight	Research ongoing	EI, LC
8.1	Develop technologies to reduce the cost per manufactured throughput of continuous R2R manufacturing processes for selected products by 50% concurrent with a 10X production capacity increase compared to 2015 typical technology.	2025	NCA	Battery Cost: $503/kWh Production: 0.9m2/min PV Cost: $0.65/W - $0.70/W Production: Analysis needed Membranes (Water De-salination) Cost: TBD Production: Analysis needed OLEDs Cost: $1850/m2 Production: 0.03m2/min	NCA	EI
9.3	Develop modular process intensification technologies with capital and operating cost parity relative to 2015 state of the art for selected existing processes.	2030	CST	Process specific. Analysis needed.	Not available	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

214 Price range and embodied energy range corresponds to injection overmolding of doors with glass fiber reinforced composites at the low end and increasing all the way up to the top of the range for compression molding of inner hood with carbon fiber composites.

215 Based on vacuum assisted resin transfer molding of a 61.5m spar cap.

216 Wet filament winding of high strength, high modulus carbon fiber for 70 MPa Type IV H_2 pressure vessel, energy estimate includes energy content of high density polyethylene (HDPE) liner, polyurethane (PU) dome protection and aluminum boss.

Develop advanced technologies to improve the lifecycle energy efficiency of domestic electric power generation

Life-cycle considerations of power generation systems can minimize long-term environmental impact. For example, AMO will be developing material reuse, recycling, remanufacturing, and reprocessing technologies that will improve the life-cycle sustainability of photovoltaic modules and system components and wind turbine blades.

Ongoing research efforts in distributed energy resources can improve the lifecycle energy efficiency of electric power generation while also providing reliable capacity response as more electric power generation is provided by renewable resources. This effort will develop cost-effective 1 – 20 MW CHP systems that can respond to control signals from the electric grid. While upgrading the efficiency of power generation would significantly reduce water usage, since less water would be needed if less waste heat needed to be removed from the power plant, AMO research into clean water technologies could be leveraged to either efficiently recover and clean the water needed for the power plant or enable the power plant to use a previously unused water source with high salinity levels. The clean water technologies program will also develop technologies to use renewable energy resources, including low-enthalpy geothermal energy, to desalinate various non-fresh waters to develop low-energy water purification systems that would improve the lifecycle energy efficiency of electric power generation.

AMO is supporting the development of commercial scale, low-cost hydrogen production from natural gas which has lower capital costs and a higher efficiency of hydrogen production than steam methane reforming and which also produces a separate stream of CO_2 for low cost capture. This technology would provide lifecycle energy benefits to hydrogen fuel cells as well as any systems taking advantage of the CO_2 captured through this process.

AMO targets that directly contribute to work in this area include development of recycling/reprocessing technologies and CHP systems for power generation, as shown in Table 3.27. A number of other targets may also contribute, either directly or indirectly, and may be found in section 3.1.9 Process Intensification (PI) and 3.2.1 Clean Water Technologies.

Table 3.27 Selected AMO Targets for Advanced Technologies to Improve Lifecycle Energy Efficiency for Clean Electric Power Generation

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
13.2	Advance the development of CHP systems that are responsive to site demands as well as grid requirements.	2030	NCA	Analysis needed	NCA	EI
14.1	Develop material reuse, recycling, remanufacturing, and/or reprocessing technologies that enable an absolute increase in recycling rate[217] by 30% of select energy-intensive materials and 25% improvement in embodied-energy efficiency.	2025	CST	Material dependent; analysis needed	Not available	LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[217] Absolute recycling rate relates to within the manufacturing system.

3.3.3 Advanced Materials and Manufacturing Processes for Clean Fuels

Overview of Technical Area

Fuels play a critical role throughout our economy. In 2013, fuels directly supplied about 99% of the energy needed by our national transportation system, 66% of that needed to generate our electricity, 68% of that needed by our industry, and 27% of that needed by our buildings.[218] A "fuel" is a carrier of chemical energy that can be released via reaction to produce work, heat, or other energy services. The economy will need to balance the various strengths and shortcomings of a broad mix of fuels during the transition from a high-carbon to a low-carbon economy. This section considers RD&D opportunities in three primary fuel pathways – biomass, hydrogen, and oil and natural gas – across the supply chain including production, distribution, and storage. End use is covered in other sections of AMO's MYPP.

In the oil and gas sector, the focus is on the prudent extraction and delivery of these resources. Biofuels activities span the entire supply chain, from feedstock supply and conversion to distribution of products. Hydrogen RD&D is needed to reduce the cost of producing hydrogen from regionally optimized renewable and other low-carbon resources for industrial and transportation uses. Hydrogen's other transportation related technical challenges include on-board storage and lack of distribution infrastructure.

With recent growth in domestic shale gas and tight oil production, near-term concerns over fuel supply and energy security are easing. However, the economic and environmental impacts of heavy reliance on fossil fuels make transition to clean fuel alternatives imperative. The trade-offs between conventional (oil and gas), alternative fuels (primarily biofuels and hydrogen), and substitution with electricity – i.e., cost, performance, infrastructure, security, climate impacts, and others – are complex.

For further discussion of the applications, challenges, and opportunities related fuels, see the 2015 QTR Technology Review, Chapter 7: *Advancing Systems and Technologies to Produce Cleaner Fuels*.

Targeted Impacts

AMO supports DOE's goals for safe, efficient, cost-effective fuels production, storage and delivery. These goals include:

1. *Validate at pilot scale at least one technology pathway for hydrocarbon biofuel production at mature modeled price of $3/gallon gasoline equivalent (GGE) (in 2014 dollars) with greenhouse gas emissions reduction of 50% or more compared with petroleum derived fuel.*[219]

Objective:
Advance technologies that improve materials and associated manufacturing processes for economical fuel resource extraction, production, distribution, and storage for three primary fuel pathways – biomass, hydrogen, and oil and natural gas.

Challenges and Barriers:

- **Reliance on fossil fuels:** Fossil fuels account for 82% of total U.S. primary energy use. Multiple technological pathways need to be explored to transition to a low carbon future.
- **Energy security:** Energy security requires stable, abundant domestic resources. Oil and gas have large resource bases for domestic production. Bioenergy has intermediate levels of potential supplies. Fossil energy and bioenergy sources have land use constraints and controversies unique to each. Hydrogen can be domestically produced from any energy resource – fossil, nuclear, or renewable.
- **Greenhouse gas emissions and other externalities**: Oil and gas have a large carbon footprint and other environmental issues that require attention to carbon capture and storage (CCS) and utilization of captured CO_2 (where possible). Bioenergy can have a small carbon footprint, and when combined with CCS, can provide a net reduction of atmospheric carbon dioxide levels. Hydrogen can be carbon neutral or not, depending on the source of the energy to produce it and whether CCS is used.
- **Economic impacts:** Low-cost fuels can contribute to economic prosperity. Oil and gas can have low cost but can also have volatile prices; biofuel costs have dropped significantly and further reductions are needed; and hydrogen costs vary significantly with the source energy used to create the hydrogen but further reductions are still needed. The economy will rely on a broad mix of fuels during the transition to a low carbon.

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[218] *Annual Energy Outlook (AEO) 2015*; Table A2. Note: For industry and buildings, most of the energy not directly supplied by fuels is from electricity, for which upstream electricity-related generation and other losses are included in the total for energy use by the sector and in the calculation for the share of energy that direct fuel use provides.

[219] *Multi-Year Program Plan.* Bioenergy Technologies Office (BETO), U.S. DOE. March 2016. Available online at: http://energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf.

2. *Reduce the cost of hydrogen production to <$4.00/gallon of gasoline equivalent (delivered and dispensed) (in 2007 dollars).*[220]
3. *By 2020, develop novel precursors and conversion processes capable of reducing the high-volume cost of high-strength carbon fiber used for hydrogen storage by 25% from $13 per pound to ~$9 per pound.*[221]
4. *Onboard light duty vehicle hydrogen storage of 2.5 kWh/kg system (7.5 wt.% H_2) and 2.3 kWh/l system (0.070 kg H_2/l) at a cost of $8/kWh ($266/kg H_2).*[222]
5. *Reduce methane emissions from the oil and gas sector by 40-45% from 2012 levels by 2025.*[223]
6. *Assess and develop technologies and best practices to mitigate the risks in offshore production activities related to controls, safeguards, and environmental impacts during drilling and production operations.*[224]

AMO Approach

AMO activities are focused on two areas: (1) developing advanced materials needed for clean fuels; and (2) developing next generation manufacturing processes and technologies for fuel production.

Develop advanced materials for clean fuels

Materials are needed that can withstand high temperature, high pressure, and harsh corrosive environments that exist in biofuels production. Current reactors are not designed to handle the harsh conditions inherent to converting feedstock, from a lack of compatibility with highly corrosive bio-oil to cost-effective handing of harsh pretreatment conditions for low-temperature deconstruction.

Novel durable transition metal catalysts are needed for biofuels production that are capable of selective sugar upgrading via hydrogenation, deoxygenation, and carbon-carbon coupling reactions. Catalysts are also needed that are capable of funneling lignin into streams of tractable intermediates for incorporation either into central metabolism or direct upgrading. More robust catalysts are needed for producing oxygenated intermediates from syngas with further processing to hydrocarbons. These processes need to be capable of selectively generating products of the desired chain lengths and overcoming challenges related to fouling from syngas contaminants.

AMO research is focused on materials for harsh service environments including high temperature, highly corrosive (acids, water vapor) environments for biomass gasification or other thermal processing; and preventing ash fouling in biomass conversion equipment. AMO's catalyst development activities are relevant to biofuels needs.

Distributed renewable liquid feedstock reforming technologies have capital costs that are too high to achieve hydrogen production cost targets. Multiple-unit operations that entail many process steps in converting bio-derived liquids to hydrogen and low energy efficiencies are key contributors to the high capital cost. Improved reforming and water-gas shift catalysts are needed to increase yield, improve performance, and achieve the high purity of hydrogen required for fuel cells. Research to advance hydrogen as a fuel source includes membranes and catalysts for hydrogen purification and recovery.

Research into new hydrogen storage materials, such as metal-ceramic composites, improved resins, and engineered fibers, is needed to meet cost targets for transportation applications without compromising performance. High-pressure containment for compressed gas and other high-pressure approaches limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required.

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[220] *Multi-Year Research, Development, and Demonstration Plan – 2015 Storage Section: 3.3 Hydrogen Storage.* FCTO/U.S. DOE. Available online at: http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf.
[221] Ibid
[222] Ibid
[223] "Methane Emissions." Office of Fossil Energy, U.S DOE. July 2016. Available online at: http://energy.gov/sites/prod/files/2016/08/f33/Methane%20Emissions.pdf.
[224] *2014 Annual Plan Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research and Development Program, Report to Congress.* Draft September 2013. U.S. DOE. Available online at: http://energy.gov/sites/prod/files/2013/09/f2/2014%20Annual%20Plan%20DRAFT%209-5-13.pdf.

Researchers at the Institute for Advanced Composites Manufacturing Innovation (IACMI) are working to develop lower-cost, higher-speed, and more efficient manufacturing and recycling processes for advanced composite materials than the state of the art. One focus of IACMI is to develop composites for storage of hydrogen and compressed natural gas.

About 40% of U.S. natural gas pipelines date from the 1960s or earlier. Older pipelines are generally constructed of steel or cast iron, and these pipelines develop leaks for numerous reasons, including corrosion, improper fabrication or construction, and damage. Our national infrastructure for fuel transport and delivery needs to be resilient towards emerging trends which should not only target natural gas transport but also other gases.[225] To contain the overall amount of pipeline network needed and associated materials, maintenance, and other costs, it would be desirable if a single pipeline network could transport multiple gases, such as natural gas, hydrogen, and carbon dioxide, either by alternating gases or by simultaneously transporting multiple gases through a blended network. Reported estimates suggest various risks for failure when adding 20%, 25%, and 50% hydrogen to natural gas. The technical breakthroughs needed will span all systems levels, from innovations at the component level (pumps, compressors, etc.) to fundamental research on materials development and to sensors and controls at the pipeline network level. The solutions for the latter may include not only conventional steel and plastic pipes and coatings, but also composites. A target will be to reach a level where energy consumption and cost (capital costs and maintenance costs) for transport of gases through pipelines will be less than the cost for conventional means of transport (via trucks or ships) of equivalent amounts of natural gas, hydrogen, and carbon dioxide. Ultimately, cost effective manufacturing pathways need to be developed, but this needs to be founded on fundamental knowledge on the failure mechanisms caused by variations in pressure and also chemical interaction effecting passivation technology.

Materials are needed that can mitigate the risk associated with drilling through the rock and fluids present in high pressure/high temperature reservoirs, and the challenges of wellbore integrity and well control. Specifically, novel hardware and techniques for drilling and completion that prevent loss of well control are needed. AMO is developing corrosion resistant materials and coatings with potential applications in offshore drilling.

A strategy to reduce the lifecycle impact of products is to develop new opportunities to use renewable feedstocks for the production of commodity chemicals, fuel, and carbon fibers. Substituting traditional structural materials such as steel with composite materials has the potential to provide lifecycle energy savings in many applications. AMO research projects are focused on new ways to use renewable feedstocks for the production of chemicals and carbon fibers.

Example AMO technical targets that directly contribute to work in this area are shown in Table 3.28 below and include the development of membrane, catalyst, and composite materials.

Table 3.28 Selected AMO Targets for Advanced Materials for Clean Fuels

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
5.4	Develop new process technologies that can provide production quantities of commercial-scale atomically precise products.	2030	SBIR	Analysis needed	Research ongoing	EI, LC
7.1	Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.	2025	CST, R&D	Press. Vess. \$36 per kg[226]	Research ongoing	EI, LC

225 *QTR 2015 Chapter 7: Advancing Systems and Technology's to Produce Cleaner Fuels.* Available online at: http://energy.gov/sites/prod/files/2015/09/f26/QTR2015-07-Fuels.pdf.

226 Wet filament winding of high strength, high modulus carbon fiber for 70MPa Type IV H2 pressure vessel, energy estimate includes energy content of HDPE liner, PU dome protection and aluminum boss.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
9.4	Develop technologies that optimize catalyst conversion rates, selectivity, activity, and stability and enable at least 20% improvement in energy intensity compared to 2015 state-of-the-art technology.	2030	CST, R&D, SBIR	Process specific. Analysis needed.[227]	Research ongoing	EI

***Key:** CST = Funded Institute or Hub R&D = Funded R&D Project SBIR = Funded SBIR Project
PRA = Practices NCA = No Current Activity

Develop next generation manufacturing process and technologies for clean fuel production

In biofuel production, feed and process variations can cause fouling, plugging, corrosion, or other disruptions. An improved understanding of process integration is essential for (1) characterizing the complex interactions that exist between unit operations, (2) identifying impacts of inhibitors and fouling agents on catalytic and processing systems, and (3) enabling the generation of predictive engineering models that can guide process optimization or scale-up efforts and enable process control.

AMO's PI projects target dramatic improvements in processing and manufacturing of chemicals and fuels by developing smaller modular equipment that can reduce waste, energy use, and capital and operating costs when compared to the state-of-the art technology. PI technologies often involve combining reactors and separators into one hybrid unit and allow for higher conversion rates of feedstock inputs, increasing product outputs, and improving overall energy intensity

Natural gas transmission, storage, and distribution emissions represented 14% of total U.S. anthropogenic methane emissions and approximately 56% of natural gas system related methane emissions in 2013. DOE is committed to developing advanced, cost-effective technologies to mitigate methane emissions from natural gas. Cost effective technologies to detect and reduce methane emissions from natural gas infrastructure are needed. AMO's process intensification area targets dramatic improvements in manufacturing chemical products by rethinking existing high-temperature operations and conducting RD&D of new methods, technologies, and equipment including capture and use of flare gas via modular systems.

AMO technical targets from process intensification that directly contribute to work in this area are shown in Table 3.29 below.

Table 3.29 Selected AMO Targets for Next Generation Manufacturing Technologies for Clean Fuel Production

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
9.1	Develop process intensification technologies with an order of magnitude energy intensity (kJ/kg) improvement relative to 2015 typical technology.	2030	CST	Process specific; analysis needed	Not available	EI
9.3	Develop modular process intensification technologies with capital and operating cost parity relative to 2015 state of the art for selected existing processes.	2030	CST	Process specific; analysis needed	Not available	EI

***Key:** CST = Funded Institute or Hub R&D = Funded R&D Project SBIR = Funded SBIR Project
PRA = Practices NCA = No Current Activity

[227] Catalytic conversion rates are calculated and then that information is used to calculate energy savings. Higher conversion rates imply lower energy consumption.

3.3.4 Advanced Manufacturing to Increase Efficiency in Building Systems and Technologies

Overview of Technical Area

Considerable potential exists to reduce building energy use. The residential and commercial buildings sector accounts for about 76% of electricity use and 40% of all U.S. primary energy use. Many building technologies are available today that would significantly reduce energy use relative to the existing building stock. By 2030, building energy use could be cut more than 20% using technologies known to be cost effective today and by more than 35% if research goals are met. Much higher savings is technically possible.[228]

These building technology and energy management advances have the potential to simultaneously provide cost reductions, service improvements, and efficiency gains. The greatest end-use energy-saving opportunities in the residential and commercial buildings are space conditioning and lighting loads. In recent years, much progress has been made in areas such as light-emitting diode (LED) lighting technology, HVAC systems to include non-vapor compression technologies, and building automation technologies such as advanced sensors and controls. Progress is also being made in the area of self-generation using CHP technologies and other distributed energy resources as well as in strategic energy management.

For further discussion of the applications, challenges, and opportunities related to building technologies, see the 2015 QTR Technology Review, Chapter 5: *Increasing Efficiency of Buildings Systems and Technologies*.

Targeted Impacts

AMO's work in this area is focused on supporting the overall DOE goal of *reducing building energy use intensity (EUI) 30% by 2030*.[229] DOE also has a specific legislative mandate to increase energy efficiency in commercial buildings, *with a goal to make the entire commercial building stock in the US net-zero energy by 2050*.[230] AMO's RD&D includes advanced materials for the buildings sector, new manufacturing approaches for producing advanced building materials and technologies, sustainable manufacturing through recycled materials, and improved CHP systems for distributed and self-generation.

AMO Approach

AMO activities are focused on three areas: (1) developing and facilitating the adoption of energy management systems (EnMS) and energy management information systems (EMIS) (i.e., Smart Controls); (2) developing advanced manufacturing materials and approaches for

Objective:
Advance cost effective manufacturing technologies, systems management, and information technologies to improve building energy efficiency, environmental footprint, and resiliency.

Challenges and Barriers:

- **High first costs:** many efficient technology options have higher initial cost, which can slow market adoption significantly.
- **Slow turnover of building stock:** most buildings last a very long time and can be difficult to retrofit; this slows down the adoption of new technologies and designs.
- **Distributed and diverse market:** the buildings sector is very large, consisting of millions of individual buildings controlled by different owners; the market is also geographically diverse, with each climate region requiring different technology solutions.
- **Complex systems and needs:** buildings are highly complex and interdependent systems that serve to meet a diverse set of needs, including comfort, safety, and aesthetics; these different drivers can place contradictory demands on new technologies.
- **Growth of miscellaneous loads:** in the modern technologically advanced society, an increasing percentage of building energy demand consist of miscellaneous electric loads; because of the disparate nature of these loads, reducing their energy consumption can be challenging.
- **Integration with smart grid:** the electric grid is fast evolving toward a highly interactive and transactive system; buildings are part of this interconnected system and need to be able to interact with it.

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[228] *QTR 2015: Increasing Efficiency of Buildings Systems and Technologies*. Available online at: http://energy.gov/sites/prod/files/2015/09/f26/QTR2015-05-Buildings.pdf.

[229] *Multi-Year Program Plan FY 2016 – 2020*. Building Technologies Office, U.S. DOE. February 2016. Available online at: http://energy.gov/sites/prod/files/2016/02/f29/BTO%20Multi-Year%20Program%20Plan%20-%20Final.pdf.

[230] Energy Independence and Security Act of 2007, Title IV Sec. 422(c), http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

building envelopes and technologies; and (3) developing CHP systems for resilient, net zero energy buildings.

Develop and facilitate the adoption of energy management systems and energy management information systems

Strategic energy management is a proven way for any energy using building and facility (including commercial buildings and institutional facilities) to achieve greater energy savings with more persistent savings over time. Adopting a comprehensive EnMS, such as the ISO 50001 International Energy Management Standard, helps a facility to establish formal policies and procedures to systematically track, analyze, and improve energy efficiency, which becomes part of corporate 'culture.' Studies have shown that energy savings from EnMs range from 2% to greater than 10% per year, depending on the facility and the rigor of the EnMS instituted. The greatest savings have been realized by AMO partners that were conformant to ISO50001. As the electric grid becomes smarter and more interconnected, buildings will need to be able to communicate with the grid, respond to price signals and other needs of the system, and integrate seamlessly with distributed generation resources, such as wind, solar, and CHP systems. To address these issues, one of AMO's focus areas is the development of new advanced technologies for building control and grid integration. For example, AMO supports development of advanced sensors for lighting and HVAC systems. AMO's work on wide bandgap semiconductors also supports the development of devices such as inverters for photovoltaic (PV) and wind power systems and AC-to-DC and DC-to-AC converters.

AMO technical targets that directly contribute to work in this area are shown in Table 3.30 below. For more information on these and other related targets, refer to MYPP sections 3.1.11 Smart Manufacturing and 3.2.3 Industrial End User Technical Assistance.

Table 3.30 Selected AMO Targets for Development and Adoption of Energy Management Systems and Energy Management Information Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
17.3	Catalyze a factor of 3 increase in the number of ISO 50001 certified or conformant facilities.	2025	PRA	4,000 facilities	Activity ongoing	EI, EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Develop advanced manufacturing materials and technologies for building envelopes and systems

Development of new advanced materials is one of AMO's focus areas, and many of AMO's material development activities are directly related to the buildings sector or applicable to multiple sectors, including buildings. One of DOE's primary goals in the buildings sector is the development of new innovative and more efficient heating and cooling solutions to replace vapor compression technologies, which utilize refrigerants that are potent greenhouse gases. AMO's work to identify and develop new caloric materials to replace conventional HVAC refrigerants is an important part of this major DOE effort. Use of LEDs is leading to significant energy savings in the buildings sector, but work is needed to improve the quality of LED lights and reduce their cost. AMO-supported work to develop phosphors and improved wide bandgap semiconductor materials for LEDs are contributing toward the needed advances and cost reductions. Wide bandgap semiconductors being developed by AMO can also be used in numerous appliances and AC-to-DC and DC-to-AC converters. AMO's other efforts in advanced materials for the buildings sector include development of new building envelope materials, composite materials for innovative building structures and components such as HVAC systems, and direct thermal energy conversion materials that can be used to build heat recovery systems.

Another AMO focus area is developing new manufacturing technologies and approaches to produce advanced materials and systems for the buildings sector. For example, AMO is supporting the development of additive manufacturing techniques to build window frames and heat exchangers for HVAC systems. AMO is also working to develop new roll-to-roll processing systems to produce advanced window films that will enable better control of heat transfer through windows and enhance the quality of light entering a building. In today's increasingly efficient buildings proper moisture control is a factor that requires much attention; to help address these concerns, AMO is developing new roll-to-roll manufacturing systems to produce membrane materials for moisture management in wall and roof insulation. AMO has also identified roll-to-roll manufacturing of organic light-emitting diodes (OLEDs) as a key opportunity. Batch processing is currently the state-of-the-art production method for OLEDs; however, as these technologies move toward mass manufacture, R2R manufacturing could offer substantial benefits in cost and performance including higher throughput and lower cycle times, smoother and thicker conformal films, a natural compatibility with flexible substrates, and potentially lower-cost materials and equipment. AMO's work in sustainable manufacturing processes that incorporate materials substitution techniques, increased recycling, and waste minimization will also benefit the buildings sector.

Several AMO technical targets that directly contribute to work in this area are shown in Table 3.31 below.

Table 3.31 Selected AMO Targets for Advanced Manufacturing Materials and Technologies for Building Envelopes and Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
3.2	Increase the efficiency of targeted power electronic systems by 2-3% (a reduction in losses of 28% or above) with respect to their silicon-based equivalents.	2020	CST, SBIR	93 - 96%, depending of the device[231]	Efficiency increase of 2-3% demonstrated for 4 devices and 5 more on track to meeting the goal[232]	EI, LC
6.3	Develop next-generation additive manufacturing systems that deliver consistently reliable parts with predictable properties to six standard deviations ("six-sigma") for specific applications.	2025	CST	Best-in-class AM technology delivers reliability on the order of one-sigma, e.g., 68% success rate.	Research ongoing	EI, LC
8.1	Develop technologies to reduce the cost per manufactured throughput of continuous R2R manufacturing processes for selected products by 50% concurrent with a 10X production capacity increase compared to 2015 typical technology.	2025	NCA	Battery Cost: $503/kWh Production: 0.9m2/min PV Cost: $0.65/W - $0.70/W Production: TBD Membranes (Water De-salination) Cost: TBD Production: TBD OLEDs Cost: $1850/m2 Production: 0.03m2/min	NCA	EI

[231] Supra 111. *Premium Efficiency Motor Selection and Application Guide: A Handbook for Industry.* AMO/EERE/U.S. DOE. 2014.

[232] The devices are an electric vehicle fast charger and three different photovoltaic DC-AC inverters. Additionally, there are projects on track to deliver 3 more DC-AC inverters, two electric vehicle inverters and one heavy-duty electric vehicle inverter.

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
14.1	Develop material reuse, recycling, remanufacturing, and/or reprocessing technologies that enable an absolute increase in recycling rate[233] by 30% of select energy-intensive materials and 25% improvement in embodied-energy efficiency.	2025	CST	Material dependent; analysis needed	Not available	LC

***Key:** CST = Funded Institute or Hub R&D = Funded R&D Project SBIR = Funded SBIR Project
PRA = Practices NCA = No Current Activity

Develop combined heat and power systems for resilient, net zero buildings

The adoption of CHP systems in the buildings sector (particularly in applications with large, steady thermal loads such as hospitals, large office buildings and hotels, multifamily buildings, colleges and universities, and military campuses) offers a number of benefits, including higher energy efficiency, reduced greenhouse gas emissions, and increased power reliability in the event of grid disruptions.

CHP systems can help to achieve the nation's net-zero energy[234] building goals: through their relatively large capacity factor (e.g., a typical 10 MW turbine CHP system can operate at an 85% capacity factor compared to photovoltaic or wind systems that have capacity factors at ~22% or 34% respectively[235]) CHP systems can provide the anchors for an energy mix of renewable energy and storage at buildings, institutions, or campuses. CHP systems also increase the resiliency of the buildings in which they are used, mitigating the impacts of an emergency by keeping critical facilities running without interruption in electric or thermal service. If the electricity grid is impaired, a specially configured CHP system can continue to operate, ensuring an uninterrupted supply of power and heating or cooling to the host facility.

Higher upfront cost for CHP systems is a significant market barrier, however. To address this challenge, AMO seeks to improve the cost efficiency of CHP systems that are suitable for commercial, institutional and multi-family residential buildings, and data centers; a major strategy to achieve this goal is the development of small packaged CHP systems that require minimal customization. AMO is also developing advanced CHP systems that would allow net zero energy buildings to provide cost-effective support to the electric grid, providing an additional value stream to lower the cost of ownership of these systems. Finally, AMO will be developing CHP systems with high electricity generation efficiency, providing buildings that have relatively low heat requirements the option of nearly doubling the efficiency of their electricity use.

AMO technical targets that directly contribute to work in this area are shown in Table 3.32 below. For more information on these and other related targets, refer to MYPP section 3.1.13 Combined Heat and Power Systems.

233 Absolute recycling rate relates to within the manufacturing system.

234 A zero-energy building (ZEB) is defined by DOE as: "An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." (Source: US Department of Energy, A Common Definition for Zero Energy Buildings, September 2015. See: http://energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf. A ZEB produces enough renewable energy to meet its own annual energy consumption requirements, thereby reducing the use of non-renewable energy in the building sector. ZEBs use all cost-effective measures to reduce energy usage through energy efficiency and include renewable energy systems that produce enough energy to meet remaining energy needs.

235 Combined Heat and Power: A Clean Energy Solution. U.S. DOE and U.S. EPA. August 2012.

Table 3.32 Selected AMO Targets for Combined Heat and Power Systems for Resilient, Net Zero Buildings

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
13.2	Advance the development of cost-effective CHP systems that are responsive to site demands as well as grid requirements.	2030	NCA	Analysis needed	NCA	EI
13.4	Support a 20% reduction in installed cost of commercially available, packaged (<10 MW) CHP systems (while maintaining >75% system efficiency at HHV).	2025	PRA	Varies by size, technology and function. Typically, between $1,800/kW and $10,000/kW installed cost based on technology, system size, and installation complexity.[236]	Not available	EM

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[236] Supra 161. "Combined Heat and Power Technology Fact Sheet Series," U.S. DOE. 2016.

3.3.5 Advanced Manufacturing for Clean Transportation Systems

Overview of Technical Area

Transportation provides personal mobility, freight delivery, and other mobile services to individuals and to the economy. It is the primary user of petroleum in the United States and a major emitter of greenhouse gases (GHGs) and EPA-regulated criteria pollutants. Currently, light-, medium-, and heavy-duty vehicles account for approximately three quarters of transportation energy use and emissions. To greatly reduce GHG emissions, a larger share of vehicles must more efficiently use fuels and/or use lower-carbon energy, as it is not currently possible to capture and store carbon dioxide emissions from small, mobile sources. In addition, research is needed to drastically reduce life-cycle carbon emissions. The technology RD&D pathways for transportation include component efficiency improvements, advanced combustion, light-weighting, battery storage, electric drivetrains, renewable fuels, fuel cell systems, recharging and refueling infrastructure, and transportation system efficiencies. Efficiency opportunities exist in all modes, and in many cases, they represent the most cost-effective mechanism to reduce petroleum use and emissions in the near term.

For further discussion of the applications, challenges, and opportunities related to transportation, see the 2015 QTR Technology Review, Chapter 8: *Advancing Clean Transportation and Vehicle Systems and Technologies*.

Targeted Impacts

AMO supports DOE's goals to help Americans reduce their transportation energy costs through two key solution pathways: (1) replace conventional fuels with cost-competitive domestically produced alternatives and (2) use conventional fuels more productively. Specific DOE goals include:[237]

1. *By 2022, enable a 30% weight reduction for light-duty vehicles including body structure, chassis and suspension, powertrain, and interior against a 2012 baseline;*
2. *By 2017, validate a 25% improvement in component strength relative to components made with 2010 baseline cast aluminum (Al) alloys (A319 or A356) for improved efficiency light-duty engines;*
3. *By 2018, validate a 25% improvement in component strength relative to components made with 2010 baseline A842 (Cast Iron) for improved efficiency heavy-duty engines.*
4. *Reduce the combined battery and electric drive system costs of a plug-in electric vehicle (PEV) by up to 50% (by 2022, from a 2012 baseline). Specific technical targets include:*
   a. *Cutting modeled high volume battery costs from $264/kWh in 2015 to $125/kWh by 2022;*

Objective:
Advance materials and manufacturing technologies to reduce vehicle weight and improve vehicle efficiency and range at a cost comparable to conventional vehicles.

Challenges and Barriers:

- **Reliance on fossil fuels:** petroleum use and emissions in U.S. transportation represents 54% of all carbon monoxide emissions, 59% of NOx emissions, and 23% of volatile organic compound emissions*.
- **Long fleet life:** vehicles remain on the road for on average fifteen years after purchase.
- **Combustion efficiency:** improving fuel economy with advanced combustion engines and more energy efficient vehicle systems offers the potential to reduce fleet fuel consumption.
- **Co-optimization of fuels and engines:** new high-performance, low-carbon fuels that are optimized with engines could improve both performance and efficiency.
- **Light-weighting:** reducing vehicle weight can significantly reduce a vehicle's fuel consumption at all vehicle speeds by reducing rolling resistance and power required for acceleration.
- **Electric drive technologies:** electric vehicles allow for petroleum free and lower carbon fueling options but need improvements in battery design and chemistry to reduce cost and recharge time; improvements to energy density and power electronics and motors efficiency is also needed.
- **Changing transportation requirements:** information technology, decentralized manufacturing, ride sharing, and other trends can displace some need for physical movement of vehicles.

** Oak Ridge National Laboratory, "Transportation Energy Data Book 2014," Table 12.1, http://cta.ornl.gov/data/chapter12.shtml.*

[237] Supra 206. *Department of Energy FY 2017 Congressional Budget Request*.

   b. *Eliminating almost 30% of vehicle weight through light weighting by 2022, compared to a 2012 baseline; and*
   c. *Reducing the cost of electric drive systems from $12/kW in 2015 to $8/kW by 2022.*
5. *Improve the freight hauling efficiency of heavy-duty Class 8 long-haul vehicles by 100% by 2020 (with respect to comparable 2009 vehicles) and demonstrate applicability with an emphasis on cost-competitiveness*

Public investment in the development of advanced transportation technologies that enable both of these pathways will improve the nation's energy security, reduce GHG emissions, and strengthen U.S. global economic competitiveness.

AMO Approach

AMO's primary focus areas in transportation include (1) advanced materials for vehicle fuel efficiency, light-weighting, and efficient energy conversion; and (2) technologies to reduce the energy intensity and/or cost of manufacturing processes for metals, components, and structures of transportation systems.

Develop advanced materials for transportation systems

Stronger, lighter materials can result in significant lifecycle energy savings through light-weighting and performance advantages in vehicles. Traditionally, reduction of vehicle weight involved a combination of design optimization, downsizing, and the use of lower-density materials with suitable mechanical properties, i.e., materials with higher strength-to-weight and/or higher stiffness-to-weight ratios. The use of lightweight materials, high-strength steels, aluminum, and composites has been the subject of extensive research and development over many years. To achieve significant vehicle weight reduction, it will be necessary to increase the content while also adding lightweight materials with higher potential for weight reduction such as aluminum alloys, magnesium alloys, carbon fiber composites, and the next generations of advanced high strength steels. The lack of infrastructure for producing these materials remains a barrier and technical challenge to achieving both near- and long-term vehicle efficiency goals.

AMO research is underway to validate material properties and reduce production costs of a promising variety of steel. Research projects are developing cutting-edge lightweight metal manufacturing processes for products using lightweight metals, including aluminum alloys, magnesium alloys, titanium, and advanced high-strength steel. The applications include lightweight subsystem design, component-level manufacturing, assembly processes, and quality control methods. In addition, research is underway to allow room-temperature stamping of high strength automotive steel using a novel steel heat treatment process which could replace the current energy-intensive hot stamping process used by the automotive industry.

Specialty applications of fiber-reinforced composites promise weight reduction in heavy trucks by their judicious use. A thermoplastic composite firewall for the truck market has demonstrated the advantages of performance, ease of processing, and recyclability. The development of suitable materials, effective processing and part manufacturing methods as well as design optimization are key enablers for increased use of fiber reinforced thermoplastics in large truck applications. Composites are also finding increased use in urban transportation such as light rail and intercity trams. In addition to the weight savings, composites allow for fabricating complex composite parts that would be difficult if not impossible to produce with other materials.

AMO has co-funded with the Vehicle Technologies Office (VTO) the Carbon Fiber Technology Facility (CFTF) at Oak Ridge National Laboratory (ORNL) since 2009. This DOE-funded facility is to demonstrate advanced technology scalability and producing market-development volumes of prototypical carbon fiber. The CFTF is the bridge from R&D to deployment and commercialization. As of today, the CFTF has successfully developed a method for producing industrial-grade structural carbon fiber and flame-retardant fibers from commercially available acrylic precursor materials. Several different precursor materials, such as lignin and polyolefin, are under research in order to achieve the ultimate goal ($5/lb.) for the low-cost carbon fiber.

The Institute for Advanced Composites Manufacturing Innovation (IACMI), managed by AMO and launched in 2015, is the fifth Institute in the Manufacturing USA network. Researchers at IACMI are working to develop lower-cost, higher-speed, and more efficient manufacturing and recycling processes for advanced composite materials than the state of the art. One focus of IACMI is to develop composites for vehicle light-weighting.

Several AMO technical targets that directly contribute to work in this area are shown in Table 3.33.

Table 3.33 Selected AMO Targets for Advanced Materials for Transportation Systems

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
5.1	Develop lightweight metals for light duty vehicles at a strength/weight ratio of at least 200 MPa/(g/cm^3) at an added cost of no more than $7/kg of weight saved.	2025	R&D, SBIR	153 MPa/(g/cm^3) Cost/Weight: Analysis needed	**Flash Bainite 1500:** 191 MPa/(g/cm^3) [238] Cost/Weight: Analysis needed	LC
7.1	Reduce production cost of finished carbon fiber composite components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.	2025	CST, R&D	Auto: $55-$78 per kg[239]	Auto: Research ongoing	EI, LC
7.3	Develop manufacturing technologies that reduce the embodied energy and production-associated GHG emissions of carbon fiber reinforced polymer (CFRP) by 75% compared to 2015 typical technology.	2025	CST, R&D, SBIR	Auto: 94-1409 MJ/kg[67]	Auto: Research ongoing	EI, LC

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

Develop advanced manufacturing processes for vehicle materials and components

In transportation, WBG semiconductors have uses in regenerative power brakes, battery charging circuits and motor drives/propulsion systems for hybrid and all-electric vehicles, and in aircraft and ships for generating and managing electric power. The efficiency improvement and superior characteristics of WBG components is an important characteristic that is synergistic in many areas. With improvements in efficiency and the ability to operate at higher temperatures, the thermal management system can be reduced, leading to overall reductions in volume, weight, and cost. Additionally, WBG devices have low switching losses, so they can operate at higher switching frequencies than Si and this allows the use of smaller passive components in the power modules. The utilization of WBG semiconductors in power electronics can thus result in significant levels of energy reduction as well as enabling substantial decreases in the overall weight and volume of the power electronics system compared to those using Si-based semiconductors.

AMO is focusing its efforts on SiC and GaN devices, which are currently the most promising WBG material systems in the power electronics industry (and the most technologically mature). GaN is suitable for power electronics applications of <600 V and <10 kW, such as DC-DC converters, power supplies, micro and string photovoltaic inverters, and SiC can be used for higher power systems, in the range of 600 V to 15 kV and 10 kW to 10 MW.

Higher energy and higher power electrode materials promise to significantly lower battery cost by reducing the amount of material and the number of cells needed for the entire battery pack. Work is needed to develop new materials and electrode couples that offer a significant improvement in either energy or power over today's technologies. Some specific technologies of interest include, but are not limited to: the design and development of second generation lithium ion batteries that contain high voltage (5 V) and/or high capacity (>300 milliampere-hours per gram (mAh/g)) cathode materials; the design and development of third generation lithium ion batteries that contain advanced metal alloy and composite anodes such as silicon carbon that offer two to four times the capacity of today's graphite anodes;

[238] "Flash Bainite" ultimate tensile strength information available at: http://www.flashbainite.com/products/flash-tubing.html; "Flash Bainite" cost estimate information available at http://www.flashbainite.com/about/cost.html.
[239] Price range and embodied energy range corresponds to injection overmolding of doors with glass fiber reinforced composites at the low end and increasing all the way up to the top of the range for compression molding of inner hood with carbon fiber composites.

and development of next generation high capacity solid-state battery systems and high voltage and solid polymer composite electrolytes.

AMO research on R2R manufacturing focuses on technologies and methods to improve yields and reduce costs by developing advanced approaches for computational materials and process modeling, deposition and processing, precision patterning processes, ever-smaller and finer size scale such as high-resolution in-line metrology techniques, in-process prediction of final properties in application, and embodied thermal energy minimization and enhanced cooling that could be applicable to battery manufacturing.

Several AMO technical targets that directly contribute to work in this area are shown in Table 3.34 below.

Table 3.34 Selected AMO Targets for Advanced Manufacturing Processes for Vehicle Materials and Components

	Target	Fiscal Year	Current AMO Activity*	Current Status (2016)		SI
				2015 Baseline	Progress to Date	
3.1	Reduce volume and weight of targeted power electronic systems by 50% with respect to their silicon-based equivalents.	2020	CST, R&D	Current equivalent silicon devices represent the baseline (i.e., 100%)	50% reduction in volume in 3 out of 8 devices under development[240]	EI, EM
3.2	Increase the efficiency of targeted power electronic systems by 2-3% (a reduction in losses of 28% or above) with respect to their silicon-based equivalents.	2020	CST, SBIR	93 - 96%, depending of the device[241]	Efficiency increase of 2-3% demonstrated for 4 devices and 5 more on track to meeting the goal[242]	EI, LC
8.1	Develop technologies to reduce the cost per manufactured throughput of continuous R2R manufacturing processes for selected products by 50% concurrent with a 10X production capacity increase compared to 2015 typical technology.	2025	NCA	Battery Cost: $503/kWh Production: 0.9m2/min PV Cost: $0.65/W - $0.70/W Production: TBD Membranes (Water De-salination) Cost: TBD Production: TBD OLEDs Cost: $1850/m2 Production: 0.03m2/min	NCA	EI

***Key:** CST = Funded Institute or Hub; R&D = Funded R&D Project; SBIR = Funded SBIR Project; PRA = Practices; NCA = No Current Activity

[240] The devices are an electric vehicle fast charger and two different photovoltaic systems' DC-AC inverters.
[241] Supra 111. *Premium Efficiency Motor Selection and Application Guide: A Handbook for Industry.* AMO/EERE/U.S. DOE. 2014.
[242] The devices are an electric vehicle fast charger and three different photovoltaic DC-AC inverters. Additionally, there are projects on track to deliver 3 more DC-AC inverters, two electric vehicle inverters and one heavy-duty electric vehicle inverter.

4.0 List of Acronyms and Symbols

>	Greater than
<	Less than
>=	Greater than or equal to
<=	Less than or equal to
µm	Micron (micrometer)
μm^2	Square micron (micrometer)
°C	Celsius
°F	Fahrenheit
2-D	Two-dimensional
3-D	Three-dimensional
A	Ampere
A319	Type of aluminum alloy
A356	Type of aluminum alloy
ABET	Accreditation Board for Engineering and Technology
AC	Alternating current
ACLCA	American Center for Life Cycle Assessment
AEO	Annual Energy Outlook
AHSS	Advanced high-strength steel
Al	Aluminum
AM	Additive manufacturing
AMM	Advanced Materials Manufacturing
AMNPO	Advanced Manufacturing National Program Office
AMO	Advanced Manufacturing Office
AMP	Advanced Manufacturing Partnership
AMP2.0	Advanced Manufacturing Partnership 2.0
AMSE	American Society of Mechanical Engineers
ANL	Argonne National Laboratory
ARPA-E	Advanced Research Projects Agency-Energy
Ar	Arsenic
As	Arsenide
ASCPMM	Advanced Sensors, Controls, Platforms and Modeling for Manufacturing
B	Boron
$BaTiO_3$	Barium titanate
BETO	Bioenergy Technologies Office
BJT	Bipolar junction transistor
B.S.	Bachelor of Science
BTO	DOE/EERE Building Technologies Office
BTU	British thermal unit
c	Centi
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
Ce	Cerium
CE	Caloric effect
CEC	California Energy Commission

CEMAC	Clean Energy Manufacturing Analysis Center
CESMII	Clean Energy Smart Manufacturing Innovation Institute
CFRP	Carbon fiber reinforced plastic
CFTF	Carbon Fiber Technology Facility
CHP	Combined heat and power
cm	Centimeter
cm^3	Cubic centimeter
CMI	Critical Materials Institute
CMOS	Complementary meta-oxide-semiconductor
CO_2	Carbon dioxide
COP	Conference of the Parties
CP	Certified Practitioner
CPU	Central processing unit
CST	Consortia, used as an abbreviation for Funded Institute or Hub
Cu	Copper
DARPA	Defense Advanced Research Projects Agency
DC	Direct current
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DTEC	Direct thermal energy conversion
Dy	Dysprosium
ED	U.S. Department of Education
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EM	Electromagnetic
EM	Energy management
EnMS	Energy management system
EOL	End-of-life
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
Eu	Europium
EUI	Energy use intensity
eV	Electron volt
FCTO	Fuels Cell Technologies Office
Fe	Iron
FLIGHT	Facility Level Information on GreenHouse gases Tool
ft.	Foot
$ft.^2$	Square foot
FY	Fiscal year
g	Gram
G	Gauss
G	Giga
Ga	Gallium
GaN	Gallium nitride
Gd	Gadolinium

GDP	Gross domestic product
Ge	Germanium
GGE	Gallon gasoline equivalent
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GHz	Gigahertz
GMI	Grid Modernization Initiative
GOP	Giga-operations per second
GPa	Gigapascal
GTO	DOE/EERE Geothermal Technologies Office
GW	Gigawatt
GWh	Gigawatt-hour
h	Hour
H	Hydrogen
H_2	Molecular hydrogen
H_2S	Hydrogen sulfide
HDPE	High density polyethylene
HEMT	High-electron-mobility transistor
HHV	Higher heating value
Hp	Horsepower
HPC	High performance computing
HPC4Mfg	High Performance Computing for Manufacturing
HVAC	Heating, ventilation, and air conditioning
Hz	Hertz
IAC	Industrial Assessment Center
IACMI	Institute for Advanced Composites Manufacturing Innovation
IACS	International Annealed Copper Standard
ICME	Integrated computational materials engineering
IEEE	Institute of Electrical and Electronics Engineers
In	Indium
InGaAs	Indium gallium arsenide
ISO	Independent system operator
IT	Information technology
ITP	Industrial Technologies Program
J	Joule
JFET	Junction gate field-effect transistor
k	Kilo
K	Kelvin
kg	Kilogram
kHz	Kilohertz
kJ	Kilo-joule
kOe	Kilo-oersted
ksi	Kilopound per square inch
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour

l	Liter
La	Lanthanum
lb.	Pound
LBNL	Lawrence Berkeley National Laboratory
LC	Lifecycle
LCA	Lifecycle assessment (or lifecycle analysis)
LED	Light-emitting diode
LEEP	Lab-Embedded Entrepreneurship Program
LFC	Lifecycle assessment
Li	Lithium
m	Meter
m	Milli
M	Mega
m^3	Cubic meter
mA	Milliampere
MAPI	Manufacturers Alliance for Productivity and Innovation
MDF	Manufacturing Demonstration Facility
MECS	Manufacturing Energy Consumption Survey
MEP	Manufacturing Extension Partnership
MG	Mega-gauss
mg	Milligram
Mg	Magnesium
MGD	Million gallons per day
MGOe	Mega-gauss oersted
MII	Manufacturing Innovation Institute
min	Minute
MIT	Massachusetts Institute of Technology
MITEC	Manufacturing Impacts Through Energy and Commerce
MJ	Mega-joule
mm	Millimeter
Mn	Manganese
MP	Megapascal
MRL	Manufacturing readiness level
MOSFET	Metal-oxide-semiconductor field-effect transistor
MOU	Memorandum of Understanding
MRL	Manufacturing readiness level
msi	Megapound per square inch
MV	Medium voltage
MV	Megavolt
MW	Megawatt
MYPP	Multi-Year Program Plan
N	Nano
N	Nitrogen
N_2	Molecular nitrogen
NAM	National Association of Manufacturers
NASA	National Aeronautics and Space Administration

NCA	No current activity
Nd	Neodymium
NDC	Nationally determined contribution
NdFeB	Neodymium magnet (Nd, Fe, and B alloy)
NIST	National Institute of Standards and Technology
nm	Nanometer
NNMI	National Network for Manufacturing Innovation
NSF	National Science Foundation
NSTC	National Science and Technology Council
NYSERDA	New York State Energy Research and Development Authority
O	Oxygen
O_2	Molecular oxygen
Oe	Oersted
OE	DOE Office of Electricity Delivery and Energy Reliability
OIP	Office of Industrial Programs
OIT	Office of Industrial Technologies
OLED	Organic light-emitting diode
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
OSTP	Office of Science and Technology Policy
Pa	Pascal
PAN	Polyacrylonitrile
PCAST	President's Council of Advisors on Science and Technology
PEV	Plug-in electric vehicle
pH	Potential of hydrogen
PI	Process intensification
PNNL	Pacific Northwest National Laboratory
ppm	Parts per million
PRA	Practices
PU	Polyurethane
PV	Photovoltaic
PWR	Power-to-weight ratio
QA	Quality assurance
QC	Quality control
QER	Quadrennial Energy Review
QTR	Quadrennial Technology Review
Quad	One quadrillion British thermal units (BTUs)
R2R	Roll-to-roll
R&D	Research and development
RD&D	Research, development, and demonstration
REE	Rare-earth element(s)
REMADE	Reducing EMbodied-energy And Decreasing Emissions
RFI	Request for Information
rpm	Revolutions per minute
s	Second
SAE	Society of Automotive Engineers (now known as SAE International)

SBIR	Small Business Innovation Research
SBV	Small Business Vouchers
SEP	Superior Energy Performance
Si	Silicon
SiC	Silicon carbide
SiO_2	Silicon dioxide
SOFC	Solid oxide fuel cell
SSL	Solid-state lighting
STTR	Small Business Technology Transfer
SWNT	Single-walled carbon nanotube
T	Tera
TAP	Technical Assistance Partnership
Tb	Terbium
TBD	To be determined
TCF	Technology Commercialization Fund
TDS	Total dissolved solids
TE	Technical education
Te	Tellurium
TFET	Tunnel field-effect transistor
Ti	Titanium
TIR	Technologist in Residence
TRL	Technology readiness level
U.S.	United States
USDA	U.S. Department of Agriculture
V	Volt
VFD	Variable frequency drive
VTO	DOE/EERE Vehicle Technologies Office
W	Watt
WBG	Wide bandgap
WHP	Waste heat to power
Y	Yttrium
ZEB	Zero-energy building

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