QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

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Issues and RDD&D Opportunities

- Manufacturing affects the way products are designed, fabricated, used, and disposed; hence, manufacturing technologies have energy impacts extending beyond the industrial sector.
- Life-cycle analysis is essential to assess the total energy impact of a manufactured product.
- State-of-the-art technologies available today could provide energy savings, but many have not yet penetrated the market due to barriers such as high capital intensity and lack of knowledge. Opportunities exist to overcome these barriers and increase technology uptake.
- Transformative manufacturing processes, materials, and technologies can provide advantages over the practices widely in use, and in many cases enable the fabrication of innovative new clean energy products.
- Industrial-scale energy systems integration technologies, such as waste heat recovery and distributed energy generation, can reduce the manufacturing sector's reliance on the electric grid and increase industrial efficiency.
- Data, sensors, and models can improve design cycles and enable real-time management of energy, productivity and costs, increasing manufacturing efficiency while improving product quality and throughput.

The chapter can help address these important questions:

- What manufacturing research and development opportunities can be developed to drive down energy intensity, carbon intensity, and use intensity?
- What innovative manufacturing technology and system improvements and innovations might result in the greatest economy-wide impacts?
- What is the appropriate balance between maturation of existing technologies and development of advanced, next-generation technologies?

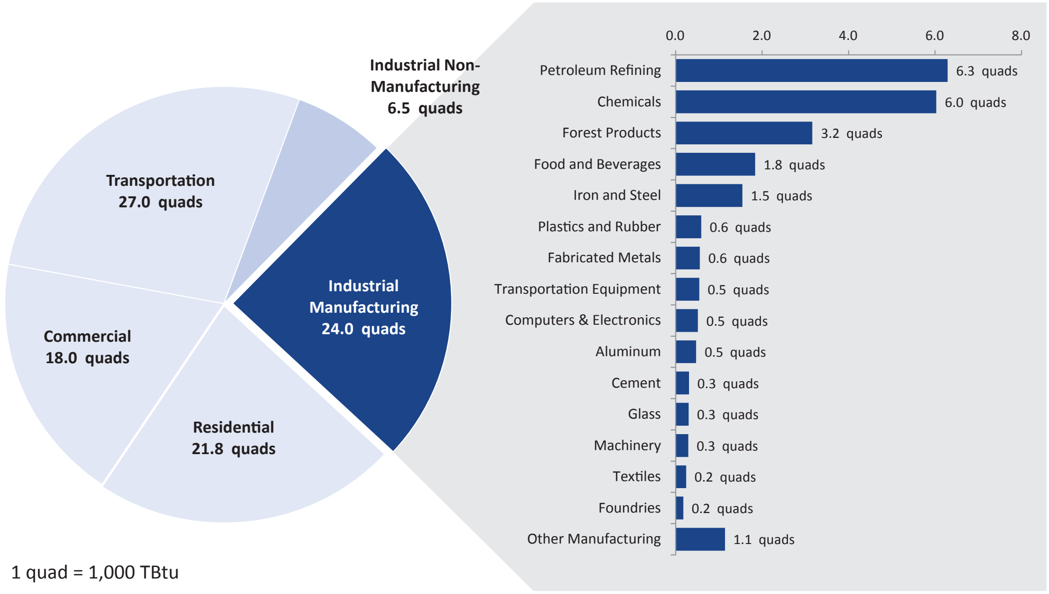
6

Innovating Clean Energy Technologies in Advanced Manufacturing

6.1 Introduction

Clean energy manufacturing involves the minimization of the energy and environmental impacts of the production, use, and disposal of manufactured goods, which range from fundamental commodities such as metals and chemicals to sophisticated final-use products such as automobiles and wind turbine blades. The manufacturing sector, a subset of the industrial sector, consumes 24 quads of primary energy annually in the United States—about 79% of total industrial energy use, as shown in Figure 6.1.[1] Clean energy manufacturing can improve energy utilization and also yield economy-wide reductions in greenhouse gas (GHG) emissions through changes in energy use enabled by the development of new materials and process technologies.

Figure 6.1 Manufacturing Share of the Nation's Overall Energy Consumption and Breakdown of Manufacturing Primary Energy (including non-fuel feedstock energy) Consumption by Subsector (2010)[2]



1 quad = 1,000 TBtu

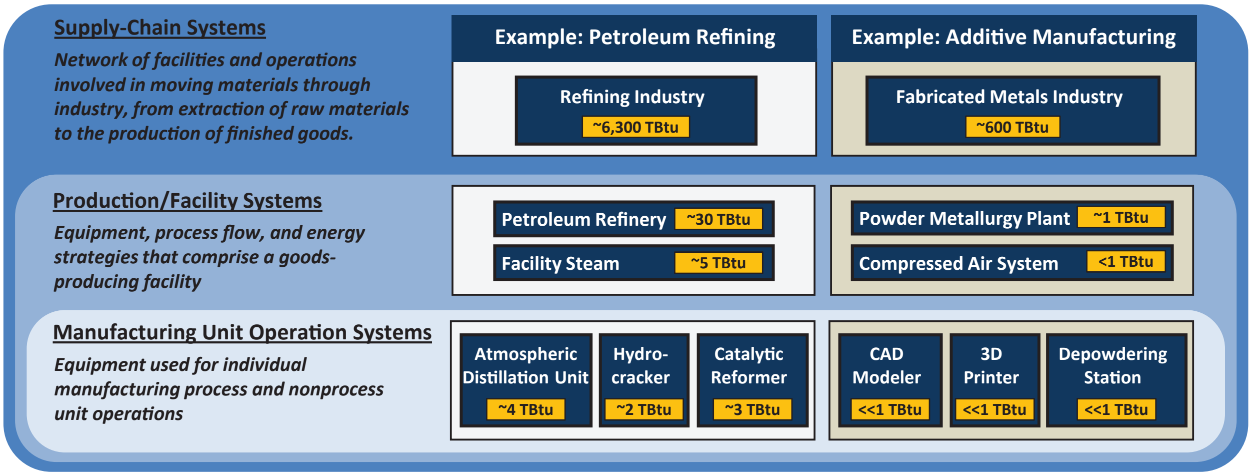
Key: **Btu** = British thermal unit; **TBtu** = trillion Btu

This chapter examines the opportunities for improvements in energy and materials utilization within three spaces:

- Individual manufacturing processes and unit operations
- Goods-producing facilities, including manufacturing business processes
- Manufacturing supply chains and manufactured goods, including impacts from all phases of the product life cycle

These opportunities correspond to three levels of manufacturing system integration: manufacturing/unit operations, production/facility systems, and supply chain systems, as illustrated in Figure 6.2. Specific objectives within each opportunity area were used to identify key technologies of interest for a balanced research, development, demonstration, and deployment (RDD&D) portfolio. These technologies were analyzed in a series of fourteen manufacturing Technology Assessments (available as appendices to this report). The Technology Assessments were informed by detailed analyses, roadmaps, and other studies that principally addressed energy impacts, but also considered other impacts as appropriate. While this report treats each manufacturing technology individually, it is important to note that the technologies are inherently interconnected, as illustrated in Figure 6.3. Each technology impacts many other technologies inside and outside of the manufacturing sphere. Some technologies may rely on similar RDD&D, and platform technologies such as automation affect manufacturing systems broadly, while other technologies can be used in combination and complement each other. Further, most technologies have impacts at every systems level—not just at a single level. This chapter organizes technologies based on the characteristics of the technology and its key energy savings opportunities, but important opportunities at all systems levels are explored.

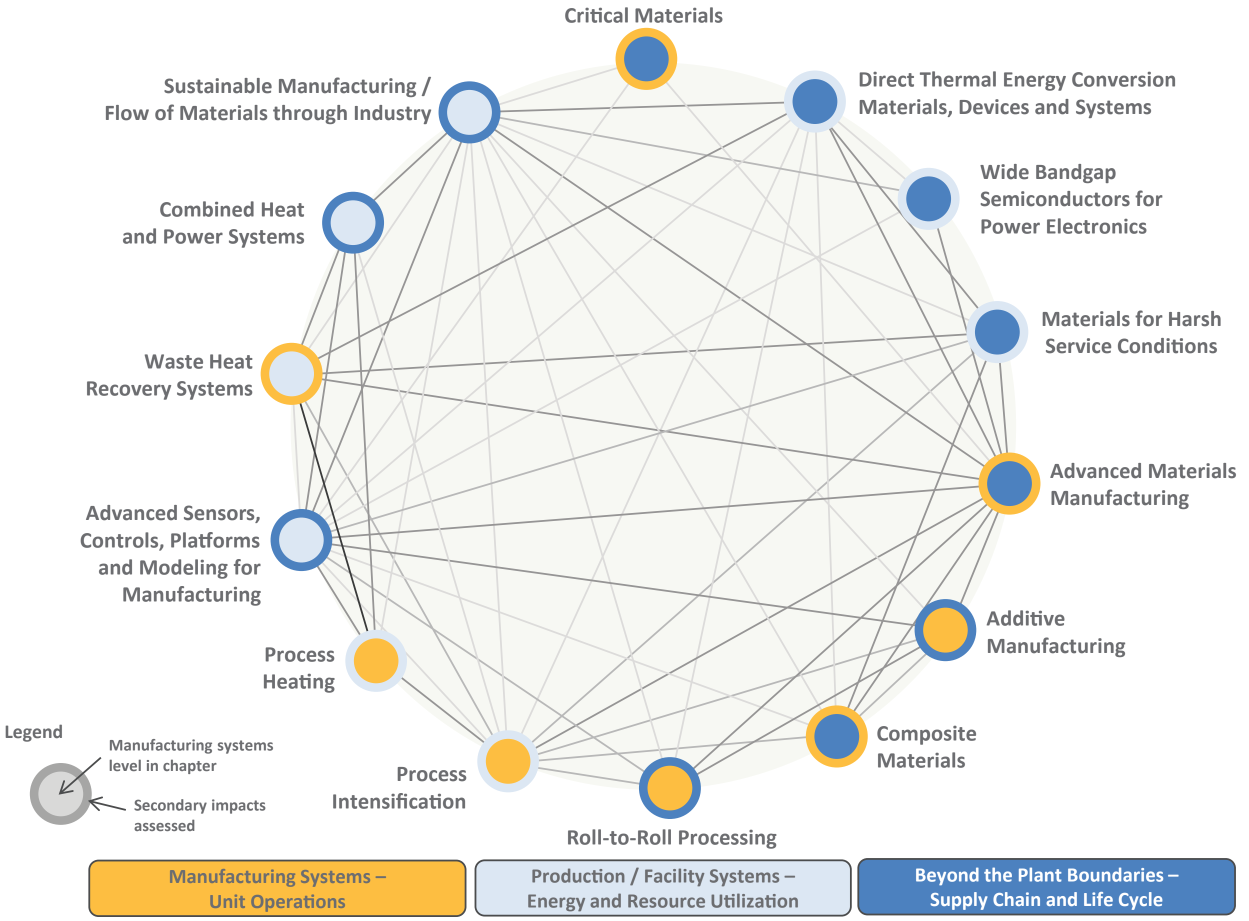
Figure 6.2 Levels of System Integration in Manufacturing. Opportunities for energy savings occur at each system level. The energy usage estimates shown (yellow boxes) represent the typical annual energy consumption levels in the United States for a single industry, production facility, or piece of manufacturing equipment.



6.1.1 Energy Opportunity Space: Manufacturing Systems – Unit Operations

A wide array of process technologies and manufacturing operations is used to convert raw materials to finished products, often through long sequences of intermediate product forms. These can be defined as unit operations. At this unit operation level, key energy opportunities include advanced equipment that enhances throughput, lessens environmental impacts, reduces wasted energy, and achieves higher energy efficiencies than existing processes. The energy consumption required for each process step is governed by the efficiency of the best-

Figure 6.3 Constellation Diagram Showing Connections Between the Fourteen Manufacturing Technologies Analyzed in Technology Assessments. QTR Technology Assessments investigate current technology status, RDD&D needs, and potential energy impacts.



available manufacturing equipment and the underlying process physics of the manufacturing operation. Further, process step elimination, process step substitution, equipment co-location, and other process integration strategies can further reduce manufacturing energy demands. These opportunities are explored in Section 6.2.

6.1.2 Energy Opportunity Space: Manufacturing Equipment Clusters and Facility Systems – Energy and Resource Utilization

The facility-level energy opportunity space includes technologies for effectively managing the use and flows of energy and materials at manufacturing facilities. Manufacturing facilities integrate manufacturing equipment and practices into complex workflows to transform raw materials into finished goods. Advanced technologies for onsite energy generation to supplement delivered energy, energy conversion, waste heat recovery and re-use, materials handling, and real-time energy consumption adjustments can improve the efficiencies of these facilities. The rise of information technologies in the manufacturing sector, for example, has enabled many next-generation technologies to leverage the use of data, machine- and plant-level monitoring and control strategies, robotics, and automation to manage and optimize energy use and flows in real time. Opportunities to improve energy and resource utilization at the facility level are analyzed in Section 6.3.

6.1.3 Energy Opportunity Space: Manufacturing Supply Chains and Life-Cycle Impacts of Manufactured Goods

The third energy opportunity space involves innovative new materials and new manufacturing technologies for products that impact supply chains and reduce life-cycle energy usage. The life cycle of a product incorporates all phases of its production and use, from resource extraction to end-of-life disposal or recycling. Energy consumption and environmental impacts in all phases of the life cycle contribute to its total energy intensity, use intensity, and carbon intensity. Manufacturing supply chains and products reach all end-use sectors and affect all parts of the energy economy. Process heating equipment; steam turbines; commercial heating, ventilating, and air conditioning (HVAC) systems; home appliances; and vehicles are all examples of manufactured goods. The life-cycle energy consumption associated with these goods drives energy use in the industrial, power generation, commercial buildings, residential buildings, and transportation sectors, respectively. Reducing these energy impacts often requires new types of materials, such as lighter-weight materials for vehicles or high-temperature superalloys for ultra-supercritical steam turbines, and new manufacturing approaches to enable the production of those goods. These opportunities are discussed in Section 6.4.

6.1.4 Foundation for a Technology Portfolio Structure

An effective technology RDD&D portfolio must balance between high-efficiency manufacturing equipment and approaches (Section 6.2), advanced technologies to improve energy and resource use at manufacturing facilities (Section 6.3), and next-generation products with potential for energy impacts throughout the economy (Section 6.4). The portfolio must also include a mixture of developmental timescales, including both short-term projects and longer-term projects that push technological boundaries or involve transformational new approaches. Over-arching goals for consideration by decision makers could include the following:

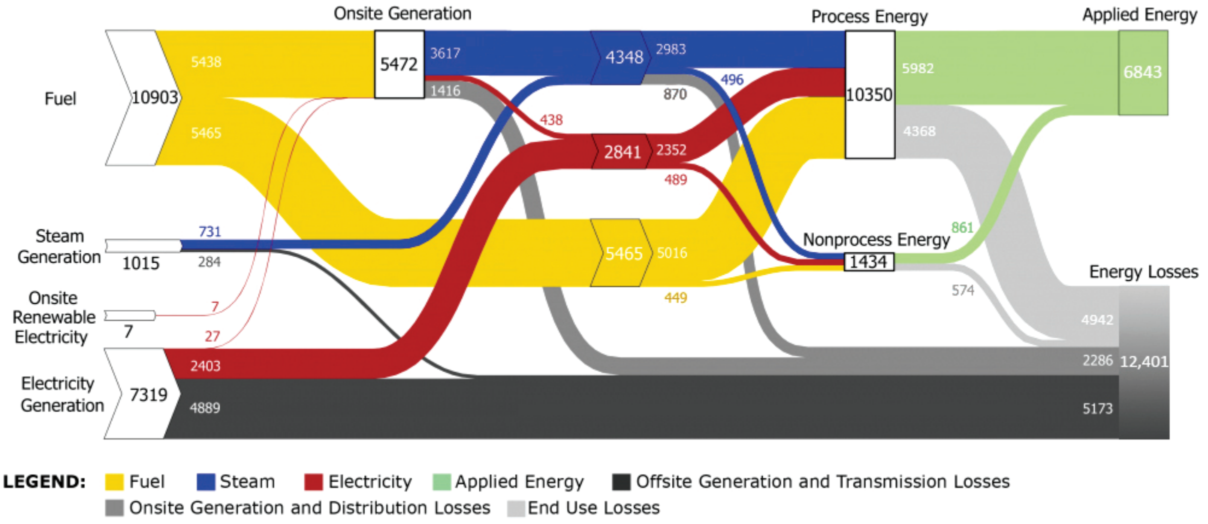
- **Goal 1:** Deploy current state-of-the-art technologies to achieve a 25% reduction in manufacturing energy intensity (energy consumed per unit of physical output) over ten years.[3]
- **Goal 2:** Pursue technology improvements to narrow the gap between current energy use and practical minimum energy requirements,[4] especially for major energy-intensive industries.
- **Goal 3:** Develop transformational next-generation materials, processes, and technologies that are not bound by current practical (energy and emissions) limitations.
- **Goal 4:** Invest in selected technologies for manufactured goods that will significantly lower energy intensity in the industrial, transportation, and buildings sectors that will achieve a minimum 50% life-cycle energy reduction within ten years, as well as technologies for clean energy generation and delivery that achieve a significant performance improvement in efficiency, cost, and/or durability.

Technologies of interest will have the potential to reduce the manufacturing sector's overall energy intensity and environmental impacts, including both direct and indirect (life cycle) impacts. Key manufacturing technologies and opportunities are explored in this chapter with goals such as these in mind.

6.2 Technology Opportunities in Manufacturing Systems – Unit Operations

Energy use at manufacturing facilities can be grouped into three key clusters of equipment: process systems, such as furnaces, dryers, pumps, and compressors; nonprocess systems, such as facility heating, lighting, and onsite transportation; and onsite generation systems, such as conventional boilers and combined heat and power (CHP) equipment used to produce electricity and steam. The Sankey energy flow diagram in Figure 6.4 illustrates the energy flow of the entire manufacturing sector, with fuel energy shown as a yellow flow line, steam as blue, and electricity as red. Approximately half of the fuel from offsite sources is transformed onsite at manufacturing facilities sector-wide to generate additional steam and electricity. The majority of energy from offsite and onsite

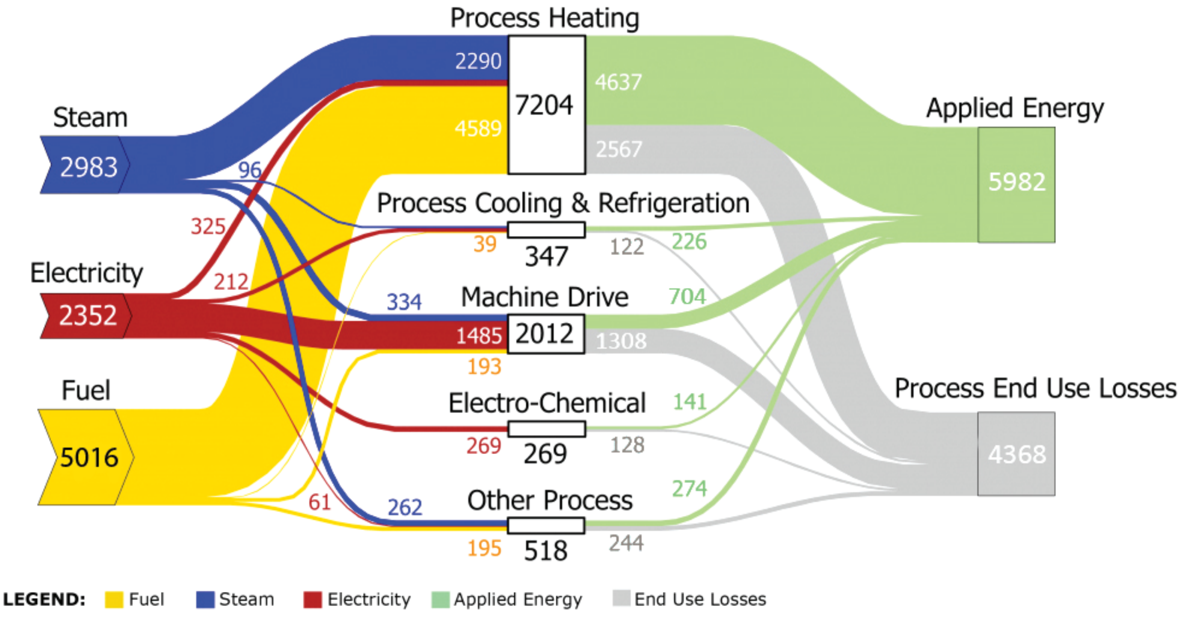
Figure 6.4 Sankey Diagram of Primary Energy Flow (feedstock energy excluded) in the U.S. Manufacturing Sector (2010). Energy units are TBtu.[5]



generation sources is consumed by process end uses, while nonprocess facility end use accounts for a small fraction of consumption. The Sankey diagram also accounts for overall estimated energy losses, shown in gray, including generation and transmission losses (offsite and onsite generation) and end use losses.

Manufacturing process end uses are detailed in Figure 6.5, which shows that process heating and motor-driven systems dominate process energy consumption, accounting for 89% of process energy consumption.[6] For process heating systems, fuel and steam are the dominant forms of energy utilized, while electricity is the

Figure 6.5 Sankey Diagram of U.S. Manufacturing Sector Process Energy Flow in 2010 (a subset of the overall manufacturing sector energy flows shown in Figure 6.4). Energy units are TBtu.[9]



prevailing form of energy for motor-driven systems. Considering a total energy consumption of 9,216 trillion British thermal units (TBtu) for process heating and motor driven systems in the manufacturing sector, a 10% overall energy efficiency improvement in these systems could provide nearly 1,000 TBtu of energy savings across all manufacturing industries. Further, transformational industry-specific unit operation technologies such as process intensification (chemicals), roll-to-roll processing (electronics), and additive manufacturing (fabricated metals) can provide direct benefits such as increased manufacturing efficiency and better product quality, as well as downstream life-cycle energy benefits.

6.2.1 Improving the Efficiency of Manufacturing Processes

Process heating and motor-driven systems collectively consume more than nine quads of end use energy in the U.S. manufacturing sector. Continued technology maturation and improvements will drive technology uptake to reduce energy intensity and can narrow the gap between current energy use and practical minimum energy requirements, especially for major energy-intensive commodities. Transformational next-generation processes and technologies that are not bound by practical (energy and emissions) limitations of current processes, such as low-thermal-budget processes and next-generation motor-driven systems, can drive manufacturing energy reductions and expand capabilities of manufacturers.

Process Heating Systems (including steam for unit operations)

Process heating accounts for approximately 61% of manufacturing end use energy use annually.[7] Energy for process heating is obtained from a combination of electricity, steam, and fuels such as natural gas, coal, biomass, and fuel oils. In 2010, process heating consumed approximately 330 TBtu of electricity, 2,290 TBtu of steam, and 4,590 TBtu of fuel.[8] Common process heating systems include equipment such as furnaces, heat exchangers, evaporators, kilns, and dryers. Characteristics of major manufacturing operations that involve process heating are shown in Table 6.1.

Table 6.1 Characteristics of Common Industrial Processes that Require Process Heating[10]

Process heating operation	Description/example applications	Typical temperature range (F)	Estimated (2010) U.S. energy use (TBtu)
Fluid heating, boiling, and distillation	Distillation, reforming, cracking, hydrotreating; chemicals production, food preparation	150–1000°	3,015
Drying	Water and organic compound removal	200–700°	1,178
Metal smelting and melting	Ore smelting, steelmaking, and other metals production	800–3000°	968
Calcining	Lime calcining	1500–2000°	395
Metal heat treating and reheating	Hardening, annealing, tempering	200–2500°	203
Non-metal melting	Glass, ceramics, and inorganics manufacturing	1500–3000°	199
Curing and forming	Polymer production, molding, extrusion	300–2500°	109
Coking	Cokemaking for iron and steel production	700–2000°	88
Other	Preheating; catalysis, thermal oxidation, incineration, softening, and warming	200–3000°	1,049
Total			**7,204**

Waste heat losses are a major consideration in process heating, especially for higher-temperatures process heating systems such as those used in steelmaking and glass melting. Losses can occur at walls, doors and openings, and through the venting of hot flue and exhaust gases. Overall, energy losses from process heating systems total more than 2,500 TBtu annually.[11] The recovery and use of waste heat offers an opportunity to re-utilize wasted heat for other purposes (see *Waste Heat Recovery Systems* in Section 6.3.1). Alternatively, 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 proportion of useful heat energy delivered to the product, reducing the occurrence of waste heat.[12] In addition, these techniques are flexible, as process parameters such as the electromagnetic frequency, energy input, and spatial extent can often be monitored and actively controlled. Because the interaction of electromagnetic energy with matter varies from material to material, electromagnetic processing techniques can enable entirely new or enhanced manufactured products.

Novel processing techniques that involve lower temperature processing or fewer heating steps can also reduce energy consumption. Hybrid process heating systems that combine multiple forms of heat transfer (radiative, conductive, and/or convective methods) or multiple operations into a single piece of equipment (such as hybrid distillation systems) can reduce heating time, increase energy efficiency, and improve product quality. Key RDD&D opportunities for energy and emissions savings in industrial process heating operations are summarized in Table 6.2. While the total energy savings opportunity (2,210 TBtu) is very large, only a portion of this opportunity is technically and economically feasible to capture, as discussed in the *Waste Heat Recovery Systems* Technology Assessment.

Table 6.2 RDD&D Opportunities for Process Heating and Projected Energy Savings[13]

R&D opportunity	Applications	Estimated annual energy savings opportunity (TBtu/yr)	Estimated annual carbon dioxide (CO_2) emissions savings opportunity (million metric tonnes [MMT]/yr)
Advanced non-thermal water removal technologies	Drying and concentration	500	35
"Super boilers" (to produce steam with high efficiency, high reliability, and low footprint)	Steam production	350	20
Waste heat recovery systems	Crosscutting	260	25
Hybrid distillation	Distillation	240	20
New catalysts and reaction processes (to improve yields of conversion processes)	Catalysis and conversion	200	15
Lower-energy, high-temperature material processing (e.g., microwave heating)	Crosscutting	150	10
Advanced high-temperature materials for high-temperature processing	Crosscutting	150	10
Net-shape and near-net-shape design and manufacturing	Casting, rolling, forging, additive manufacturing, and powder metallurgy	140	10
Integrated manufacturing control systems	Crosscutting	130	10
Total		**2,210**	**155**

Motor-Driven Systems

Industrial machine and motor-driven systems include pumps, fans, compressors, air conditioners, refrigerators, forming and machining tools, robots, and materials processing and handling equipment. These systems account for 68% of manufacturing electricity consumption.[14] The majority of this energy is consumed in just three manufacturing sectors: chemicals, forest products, and food and beverage manufacturing. While electric motors have high efficiencies, end-use motor-driven systems have much lower system efficiencies, particularly for pumps, fans, compressed air and materials processing equipment. As a result, overall machine-driven system losses total 1,470 TBtu annually.[15] The total energy use for major categories of machine-driven systems in U.S. manufacturing is shown in Table 6.3.

Table 6.3 Energy Use of Major Motor-Driven Systems in U.S. Manufacturing[16]

Primary manufacturing motor-driven systems	Estimated U.S. manufacturing energy use (2010)	
	(TBtu)	(GWh)
Pumps	614	180,100
Fans	291	85,240
Compressed air	333	91,560
Materials handling (e.g., conveyers, belts, materials movers)	175	51,300
Materials processing (e.g., grinding, agitating/mixing, debarking, drilling, pressing)	497	145,530
Process cooling and refrigeration	212	62,120
Facility heating, ventilating, and air conditioning (HVAC)	241	70,610

Key energy savings opportunities can be identified by focusing on opportunities to improve the motor system, rather than focusing solely on the motor. A 2004 study estimated the electricity savings opportunities from the use of available technologies on motor-driven systems.[17] Only 13% of these opportunities were from the motors, while variable speed drive adoption accounted for an additional 25%, and improvements to applications would account for the remaining 62%. In some cases, the efficiency of motor-driven systems can be enhanced by upgrading a motor to take advantage of newer, high-efficiency technologies, but system design and appropriate sizing of motor and drive system to its application is critical to minimize energy losses.[18] Many industrial motors are sized to handle peak demand, and are often part of a system that is poorly engineered and inefficient.[19] Therefore, motor systems often use much more power than is needed, especially when the facility is running below peak throughput. Variable frequency drive (VFD) motors dynamically adjust motor speed to match power demands, and can thereby reduce energy consumption in industrial facilities. Opportunities also exist to better harmonize alternating current (AC) and direct current (DC) power to reduce conversion losses and improve power quality for industrial applications.[20]

Next-generation motor-driven systems will benefit from the development of improved wide bandgap (WBG) semiconductors (see *Wide Bandgap Semiconductors for Power Electronics* in Section 6.4.2), which are expected to enable more cost-effective and higher efficiency VFD systems. For example, WBG semiconductors are expected to accelerate the motorization of large compressors prevalent in the chemical, oil and gas industries, which could improve efficiencies and reduce fugitive methane emissions. In addition, 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 VFDs. The resulting high-speed, high-frequency motor system may allow for elimination of a speed-increasing gearbox,[21] resulting in improvements in power density and footprint of the overall system and providing benefits in space-constrained applications.

Lastly, information technology is enabling more intelligent power use for a step-change impact in electric machines and motors. Beyond energy consumption reductions, benefits include more integrated and intelligent motor systems that can increase facility productivity.

6.2.2 New Manufacturing Approaches

Entirely new manufacturing approaches such as additive manufacturing and roll-to-roll processing, and highly optimized manufacturing operations based on process intensification paradigms, can form the basis for manufacturers to narrow the gap between current energy use and practical minimum energy requirements and can lead to transformational next-generation processes and technologies that are not bound by practical limitations of current processes.

Process Intensification

Process intensification (PI) targets dramatic improvements in manufacturing and processing by rethinking existing operation schemes into ones that are both 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 economical manufacturing process. At the molecular level, PI technologies can significantly enhance mixing, which improves mass and heat transfer, reaction kinetics, yields, and specificity. These improvements translate into reductions in energy use, waste generation, environmental impact, and amount of equipment, and thereby minimize cost and risk in chemical manufacturing facilities.

Applications for PI technologies crosscut energy-intensive industries with opportunity space in chemicals, petroleum refining, plastics, forest products, and food industries, among others. PI innovation could deliver solutions to energy security, environmental, and economic challenges in areas including stranded gas recovery, carbon capture, and water treatment. PI is a key development platform for eco-efficient chemicals production. The chemicals sector has an annual onsite energy consumption of approximately 3,221 TBtu (not including chemical feedstocks) and combustion emissions of about 145 million metric tonnes CO_2-equivalent (CO_2-eq).[22] A European roadmapping analysis[23] concluded that R&D investment in PI technologies could lead to a 20% improvement in overall energy efficiency of petrochemical and bulk chemical production in thirty to forty years and to a 50% reduction in costs for specialty chemicals and pharmaceuticals production in ten to fifteen years.

The *2015 Bandwidth Study on Energy Use and Potential Energy Savings in U.S. Chemical Manufacturing*[24] analyzed energy consumption and savings opportunities for some of the top energy-consuming chemicals in the United States. Based on the bandwidth analysis, eleven chemicals (listed in descending order of energy consumption in Table 6.4) were found to have significant opportunities for energy savings via implementation of PI technologies. In 2010, the production processes for these eleven chemicals consumed an estimated 1,370 TBtu of energy,[25] accounting for 43% of the total onsite energy consumed in the chemicals industry. Table 6.4 shows estimates of the energy savings opportunity from successful development and implementation of PI technologies for each of the chemicals, totaling 695 TBtu/yr.[26]

Although PI is a promising approach for increasing the energy efficiency of chemical processes and reducing costs, PI for many potential applications is still in the early stages of technology readiness. Considerable potential exists for near- and long-term energy use and carbon emission reductions through the development of PI technologies and novel processes. RDD&D investment in PI technologies could have wide ranging applicability across the chemical industry as well as other industries. PI approaches that optimize energy recovery through process integration may be particularly impactful. Metrics of successful PI RDD&D

Table 6.4 2010 Production, Calculated Onsite Energy Consumption, and Energy Savings Potential for Eleven Chemicals[27]

Chemical	Annual production (million lbs/yr)	Calculated onsite energy (TBtu/yr)	Energy reduction opportunity (TBtu/yr)
Ethanol	66,100	307	264
Ethylene	52,900	374	107
Ammonia	22,700	133	78
Benzene	13,300	104	67
Chlorine/sodium hydroxide	21,500/16,600	203	87
Nitrogen/oxygen	69,600/58,300	99	18
Ethylene dichloride	19,400	66	37
Propylene	31,100	42	11
Acetone	3,180	25	18
Ethylene oxide	5,880	11	4
Methanol	2,020	10	4
Total	**382,000**	**1,370**	**695**

include cost reduction, energy efficiency, carbon efficiency, and waste reduction compared to state-of-the-art technologies. Key areas for RDD&D include the following:

- **PI equipment,** involving improved physical hardware and optimized operating parameters for improved chemicals processing environments and profiles, such as novel mixing, heat-transfer and mass-transfer technologies.
- **PI methods,** including improved or novel chemical processes (e.g., new or hybrid separations, integration of reaction and separation steps, improved heat exchange) or phase transition (multifunctional reactors), the use of a variety of energy sources (light, ultrasound, magnetic fields), and new process-control methods (intentional non-equilibrium-state operation).
- **PI supporting practices,** such as improved manufacturing processes for new equipment and improved systems integration, common standards and interoperability, modular systems design and integration, supply chain development and flexibility, workforce training, and financing.

Roll-to-Roll Processing

Roll-to-roll (R2R) manufacturing is an important class of substrate-based manufacturing processes in which additive and subtractive processes are used to build structures in a continuous manner. Typical R2R operations include casting, extrusion, coating, and printing of two-dimensional products. 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. Examples of applications for R2R manufacturing include the following:

- **Flexible electronics** for solar panels, printed electronics, displays, thin film batteries, multilayer capacitors, smart labels (e.g., radio frequency identification tags and antennas), and thin-film detectors and sensors.

- **Separation membranes,** such as indoor air quality and dehumidification membranes, gas separation membranes for natural gas processing and CO_2 capture, forward-osmosis capacitive polarization membranes for water processing, and polymer electrolyte membranes for fuel cells.
- **Photovoltaics** for flexible organic solar cells, power provision (especially lighting) for buildings, and battery charging.

Technical advances in R2R manufacturing for these applications can be realized by RDD&D in the following areas:

- **Deposition and patterning technologies:** Process tools for core capabilities such as deposition processes, including evaporation, sputtering, electroplating, chemical vapor deposition, atomic layer deposition, laser ablation, and imprint/soft lithography.
- **Precursors and inks:** Development of precursor materials and inks for printed materials with stable, uniform material properties.
- **Multilayer processing:** Fabrication techniques for layered and functionally graded materials.
- **Metrology for inspection and control:** Metrology and instrumentation for inspection and quality control of R2R manufactured products. Real-time data monitoring systems and process models are needed for adaptive and predictive process control at speeds relevant to production.

Additive Manufacturing

Emerging additive manufacturing (AM) technologies are projected to have a transformational impact on manufacturing by dramatically reducing materials and energy use, eliminating production steps, enabling simpler component designs, eliminating costly part tooling, and supporting increased distributed manufacturing at the point-of-use. Unlike conventional fabrication methods that use machining processes to cut away material from molded or cast objects, AM techniques build up objects layer-by-layer to create end products directly from a computer model, reducing material use by up to 90%.[28] Additive manufacturing enables the production of many complex structures that cannot be manufactured by other means, such as embedded features and other complex geometries; however, it is important to note that AM processes are associated with size and material property limitations that restrict their use to certain applications. AM technologies that have been introduced into the commercial market, along with their material compatibilities, are shown in Table 6.5.

Additive manufacturing can provide life-cycle benefits in multiple sectors compared to conventional manufacturing by reducing the amount of required raw material, reducing the ultimate weight of a component, and minimizing part count. As an example, Figure 6.6 shows the projected impacts for the penetration of AM components into the U.S. aircraft fleet over the next thirty-five years. With rapid adoption, annual energy savings could approach 100 TBtu by 2040 for this application area alone. Energy benefits attained through use of additive manufacturing depend on the specific product being manufactured; life-cycle analysis is useful to assess the actual energy savings possible.

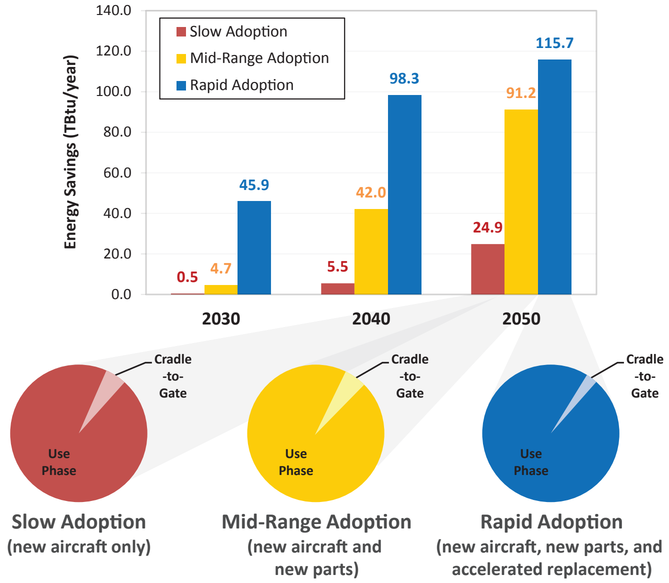
To realize the full potential of additive manufacturing, technology solutions are needed to improve dimensional accuracy, improve the mechanical and physical properties of the finished part, increase throughput, and reduce the minimum feature size that can be fabricated, requiring RDD&D to address the following key technical challenges:[29]

- **Process control:** Feedback control systems and metrics are needed to improve the precision and reliability of the manufacturing process and to increase throughput while maintaining consistent quality. Feedback control is especially challenging for AM processes with rapid deposition rates. The ability to tailor the material microstructure *in situ* could improve performance properties.
- **Tolerances:** Some potential applications would require micron-scale accuracy in printing.

Table 6.5 Additive Manufacturing Process Technologies and Materials Compatibilities (as classified by ASTM F42)[30]

Process type	Brief description	Related technologies	Materials
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)	Metals, polymers
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser metal deposition (LMD)	Metals
Material extrusion	Material is selectively dispensed through a nozzle or orifice	Fused deposition modeling (FDM)	Polymers
Vat photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Stereolithography (SLA), digital light processing (DLP)	Photopolymers
Binder jetting	A liquid bonding agent is selectively deposited to join powder materials	Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)	Polymers, foundry sand, metals
Material jetting	Droplets of build material are selectively deposited	Multi-jet modeling (MJM)	Polymers, waxes
Sheet lamination	Sheets of material are bonded to form an object	Laminated object manufacturing (LOM), ultrasonic consolidation (UC)	Paper, metals

Figure 6.6 Projected Annual Energy Savings (TBtu/year) for Fleet-wide Adoption of Additive Manufactured Components in Aircraft, Assuming Slow, Mid-range and Rapid Adoption Scenarios. In this example, energy savings were driven by the use phase.[31]



- **Finish:** The surface finishes of products manufactured using additive technology require further refinement. With improved geometric accuracy, finishes may impart improved tribological and aesthetic properties.
- **Electrical power:** The impact of power quality on additive manufacturing equipment is not well understood. Power variations and interrupts can impact the quality of the item produced using additive manufacturing by introducing defects that may not be detected. To evaluate the power quality characteristics of AM equipment and develop a better understanding of the design and makeup of this new type of manufacturing system requires research.

Automotive Applications of Additive Manufacturing

Figure 6.7 Delphi Diesel Engine Pump Housing Fabricated via Selective Laser Melting

Credit: Delphi Automotive

Delphi Automotive, a Tier 1 automotive parts manufacturer, currently uses an additive manufacturing technique (selective laser melting) to produce aluminum diesel pumps, as shown in Figure 6.7.[32] The life-cycle energy consumption for the additive process and the conventional gravity die casting process are compared in Table 6.6. Energy savings result from reduced material requirements for the additive process. Selective laser melting reduces the amount of scrap produced during manufacturing of the part; the reduced weight of the finished component also provides use phase energy savings.

Table 6.6 Life-Cycle Energy Comparison for an Aluminum Diesel Engine Pump Housing Manufactured via Gravity Die Casting and Selective Laser Melting[33]

Life cycle stage	Gravity die casting energy use (kBtu)	Selective laser melting energy use (kBtu)
Raw materials	305	64
Manufacture	5	28
Transportation	45	7
Use phase	324	73
End of life*	1	0
Total	**681**	**173 (75% energy savings)**

* End-of-life energy use is negligibly small for the selective laser melting process.
Key: **kBtu** = thousand Btu.

- **Material compatibility:** Materials that can be used with additive manufacturing technologies are currently limited to a relatively small set of compatible materials. There is a need for new polymer and metal materials formulated for additive manufacturing to provide materials properties such as flexibility, conductivity, transparency, safety, and low embodied energy.
- **Validation and demonstration:** Manufacturers, standards organizations, and others maintain high standards for critical structural materials, such as those used in aerospace applications. Providing a high level of confidence in the structural integrity of components built with additive technology may require testing, demonstration, and data collection.
- **Modeling:** Data-based models of additive manufacturing processes are needed to promote real-time process control and to increase understanding of multi-material additive processes, where interface issues such as bonding and thermal expansion can present significant issues.

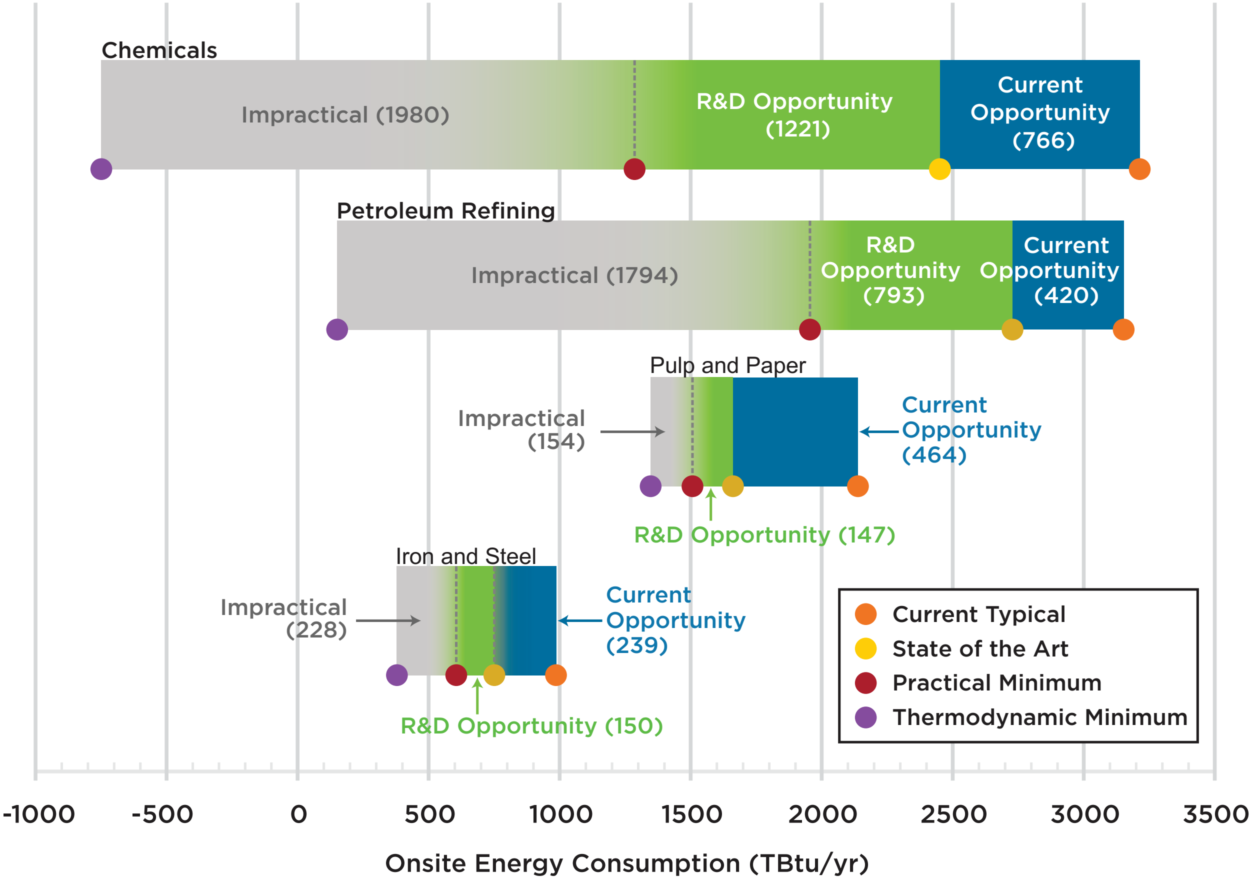
In addition to technological challenges, there are business challenges to be addressed; for example, industry designers are familiar with conventional manufacturing methods, and parts are often designed based on conventional manufacturing processes. Widespread adoption of additive manufacturing will require education, training, and approaches to mitigate business risks associated with the transition to a rapidly advancing technology.

6.3 Technology Opportunities for Production/Facility Systems – Energy and Resource Utilization

Numerous studies have examined the potential for energy efficiency improvements in production/facility systems, which integrate manufacturing equipment and practices into goods-producing facilities. For example, bandwidth studies assess potential energy savings opportunities by comparing the amount of energy typically consumed at a manufacturing facility to produce a particular product to the state-of-the-art and practical minimum amounts of energy needed to achieve the same results.[34]

Figure 6.8 shows the bandwidth summaries for four energy-intensive manufacturing sectors. The lower bound of the energy bandwidth is defined by the theoretical minimum energy requirement, assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption). The upper bound represents the current energy consumption (based on average energy intensities for key processes at existing

Figure 6.8 Bandwidth Diagrams Illustrating Energy Savings Opportunities in Four Energy-Intensive U.S. Manufacturing Industries. Current opportunities represent energy savings that could be achieved by deploying the most energy-efficient commercial technologies available worldwide. R&D opportunities represent potential savings that could be attained through successful deployment of applied R&D technologies under development worldwide.[35]



manufacturing facilities). The current energy savings opportunity, shown in blue for each sector, represents the savings potentially attainable through state-of-the-art technology adoption. The R&D savings opportunity, shown in green, represents additional energy savings potentially attainable through adoption of applied research and development. The point of transition labeled Practical Minimum is inexact and for this reason is shown as a dashed line between the future savings opportunity and the impractical region (shown in gray). The current and R&D opportunity bandwidths are based on technical energy savings potential and do not take costs into account. Bandwidth diagrams can help one to quickly and holistically assess the magnitude of potential opportunities for energy savings for a sector or manufacturing process.

6.3.1 Improving Fuel Flexibility and Reducing Waste Energy

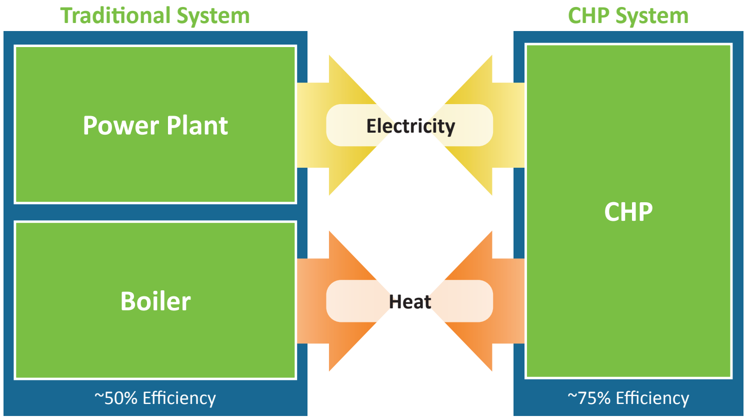
Industrial-scale energy systems integration provides a systems approach to optimize energy use at manufacturing facilities through technologies that can increase energy flexibility and reduce/recover/re-use waste energy, leading to reduced energy intensity, and narrowing the gap between current energy use and practical minimum energy requirements.

Combined Heat and Power Systems

CHP is the concurrent production of electricity or mechanical power and useful thermal energy from a single energy input, as shown in Figure 6.9. CHP technologies provide manufacturing facilities, commercial and institutional buildings, and communities with ways to reduce energy costs and emissions while also providing more resilient and reliable electric power and thermal energy. CHP systems combine the production of heat (for both heating and cooling) and electric power into one process, using much less fuel than when heat and power are produced separately. CHP systems can achieve overall energy efficiencies of 75% or more,[36] compared to separate production of heat and power, which collectively averages about 50% efficiency.[37] A recent executive order has set a national target of 40 gigawatts (GW) of additional CHP capacity by 2020,[38] an increase of nearly 50% above the current installed capacity of 83 GW.[39]

DOE analyses have identified R&D opportunities to increase the power-to-heat ratio of 1–10 MW CHP systems while maintaining the high overall system efficiencies of traditional thermally-sized CHP systems. This would entail the development of ultra-high-efficiency generation technologies. Existing CHP systems on average generate much more steam than electricity, with power-to-heat ratios[40] of individual systems as low as 0.1 but

Figure 6.9 CHP systems produce thermal energy and electricity concurrently from the same energy input, and can therefore achieve higher system efficiencies than separate heat and power systems.



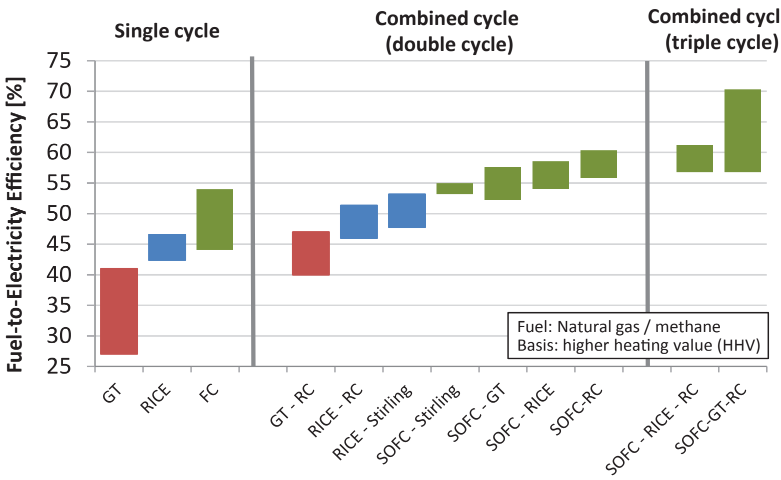
more commonly between 0.5 and 1, depending on the technology utilized.[41] If highly efficient CHP systems with a power-to-heat ratio of 1.5 were deployed, energy savings of up to 144 TBtu could be realized in the manufacturing sector, with economy-wide energy savings of 1,310 TBtu, as shown in Table 6.7.

Table 6.7 Technical Potential and Energy and Cost Savings for High Power-to-Heat CHP Operation

	Energy benefits for high power-to-heat CHP operation		
	Manufacturing sector	Commercial/ institutional sector	**Total**
Incremental capacity potential (GW)*	4.7	45.1	**52.9**
Incremental annual primary energy savings (TBtu)**	144	1,160	**1,310**
User incremental energy cost savings ($ Millions)	$1,316	$8,660	**$9,976**

* Incremental CHP capacity based on a power-to-heat ratio of 1.5.
** Incremental primary energy savings based on a 33% average grid efficiency.

Figure 6.10 Theoretical Efficiencies (electric generation only) for Various CHP Configurations, Ranging from Single-Cycle Systems to Double- and Triple-Cycle Systems that Make Use of Multiple Generation Technologies. Efficiencies of up to 70% are theoretically possible.[42]



Key: **GT** = gas turbine; **RICE** = reciprocating internal combustion engine; **FC** = fuel cell (molten carbonate or solid oxide); **SOFC** = solid oxide fuel cell; **RC** = Rankine cycle; **Stirling** = Stirling cycle.

Based on thermodynamic analysis of several generation equipment configurations, electrical efficiencies up to 70% are theoretically possible with reconfigurations of existing generating technologies, as shown in Figure 6.10. The amount of thermal energy available for use will vary based on the electrical efficiency and technologies employed.

R&D opportunities and research targets for the development of ultra-high efficiency CHP generation technologies are shown in Table 6.8 for consideration by decision makers.

Waste Heat Recovery Systems

Industrial process heating, which consumes more than 7,000 TBtu of energy annually,[43] is used for fundamental materials transformations including heating, drying, curing, and phase change. Process heating systems are associated with significant thermal losses; nearly 36% of the total energy input to process heating is lost as waste heat.[44] The largest sources of waste heat for most industries are exhaust gases from burners, heat treating furnaces, dryers, and other equipment. Waste heat can also be released to liquids such as cooling water, heated wash water, boiler and blow-down water. Solid waste heat sources include hot products that are discharged after processing or after reactions are complete, hot by-products from processes or combustion of solid materials,

Table 6.8 Strategic R&D Opportunities and Performance Targets for Consideration by Decision Makers

Near-term areas (< five years)		Long-term areas (> five years)	
R&D opportunity	Goals	R&D opportunity	Goals
CHP packaging for single buildings/facilities: Packaged systems to avoid need for custom equipment design and onsite engineering expertise	■ Target equipment size range 1–5 MW ■ Capital cost less than $1,500/kW ■ Levelized cost of electricity less than $0.10/kWh	**High power-to-heat ratio CHP:** Systems with efficient onsite electricity generation for facilities dominated by electrical loads	■ Target equipment size range 1–10 MW ■ 65% electric generation efficiency, with high (>75%) overall CHP efficiency ■ Power-to-heat ratio up to P/H = 1.5
Grid integration: Technical solutions to enable grid interconnection, demand response and ancillary services	Facility needs met while safely and seamlessly providing grid support	**Waste heat recovery and waste heat to power:** Technologies for improved thermal recovery in CHP	Improved reliability, availability, maintainability, and durability for low-temperature recovery
Microgrid with CHP: Small-scale autonomous energy grids with CHP generation, and possible facilitation of intermittent renewable sources, storage, energy efficiency measures, etc.	Improved synchronization, controls, and cybersecurity	**Smart CHP:** Full integration of onsite generation and CHP into a smart grid	Specific technical goals in development
District energy with CHP: Systems to enable use of rejected heat from CHP facilities to provide steam, hot, and chilled water to network buildings	Reduced system capital and installation costs		

and hot equipment surfaces. The quality of these heat sources varies. Industrial waste heat generally occurs in four forms:

- Sensible heat of solids, liquids, and gases
- Latent heat contained in water vapor or other type of vapors and gases
- Radiation and convection from hot surfaces
- Direct contact conduction (in a few instances)

While every effort should be made to reduce waste heat losses (for example, by integrating advanced insulation techniques and selective heating technologies into process heating equipment, as discussed in *Process Heating Systems*—see Section 6.2.1), some heat losses are unavoidable. The recovery and reduction of waste heat generated in manufacturing systems offers an opportunity to reduce manufacturing energy use and associated emissions. Waste heat can be recycled either by redirecting the waste stream for use in other thermal processes (e.g., flue gases from a furnace could be used to pre-heat a lower-temperature drying oven) or by converting the waste heat to electricity in a process called waste heat-to-power (WHP). In some cases, the technologies needed to economically recover waste heat from hot gases, liquids, or solids are already available. However, industrial facilities often do not implement these technologies, based in part on technology issues (e.g., fouling, corrosion, and high maintenance requirements). According to U.S. Energy Information Administration (EIA) *Manufacturing Energy Consumption Survey* data, approximately 6% of U.S. manufacturing facilities were using some type of waste heat recovery as of 2010.[45]

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 over acceptable life. For low-temperature waste heat streams (i.e., less than 400°F), low heat transfer rates and large recovery equipment footprints are major barriers. For high-temperature waste heat streams (i.e., above 1200° F), materials are needed that can withstand high-temperature gases that may be contaminated with particulate matter or corrosive chemicals.[46] To address these challenges requires RDD&D in the following:

- Anti-fouling technologies that can remove contaminants from waste heat streams or mitigate build-up of debris on heat exchanger surfaces, promoting long-term operation of heat recovery equipment and avoiding service interruptions for cleaning
- Advanced materials that can withstand high-temperature waste heat sources
- Compact, low-cost heat exchangers to reduce the size or footprint of heat recovery equipment
- Secondary heat recovery technologies to supplement and enhance the performance of primary waste heat recovery equipment
- Heat recovery chillers that capture waste heat from chilled water systems
- Integrated heat recovery technologies that combine heating elements with heat recovery equipment, eliminating the need for hot-air piping and external heat recovery equipment
- Innovative condensing heat exchangers for gases containing high moisture levels and particulates, such as the waste streams discharged from paper and food production equipment
- Liquid-to-liquid heat exchangers for heat recovery from wastewater that contains contaminants
- Solid-state (e.g., thermoelectric) generators for electricity production from otherwise unusable waste heat streams (see *Direct Thermal Energy Conversion Materials, Devices, and Systems* in Section 6.4.2)
- Industrial heat pumps, including chemical heat pumps (e.g., adsorption/desorption and chemical looping reactions)

6.3.2 Harnessing Data for Energy Impacts

Data and automation can accelerate processing, increase real-time feedback, and optimize energy use at every manufacturing systems level. Advances made in production/facility systems can optimize manufacturing systems utilization and enable increased industrial energy systems integration, driving improvements through supply chains and narrowing the gap between current energy use and practical minimum energy requirements across industries.

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Advanced sensors, controls, platforms and modeling for manufacturing (ASCPMM) represents an emerging opportunity for the U.S. manufacturing sector. ASCPMM technologies include infrastructure, software and networked solutions for sensing, instrumentation, control, modeling, and platforms for manufacturing applications. These technologies interact in a machine-to-plant-to-enterprise-to-supply-chain ecosystem of real-time data and models networked for enterprise and ecosystem optimization. When aligned with business models and communication networks, the use of ASCPMM technologies can improve manufacturing efficiency through the real-time management of energy, productivity and costs at the level of the machine, factory and enterprise, including improved integration with the electric grid. Data, information technology, and advanced models make it possible to dynamically and proactively manage power together with other integrated aspects such as machine configurations to manage production volume and energy, minimize defects, and avoid abnormal situations that result in energy losses. In addition, data and advanced control systems make it possible to manage to tighter power quality constraints while also managing variations expected with two-way power flows and a wider range and diversity of power sources.

The White House Advanced Manufacturing Partnership (AMP) 2.0 Steering Committee provided a few examples of ASCPMM energy and cost impacts in their recent *Accelerating U.S. Advanced Manufacturing* (2014) report:[47]

- With advanced sensing and model-based optimization techniques, an aerospace metal parts manufacturer expects to save on the order of $3 million per year on furnace operations alone in a plant that includes both continuous and discrete processes.
- A chemicals company projects 10%–20% energy savings for a hydrogen production plant with improved sensors and modeling, translating to a reduced natural gas cost of $7.5 million per year.
- A three-mill cement grinding plant reduced specific energy consumption by as much as 5% with a customized model-predictive control approach.
- A robotic assembly plant for a large original equipment manufacturer anticipates reducing energy consumption by 10%–30% using optimization tools for robot motion planning.

Key technical needs to fully realize the energy benefits of ASCPMM include the following:

- Open standards and interoperability for manufacturing devices and systems
- Real-time measurement of machine energy consumption and waste streams
- Integration of manufacturing facilities with the electric grid to allow dynamic energy optimization and guide choices of fuel/power use and generation and purchase decisions
- Low-power, resilient wireless sensors and sensor networks for pervasive sensing
- Platform infrastructures for orchestration of data across heterogeneous and human systems while addressing issues of privacy and cybersecurity
- Theory and algorithms for model-based control of manufacturing processes
- Cybersecurity and privacy protection for sensitive data and systems

Industrial Demand-Side Management

Managing the energy requirements (demand) of industrial facilities can be accomplished through energy-use reductions, as well as via temporal shifts in energy use. While end-use efficiency technologies can reduce average energy consumption, utility demand-side management (DSM) programs seek to change consumers' energy use patterns.[51] Industrial customer electricity bills are typically composed of time-of-use based electricity rates and demand charges, which incentivize load reductions during the utility system peak and the industrial facility peak. Industrial customers can further reduce electricity costs through interruptible and curtailable electricity rates, in exchange for allowing the utility to reduce a portion of the facility load when needed. Economically, this approach benefits both the grid and rate payers by enabling efficient dispatch of electric generators and by avoiding the building of costly excess capacity to meet peak demands. Industrial customers constitute the largest demand-side contribution to peak load reduction potential with an estimated 47% of the total across all retail programs,[52] as well as additional peak load reduction potential through wholesale programs in regions with organized wholesale electricity markets.

Typically, DSM programs have focused on large commercial and institutional customers that have noncritical loads or can compensate for power variations with backup power generation. Many manufacturing facilities already participate in manual DSM programs (e.g., peak shaving programs), but their peak-shaving

Applications of Advanced Sensors, Controls, Platforms and Modeling for Strategic Energy Management

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

The data-driven approach enabled by ASCPMM technologies is being facilitated by manufacturing facilities adopting a systematic approach to energy management that helps to institutionalize the important role played by ASCPMM technologies to improve energy performance and optimize operations. While manufacturers have traditionally viewed energy as a fixed monthly expense, a systematic approach to managing energy that continuously monitors energy performance is proving to yield sustained energy savings and reduced operational costs.[48] This strategic, data-driven approach to facility energy management reveals the need for improved data collection methods such as submetering of significant energy uses. Submetered manufacturing processes can provide real-time, equipment-specific energy consumption data and automated process alerts. In addition, equipment submetering also helps to identify equipment that is nearing failure, proactively reducing equipment downtime through preventive maintenance and extending the service life of facility equipment.

One example of a DOE program that emphasizes a systematic approach to energy management in U.S. manufacturing facilities is the U.S. DOE Superior Energy Performance® (SEP™) Program. Launched in 2014, SEP is an industrial energy management certification program that is accelerating the realization of ASCPMM benefits by emphasizing the value of improved data measurement and operational control for enhanced energy performance. SEP utilizes the ISO 50001 energy management standard as its foundation, augmented with quantitative energy performance improvement targets and requirements for third-party measurement and verification of energy savings. The SEP program requires that manufacturers meter, monitor, and record energy consumption data at their SEP-certified facilities.[49] As a result, SEP-certified facilities are installing energy management metering systems to measure, manage, and optimize energy performance as a key performance variable. Such metering and monitoring equipment demonstrates that energy efficiency activities yield a positive return on investment, helping to accelerate the adoption of cost-effective, energy-efficient technologies in manufacturing facilities.[50]

contribution is often limited to less-critical and/or time-flexible process loads such as HVAC. HVAC electricity usage constitutes just 8% of total manufacturing sector electricity consumption—relatively low compared to process electricity uses such as pumps, compressed air, and materials processing equipment.[53] However, there are a number of examples where manufacturing facilities have implemented DSM for more critical process loads, for instance electrolysis loads found in aluminum production.[54] The state of Texas has a long history of industrial customer participation in DSM programs, which transitioned to the wholesale market with the formation of the Electric Reliability Council of Texas (ERCOT). Most of the load resource capacity in ERCOT comes from large industrial electro-chemical process loads. The ten largest resources account for more than one GW in load reduction capacity.[55] In 2012, electric utility providers reported peak demand savings of 5.7 GW from industrial customer participation in demand response programs—an increase of 19% since 2010, when peak demand savings were reported as 4.8 GW.[56]

The U.S. industrial base is large, and facilities are typically managed by staff comfortable with sophisticated processes and controls; as a result, the technical potential for industrial participation in flexible load programs is significant.[57] Industrial loads depend on a wide range of variables including end-uses and equipment, industry sub-sector, facility type, facility capacity size, age, and product specialization; as a result, technical potential and cost evaluations are often specific to individual facilities. This heterogeneity creates significant challenges for utilities and policy makers seeking to develop programs that provide attractive value incentives to industrial ratepayers.[58]

Historically, DSM has focused on reducing utility peak loads; however, there is also a growing interest in a wider range of grid ancillary and flexible load services that shape loads to balance renewable generation, provide demand-side capacity reserves, and enhance frequency control for electricity quality to ensure a stable and reliable grid. These services are collectively termed "grid integration."[59] Efforts are currently underway to understand how the electric grid might operate in the future, especially if the generation capacity were significantly altered to accommodate larger contributions from naturally variable renewables such as wind and solar energy,[60] significant penetration of electric vehicles,[61] greater distributed generation capacity,[62] and flexible load services to reduce electricity costs and enhance grid reliability.[63] ASCPMM technologies[64] combined with a Smart Grid[65] offer new opportunities for the next generation of manufacturing to integrate and optimize their power flows.[66] These opportunities will require substantially different optimization protocols to manage and proactively shape peak loads, dynamically manage two-way power flows, and dynamically manage, control, and adjust to load and frequency variations as a result of a more diverse portfolio of source services. Data, predictive models, control, and enterprise optimization are crucial.

However, attracting large-scale manufacturing sector participation in these programs will require key technology developments and a demonstration of value:

- **Demand-response-ready equipment:** Manufacturing equipment that is compatible with demand response without compromising production quality
- **Compatible energy management systems:** Energy management systems with submetering to provide actionable information for manufacturing facility managers
- **Protocols for demand response:** Automated demand response (AutoDR) standards for communications between the electric grid and manufacturing facility processes
- **Value proposition:** Economically attractive demand response (DR) rate tariffs that provide incentives for load flexibility over a wide range of time periods (i.e., sub-second to days)

Because the value proposition for industrial customers is not yet well understood, the cost-effective potential for participation in flexible load programs is also poorly understood. Some efforts have been introduced to evaluate industrial load flexibility,[67] but many facility managers lack the detailed data of their own energy flows required to have confidence in demand management decisions and long-term capital investments. These information gaps can be addressed through improved industrial facility auditing and evaluation methods and tools, and ubiquitous ASCPMM technologies to measure and control energy flows. Successful technology options could result in a tighter link between the electric grid and industry, wherein industry increasingly integrates electricity generation and electric grid ancillary services into their operations. This approach can lead to a more integrated approach to energy production and manufacturing, with highly optimized coordination of industrial production, clean power generation, and energy management.

6.4 Beyond the Plant Boundaries: Technology Opportunities for Supply Chain Systems and Manufactured Goods

Manufactured products reach all end-use sectors, and as a result it is important to consider the energy impacts of manufactured goods in a life cycle accounting of overall energy and emissions effects. Lightweight materials such as aluminum, magnesium, advanced high strength steel, and composites are currently enabling reductions in the weight of light-duty vehicles, providing use phase energy savings—and additional materials and manufacturing technology advances could extend the applicability and benefits of these materials.[68] In some cases, next-generation technologies may have an outsized effect on energy consumption in the manufacturing sector, delaying or reducing the energy savings in the overall life cycle of the product. For example, carbon fiber composites are being introduced for vehicle lightweighting, despite the fact that carbon fibers now require significantly more energy to manufacture than a performance-equivalent quantity of steel. The application of carbon fiber technology for lightweighting vehicles can provide fuel economy energy benefits during the vehicle use phase that exceed the additional energy it takes to manufacture the material;[69] although fleet-wide energy benefits are not realized immediately. Similarly, the production of solid state lighting products (i.e., light-emitting diode [LED] lamps) is more energy intensive than the production of traditional incandescent light bulbs. However, LED lamps have a significantly longer lifespan and use less energy than incandescent bulbs, leading to lower life-cycle energy consumption.[70]

Manufacturing technology opportunities that could provide significant energy impacts in other sectors include the next generation of energy-efficient products and materials, such as wide bandgap power electronics, lightweight structural materials, and advanced materials for harsh service conditions. Additionally, technologies that minimize material intensity or increase material flexibility could provide benefits throughout the supply chain. Smart manufacturing technologies support interoperable data communications across the supply chains, providing benefits to the entire value chain. The energy, environmental, and national security impacts associated with the extraction, refinement, transportation, and processing of materials used in manufactured goods could be improved in many ways:

- Reducing the amount of bulk material needed to form a product
- Developing alternative materials that can be used in place of critical materials or other high-cost, high-energy commodities
- Increasing recycling and re-use of materials from end-of-life products
- Modifying manufacturing processes to enable the use of cleaner, more reliable, or more plentiful fuels or feedstocks

Table 6.9 lists significant recent federal investments in manufacturing technology areas with strong potential for life-cycle impacts. While life-cycle assessment is an important screening tool, it is not a comprehensive impact analysis methodology; a complete analysis must incorporate all environmental, societal, and economic burdens of a technology to avoid unwanted burden shifting.[71]

6.4.1 Manufacturing to Reduce Material Criticality

Manufacturing approaches to increase material flexibility, increase recycling, and minimize reliance on critical and costly materials can narrow the gap between current energy use and practical minimum energy requirements, will decouple manufacturing from the practical limitations of current processes, and will provide for life-cycle benefits.

Table 6.9 Examples of Manufacturing Technologies with Strong Potential for Life-Cycle Impacts

Impact modality	Key topics	Major federal investments
Sustainable materials flows through the life cycle	■ Critical materials and critical material alternatives ■ Recycling and re-use	■ Critical Materials Institute (CMI), an energy innovation hub ■ Rare Earth Alternatives in Critical Technologies for Energy (REACT) program
Lightweight materials for use phase energy impacts	■ Lightweight metals ■ Low energy/low cost carbon fiber ■ Thermosetting and thermoplastic polymer resins ■ Joining and fabrication ■ Recycling of lightweight structural materials	■ Institute for Advanced Composites Manufacturing Innovation (IACMI) ■ Carbon Fiber Technology Facility (CFTF) ■ Lightweight Innovations for Tomorrow (LIFT) consortium
Advanced materials manufacturing for clean energy products	■ Roll-to-roll processing ■ Additive manufacturing ■ Wide bandgap semiconductors ■ Direct energy conversion devices ■ Computational manufacturing	■ Manufacturing Demonstration Facility (MDF) ■ Materials Genome Initiative (MGI) for Global Competitiveness ■ National Additive Manufacturing Innovation Institute ("America Makes") ■ Next Generation Power Electronics National Manufacturing Innovation Institute ("PowerAmerica") ■ Digital Manufacturing and Design Innovation Institute (DMDII) ■ Integrated Photonics Institute for Manufacturing Innovation (IP-IMI)

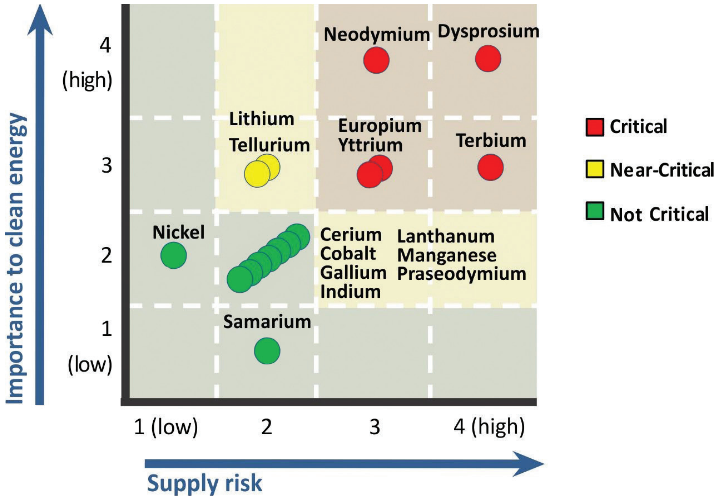
Critical Materials and Critical Material Alternatives

Specific materials enable clean energy technologies by virtue of their unique chemical and physical properties. As part of efforts to advance a clean energy economy, in 2010 and 2011 DOE authored a *Critical Materials Strategy* that examined the role of key materials in four specific clean energy technologies: photovoltaics, wind turbines, electric vehicles, and energy-efficient lighting.[72] The results of the DOE assessment are shown in Figure 6.11. Each material's criticality was assessed by considering its importance to those clean energy applications, as well as supply challenges such as a small global market, lack of supply diversity, market complexities caused by co-production, and geopolitical risks. As an example, aggressive deployment goals for clean energy technologies contribute to the rising demand for rare earth permanent magnets using neodymium and dysprosium:

- An electric drive vehicle may use up to a kilogram of neodymium, and a wind turbine can contain several hundred kilograms of neodymium.[73]
- Industry trends drive materials criticality. For example, as the wind industry transitions toward turbines that are larger and more powerful,[74] the use of rare earth permanent magnets has increased to reduce the size and weight of the generators. Additionally, demand has increased for wind turbines that can operate at slower speeds, which can be achieved through a direct-drive arrangement that requires as much as several hundred kilograms of rare earth content per megawatt of power rating.[75]

- One study estimated that the demand for dysprosium and neodymium could increase by 700% and 2600%, respectively, over the next twenty-five years in a business-as-usual scenario.[76]

Figure 6.11 Medium-Term (from 2015 to 2025) Criticality Matrix for Elements Important to Wind Turbines, Electric Vehicles, Photovoltaic Cells, and Fluorescent Lighting[66]



A secure, sustainable supply chain for these materials is needed to help enable invention, manufacturing and deployment of clean energy technologies in the United States. DOE's strategy for addressing this challenge has focused on three pillars. First, diversified global supply chains diffuse supply risk, and the United States could simultaneously facilitate domestic extraction, processing and manufacturing while encouraging other nations to expedite alternative supplies. Second, the development of material and technology substitutes will serve to improve supply chain flexibility. Finally, recycling, re-use, and more efficient use will reduce the demand for newly extracted materials.[77]

It is important to note that the criticality of a material is dynamic and depends on how "criticality" is defined, as evidenced by comparing the DOE *Critical Materials Strategy* with similar analyses.[78] Current efforts on critical materials at DOE are focused on rare earth elements, given their importance to wind energy, electric vehicles and energy-efficient lighting. Expanding the focus beyond these specific clean energy applications, materials such as tungsten, bismuth, and helium also require attention as they are essential to the manufacture of clean energy technologies, though not always physically present in the final products.[79] Additionally, materials such as rhenium and hafnium are essential to the superalloys used in high-temperature applications, such as natural gas turbine blades and components. Without such superalloys, the turbines operate at lower temperatures with lower efficiency.[80] When considering this wider array of technologies, numerous key elements provide unique properties for energy applications and face potential supply chain challenges, as shown in Table 6.10. Additional details and examples may be found in the *Critical Materials* Technology Assessment.

Sustainable Manufacturing – Flow of Materials through Industry

Sustainable manufacturing[81] encompasses a wide range of systems issues, including energy intensity, carbon intensity, and use intensity. Energy considerations alone are insufficient to capture the full range of impacts. A more complete understanding can be gained by tracking how materials flow through manufacturing supply chains and where resources such as materials, water, and energy are used throughout product life cycles. Pursuing strategies to increase material efficiency will reduce the material use intensity of supply chains, and in turn provide additional opportunities for energy efficiency.

U.S. per capita materials consumption is estimated to have grown by 23%, and total material consumption by 57%, between 1975 and 2000.[82] Gutowski *et al.*[83] estimated that a 75% reduction in average energy intensity of material production is needed to meet the Intergovernmental Panel on Climate Change (IPCC) climate goals to reduce global energy use by half from 2000 to 2050. In 2005, the United States used nearly 20% of the

Table 6.10 Key Elements for Energy-Related Technologies

Technology	Key elements
Permanent magnets (for wind turbines and electric vehicles)	Dysprosium, neodymium, praseodymium
Fluorescent lighting	Cerium, europium, lanthanum, manganese, terbium, yttrium
Light-emitting diodes (LEDs)	Cerium, europium, gallium, germanium, indium, lanthanum, nickel, silver, terbium, tin, yttrium
Photovoltaics	Gallium, indium, nickel, silver, tellurium, tin
Batteries (for electric vehicles and storage)	Cerium, cobalt, graphite, lanthanum, manganese, lithium, nickel, terbium, vanadium
Catalytic converters	Cerium, lanthanum, palladium, platinum, rhodium
Fuel cells	Cerium, cobalt, gadolinium, lanthanum, palladium, platinum, rhodium, yttrium
Gas turbines	Hafnium, rhenium, yttrium
Hydrogen electrolysis	Palladium, platinum, rhodium
Nuclear power	Cobalt, indium, gadolinium
Thermoelectrics	Antimony, bismuth, cerium, cobalt, lanthanum, lead, tellurium, ytterbium
Vehicle lightweighting	Gadolinium, magnesium, titanium

global primary energy supply and 15% of globally extracted materials, equivalent to 8.1 billion metric tons. At roughly 27 metric tons per person, U.S. per capita material use is higher than most high-income countries and is approximately double that of Japan and the United Kingdom.[84]

Material consumption reflects the input side of the equation. On the output side, the United States generated close to 2.7 billion metric tons of waste in 2000. This waste generation has increased 26% since 1975, with a 24% increase in harmful waste products (e.g., radioactive compounds, heavy metals, and persistent organic chemicals). It is estimated that 75% of carbon emissions are from scope 3 sources (i.e., indirect emissions from the extraction and production of materials, waste disposal, etc.),[85] indicating that the supply chain is a prime opportunity space for emissions reductions.

A fundamental problem with the way that products are designed and built today is that design for re-use is not typically a consideration. Consumer awareness of recycling and sustainability has helped to reduce demand for primary materials, but far more could be done if materials and products were designed with recycling and re-use in mind. Secondary (recycled) metals often require a fraction of the energy to process into usable materials than primary metals do. A comparison of energy demands for primary and secondary aluminum ingot production is shown in Table 6.11. Increased recycling of aluminum could provide savings of up to 52.4 MMBtu for every metric ton of primary aluminum replaced by secondary aluminum, although this strategy is currently limited due to the mixture of alloys in secondary aluminum.[86] Strategies for lightweighting, reduced yield loss, component re-use, extended product life, and more intense use also can result in decreased total demand.

Substantial energy and cost benefits can also be realized from technologies that allow goods to be produced using smaller quantities of raw materials than traditional manufacturing technologies. Additive manufacturing (3D printing), discussed in more detail in Section 6.2.2, is an important example. Since materials are deposited layer-by-layer and only where needed, additive manufacturing processes create very little waste compared to machining and other fabrication processes. Additive manufacturing also offers the ability to use recycled materials in certain applications.[87] Product and product packaging design can also be optimized to reduce materials use and minimize waste.

Table 6.11 Current Energy Demands for Primary and Secondary Aluminum Ingot

	Primary aluminum (MMBtu/MT)	Secondary aluminum (MMBtu/MT)
Manufacturing facility energy demand (production only)	57.2	4.8
Supply chain energy demand (extraction through production)	117	22.7

In the areas of both critical materials management, as well as in this broader topic of sustainable manufacturing, complementary social science research can identify strategies to increase rates of material recovery so as to reduce virgin material requirements, costs, and energy consumption. Even modest increases in recovery rates could help stabilize prices of critical materials and mitigate environmental impacts of energy-intensive materials.

6.4.2 Advanced Materials Manufacturing for Clean Energy Products

Advanced materials manufacturing encompasses innovative materials and processes—plus the devices and systems that incorporate them—that can lead to step-change improvements in energy, emissions, and functionality compared to the historical development trajectories of conventional materials. Transformational next-generation materials and products could narrow the gap between current energy use and practical minimum energy requirements in the manufacturing sector, and could enable life-cycle benefits in the other energy consuming and energy generation sectors.

Direct Thermal Energy Conversion Materials, Devices and Systems

Direct energy conversion (DEC) is a broad category of materials, devices, and systems that convert energy from one form to another without intermediate steps (such as a working fluid). Many clean energy technologies are based on direct energy conversion. For example, LEDs directly convert electricity to light, taking advantage of unique photonic properties of specific materials (e.g., gallium nitride for white LEDs). Solar photovoltaics, which convert solar energy directly to electricity, are another example of direct energy conversion devices. Solar photovoltaic efficiencies have improved dramatically since the discovery of the solar cell, with many cells doubling, tripling or quadrupling in efficiency over the past forty years.[88]

With process heating waste heat losses in the United States exceeding 2,500 TBtu annually[89] (see *Waste Heat Recovery Systems* in Section 6.3.1), the manufacturing sector could derive benefits from a class of DEC technologies that convert thermal energy to electricity. Technologies for direct thermal energy conversion are in various stages of maturity, and include phase-change-material engine, magnetocaloric, thermo-acoustic-piezoelectric, thermionic, thermophotovoltaic, and thermoelectric generators.

Thermoelectric systems, in particular, are among the most promising heat-to-electricity energy conversion technologies. Thermoelectric systems convert heat energy to electricity and vice versa, and can be used in applications ranging from waste heat recovery to refrigeration. While thermoelectric heat pumps for heating and cooling applications are used in commercial applications such as optical equipment and automotive seat heaters, thermoelectric generators (TEGs) have shown limited commercial market penetration in waste heat-to-power conversion due to high system costs compared to conventional power generation technologies. At present, the thermoelectric market for energy harvesting has been limited primarily to military and aerospace markets where reliability, quiet operation, and remote operability are critical.[90] If the installed system cost of thermoelectric generation were reduced to about $1 per watt,[91] thermoelectric generation could be competitive with the current average U.S. industrial electricity price of $0.0682 per kilowatt hour (kWh).[92] Pathways to achieving this $1 per watt target include the development/identification of lower-cost materials and more favorable manufacturing techniques enabling higher production volumes. Material cost is significantly high in TEGs, typically accounting for 50%-80% to the overall thermoelectric system generation cost.[93] Furthermore, TEG manufacturing techniques still consist of manual "pick-and-place" (hand loading) operations, contributing to high production costs.

Research and development focused on driving improvements in the capabilities and costs of thermoelectric materials could greatly benefit TEG performance. The most common thermoelectric materials today are alloys of chalcogenides with a dimensionless figure of merit value (ZT) of around 1[94] and an average overall efficiency of 5% for a temperature difference of 200°C–250°C.[95] High-ZT materials developed in recent years include skutterudites, calthrates, Half-Heuslers, and oxides such as cobaltites and perovskites; these systems have shown efficiencies as high as 16%.[96] Further, the use of three-stage cascade-type thermoelectric modules could yield an overall thermoelectric efficiency of 20% for a heat transfer rate of 400 kW/m^2.[97] Introduction of automation into product assembly will improve the reliability of the TEGs and ultimately drive down the costs for producing these devices. Promising fabrication techniques include additive manufacturing and wafer processing (similar to that used in integrated circuit manufacturing). Challenges associated with these techniques include kerf (wafer cutting) losses and scalability to production volumes.

Additional research is also needed to improve heat transfer capabilities in thermoelectric generators. This includes cost optimization of heat exchangers that collect and transfer heat to cooling water, but it also applies to heat transfer within the module. Studies to co-optimize the thermal and electrical properties of the whole TEG system while maintaining its mechanical integrity are also important.[98] Materials testing standards and device testing procedures are also critical to the commercialization of thermoelectrics as power generation devices. System-level TEG demonstrations in near-term potential applications—similar to those demonstrated in Japanese steel plants[99]—would help to establish the efficacy of TEG waste heat recovery for industrial processes. Table 6.12 estimates the quantities of waste heat generated by several energy-intensive manufacturing industries on a yearly basis and the amount of energy that could be recovered with TEG technology based on an assumed efficiency of 2.5%. The energy savings opportunity could be considerably enhanced with advanced materials, better coupling through improved heat exchangers, and other technology improvements.

Materials for Harsh Service Conditions

The physical limitations of materials in demanding environments have long constrained engineers in the design of innovative new products and technologies. Aggressive service environments can involve high temperatures or thermal cycling, high pressures, corrosive chemicals, dust and particulates, mechanical wear, neutron irradiation, and hydrogen attack. These aggressive environments—and the associated materials durability challenges—are common across multiple applications and sectors. To meet stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits requires new materials and new materials processing solutions. Examples include the following:

- **Ultra-supercritical steam turbines:** Gas and steam turbine power plants could achieve higher efficiencies if they operated at higher inlet temperatures, but operating temperatures are constrained by the thermal stability of existing turbine and boiler-tube alloys at high temperatures and pressures.
- **Waste heat recovery in harsh environments:** There are significant opportunities to recover waste heat from industrial process heating operations (see *Waste Heat Recovery Systems* in Section 6.3.1).

Table 6.12 Estimate of Waste Heat that Could be Recovered with Thermoelectric Technology for Various Process Industries

Manufacturing process industry	Process heating energy use (TBtu/yr)[100]	Process heating energy losses (TBtu/yr)[101]	Estimated recoverable heat range (TBtu/yr)[102]	Estimated thermoelectric potential (TBtu/yr)[103]	Estimated thermoelectric potential (GWh/yr)[104]
Petroleum refining	2,250	397	40–99	1–2	291–727
Chemicals	1,460	328	33–82	1–2	240–601
Forest products	980	701	70–175	2–4	513–1,280
Iron and steel	729	334	33–84	1–2	245–612
Food and beverage	518	293	29–73	1–2	215–537
Glass	161	88	9–22	0–1	64–161
Other manufacturing	1,110	426	43–107	1–3	312–780
All manufacturing	**7,200**	**2,570**	**257–642**	**6–16**	**1,880–4,700**

However, many sources of industrial waste heat are unrecoverable because existing heat exchanger alloys and power conversion materials are incompatible with corrosive, high-flow-rate, and/or high-temperature flue gases. Improved heat transfer equipment and hot gas cleanup operations would benefit from materials development.

- **Corrosion-resistant pipelines:** Corrosion of iron and steel pipelines can cause leaking of natural gas into the environment, leading to wasted energy, explosion hazards, and methane emissions. Pipeline corrosion has accounted for more than 1,000 significant pipeline incidents over the past twenty years, directly resulting in twenty-three fatalities and more than $822 million in property damage.[105]
- **Irradiation-resistant nuclear fuel cladding:** Conventional nuclear fuel cladding materials have very good performance at design conditions but leave room for improvement at the very high temperature steam environments possible in beyond-design-basis accidents.[106] Irradiation-resistant, phase-stable nuclear fuel cladding materials with improved performance at beyond-design-basis accident conditions could mitigate accidents at nuclear facilities.

Energy and emissions savings opportunities for these selected application areas are estimated in Table 6.13. Broadly, research needs can be roughly divided into three crosscutting materials challenges. Applications requiring material stability in extreme environments, such as ultra-high pressure or ultra-high temperature, require phase-stable materials. Research in functional surfaces is needed to develop advanced coatings and surface treatments that provide outstanding material properties, such as corrosion and wear resistance. Embrittlement-resistant materials are needed to resist material aging effects in certain extreme environments, including exposure to hydrogen (which can cause hydrogen embrittlement) and radiation (which can cause neutron embrittlement and radiation-induced swelling).

Wide Bandgap Semiconductors for Power Electronics

Promising WBG semiconductor materials for power electronics applications include silicon carbide (SiC) and gallium nitride (GaN). Of these two materials, SiC is relatively more mature for power electronics applications. Both materials offer the benefits of higher temperature, frequency and voltage operation compared to conventional silicon (Si) devices, enabling smaller, lighter, and higher efficiency power electronics. GaN

Table 6.13 Materials Challenges and Energy Savings Opportunities for Selected Harsh Service Conditions Application Areas

	Materials challenges							
Application area	High pressure stability	High temperature or thermal cycling stability	Corrosion or fouling resistance	Wear or erosion resistance	Resistant to neutron embrittlement	Resistant to hydrogen embrittlement	**Estimated annual energy savings opportunity (TBtu)**	**Estimated annual GHG emissions savings opportunity (million tons CO_2-eq.)**
Advanced ultra-supercritical steam turbines[107]	X	X	X	X			859	88.2
Waste heat recovery equipment for harsh environments[108]		X	X	X			247	14.5
Corrosion-resistant gas pipelines[109]	X		X			X	67	28.6
Irradiation-resistant nuclear fuel cladding[110]	X	X			X		n/a[111]	34.7
Total energy and emissions savings opportunities							**1,170**	**166**

transistors are likely to dominate in 200V–900V applications with power levels up to 10kW. These include power supplies for data farms, laptops, TVs, and solar micro and string converters. SiC switches and diodes are expected to be a better fit for higher power use in 900V–15,000V applications, including central solar, automotive, and fuel cell inverters, quick chargers, medium-voltage motor drives, and distribution grid-based power flow controllers.

If high adoption of these technologies is realized in just the limited set of applications shown in table 6.14, about 40,000 GWh (137 TBtu) of electrical power savings in the United States could be achieved annually. If WBG semiconductors could capture the estimated 10% worldwide variable frequency drive market, global energy savings of 117,000 GWh/year (400 TBtu/year) could be achieved. See the *Wide Bandgap Semiconductors for Power Electronics* Technology Assessment for further details.

The current low adoption rate of WBG semiconductors for power electronics applications can be primarily attributed to the high costs of substrate and epitaxial materials compared to conventional Si devices. These high costs are tied to small production volumes and high manufacturing costs. With higher volume production, it is anticipated that WBG substrate and epitaxial deposition costs can be reduced to $800 per six-inch wafer. Using the open commercial foundry model, analysis shows that a 1200V/20A SiC metal-oxide-semiconductor field-effect transistor (MOSFET) die with an on-state resistance of $5\text{m}\Omega/\text{cm}^2$ can be fabricated in a high-volume six-inch foundry for $0.037/amp. As the market increases and the inevitable move is made to eight-inch substrates, it is anticipated that the price can reach $0.01/amp[116]—less than the current cost of Si devices ($0.10/amp). 10kV–15kV WBG devices will enable more-efficient industrial motor drives and power controllers for grid modernization.

Computational Manufacturing and the Materials Genome Initiative

At present, the time frame for incorporating new classes of materials into applications is remarkably long—typically about ten to twenty years from initial research to first use.[112] The prolonged time frame for materials to transition from discovery to market is due in part to traditional materials research and development methods, which rely largely on scientific intuition and trial-and-error experimentation. Design and testing of materials is typically performed through time-consuming and repetitive experiment and characterization loops. Some experiments could potentially be performed virtually using powerful and accurate computational tools, but physics-based models with the required accuracy are not available off-the-shelf for most applications. Custom models require significant investment in specialized software and dedicated engineering talent.

The application of computational manufacturing techniques in material and process design has the potential to greatly reduce the development time of advanced materials. "Predictive theory and modeling of materials" employs a combination of physical theory, advanced computer models, and vast materials properties databases to accelerate the design of a new material with application-specific properties by optimizing composition and processing to develop the desired structure and properties. Applications could include the synthesis and development of an extremely tough, lightweight composite for a wind turbine blade or a high-surface-area catalyst for a proton exchange membrane fuel cell. Computational modeling and simulation holds great promise for accelerating scale-up and minimizing the "trial and error" approach of traditional manufacturing, which can lock in inefficient or suboptimal systems for decades. A challenge for computational modeling of materials is the lack of reliable simulation models to predict the impact of a manufacturing process on the material's mechanical properties and functional behavior.

Developing the next generation of computational tools, databases and experimental techniques for materials research is one of the primary goals of the multiagency Materials Genome Initiative (MGI).[113] The MGI aims to halve the amount of time required from conception of a new material to implementation by increasing transparency of data and creating opportunities for feedback between development stages. Similar computational initiatives are underway for discovery and manufacturing process planning within specific industries.[114]

Table 6.14 Energy Savings Opportunities for Selected Application Areas[115]

Application area	**Estimated annual energy savings opportunity**	
	(TBtu)	(GWh)
Laptops and tablets	8	2,300
Cell phones	19	5,600
Data centers	37	10,800
Variable frequency drive motors	38	11,100
Renewable power generation	36	10,600
Total	**137**	**40,100**

Composite Materials

Lightweight, high-strength, and high-stiffness composite materials have been identified as a key crosscutting technology in U.S. clean energy manufacturing, with the potential to reinvent an energy efficient transportation sector, enable efficient power generation, and increase renewable power production.[118] In order to meet this potential, advanced manufacturing techniques are required that will enable an expansion of cost-competitive production at commercial volumes and performance. Technology advances and research in manufacturing—from constituent materials production to final composite structure fabrication—are needed to reach cost and performance targets at production volumes and transform supply chains for these and associated markets.[119] High priority challenges include high costs, low production speeds (long cycle times), high manufacturing energy intensity of composite materials, recyclability challenges, and a need to improve design, modeling, and inspection tools for composites to meet commercial and regulatory demands.

A subcategory of composite materials, fiber-reinforced polymer (FRP) composites are made by combining a polymer resin matrix with strong, reinforcing fibers such as glass or carbon. A number of applications benefit specifically from carbon fiber reinforced polymer (CFRP) composites, which offer a higher strength-to-weight ratio and stiffness-to-weight ratio than many structural materials. These lightweight composites, when utilized appropriately and with further technology advancements, could provide use phase energy and carbon emissions savings from opportunities such as fuel savings as gained by introduction of lighter weight vehicles, efficient operation at a lower installed cost in wind turbines, and use of compressed gas tanks for natural gas and hydrogen fuel storage.

The Corporate Average Fuel Economy (CAFE) standard targeting 54.5 mpg by 2025 is driving increasing industrial interest in a range of lightweighting technologies, including high-performance composites, as a means to achieve required mass reductions. A 10% reduction in vehicle mass can yield a 6%–8% reduction in fuel consumption.[120] CRFP composites have a weight savings potential in the range of 50%–60%, but they are very energy intensive to manufacture and one and one-half to five times more expensive than conventional steel.[121] With major advancements in the next fifteen years, the cost is expected to drop from $10 per pound to $5 per pound for composite materials suitable for the automotive sector.[122] Manufacturing speed is critical, particularly for high volume applications like the automotive sector where the capability to produce more than 100,000 parts per year at cycle times of less than three minutes is needed. One current technology used today for carbon fiber composites in low- to mid-production volume vehicle parts has a cycle time of less than twenty minutes,[123] and while cycle times under two minutes have been shown at laboratory scale,[124] significant effort is needed to develop full scale capabilities. Furthermore, to fully realize use phase benefits in vehicle lightweighting, the energy intensity of CFRPs must be addressed. Figure 6.12 shows potential energy savings opportunities in the fabrication of one pound of CFRP composite, based on a review of state-of-the-art and RDD&D technologies under development.

Another application for fiber-reinforced composites is compressed gas storage tanks. Analysis has shown that fuel cell electric vehicles using hydrogen can reduce oil consumption in the light-duty vehicle fleet by more than 95% when compared with today's gasoline internal combustion engine vehicles, by more than 85% when compared with advanced hybrid-electric vehicles using gasoline or ethanol, and by more than 80% when compared with advanced plug-in hybrid electric vehicles.[124] However, the high costs of hydrogen fuel storage tanks are a barrier to deployment of fuel cell electric vehicles. Figure 6.13 shows a potential cost reduction strategy for a composite overwrapped pressure vessel (COPV) hydrogen storage tank. CFRP composites currently dominate the system cost, and reductions in these costs could help accelerate deployment of energy-efficient fuel cell electric vehicles.

Figure 6.12 Energy Savings Opportunities for One Pound of Carbon Fiber Reinforced Polymer Composite, Broken Down by Subprocess. Energy intensities and savings opportunities are based on a 40% epoxy/60% carbon fiber (by weight) composite part fabricated via resin transfer molding.[125] Energy intensity depends on the ratio of fibers to polymer, the type of resin and manufacturing process chosen.

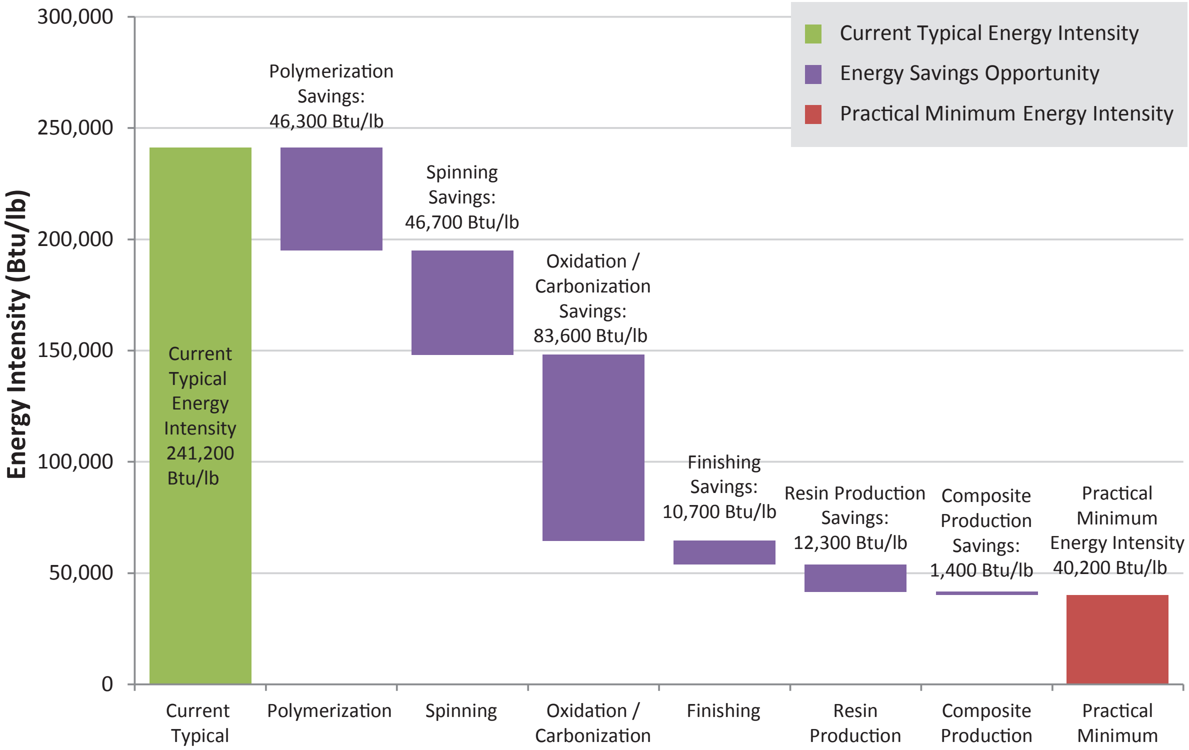
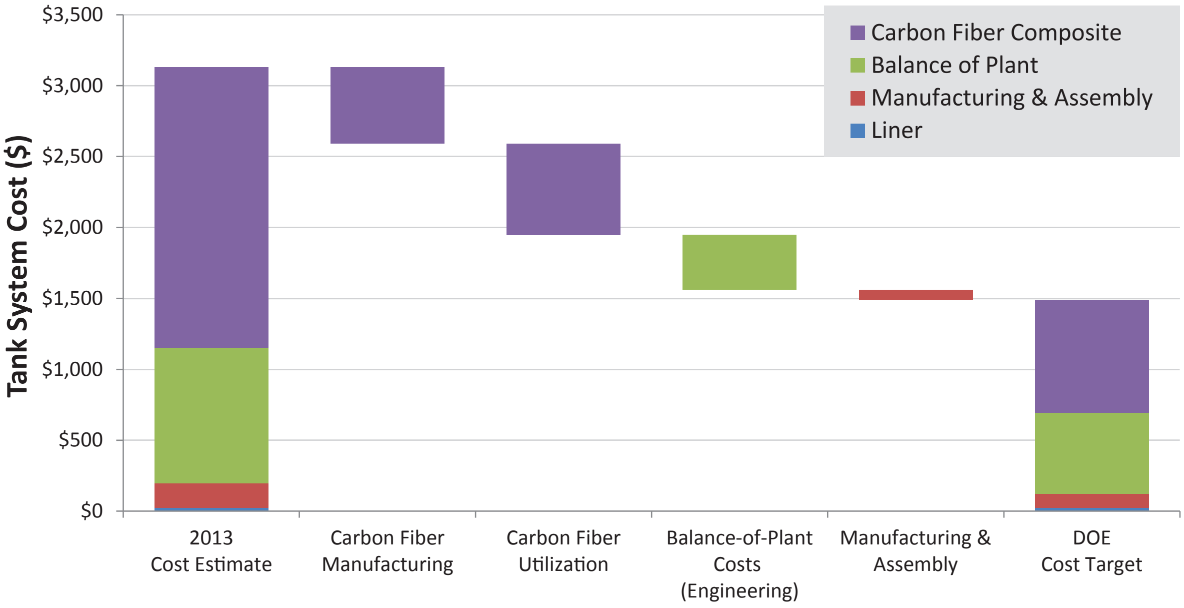


Figure 6.13 Potential Cost Reduction Strategy for Composite Overwrapped Pressure Vessels to Meet the 2020 U.S. DRIVE Cost Target.[127] Innovations in carbon fiber manufacturing and use can play key roles in reducing the cost to achieving DOE's ultimate cost target.



Open Commercial Foundry Model to Accelerate WBG Power Electronics Impact

The relatively high costs of WBG power electronics devices are tied to small production volumes and high manufacturing costs. A capital investment of approximately $100 million is needed for a dedicated foundry to fabricate WBG semiconductors, and unless the market exists to fully utilize the foundry, this initial investment may not be be recovered. A secondary effect of dedicated foundries is that the technology is essentially closed to new companies and researchers.

The open commercial foundry model concept is based upon utilizing existing six- and eight-inch Si foundries in the U.S. and repurposing their idle plant capacity to produce WBG devices. These six- and eight-inch foundry lines are becoming available for repurposing as the Si chip industry transitions to state-of-the-art twelve-inch Si wafers. Given that approximately 90% of the processes needed to manufacture WBG chips are the same processes as for Si chips, an investment of approximately $10M to establish the required additional processing steps in an existing silicon foundry would enable the production of WBG devices at significantly lower cost compared to establishing a dedicated WBG foundry. These open foundries would then be open to researchers, universities, and small companies, similar to the Silicon Metal Oxide Semiconductor Implementation System (MOSIS) foundry service, which facilitates the sharing of integrated circuit fabrication costs among multiple users. Educational activities can be promoted with open foundries through the development of classes concentrating on the specifics of WBG chip design and process flow steps, knowledge which can then be implemented directly at the foundry. In addition, establishing a mechanism to enable new companies to form with significantly reduced capital investment and opening the foundries to university students will help to expand the U.S. workforce and expertise in this critical technology area, helping to create an ecosystem for power electronics manufacturing in the United States. This open commercial concept is currently being explored by the DOE PowerAmerica Institute that was established at North Carolina State University in 2014.[117]

Composite materials offer the potential for energy savings but have cost, energy, production and recyclability challenges that need to be further addressed through advanced manufacturing RDD&D. Addressing these and other technical challenges may enable U.S. manufacturers to capture a larger share of the high-value-added composites market segment and could support domestic manufacturing competitiveness.

6.5 Conclusion

The systems framework outlined in this chapter reveals opportunities to improve the energy and emissions footprint of the manufacturing sector, highlighting technologies that can enable energy and environmental life-cycle impacts and those that can provide a competitive advantage over practices widely in use. Opportunities were informed by a series of fourteen manufacturing Technology Assessments (see Table 6.15). These technologies span a range of maturities across the RDD&D innovation spectrum, but all have the potential to transform the manufacturing sector and the energy economy through higher manufacturing throughput, increased energy efficiency, and positive life-cycle impacts.

This chapter demonstrates that opportunities extend beyond the industrial sector. The manufacture of clean energy products impacts the entire energy economy, with cross-sectoral and life-cycle energy benefits. Opportunities beyond the plant boundaries include improvements to the networks of facilities, business processes, and operations involved in moving materials through industry, from extraction of raw materials to the production of finished goods. The manufacturing sector also supports U.S economic growth, as a strong manufacturing base can lead to competitive advantages gained through manufacturing innovations.

Table 6.15 Manufacturing Technologies Assessed in QTR Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessment	Overview of key opportunities
Additive Manufacturing	In comparison with conventional subtractive manufacturing techniques, additive (3D printing) techniques can reduce materials waste, eliminate production steps, and enable new products that cannot be fabricated via conventional methods.
Advanced Materials Manufacturing	New-paradigm materials manufacturing processes, such as electrolytic metal production processes and electric field processing, are enabling advanced materials with superior properties or lower energy requirements than prior techniques. Further, computational modeling and data exchange is accelerating the process of new materials discovery by minimizing trial and error.
Advanced Sensors, Controls, Platforms and Modeling for Manufacturing	Automation, modeling and sensing technologies enable real-time management of energy, productivity and costs at the level of machine, factory, and enterprise for crosscutting impacts.
Combined Heat and Power Systems	The concurrent production of electricity and useful thermal energy from a single energy source can reduce fuel requirements compared to generating power and heat separately. CHP generation is typically performed onsite, increasing resiliency.
Composite Materials	Structural composite materials could provide energy and environmental benefits in lightweighting applications such as vehicles, wind turbines, and gas storage.
Critical Materials	Many clean energy technologies rely on critical materials (e.g., neodymium in a wind turbine permanent magnet); sustainable supply chains will advance these technologies.
Direct Thermal Energy Conversion Materials, Devices, and Systems	Direct thermal energy conversion technologies convert energy from one form to another without intermediate steps; promising heat-to-electricity conversion technologies like thermoelectrics can be used in applications ranging from waste heat recovery to refrigeration.
Materials for Harsh Service Conditions	Opportunities include higher-temperature, higher-efficiency power plants; corrosion-resistant pipelines for natural gas and hydrogen delivery; improved waste heat recovery in corrosive environments; and improved nuclear fuel claddings.
Process Heating	Process heating accounts for nearly two-thirds of onsite manufacturing energy; opportunities to reduce energy consumption include lower-energy processing (e.g., microwave heating), integrated systems, waste heat recovery, and advanced controls.
Process Intensification	Process intensification techniques such as the integration of multiple unit operations into a single piece of equipment and modular system design can improve manufacturing throughput, quality, and energy efficiency.
Roll-to-Roll Processing	This fabrication technique enables many 2D clean energy products, such as flexible electronics for solar panels and membranes for low-energy separations.

Table 6.15 Manufacturing Technologies Assessed in QTR Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing (continued)

Technology Assessment	Overview of key opportunities
Sustainable Manufacturing - Flow of Materials through Industry	Material flow analyses reveal expanded technology opportunities; for example, recycled materials can require much less energy to process than primary materials, but to fully realize these benefits requires a broader systems approach, products designed for re-use, and technologies that enable greater use of secondary materials.
Waste Heat Recovery Systems	Manufacturing waste heat can be captured and re-used by redirecting waste streams for use in another thermal process or by converting the waste heat to electricity.
Wide Bandgap Semiconductors for Power Electronics	Wide bandgap semiconductors can enable smaller, lighter, and higher-efficiency power electronics compared to silicon-based devices.

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

[See online version.]

Supplemental Information

[See online version.]

Endnotes

[1] Industrial energy consumption is diverse. See industry sector energy supply shown in Chapter 1, Figures 1.3b.

[2] EIA. "Annual Energy Review." April 2014, Table 2.1. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351504.pdf. EIA. "2010 Manufacturing Energy Consumption Survey (MECS)," Table 1.2. Available at: http://www.eia.gov/consumption/manufacturing/data/2010/. "Manufacturing Energy and Carbon Footprints (2010 MECS)," U.S. DOE, Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs. Note: Numbers may not add up correctly owing to independent rounding.

[3] This goal is consistent with voluntary goals for industrial energy intensity laid out in the Energy Policy Act (EPAct) of 2005, Public Law 109-58, August 8, 2005 (119 STAT 594). Available at: http://energy.gov/sites/prod/files/2013/10/f3/epact_2005.pdf.

[4] For more details, see the "Energy Bandwidth Studies." Available at: http://www.energy.gov/eere/amo/energy-analysis-sector.

[5] "Sankey Diagram of Energy Flow in U.S. Manufacturing." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/sankey-diagram-energy-flow-us-manufacturing. Note: Electricity generation includes electricity generated from off-site sources, including coal- and natural-gas-fired power plants, nuclear power plants, and off-site renewable energy sources.

[6] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[7] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[8] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[9] "Sankey Diagram of Process Energy Flow in U.S. Manufacturing." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/sankey-diagram-process-energy-flow-us-manufacturing-sector.

[10] Process heating operations, applications, and temperature ranges were drawn from the following sources:

- Energy Use, Loss, and Opportunities: U.S. Manufacturing and Mining." Prepared by Energetics Inc. for the U.S. DOE Office of Energy Efficiency and Renewable Energy Industrial Technologies Program, 2004. Available at: http://energy.gov/sites/prod/files/2013/11/f4/energy_use_loss_opportunities_analysis.pdf.
- "Improving Process Heating System Performance: A Sourcebook for Industry." U.S. DOE Office of Energy Efficiency and Renewable Energy, 2nd edition, 2007. Available at: http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/process_heating_sourcebook2.pdf.
- For the 2002 energy breakdown by process heating equipment category, see Chapas, R. B.; Colwell, J. A. "Industrial Technologies Program Research Plan for Energy-Intensive Process Industries." Prepared by Pacific Northwest National Laboratory for DOE, 2007. Available at: http://www1.eere.energy.gov/manufacturing/pdfs/itp_research_plan.pdf. To estimate the 2010 energy breakdown, 2002 energy use was scaled based on the "2010 Manufacturing Energy and Carbon Footprints (2010 MECS). Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs. Engineering judgment was used to map process heating and steam equipment to the nine major process heating categories shown in the table.

[11] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[12] Leonelli, C.; Mason, T. J. "Microwave and Ultrasonic Processing: Now a Realistic Option for Industry." *Chemical Engineering and Processing*, 49, 2010; pp. 885-990.

[13] Chapas, R. B.; Colwell, J. A. "Industrial Technologies Program Research Plan for Energy-Intensive Process Industries." Prepared by Pacific Northwest National Laboratory for DOE, 2007. Available at: www.efce.info/efce_media/-p-531.pdf. Energy and emissions savings correspond to 2030 projections in the report. Opportunities greater than 100 TBtu have been tabulated; see the report for additional opportunities.

[14] "Manufacturing Energy and Carbon Footprints (2010 MECS)," U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs. Note: The proportion of manufacturing electricity indicated (68%) includes electricity for facility HVAC in addition to electricity for machine drive and process cooling and refrigeration as shown in Figure 6.5.

[15] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs. Note: The on-site system losses stem from the electricity portion of process cooling and refrigeration and facility HVAC in addition to all energy for machine drive.

[16] "Manufacturing Energy and Carbon Footprints (2010 MECS)." U.S. DOE Office of Energy Efficiency & Renewable Energy. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs. Note: Table 6.3 includes the electricity portion of process cooling and refrigeration and facility HVAC in addition to all energy in the machine drive category shown in Figure 6.5. The GWh values were calculated based on an energy-equivalent basis to the TBtu values shown; a portion of the machine drive energy derives from fuel and steam use.

[17] "U.S. Adoption of High-Efficiency Motors and Drives: Lessons Learned." Duke University Center on Globalization, Governance & Competitiveness. Available at: http://www.cggc.duke.edu/pdfs/CGGC-Motor_and_Drives_Report_Feb_25_2010.pdf.

[18] "Improving Motor and Drive Performance." U.S. DOE Office of Energy Efficiency and Renewable Energy. Available at: http://www.energy.gov/sites/prod/files/2014/04/f15/amo_motors_sourcebook_web.pdf.

[19] Baldwin, S.F. “The Materials Revolution and Energy-Efficient Electric Motor Drive Systems.” *Annual Review of Energy*, Vol. 13, 1988.

- “United States Industrial Electric Motor Systems Market Opportunities Assessment.” Prepared for the U.S DOE Office of Industrial Technologies and Oak Ridge National Laboratory by Xenergy Inc., December 1998 (updated December 2002). Available at: http://cms.doe.gov/eere/amo/us-doe-motor-system-market-assessment.

[20] Wang, P.; Goel, L.; Liu, X.; Choo, F. H. “Harmonizing AC and DC.” IEEE Power & Energy Magazine, May/June 2013. Available at: http://magazine.ieee-pes.org/files/2013/04/2245587.pdf.

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[35] Data source: “Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S Chemical Manufacturing,” “Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S Petroleum Refining,” “Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S Pulp and Paper Manufacturing,” and “Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S Iron and Steel Manufacturing,” prepared by Energetics Inc. for U.S. DOE Advanced Manufacturing Office, 2015 (to be published).

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