Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

U.S. DEPARTMENT OF ENERGY

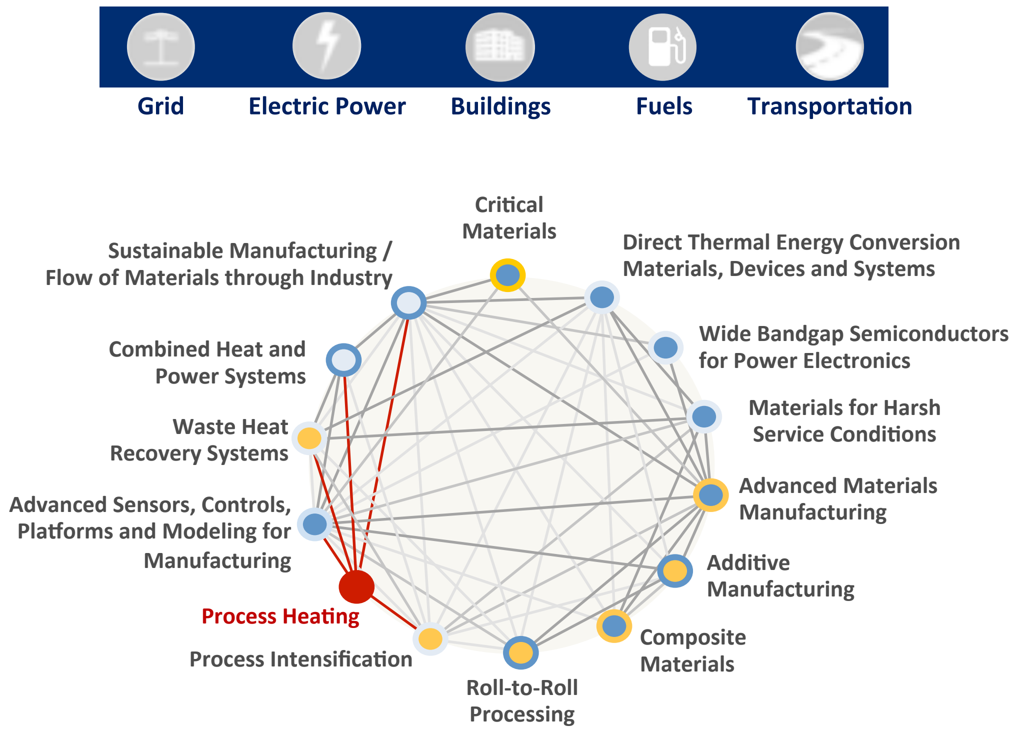
Quadrennial Technology Review 2015

Process Heating

Chapter 6: Technology Assessments

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

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **Combined Heat and Power:** integration of CHP with process heating equipment ■ **Sustainable Manufacturing:** shared ownership of equipment to maximize production intensity ■ **Waste Heat Recovery Systems:** waste heat recovery from process heating equipment; facility integration to enable re-use of exhaust gases in lower-temperature processes ■ **Process Intensification:** integrated control systems; replacement of batch operations with continuous ones	None, as this is a manufacturing-specific technology

Introduction to the Technology/System

Industrial Process Heating Overview

Process heating operations supply thermal energy to transform materials like metal, plastic, rubber, limestone (cement), glass, ceramics, and biomass into a wide variety of industrial and consumer products. Industrial heating processes include drying, heat treating, curing and forming, calcining, smelting, and other operations.[1] Examples of process heating systems include furnaces, ovens, dryers, heaters, and kilns. Many of these systems are mature technologies used ubiquitously throughout manufacturing. Process heating is used to raise or maintain the temperature of substances involved in the manufacturing process, such as the use of heat to melt scrap in electric arc furnaces to make steel, to separate components of crude oil in petroleum refining, to dry paint in automobile manufacturing, or to process food for packaging.

Process heating accounts for about 70% of all process energy (energy applied to convert material into manufactured products) used in the U.S. manufacturing sector.[3] As shown in Figure 6.I.1, U.S. manufacturing process energy (steam, electricity, and fuel used onsite at manufacturing facilities) totaled about 10.4 quads in 2010 (the most recent year for which data were available). In addition, there were about 4.9 quads of energy losses upstream as a result of electricity generation, bringing the total process energy requirement to about 15.3 quads, not including non-energy use of fuels as feedstocks. Of this total, approximately 7.2 quads of energy were used for process heating. The other categories of process energy include process cooling and refrigeration, machine drive, electrochemical processes, and other processes.

Figure 6.I.1 Sankey Diagram of Process Energy Flow in the U.S. Manufacturing Sector[2]

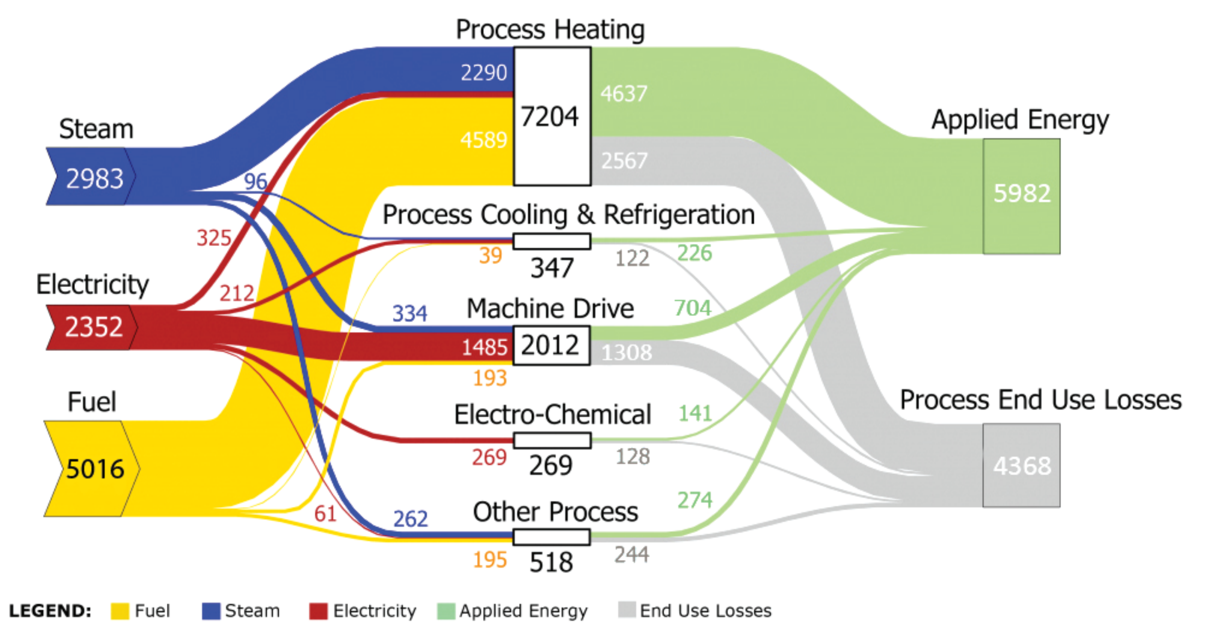


Table 6.I.1 shows the amount of energy used in each manufacturing industry and each industry's process energy use as a percent of total U.S. process energy use. In addition, Table 6.I.1 shows the percent of process heating energy used in each industry that is lost during process heating operations.[4] These losses vary by industry and on average the percent of process heating energy that is lost in the entire manufacturing sector (Figure 6.I.1) is estimated to be 36%.[5] A portion of these losses can be recovered; however, a portion are thermodynamically unrecoverable (see the technology assessment 6M, *Waste Heat Recovery Systems*, for additional details).

Five industries account for more than 80% of all energy used for process heating in U.S. manufacturing. Specifically, the petroleum refining and chemicals industries each use more than 1,000 TBtu (1 quad) of energy for process heating, while the forest products, iron and steel, and food and beverage industries each use more than 500 TBtu. These data can be explored using the U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO) *Dynamic Manufacturing Energy Sankey Tool*, which allows for a customized examination of process heating energy consumption in each of the U.S. manufacturing industries listed in Table 6.I.1.[6]

The energy used for process heating in 2010 included approximately 4,589 TBtu of mostly fossil fuels, 2,290 TBtu of steam, and 325 TBtu of electricity.[7] The types of fuels included natural gas, coal, biomass, fuel oils, and liquefied gases. In addition, byproduct fuels are used by the petroleum refining, chemicals, pulp and paper, and iron and steel sectors. Overall, approximately 13% of manufacturing fuel is used to generate electricity and steam onsite.

Table 6.I.1 U.S. Manufacturing Industries Ranked by Process Heating Energy Use in 2010

Manufacturing Industry	NAICS codes	Process heating energy use (TBtu)	Percent of total U.S. manufacturing process heating energy use (%)	Process heating energy losses (TBtu)	Percent of process heating energy lost within sector (%)	Percent of total U.S. manufacturing process heating energy losses (%)
Petroleum refining	324110	2,250	31%	397	18%	15%
Chemicals	325	1,455	20%	328	23%	13%
Forest products	321-322	980	14%	701	72%	27%
Iron and steel	3311-3312	729	10%	334	46%	13%
Food and beverage	311-312	519	7%	293	56%	11%
Cement	327310	213	3%	84	39%	3%
Glass	3272, 327993	161	2%	88	55%	3%
Fabricated metals	332	138	2%	49	36%	2%
Plastics and rubber products	326	87	1%	20	23%	1%
Alumina and aluminum	3313	82	1%	37	45%	1%
Transportation equipment	336	65	1%	23	35%	1%
Foundries	3315	61	1%	28	46%	1%
Computers, electronics, and electrical equipment	334-335	43	1%	15	35%	1%
Textiles	313-316	41	1%	23	56%	1%
Machinery	333	38	1%	13	34%	1%
Other Mfg.*	All Other in 31-33	342	5%	134	39%	5%
All Manufacturing	**31-33**	**7,204**	**100%**	**2,567**	**36%**	**100%**

*Note – The Other Manufacturing category is diverse and represents unaccounted energy use in the 15 manufacturing subsectors listed. The data shown for "Other Mfg." is the difference between the total process heating energy use and loss for "All Manufacturing," and the sum of the 15 manufacturing subsectors for which data were specifically collected.

Process heating technologies can be grouped into four general categories based on the type of fuel consumed: fuel, steam, electric, and hybrid systems (which utilize a combination of energy types). These technologies are based upon conduction, convection, or radiative heat transfer mechanisms—or some combination of these. In practice, lower-temperature processes tend to use conduction or convection, whereas high-temperature processes rely primarily on radiative heat transfer. Systems using each of the four energy types can be characterized as follows:

- Fuel-based process heating systems generate heat by combusting solid, liquid, or gaseous fuels, then transferring the heat directly or indirectly to the material. Hot combustion gases are either placed in direct contact with the material (i.e., direct heating via convection) or routed through radiant burner tubes or panels that rely on radiant heat transfer to keep the gases separate from the material (i.e., indirect heating). Across U.S. manufacturing, fuel accounts for 64% of process heating energy consumption. Examining the three largest process heating energy consumption sectors, fuel accounts for 16% of the process heating energy used in the pulp and paper industry, 53% of the process heating energy used in the chemical industry, and 82% of the process heating energy used in the petroleum refining industry.[8] Examples of fuel-based process heating equipment include furnaces, ovens, fired heaters, kilns, melters, and high-temperature generators.
- Steam-based process heating systems introduce steam to the process either directly (e.g., steam sparging) or indirectly through a heat transfer mechanism. Large quantities of latent heat from steam can be transferred efficiently at a constant temperature, useful for many process heating applications.[9] Steam-based systems are predominantly used by industries that have a heat supply at or below about 400°F and access to low-cost fuel or byproducts for use in generating the steam. Cogeneration (simultaneous production of steam and electrical power) systems also commonly use steam-based heating systems (see the technology assessment 6D, *Combined Heat and Power*). Across U.S. manufacturing, steam accounts for 32% of process heating energy consumption. Examining the three largest process heating energy consumption sectors, steam accounts for 82% of the process heating energy used in the pulp and paper industry, 45% of the process heating energy used in the chemical industry, and 18% of the process heating energy used in the petroleum refining industry.[10] Examples of steam-based process heating technologies include boilers, steam spargers, steam-heated dryers, water or slurry heaters, and fluid heating systems.
- Electricity-based process heating systems also transform materials through direct and indirect processes. For example, electric current is applied directly to suitable materials to achieve direct resistance heating; alternatively, high-frequency energy can be inductively coupled to suitable materials to achieve indirect heating. Electricity-based process heating systems (sometimes called electrotechnologies) are used for heating, drying, curing, melting, and forming. Across U.S. manufacturing, electricity accounts for 5% of process heating energy consumption. Examining the three largest process heating energy consumption sectors, electricity accounts for 1% of the process heating energy used in the pulp and paper industry, 2% of the process heating energy used in the chemicals industry, and less than 1% of the process heating energy used in the petroleum refining industry.[11] Examples of electricity-based process heating technologies include electric arc furnace technology, infrared radiation, induction heating, radio frequency drying, laser heating, and microwave processing.

- Hybrid process heating systems utilize a combination of process heating technologies based on different energy sources and/or heating principles to optimize energy performance and increase overall thermal efficiency. For example, a hybrid boiler system may combine a fuel-based boiler with an electric boiler to take advantage of access to lower off-peak electricity prices. In an example of a hybrid drying system, electromagnetic energy (e.g., microwave or radio frequency) may be combined with convective hot air to accelerate drying processes; selectively targeting moisture with the penetrating electromagnetic energy can improve the speed, efficiency, and product quality as compared to a drying process based solely on convection, which can be rate-limited by the thermal conductivity of the material. Optimizing the heat transfer mechanisms in hybrid systems offers a significant opportunity to reduce energy consumption, increase speed/throughput, and improve product quality.

Major process heating operations used in manufacturing are characterized in Table 6.I.2. The performance of a process heating system is determined by its ability to achieve a specified product quality under given manufacturing requirements (e.g., high throughput and fast response time). The energy efficiency of a process heating system is determined by the energy it uses per unit processed (heated, melted, etc.). Energy-efficient process heating systems use the least amount of energy per unit of product heated or melted at the required temperature range to achieve the desired product specifications.

Table 6.I.2 Characteristics of Common Industrial Processes that Require Process Heating and Estimated Energy Use

Process heating operation	Description/example applications[12]	Typical temperature range (F)[13]	Estimated (2010) U.S. energy use (TBtu)[14]
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**

Technology Assessment and Potential

Status of Industrial Process Heating Technologies

As outlined in the Introduction above, process heating consumes a large share of energy in the U.S. manufacturing sector. Past research investments in process heating and related topics have led to innovations that have improved industrial energy efficiency. Although no significant, pervasive process heating breakthroughs have been adopted recently by industry, incremental technology advances have been achieved in the following areas:

- Digital control equipment
- Reduction of NO_x, SO_x, and particulate emissions
- Increased thermal efficiency of selected processes
- Availability of high-temperature materials
- Enhanced heat transfer
- Improved combustion system components (e.g., air/fuel ratio control mechanisms, burners)

Process heating unit operations are fundamental to materials transformations and a wide range of manufacturing operations. Advances in process heating technologies could not only lead to lower manufacturing energy and emissions and associated costs, but could enable the manufacture of improved materials, technologies, and products.

Energy Savings Potential for Process Heating Technologies

Recovering waste heat losses represent a major opportunity to save energy in process heating, especially in higher-temperature systems like those used in steel or glass making. Overall, process heating systems account for more than 2,500 TBtu annually of on-site energy losses.[15] These losses can occur through walls, doors, and other openings like vents for exhaust of hot flue gases. For a discussion of specific opportunities to recover waste heat, refer to the technology assessment 6.M, *Waste Heat Recovery Systems*. Alternatively, for the processing of some materials, the generation of waste heat can be minimized or avoided by using lower-energy or lower-temperature processing techniques, such as microwave, radio frequency, ultraviolet, and other electromagnetic processing techniques that deliver heat directly to the material instead of heating the environment. Electromagnetic energy interacts with different materials in unique ways so these techniques can also be used to produce enhanced or entirely new products. Opportunities to save energy and reduce emissions in industrial process heating are summarized in Table 6.I.3. Energy savings potential and research activities that could lead to improvements are discussed in the following section.

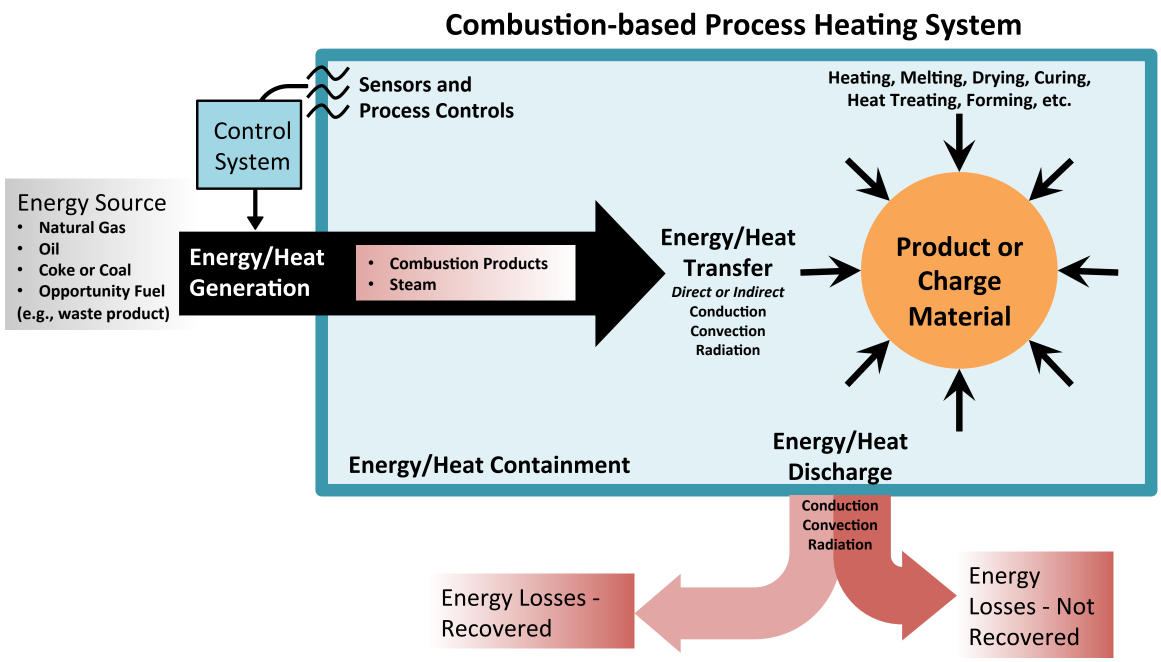
Table 6.I.3 Candidate Technology Opportunities for Process Heating, with Associated Energy Savings[14]

Technology 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**

Combustion-based Process Heating Systems

In combustion-based process heating systems, fuel in the form of natural gas, oil, coal, or waste products is combusted to generate heat, as shown in Figure 6.I.2. In general, combustion-based process heating systems can be categorized by whether they transfer heat to the product via direct use of fuel, e.g. contact with combustion gases, or indirect use of fuel, e.g. steam-based systems. For these fuel-fired systems, a key challenge is to optimize overall system thermal efficiency and operating costs, while maintaining compliance with emissions regulations resulting from the combustion processes. Optimization of the combustion processes depends on such factors as control of air-to-fuel ratios during all stages of combustion, fuel-mix variability, completeness of combustion, and burner performance over the range of its operation. With current technology it can be difficult to cost-effectively reduce emissions and increase efficiency simultaneously, especially in the case where preheating of combustion air is used to increase the available heat. The pre-heated air increases the flame temperature, which can lead to an undesirable increase in NO_x formation. More effective heat generation could deliver cost savings by improving energy efficiency and reducing emissions.[16] Beyond improvements to combustion efficiency, the overall thermal efficiency of the system can be increased through improved heat transfer, reduced losses, and waste heat recovery; these are addressed in greater detail in the section below entitled "Opportunities to Improve Process Heating Subsystems." Improvements to the overall system efficiency can lead to energy and productivity benefits.

Figure 6.I.2 Schematic Illustration of a Combustion-based Process Heating System[12]



Technology opportunities exist across the system components as well as for enabling technologies such as sensors and controls, advanced materials, and auxiliary systems, and include the following:

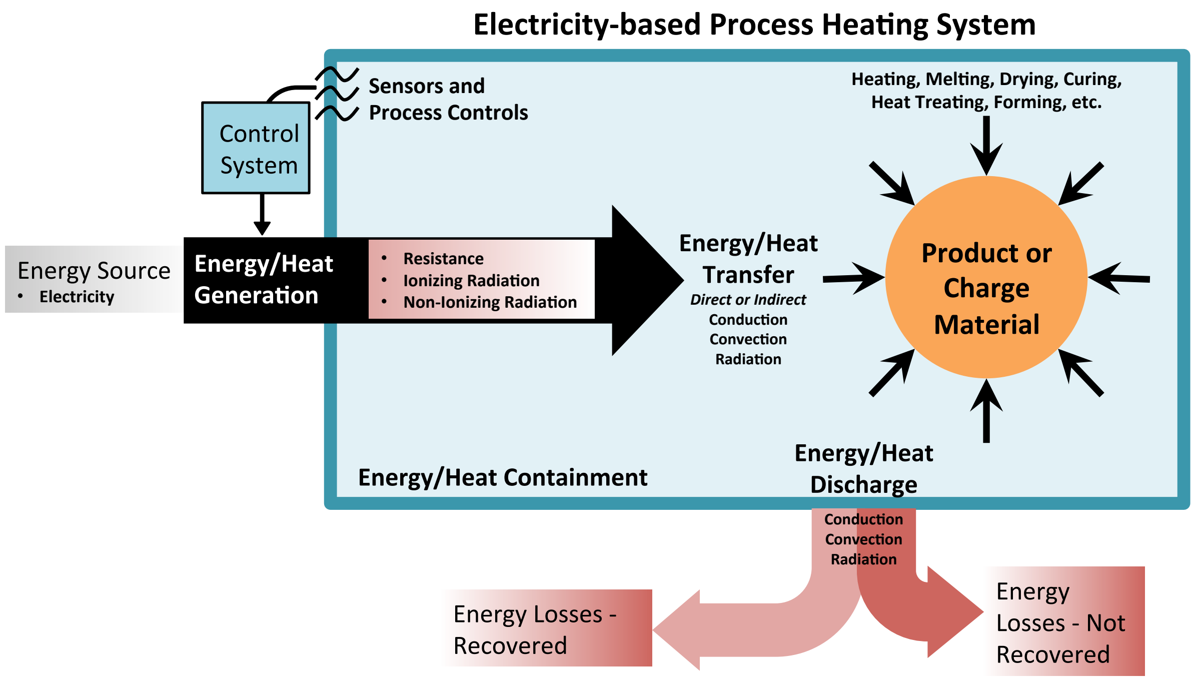
- Cost-effective technologies for high-temperature indirect heating.
- Technologies to limit/eliminate fouling (which reduces system efficiency).
- Technologies to extend equipment service life while maintaining their functional integrity.
- Improved fundamental understanding of combustion processes (turbulent mixing, soot properties/ formation/loading).
- Combustion technologies that enable use of low heat-value fuels (e.g., waste fuels).
- Technologies to increase fuel flexibility.
- Efficient air handling technologies.

In addition to the direct use of fuel for process heating, steam is used commonly as a basis for process heating. There are a wide range of steam-based process heating technologies and each system is customized for the operation. Many of the technology opportunities specific to steam-based process heating technologies are similar to direct fuel-fired systems. This technology assessment does not address technological improvements specific to steam generation and distribution systems.

Electrotechnologies

Electricity currently represents only 5% (325 TBtu) of the energy used for process heating in U.S. manufacturing. In electricity-based process heating technologies, an electric current is applied directly to materials or the electricity is used indirectly to power processes. Electrotechnologies encompass a broad spectrum of electric-based technologies and unit operations. Many electrotechnologies are used in manufacturing for thermal processing such as heating, melting, forming, curing, and drying. Electrotechnologies convert incoming electricity at line voltage to a form of applied energy that can efficiently achieve the necessary thermal effect. Expanded use of electrotechnologies can offer significant potential to reduce energy use and improve energy productivity in the process industries, materials production, and materials fabrication.

Figure 6.I.3 Schematic Illustration of an Electricity-based Process Heating System



Examples of electrotechnologies that have demonstrated benefits over traditional industrial process heating technologies include infrared, microwave, and radio frequency for heating, curing, and drying operations as well as induction for heating, heat treating, and melting.[17] Other thermal applications include laser sintering, resistive heating, and electric arc furnaces. In addition, there are non-thermal based electrotechnologies such as ultraviolet and electron beam used in manufacturing that can be used in place of thermal based technologies. Table 6.I.4 shows examples of electrotechnologies utilized in manufacturing.[18] For electrical systems, performance and cost depend on the reliability of the power supply, the power losses associated with transmission and distribution, and the losses from system cooling (particularly in induction heating).

Table 6.I.4 Examples of Electrotechnologies Used in Manufacturing.[18]

Electrotechnology	Applications	Primary Industries	Competing Technologies
Arc Furnaces	Steel production, melting steel, melting iron and refractory metals, smelting	Primary metal production, especially steelmaking	Oxygen furnaces (coal), plasma processing
Electric Infrared Processing	Heating, drying, curing, thermal-bonding, sintering, sterilizing	Fabricated metal products, transportation equipment, plastics and rubber	Electron beam processing, ultraviolet curing, resistance heating, induction heating
Electron Beam Processing	Melting, drying, welding, machining, curing, crosslinking, grafting	Fabricated metal products, machinery, transportation equipment, plastics and rubber	Infrared processing, laser processing, ultraviolet curing, induction melting, arc welding
Induction Heating and Melting	Heating, heat treating, melting	Fabricated metal products, primary metals, transportation equipment, machinery	Resistance heating, infrared processing, electron beam processing, gas furnaces
Laser Processing	Heat treating, hardening, trimming and cutting, welding	Transportation equipment, fabricated metal products, electronics	Electron beam processing, plasma processing, induction heating, arc welding
Microwave and Radio Frequency Processing	Heating, tempering, drying, cooking, plasma production	Food/beverage, plastics and rubber, wood products, chemicals	Resistance heating, induction heating, ovens
Plasma Processing	Melting scrap, remelting for refining, reduction, surface hardening, welding, cutting	Primary metals (titanium, high-alloy steels, tungsten)	Arc furnaces, oxygen furnaces, electron beam processing, laser processing
Resistance heating and melting	Heating, brazing, sintering, melting	Glass production, metal products, plastics and rubber, chemicals, food	Induction heating and melting, infrared processing, microwave/ radio frequency processing, gas furnaces
Ultraviolet Curing	Curing, coatings, printing, adhesives, purifying	Computers, electronics, printing, fabricated metal products, transportation equipment	Electron beam processing, infrared processing

High-frequency electrotechnologies[19] offer an opportunity to reduce energy use in process heating applications that could benefit from selective and/or volumetric heating; examples of three high-frequency electrotechnologies that provide this functionality are microwave, radio frequency, and induction, and are described below.

Microwave – The microwave portion of the electromagnetic spectrum is between 300 and 300,000 megahertz (MHz). Industrial sources of microwaves are generally limited to Federal Communications Commission (FCC)-allocated frequencies of 915 MHz, 2,450 MHz and 5,800 MHz.[20] The microwave source for industrial systems is typically a magnetron, and energy is directed to the part through a series of waveguides. Microwaves are typically used to heat materials that are electrically non-conducting (dielectrics) and composed of polar molecules, but applications have been demonstrated to heat conductive materials, such as metals.[21]

Radio frequency – The radio frequency portion of the electromagnetic spectrum is between 2 and 100 MHz. Radio frequency energy is produced by generators that use either a controlled frequency oscillator with a power amplifier (also called "50-ohm" or "fixed impedance"), or a power oscillator in which the load to be heated is part of the resonant circuit (also known as "free-running" oscillators). The 50-ohm generators are used most prevalently in industrial processes, and typical frequencies for industrial applications are 13.56 MHz and 27.12 MHz. Like microwaves, radio frequency energy is typically used to heat materials that are electrically non-conducting (dielectrics) and composed of polar molecules, but the longer wavelengths are often used for materials/products with larger geometries, as radio frequency can penetrate more deeply.

Induction – Induction technologies typically utilize electromagnetic energy in the 5 to 450 kHz range, where a solid-state power supply sends an alternating current (AC) through a copper coil creating an electromagnetic field; close proximity of the coil to the material to be heated causes circulating eddy currents to be induced within the part, generating heat. Induction heating only works with electrically conductive materials, and metals are the usual application. However, carbon fiber is a conductive material and some carbon fiber composites can also be heated using induction.[22] It is possible to introduce heat indirectly into non-conductive materials such as plastics by use of electrically conductive susceptors.[23]

Figure 6.I.4 (microwave), Figure 6.I.5 (radio frequency), and Figure 6.I.6 (induction) show schematics for three high-frequency electrotechnologies typically used for process heating applications. A commonality across these different technologies is that the applicator must be designed based on the physical properties and geometry of the product. Because the energy is directed, penetrating, and controlled, it can be applied efficiently with minimal energy losses. More importantly, high-frequency electromagnetic energy as a process heating technology can enable the manufacture of improved or novel products due to attributes such as selective and volumetric heating. As such, in addition to offering greater efficiency, electrotechnologies can enable the manufacture of materials and products with properties unattainable by conventional thermal processing methods. For example, microwave energy has been shown to sinter ceramics, alter grain structure in sintered metals,[24] provide new pathways[25] for the manufacture of carbon fiber, and accelerate chemical reactions by orders of magnitude.[26,27,28]

Figure 6.I.4 Schematic of Single-Mode Industrial Microwave Heating System. Energy is applied via waveguides to an applicator which focuses energy on the product. Systems are designed with control features to increase the energy absorbed by the product and minimize energy that is reflected to a dummy load (to protect the source).

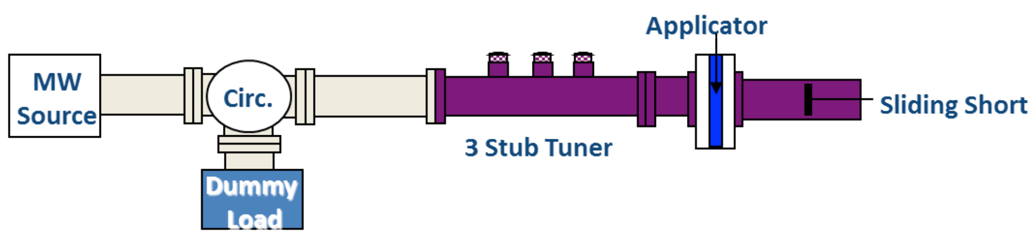


Figure 6.I.5 Schematic of Three Variations of an Industrial Radio Frequency Heating System. Energy is introduced via capacitive fields in which the applicator design is adjusted to product geometry to optimize field orientation for maximum energy absorption.

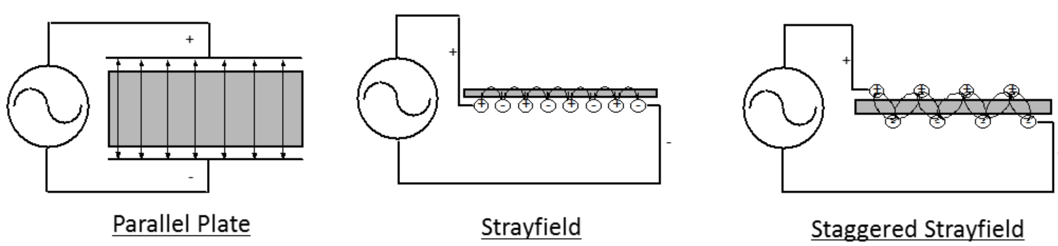
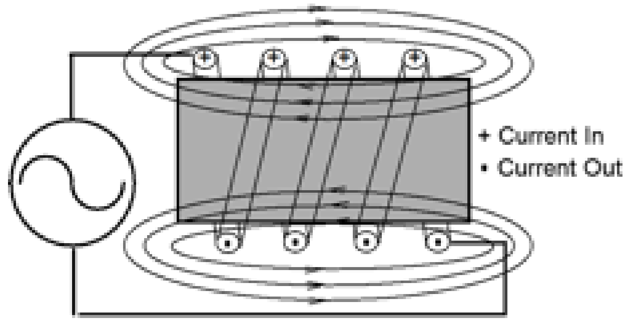


Figure 6.I.6 Schematic of Industrial Induction Heating System. Energy is introduced via inductive coupling between a coil applicator and the product.



The successful development of microwave and radio frequency processes requires a comprehensive understanding of the process and system physics. The electromagnetic wave/material interaction is complex, which is compounded by the changes to the heat and mass transfer, materials physics, and chemistry as the material is processed. Further, because the material to be processed (the load) becomes an integral part of the overall system, equipment design—especially applicator design—is more critical than in traditional heating processes. Approaches to model the nonlinear effects attributable to these highly coupled systems (that can lead to uneven heating and hot spots) reach back several decades.[29] In recent years, commercial electromagnetic simulation programs have been adapted from communications applications to microwave heating applications, but these packages can be limited in their capability to model all aspects of the process. Computational modeling and optimization can improve the design process[30] and facilitate technology development by enabling improved simulations of the electromagnetic, thermal, and materials interactions.

An example opportunity for electromagnetic heating to reduce energy intensity is the use of microwave energy to facilitate cracking of hydrocarbons in the production of ethylene. This step consumes the most energy of all chemicals manufactured domestically,[31] and microwave-enhanced cracking of hydrocarbons has the potential to replace energy-intensive cracking furnaces and lead to significant energy savings. In a conventional furnace, heat is transferred through the outer surface of coils or tubes via conduction or convective heat transfer. Microwave-enhanced cracking technology takes advantage of radiative heat transfer by high-frequency electromagnetic energy to cause direct, volumetric heating of the reactants, and is expected to save 30%–50% of direct process energy requirements, as compared to conventional furnace energy consumption in the cracking process step.[32,33] This type of direct, volumetric heating is a cross-cutting technology in that it can provide advantages to similar unit operations in other manufacturing subsectors. For example, microwave volumetric heating of a flowing liquid (or suspensions) in food manufacturing can efficiently heat products while minimizing thermal damage to heat sensitive components. It also provides a means of microbial inactivation (pasteurization and sterilization) for food products with the advantage of more rapid, uniform heating.[34]

It is important to note that the examples described above (microwave, radio frequency, and induction) utilize non-ionizing sources of electromagnetic energy. Other sources may utilize ionizing radiation; for example, electron beam technology uses high energy electrons to transfer energy and accomplish material transformations. This allows for precisely-controlled local materials processing, and rapid heating and cooling rates. This method has been applied to processes for welding, heating, curing of composite materials,[35] and surface hardening.[36]

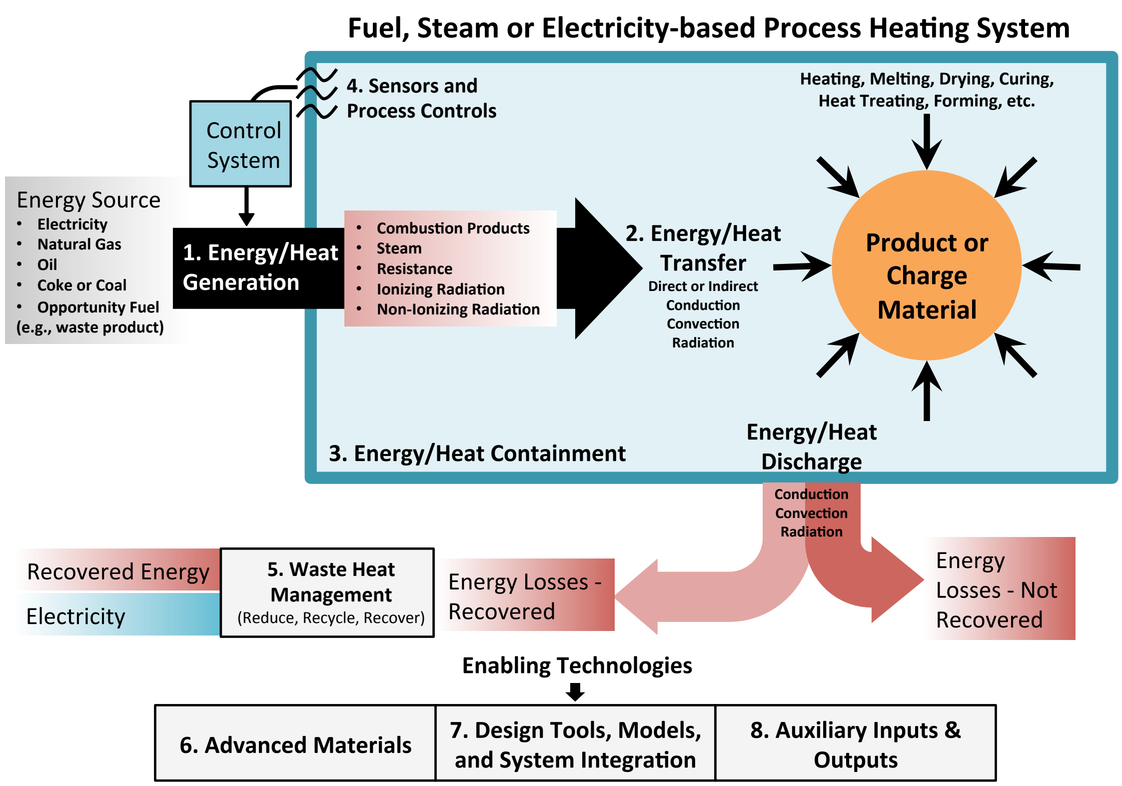
Examples of technology opportunities specific to electrotechnologies include the following:

- Hybrid systems that utilize more than one type of energy source.
- Conformable/adaptable applicators for microwave, radio frequency, and induction systems that can adjust to changes in product size/shape.
- Cost-effective, large-scale solid-state power supplies to provide high frequency energy sources.
- Intelligent selection of induction coils for induction systems.
- Heat recovery from melting systems, including arc furnaces and induction melting systems.
- Improved materials for electrical heating elements in higher-temperature applications, survival in heat treating atmospheres, radiant tubes (used for enclosing heating elements), etc.
- Development of high-capacity electric glass melting furnaces.
- Multi-physics modeling software that allows proper parameter selection for electricity/fuel-fired hybrid systems to optimize energy use and production in high-temperature applications.

Opportunities to Improve Process Heating Subsystems - Components and Enabling Technologies

An industrial process heating system, as defined broadly by the industry and the DOE Advanced Manufacturing Office (AMO), includes the entire system used for the heating or melting of materials. Figure 6.I.7 shows a diagram of the major process heating components.

Figure 6.I.7 Major Components or Modules of Typical Industrial Heating Systems.



Process heating systems include the following major features:

- **A source of energy** (fuel, electricity, or steam) which enables heat generation, and a mode of heat transfer to the heating equipment or material from heat generation source (e.g., hot gases produced by combustion).
- **A material handling system** which feeds product into or through the thermal processing system. Thermal processing takes place within a system that provides heat containment, which coupled with a process control system allows the user to maintain desired temperature and operating conditions (such as a specified process atmosphere). In some cases, advanced materials are used in construction and operation of the system.
- **Auxiliary systems.** Some systems include flue gas processing systems, as required to meet environmental regulations prior to flue gas discharge, or a waste heat recovery system to save energy and associated energy costs.

Each of the features listed above presents opportunities for technological improvement; however, system-wide improvements to optimize operation require complex, multi-physics solutions. Here, High Performance Computing (HPC) approaches could enable significant technology improvements.[37]

The performance of various process heating components is heavily impacted by a number of enabling technologies like sensors and process controls, advanced materials, and design tools/systems integration. Opportunities to improve process heating performance through advanced process heating approaches as well as through enabling technologies are summarized below. The opportunities to overcome technology barriers to improved process heating are presented in the following section.

1. Heat Generation Systems

Heat generation refers to the conversion of fuel products or electricity to heat. Heat sources can be fuel-based, electricity-based, or steam-based, and some processes utilize hybrid heat source systems. Figure 6.I.7 lists natural gas, coal, oil, and waste products as typical fuel-based energy sources. Fuel- and electricity-based heating systems generate heat at the point of use, whereas steam-based heating can provide advantages for facilities with distributed heating requirements, where the latent heat of the steam (typically 1,000 to 1,250 Btu/lb) is largely used to achieve heat transfer at constant temperature.[38] The following improvement opportunities apply to fuel- and electric-based heat generation sub-systems; many of these are already practiced in some cases, but further advances in these technologies might significantly improve their cost and performance and broaden their application:

Fuel-Based Processes:

- **Pre-Heated Combustion Air:** A recuperator system can be used to transfer heat from the exhaust flue gases to the combustion air stream to improve the efficiency of the combustion process. Alternatively, a regenerator system uses two or more heat storage systems and alternates the flow of combustion air and exhaust gases such that the incoming combustion air recovers some of the heat from the outgoing exhaust gases.[39]
- **Methods to Pre-heat Fuel**: Fuel preheating can be used for low-Btu gases such as blast furnace gas (BFG) where the fuel-to-combustion air mass flow is relatively high. It can help increase flame temperature, available heat, and flammability properties. Preheating natural gas is not recommended for most applications due to its tendency to dissociate and form carbon at temperatures >620°F.
- **Fuel-Flexible Gas Turbines:** Fuel-flexible combustor nozzle concepts allow for the use of off-gas and waste streams with low energy content as an alternative fuel source for process heating.[40]

- **Fluidized Bed Combustion Systems:** These combustion systems present opportunities for fuel flexibility in combustion, high combustion efficiency, and reduced emissions of pollutants such as sulfur- and nitrogen-oxides. The fuel flexibility of fluidized bed systems allows for opportunities to use less common fuel sources such as biomass and waste products.[41]
- **Multi-fuel Burners:** Burners designed to operate efficiently on a range of fuel types can make use of waste streams, reducing fuel costs and facility emissions. Fuel options can include coal dust, heavy oil, light oil, natural gas, liquefied petroleum gases, and landfill gas.[42,43] For example, gas-oil burners in industrial furnaces can be used to burn gas only, waste oil only, or gas and waste oil at the same time.
- **Oxygen-Enriched Combustion:** During air–fuel combustion, the chemically inert nitrogen in the air dilutes the reactive oxygen and carries away some of the energy in the hot combustion exhaust gas. An increase in oxygen in the combustion air can reduce the energy loss in the exhaust gases and increase heating system efficiency. Lower-cost oxygen generation methods could reduce the implementation and operating costs.

Additional opportunities for improvement include:

- Investigation of advanced gasification methods
- Development of a high-pressure feeder
- Examining existing technologies that can be applied to fuel reforming to increase fuel flexibility
- Expanded use of ash from boilers (particularly those using low-NO_x burners) burning a variety of fuels

Electric-Based Processes:

- **Electrotechnologies** (see also 'Electrotechnologies' under the 'Technology Assessment and Potential section): Examples include microwave systems for material modification, radio frequency heating, induction heating, and electron beam treatments. These technologies provide alternatives to thermal radiation process heating while avoiding the significant thermal losses that come with the combustion of fuels.
- **Hybrid Technologies:** Using a hybrid system involves using an electric process heating system as a booster element to preheat the work pieces that are then processed with a fuel-based heating system, such as natural gas, or vice versa.[44] These systems can improve efficiency, quality, and productivity; and reduce operational cost.

2. Heat Transfer Systems

Advancements in heat transfer techniques and in designers' abilities to reliably predict the performance of thermal systems under varied production requirements could improve process productivity, product loss rates, energy efficiency, and operating costs.[45] Opportunities to advance heat transfer technologies that might significantly improve their cost and performance and broaden their applicability include the following areas:

- **Uniform Heat Transfer:** This can help reduce the cycle time, improve the quality of products, increase the productivity, and reduce the overall energy intensity of the process heating systems. Soot blowers used in coal-fired boilers help maintain clean heat transfer surfaces, improving heat transfer efficiency and reducing heat losses.[46]
- **Computational Optimization of Heat Transfer:** Computational models can be used to adjust variables such as the percentage of excess air, oxygen concentration, and material flow temperatures to determine the optimal conditions for heat transfer, improving energy efficiency.[47]
- **High-Speed Gas Injection:** In heat treatment furnaces, high-speed gas injectors can improve gas convection, resulting in more homogeneous temperature distributions and improved heat transfer.[48]

- **Process Intensification:** Thermal process intensification can minimize the footprint of the heat transfer system, which can serve to maximize thermal efficiency, and minimize emissions per unit volume processed.

3. Energy/Heat Containment System

Controlled heat generation and heat transfer for industrial processes require the use of a heat containment system to maintain the desired atmosphere, assist in heat transfer, reduce energy losses, and facilitate material handling. Proper design, construction, operation, and maintenance of this part of the system can affect energy costs, emissions and productivity. Additional benefits can include improved product quality, and personnel safety. Opportunities to advance technologies in heat containment that might significantly improve their cost and performance and broaden their applicability include the following:

- **Seals, furnace curtains, liners, and heat shields:** Resilient, high-temperature seals can reduce cold air infiltration, improving thermal efficiency.
- **Insulation:** Particularly at temperatures above 1,000°F, heating equipment can suffer significant radiation losses.[49] Proper use of low-density and low-permeability insulation products, such as refractory ceramic fibers, can cut down on thermal losses. As another example, aerogels are solid materials with high porosity (<0.04 micro inches) and hence possess extremely low density (~0.0001 lb/inch^3) and very low conductivity (~10 mW/mK), and with further development could be very effective insulants.[50]

4. Sensors and Process Controls

The ability to effectively measure, monitor, and control process heating operations is essential to minimize product variability and maintain product quality. This level of control requires reliable and affordable sensors and control systems that can withstand harsh environments and not require recalibration for at least one year.[51] Process heating could become far more effective with access to more reliable, robust, and affordable sensors and process controls. There is a need for reliable, cost effective sensors for harsh environments and for the real-time measurement of the chemical composition of the fuel, oxidant, and flue gas in combustion processes. Real-time combustion controls for multiple fuel applications could help maximize fuel flexibility, while improved sensors as part of smart control systems could increase efficiency, safety, and reliability. In electromagnetic processes, low cost, robust, and reliable sensors are needed to measure field strength, as well as sensors that can measure process parameters but are immune to direct excitation by the electromagnetic energy. Technology opportunities for sensors and process controls to improve the overall control and performance of process heating systems include the following:

- **Sensors for Harsh, High-Temperature Environments:** Technologies and methods are needed to reliably monitor and control critical product parameters (temperature, chemistry, pressure, etc.), especially robust sensors to measure critical parameters in harsh combustion environments. This includes direct process measurement sensors, and more accurate and reliable thermocouples and other sensors. The development of sensors that can provide accurate readings in high-temperature environments could enable opportunities to optimize heat transfer and containment systems in those conditions.[52]
- **Furnace Control:** In fuel-fired equipment, reliable sensing and control technologies can provide better fuel utilization, energy savings, temperature control, and system performance over time. This includes sensors that can accurately measure compositional characteristics of fuels and oxidant; low-cost, highly reliable flame monitoring systems to control flame quality and stability; and continuous flue gas analysis. By regulating and stabilizing internal furnace pressure, pressure controllers can eliminate cold air infiltration, maintain uniform temperatures, and reduce wear that would require more frequent and costly maintenance.[53]

- **Cost-Effective Optical, Laser-Based, and Other Sensors for Process Control:** Non-traditional sensors have the potential to provide for more accurate measurement of temperatures and physical properties. These can include Image-based sensing to monitor surfaces, and capacitive sensors to monitor moisture content, providing in-situ, real-time sensing of a control variable. Laser-based gas sensors provide one means of real-time monitoring, allowing for more responsive process control.[54]
- **Advanced Control Strategies to Optimize Process Heating:** Cost-effective smart process controls that can be integrated with the overall manufacturing system are needed. Analysis of flue gases can be used to optimize the inlet fuel/air ratio. By using sensors to measure oxygen and carbon monoxide in the flue gas stream, conditions can be created for ideal combustion stoichiometry.[55]

5. Waste Heat Management: Heat Recovery and Heat Integration Systems

A large percentage of the total energy lost in heating systems can be recovered in the form of waste heat (see the *Waste Heat Recovery Systems* technology assessment (6M) for additional details). Waste heat is produced in many forms. It can be found in the exhaust gases from combustion equipment; cooling water; trays, belts, and fixtures; or, in some cases, the heated product itself. Today's methods to collect, recover, and use waste heat are often not economically justifiable, particularly for low-temperature or low-grade heat (e.g., hot water or low-temperature flue products). Advanced heat recovery systems could potentially deliver energy cost savings.[56] Technology opportunities in heat recovery include:

- **Adjusting Waste Stream Composition for Low-temperature Waste Heat Recovery:** Approximately 60% of unrecovered waste heat is at low temperatures (below 450°F). In some cases, these low-temperature waste streams may have contaminants that can foul heat exchangers and limit heat exchange. This may be addressed by cleaning the exhaust streams, implementing components that can withstand corrosive environments, or modifying process technologies to avoid the introduction of these compounds in the waste stream.[57]
- **Heat Exchanger Design for Low-temperature Waste Heat Recovery:** Due to the large heat transfer area required for low-temperature waste heat recovery, a significant opportunity area is advanced heat exchanger designs that can increase effectiveness while lowering cost, including: ceramic inserts, dimpled/finned heat exchangers, and heat pipes.[58]

Beyond heat recovery, there exist facility-wide opportunities for improving energy and associated heat utilization. Heat integration techniques are integral to the design of inherently energy-efficient plants. These techniques have the potential to improve the chemical and petrochemical industries, especially given the significant thermal use for separations (e.g. distillation). Overall heat management could result from the design and deployment of highly efficient, integrated systems, utilizing approaches such as:

- **Optimal Design of Heat Exchanger Networks:** One of the most commonly used methods to optimize heat exchanger network design is pinch analysis. This involves estimating thermodynamically feasible energy targets and determining the 'pinch point,' which determines at what levels heating and cooling must be added to the system. Components in the system are then modified to minimize heating and cooling that is unnecessary.[59]
- **Combined Heat and Power:** The need for process heating can provide an additional incentive for installation of a combined heat and power system. Often, this involves using the sensible heat of exhaust gases to heat the process heating material directly or to produce steam.[60]

6. Advanced High-Temperature Materials

Process heating equipment is subjected to unique loads and stresses, in addition to significant temperature changes and thermal gradients in high-temperature applications. To make equipment strong and resilient, materials are typically selected on the basis of strength and corrosion resistance. Thermal processing efficiency is severely restricted by the high cost and limited availability of high-performance, high-temperature materials (see the technology assessment 6.H, *Materials for Harsh Service Conditions*). High-performance materials can enable the design of compact equipment, reduce energy use and emissions, lower operating and maintenance costs, and increase productivity.[61] Technology opportunities for advanced high-temperature materials include:

- **High-Temperature Materials for Heat Exchanger and Equipment Design:** Materials that can operate at extremely high temperatures (furnace temperatures great than 1500°C) provide opportunities for improved heat containment and heat exchanger designs.[62] The major priorities for advanced high-temperature materials development are machinability, reducing cost, and improving creep and crack resistance. In addition, advanced manufacturing methods like additive manufacturing may enable optimized designs not achievable by conventional manufacturing methods.
- **High-Temperature Corrosion-Resistant Coatings:** The development of advanced coatings for furnace components can reduce maintenance requirements and improve the service life of equipment. One example is the demonstration of a ceramic coating for a recuperator through a Department of Energy grant. This coating proved to lessen the impact of high-temperature (2200°F) corrosive flue gases on the recuperator in an aluminum melting furnace.[63] The development of advanced coatings could enable the economic viability of components like recuperators, which could significantly improve the thermal efficiency of process heating.

Current heat exchanger designs rely heavily on fin-and-tube or plate heat exchanger designs, often constructed using copper, aluminum, or stainless steel. Recent developments in material science—in particular, advances in ceramics and ceramic matrix composites (CMCs)—have opened opportunities for new heat exchanger designs. There are advantages and disadvantages to the use of advanced ceramics and CMCs for new heat exchanger designs. Table 6.I.5 shows a comparison between conventional materials, and a candidate alternative ceramic material (silicon carbide) and a CMC (silicon carbide/silicon carbide) for new heat exchanger designs. Other candidates for next generation heat exchangers include monolithic or CMCs based on combinations of ceramics such as silicon carbide, silicon nitride, alumina, zirconia, aluminum titanate, and aluminum nitride.

Table 6.I.5 Rating grades for properties of ceramics versus conventional materials for new heat exchanger designs[64]

Criterion	Copper	Aluminum	Stainless steel	Ceramics SiC	Ceramic Matrix Composites (CMC)
Shaping (Machining)	Very easy	Very easy	Very easy	Difficult	Difficult
Material cost	High	Low	Moderate	Low	Moderate
Thermal conductivity (W/mK)	250-400	100-250	10-100	100-250	250-400
Temperature limit (°F)	930-1800	930-1800	930-1800	1800-3000	1800-3000
Material strength	Very high	Very high	Very high	Low	Moderate
Compatibility with halocarbon (e.g., Freon (TM), a common refrigerant)	Excellent	Excellent	Excellent	Excellent	Excellent
Compatibility with LiBr-H_2O (widely used in refrigeration systems)	Moderate	Moderate	Moderate	Excellent	Excellent
Compatibility with corrosive fluids	Poor	Poor	Good	Excellent	Excellent
Fouling resistance	Moderate	Moderate	Moderate	Excellent	Excellent
Material density (lb/inch^3)	>0.29	0.04-0.07	>0.29	0.11-0.14	0.11-0.14

7. Design Tools, Models and System Integration

System performance is the result of equipment/component design and system integration both within and across complex process heating operations. Models and other design tools can help identify opportunities for thermal efficiency improvements of process heating system components as well as the overall system.[65] The development of improved tools, models, and algorithms can facilitate the design of advanced process heating and furnace systems. Computational design tools have significantly improved many industrial processes, but their utility in combustion-based systems has been constrained by deficiencies in accuracy and robustness, for example for burner and furnace design. For computational tools such as computational fluid dynamics (CFD) and other design tools to achieve their potential in this field, researchers require more accurate physical property data. Computational design tools can, for example, help achieve energy, emission, and fuel flexibility goals in combustion-based systems, and in electromagnetic based systems can help solve complex multi-physics problems needed to optimize the materials heating response. Further, system integration often entails effectively joining existing process heating technologies with newer process heating methods (e.g. combining combustion technologies and electrotechnologies) to create a system that provides a higher overall level of performance. There are opportunities to advance and improve tools and models that can lead to improved component/system design and operation, including:

- **Process Design Tools:** Accessible design tools for complex process heating applications with high-fidelity models that incorporate process controls, heat recovery operations, and fluid mechanics.
- **Models for Electrotechnology Heating Operations:** Tools for modelling process heating alternatives such as electromagnetic field technologies (e.g. microwave, radio frequency, induction heating).
- **Maintenance:** Technologies to enable repair and maintenance without requiring a system shutdown, and techniques to identify and prevent sources of failure.

8. Auxiliary Inputs and Outputs

The process atmosphere (i.e., mix of gases) present during several critical thermal processing operations can influence heating system performance and determine final product quality. These protective or process-enhancing atmosphere gases are either generated on-site or are obtained by using a mixture of stored gases (e.g., N_2, H_2, CO_2, NH_3). Equipment and methods for creating the optimal process atmosphere significantly impact productivity and operating costs. Use of relatively pure oxygen for combustion is also becoming more common. Technologies that can reduce the cost of producing, storing, mixing, and controlling these gases will increase process heating efficiency, reduce emissions, and, in some cases, improve productivity and product quality, which can be particularly important where waste heat recovery systems are incorporated as part of the overall process heating system.[66] Technology opportunities in this area include the following:

- **Oxygen-Enriched Combustion:** Increasing oxygen concentration in the combustion air can improve process heating efficiency as less heat is lost to inert nitrogen in the combustion air stream. Methods include inserting oxygen into the combustion air stream, or removing nitrogen using pressure swing adsorption units.[67] Supplying this oxygen for enriching the combustion air stream requires advances in low-cost oxygen generation, including cryogenic air separation, oxygen transport membranes, or oxygen and thermal storage in perovskites,[68] or other materials. The uses for oxygen are many and include: glass furnaces, coal gasification, municipal solid waste gasification, gas-to-liquid technologies, and metals oxidation.[69]
- **Optimized Fuel/Air Ratio:** The fuel/air ratio can have a significant impact on process efficiency. One method for identifying the optimal input conditions involves using sensors to measure the excess oxygen and carbon monoxide content in the flue gas stream. The design of accurate, real-time sensors is a key technology opportunity for enabling this capability.[70]
- **Low-cost Separation of Hydrogen from Water:** A barrier to cost-effective production of hydrogen fuel is the expensive catalysts used to produce hydrogen fuel from water via electrolysis. Finding alternative methods or materials for producing lower cost catalysts could reduce hydrogen production costs.
- **Low-cost, Reliable Sensors and Analyzers for Combustion and Process Emissions:** Accurate sensing and control is a key tool for process optimization. In addition, research on noninvasive sensors (acoustic, magnetoacoustics, eddy current, penetrating radiation, thermography, thermal wave, ultrasonic, etc.) is needed. In addition to controlling the process atmosphere, process emissions often need to be controlled due to environmental regulations. Innovative emissions control technologies for process heating could reduce emissions levels and compliance costs.[71]

Program Considerations to Support R&D

Some of the primary organizations conducting R&D on process heating technologies include the Gas Technology Institute (GTI), Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, vendors of combustion system components (in collaboration with industrial companies), and various universities and private companies. Over the last 40 years, these organizations have invented and advanced numerous technologies, generating more than 500 U.S. patents.[72] A large percentage of these patents are for technologies related to process heating or combustion. The majority of this development work has been focused in the following areas:[73]

- Flame-based combustion devices, such as burners that improve combustion efficiency, reduce emissions, and enhance heat transfer in a variety of applications
- Combustion systems that incorporate heat recovery devices, such as self-recuperative burners
- Integrated heating systems, such as superboilers, and customized applications of combined heat and power (CHP) systems

- Other combustion systems (non-burner type), such as catalytic combustion
- Sensors and control systems used in monitoring flames and combustion products

This development work has produced important advancements in process heating/combustion technologies, including the following:

- Reduction in combustion-generated nitrogen oxides
- Development of high-temperature silicon carbide or silicon nitride radiant tubes
- Oscillating combustion systems
- Flameless combustion for high-temperature processes
- Oxygen-enriched air and pure-oxygen-based combustion
- Regenerative burners or combustion systems
- Flame impingement heating

Future Process Heating Technology Needs and Potential R&D Efforts

Optimizing the performance of industrial process heating systems will require R&D to improve individual components of the process and to progressively integrate those improved components into highly energy-efficient and cost-effective systems. Eventually, these systems will require further research for efficient integration into the broader manufacturing process. R&D activities can be designed to improve the productivity, product quality, and efficiency of the system as a whole, incorporating GHG emission reduction as one of the critical issues.

Improved Fundamental Understanding

R&D is needed to improve fundamental scientific understanding of combustion processes, particulate generation during combustion, heat generation, and transfer mechanisms. An example of current work that is advancing the fundamental understanding of high temperature and pressure combustion processes is the modeling and simulation using the Titan supercomputer at ORNL to better understand flame stability in combustors in advanced gas turbine designs.[74] Areas that would benefit from better fundamental understanding include the following:

- Physics of particulate generation in combustion
- Mechanisms of product degradation
- Formation of dioxins and furans below 1,400°F in flue gas streams
- Flue gas stream characteristics to enable prediction of behavior in a heat recovery system
- Mechanisms for capturing fine particulates under wet conditions (NO_x conversion)
- Efficient conversion of all fuels to H_2O and CO_2 (for catalytic combustion systems)
- Chemistry of the conversion of fuel nitrogen to NO_x
- Heat transfer characteristics of flames and combustion products
- Water treatment chemistry.

Technology Transition

Even the best new technologies often require time to transition into the marketplace and become widely implemented. An extensive examination of these issues is separately provided in the Chapter 6 Supplemental Information Appendix, *Public-Private Consortia and Technology Transition Case Studies.*

Risk, Uncertainty, and Other Considerations

Many technological, regulatory, and institutional barriers prevent industrial process heating systems from achieving optimal performance levels today. Risk and uncertainty hinder the uptake of technological improvements and restrict widespread technology adoption. Some barriers to deployment affect the entire industry while others are specific to fuel-based, electric-based, or steam-based systems.

Industry-Wide Barriers to Technology Adoption

Industry-wide challenges for advances in process heating technologies include the following:

- **Financial risk:** Industries that use costly, energy-intensive process heating equipment are typically averse to assuming the financial risks associated with new, unproven technology. As a result, these industries tend to be technologically conservative. Industry as a whole is averse to the risk exposure from the potentially heavy financial burden of a system that has a significant chance of failing to perform as intended.[75]
- **Lack of standards:** New process heating technology systems generally have limited data on their performance in production operations, there are generally no standards for measuring or reporting their performance under agreed-upon operating conditions, and technologies for accurately measuring key process heating parameters are often not adequately advanced. Further, industry may not be able to take advantage of existing state-of-the-art heat transfer, combustion, or materials laboratories because the resulting micro-level data requires too much analysis for effective application, particularly for small- and medium-sized companies. The type or scale of the available laboratory test equipment is also often not well matched to industry needs.[76]
- **Knowledge gap:** A wide gap exists between researchers, who often work on a relatively small scale, and the designers who work at the component, equipment, or system scale. The national laboratories and other research or academic institutions have amassed considerable fundamental knowledge, but the transfer and use of this knowledge can often require tools and capabilities that industry may not adequately access because of cost and training barriers.[75]

Barriers to Technology Adoption: Fuel-Based Process Heating Systems

For fuel-based systems, challenges include the following:

- **Communications gaps between suppliers and end users:** As previously indicated, the furnace and industrial heating industry has been relatively slow to develop and adopt new technologies. This conservatism is due in part to the relatively small size of the companies that offer industrial heating systems and the associated financial exposure they face, as well as due to a lack of communication and integration among equipment suppliers and end users.[77]
- **Integration of existing systems:** Another barrier to furnace system development is the extensive integration of industrial heating equipment with other process steps and equipment within a plant. This high level of integration often means plant-wide operations depend on the furnace system, and a new furnace technology could raise the risk of shutting down production plantwide.[78]
- **Need for flexibility:** The end user's requirement for system flexibility may also pose a problem for furnace technology development. The end user will likely prefer a reliable furnace system (that meets plant needs without exception) to a new technology that might limit the plant's ability to adapt to changing conditions, even if there is an energy efficiency advantage.[79]

Barriers to Technology Adoption: Electric-Based Process Heating Systems

For electric-based systems, challenges include:

- **High cost of electricity:** The often lower cost of thermal processing generated by fuels relative to thermal processing generated by electricity tends to favor investment in fuel-based systems.
- **Lack of electrical systems for high-temperature processing:** Industries that require energy-intensive, high-temperature processing (>1600°F), such as steel (except electric arc furnaces), petroleum refining, and chemicals, rarely use electric systems because conventional electric heating systems are very expensive or limited in these temperature regimes, with limited ability to provide other benefits. Overall, less than 5% of the total energy used by industrial process heating systems is from electricity,[80] and electricity accounts for less than 13% of process heating in the iron and steel industry and less than 2% in the chemical industry.
- **Lack of hybrid systems:** Few hybrid systems have been developed to make optimum use of electrical and fuel-fired systems.
- **Materials constraints in process environments:** Materials for electric systems that can be used in high-temperature, contaminated process environments are typically very costly or unavailable.

Barriers to Technology Adoption: Steam-Based Process Heating

For steam-based systems, challenges include the following:

- **Temperature limitations of steam-based heating:** Steam temperatures restrict most steam-based systems to less than 500°F, even at very high steam pressures and in superheated systems.[81]
- **Access to steam:** Many small and medium-size plants do not have access to steam, and the installation of steam generators entails large investments and operating costs.[82]
- **High NO_x emissions:** The variety of boilers in use today acts as a barrier to the development of combustion technologies that reduce emissions uniformly because advanced burners developed for a particular boiler design may not transfer successfully to other boiler types. The turndown instability of lean premixed combustion systems also presents a barrier to reducing NO_x emissions. In addition, because various fuels have different NO_x control requirements, achieving NO_x goals as well as targets for systems operations and fuel flexibility is complicated and difficult.[83]
- **Technologies to meet emissions regulations:** More stringent emissions regulations may make it necessary to install a particulate control system on new installations. Commercial and developing technologies often have not adequately demonstrated the ability to effectively control fine particulate emissions (<2.5 microns) under diverse process conditions.[84]

Table 6.I.6 Examples of Current EERE R&D Projects Involving Process Heating

Project	EERE Office	R&D Partner	Process Heating Component
Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells[85,86]	FCTO	Redox Power Systems	Heat treatment in the form of firing and sintering of cell components is a key process in the manufacture of solid oxide fuel cells and presents an opportunity for reducing fuel cell system cost ($/kW).
Development of Ultra-low Doped-Pt Cathode Catalysts for PEM Fuel Cells[87]	FCTO	University of South Carolina	Understanding the effect of heat treatment processes on platinum catalyst development and particle size is used to optimize catalyst performance.
Development of 3rd Generation Advanced High Strength Steels (AHSS) with an Integrated Experimental and Simulation Approach[88]	VTO	Pacific Northwest National Laboratory	Heat treating of advanced high strength steels for lightweight vehicle components is used to achieve strengths comparable to those of conventional, heavier steels.
Enhanced Room-Temperature Formability in High-Strength Aluminum Alloys through Pulse-Pressure Forming (PPF)[89]	VTO	Pacific Northwest National Laboratory	A key milestone in the development of high strength aluminum alloys is the identification of the optimal heat treatment parameters (e.g. temperature and time) to achieve strengths required for vehicle components.
A Novel Flash Ironmaking Process [90]	AMO	American Iron and Steel Institute, University of Utah	This project involves the development of a process to produce iron using less thermal energy than a blast furnace. H_2-based and reformer-less natural gas processes are compared as alternatives.
High Magnetic Field Processing[91]	AMO	Oak Ridge National Laboratory	This research presents a non-thermal alternative for materials processing using magnetic fields to accomplish treatments conventionally conducted using process heating.
Energy-Efficient Thermomagnetic and Induction Hardening[91]	AMO	Eaton Corporation	Thermomagnetic processing and inductive high-frequency heat treatment are being researched to replace conventional heat treatment processes while reducing energy requirements and costs.
Induction Consolidation Using Smart Susceptors[92]	AMO	Boeing	This Boeing project uses smart susceptors for large part fabrication using induction consolidation heating. This process improvement is expected to reduce energy consumption and cycle time, as well as allowing for more precise heating of components.

Case Study: Use of Infrared Heating to Reduce Energy Use and Improve Material Properties in Aluminum Forging

DOE's Advanced Manufacturing Office identified the preheating of metal billets prior to hot forging as an opportunity for significant energy savings in the U.S. forging industry. Aluminum billet preheating is traditionally slow, costly, and energy intensive. Rapid infrared heating (Figure 6.I.8) offers a faster, cheaper, and less-energy-intensive alternative to the gas-fired convection ovens that traditionally preheat forgings to above 800°F.[93,94] In this DOE-sponsored project, Oak Ridge National Laboratory (ORNL) worked with Queen City Forging, Komtek, Infrared Heating Technologies, Northeastern University, and the Forging Industry Association. The team scaled up a laboratory-based, batch-type infrared (IR) furnace from ORNL to create an optimized, hybrid, continuous IR furnace for industrial forging. Demonstration of this IR furnace at the Queen City Plant reduced preheating times for aluminum forgings from 1-6 hours to 14-18 minutes. The infrared pretreatment was 75% more energy efficient than conventional ovens, and the system proved robust under industrial conditions. The IR furnace demonstrated a downtime of less than 5% over three years of use in preheating billets.

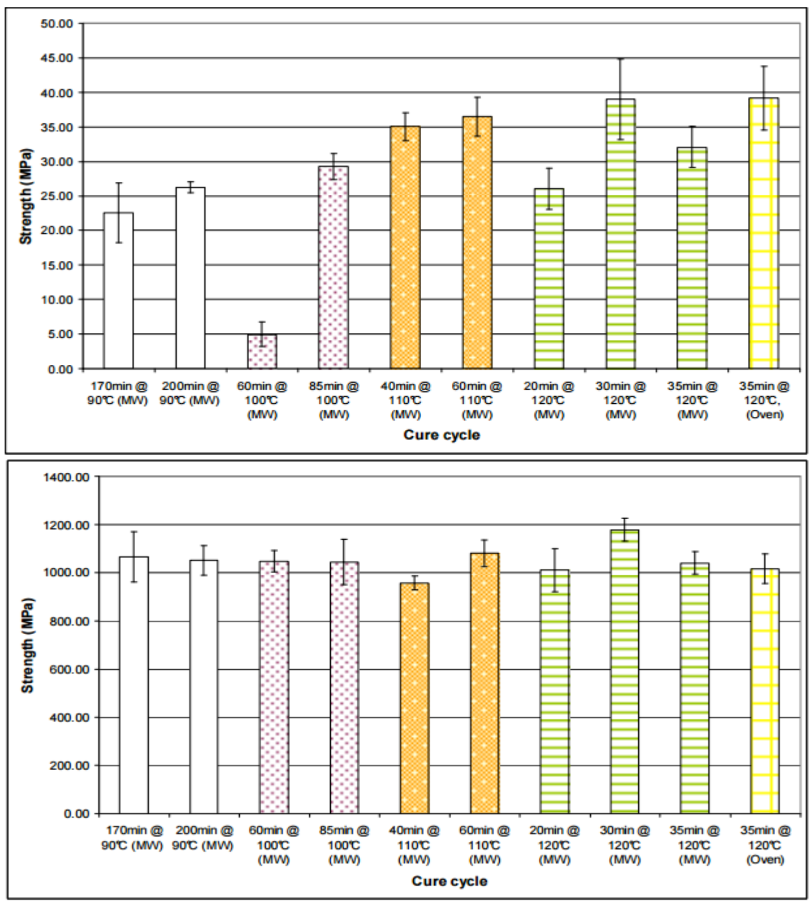
Figure 6.I.8 Continuous-belt IR heating furnace installed at Queen City Forging Company, Cincinnati, Ohio.[93]

Case Study: Curing of Composite Materials Using the HEPHAISTOS Microwave Processing System

The HEPHAISTOS (High Electromagnetic Power Heating Automated Injected STructures Oven System) microwave system was developed at the Karlsruhe Institute of Technology in Karlsruhe, Germany. This system uses microwaves for the curing of composite materials, and provides an alternative to conventional process heating systems such as an autoclave or oven. The use of microwaves can reduce energy consumption by cutting down on thermal losses in the process heating step while achieving similar tensile strength in the finished materials.[95]

Current models of the HEPHAISTOS system can achieve up to 75% energy savings in comparison to a conventional process heating system and can cut down on processing time by up to 50%. This is because microwave systems heat the product directly, and not the chamber, resulting in significantly better thermal efficiency compared to fuel-fired systems.[96]

Figure 6.I.9 Comparative tensile strength tests for oven-cured (yellow) and microwave-cured (other colors) composite samples, demonstrating similar performance. The top chart shows 90° tensile tests and the bottom shows 0° tensile tests.[97]



The most recent iteration of this system is the VHM (Vötsch Hephaistos Microwave). In testing with carbon-fiber reinforced pre-preg laminates, the microwave-cured samples showed similar tensile test results when compared with an oven-cured sample. Figure 6.I.9 shows the results of these tests for 90° (perpendicular to fibers) and 0° (parallel to fibers) tensile tests. The right-most yellow bar shows the results of the oven-cured sample, and the other bars show the results from the VHM system for various cure cycles, demonstrating statistically comparable performance.[97]

Endnotes

1 *Manufacturing Energy and Carbon Footprints* (2010 MECS), U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: -energy-and-carbon-footprints-2010-mecs; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

2 *Sankey diagram of energy flow in U.S. manufacturing,* U.S. DOE Office of Energy Efficiency & Renewable Energy, available from: http://energy.gov/eere/amo/sankey-diagram-energy-flow-us-manufacturing. The data source for the Sankey Diagram is the DOE/AMO Manufacturing Energy and Carbon Footprints (2010 MECS).

3 *Manufacturing Energy and Carbon Footprints* (2010 MECS), U.S. DOE Office of Energy Efficiency & Renewable Energy, available from: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs; 2010 *Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available from: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf.

Additional detail of the process heating energy consumption of U.S. manufacturing sectors, using data from the 2006 EIA *Manufacturing Energy Consumption Survey*, is available in U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis, prepared by Energetics Inc. for Oak Ridge National Laboratory, ORNL Report ORNL/TM-2012/504, November, 2012. Appendix F of this report also details the methodology used to estimate the process heating losses shown in this table.

4 Ibid

5 *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis*, Energetics Incorporated for Oak Ridge National Laboratory, prepared for the U.S. Department of Energy, Industrial Technologies Program, 2012. Appendix F of the 2013 report U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis provides a detailed examination of the methodology used to determine these process heating losses Available at: http://www.energy.gov/eere/amo/downloads/us-manufacturing-energy-use-and-greenhouse-gas-emissionsanalysis.

6 Dynamic Manufacturing Energy Sankey Tool, U.S. DOE Office of Energy Efficiency & Renewable Energy, available from: http://energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

7 *Sankey diagram of energy flow in U.S. manufacturing*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available from: http://energy.gov/eere/amo/sankey-diagram-energy-flow-us-manufacturing. The data source for the Sankey Diagram is the DOE/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; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

9 *Improving Process Heating System Performance: A Sourcebook for Industry*, Second Edition, U.S. Department of Energy, Industrial Heating Equipment Association (IHEA), 2007. Available at: http://www.nrel.gov/docs/fy08osti/41589.pdf.

10 *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; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

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; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

12 *Improving Process Heating System Performance: A Sourcebook for Industry*, Second Edition, U.S. Department of Energy, Industrial Heating Equipment Association (IHEA), 2007. Available at: http://www.nrel.gov/docs/fy08osti/41589.pdf.

13 "Waste heat to power – Economic tradeoff and consideration," presented by Dr. Arvind Thekdi, E3M Inc., 3rd Annual Waste Heat to Power Workshop 2007, September 25, 2007, Houston, TX.

14 Chapas, R.B. and Colwell, J.A., "Industrial Technologies Program Research Plan for Energy-Intensive Process Industries," prepared by Pacific Northwest National Laboratory for the U.S. DOE (2007), available from: http://www1.eere.energy.gov/manufacturing/pdfs/itp_research_plan.pdf. Energy use scaled to *2010 Manufacturing Energy and Carbon Footprints* (2010 MECS) data.

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; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

16 For discussion on the issues of NO_x the following references describe conditions for formation and/or approaches to reduce NO_x formation:

- Everything You Need to Know About NO_x, By Charles Baukal, Director of R&D, John Zinc Co. LLC, Tulsa, Okla., Available at: http://www.materialstoday.com/metal-finishing/features/everything-you-need-to-know-aboutnitric-oxides/

- Alternative Control Techniques Document – NOx Emissions from Process Heaters, U.S. Environmental Protection Agency, EPA-453/R-93-034. Available at: https://www3.epa.gov/ttncatc1/dir1/procheat.pdf
- An Overview of Technologies for Reduction of Oxides of Nitrogen from Combustion Furnaces, Ron D. Bell, P.E., MPR Associates, Inc., Fred P. Buckingham, Ph.D., P.E., MPR Associates, Inc., Available at: http://www.mpr.com/uploads/news/nox-reduction-coal-fired.pdf
- U.S. Department of Energy. "Waste Heat Recovery: Technology and Opportunities in U.S. Industry." March 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed April 2016).

[17] Electrotechnology Applications in Industrial Process Heating. EPRI, Palo Alto, CA: 2012 1024338.

[18] DOE. “Improving Process Heating System Performance – A Sourcebook for Industry, 3rd Edition.” In production, publication anticipated 2016.

[19] Cresko, J.W. “Fundamentals and Application of Dielectric Heating Technologies For Materials Processing: A review,” Microwave Solutions for Ceramic Engineers; Clark, D.E. (editor), Wiley 2005 ISBN: 978-1-57498-224-4

[20] Note – these frequencies and those used in radio frequency applications are designated as ISM bands (Industrial, Scientific, and Medical)

[21] Roy, Rustom, Dinesh Agrawal, Jiping Cheng, and Shalva Gedevanishvili. "Full sintering of powdered-metal bodies in a microwave field." Nature, 1999: 668-670.

[22] Cresko, J.W., “Method of Induction Curing Conductive Carbon Fiber Composites with Radio Frequency Energy” Proceedings of the 3rd World Congress on Microwave and Radio Frequency Processing, Sydney, Australia September 22-26, 2002.

[23] Ambrell. "About Induction Heating.". n.d. http://pdfo.ambrell.com/411-0169-10.pdf?__hssc=167356385.2.1459878229878&__hstc=167356385.20189c287338203b63ce84dcd0f53bb4.1459878229877.1459878229877.1459878229877.1&__hsfp=1102690733&hsCtaTracking=071571f9-2d4c-4972-b197-919c68121865%7C05699bcb-8277-4aa8 (accessed April 2016).

[24] Agrawal, Dinesh; “Microwave sintering of ceramics, composites, metals, and transparent materials,” *Journal of Materials Education*, Volume 19, 1997.

[25] For information about the Microwave Assisted Plasma (MAP) process that combines the carbonization, graphitization, and surface treatment process steps with a signal processing step for the manufacture of carbon fiber, see: http://techportal.eere.energy.gov/technology.do/techID=672

[26] Polshettiwar, Vivek; Varma, Rajender; and Kappe, Oliver *Aqueous Microwave-Assisted Chemistry, Chemistry and Sustainability,* Volume 3, Issue 9, page 1085, September 2010.

[27] Leonelli, C. and Mason, T.J. “Microwave and ultrasonic processing: now a realistic option for industry,” *Chemical Engineering and Processing* 49 (2010) 885-990.

[28] Z. Z. Fang, S. Middlemas, J. Guo, and P. Fan, “A new, energy-efficient chemical pathway for extracting Ti metal from Ti minerals,” J*ournal of the American Chemical Society* 135 (2013) 18248-18251.

Industrial Combustion Technology Roadmap – A Technology Roadmap by and for the Industrial Combustion Community. This roadmap document was prepared by Energetics Incorporated based on input provided by participants in an August 2001, facilitated workshop, October 2002.

[29] Hill, J.M. and Marchant, T.R. “Modelling microwave heating,” Applied Mathematical Modelling, Elsevier, Vol. 20, Issue 1, January 1996. Article can be accessed here: http://www.sciencedirect.com/science/article/pii/0307904X9500107U

[30] See, for example, efforts to improve computational approaches of microwave heating applications by the Industrial Microwave Modeling Group at WPI: http://www.wpi.edu/academics/math/CIMS/IMMG/

[31] DOE. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Chemical Manufacturing. June, 2015. Can be accessed here: http://www.energy.gov/eere/amo/downloads/bandwidthstudy-us-chemical-manufacturing

[32] Ng, S.; Fairbridge, C.; Mutyala, S.; Liu, Y.; Bélanger, J. R.; Paré, J. R. J. “Microwave-Assisted Conversion of Ethane to Ethylene,” Applied Petrochemical Research, vol. 3, 2013; pp. 55-61.

[33] Fall, M.; Wagner, E.; Cabe, F.; Eagleson, G.; Carnahan, J.; Lal, R., et al., “Microwave Enhanced Cracking of Ethane for Ethylene Production,” presented at the 24th Annual Ethylene Producers Conference, Houston, Texas, 2012.

[34] See for example:

- Microwave Pastuerization http://microwavepasteurization.wsu.edu/
- U.S. FDA - http://www.fda.gov/Food/FoodScienceResearch/SafePracticesforFoodProcesses/ucm100250.htm

[35] Norris, Robert E., Christopher J. Janke, Cliff Eberle, and George E. Wrenn. "Electron Beam Curing of Composites Overview." Society of Automotive Engineers. 2000. http://web.ornl.gov/~webworks/cpr/pres/105990.pdf (accessed March 2016).

[36] Song, R. G., K. Zhang, and G. N. Chen. "Electron beam surface treatment. Part I: surface hardening of AISI D3 tool steel." Chinese Academy of Sciences. August 2002. http://sourcedb.cas.cn/sourcedb_imech_cas/zw/lwk1/200908/P020090831401568487068.pdf (accessed March 2016).

[37] For examples of high performance computing (HPC) as applied to manufacturing problems, see the DOE announcements "High-Performance Computing for Manufacturing (HPC4Mfg) Program" (http://energy.gov/eere/articles/energy-department-announces-ten-new-projects-apply-high-performancecomputing) led by Lawrence Livermore National Laboratory (LLNL), with partners Lawrence Berkeley National Laboratory (LLNL) and Oak Ridge National Laboratory (ORNL). Examples of HPC as applied to process heating problems (https://hpc4mfg.llnl.gov/proposal-call.php) include:

- "High Performance Computing Analysis for Energy Reduction of Industry Spray Drying Technology"
- "Development of Reduced Glass Furnace Model to Optimize Process Operation"

[38] U.S. Department of Energy. "Improving Process Heating System Performance: A Sourcebook for Industry." nrel.gov. 2007. http://www.nrel.gov/docs/fy08osti/41589.pdf (accessed March 2016).

[39] U.S. Department of Energy. "Preheated Combustion Air." November 2007. http://energy.gov/sites/prod/files/2014/05/f16/et_preheated.pdf (accessed March 2016).

[40] U.S. Department of Energy. "Reduced Energy Consumption Through the Development of Fuel Flexible Gas Turbines." May 2014. http://energy.gov/eere/amo/reduced-energy-consumption-throughdevelopment-fuel-flexible-gas-turbines (accessed March 2016).

[41] United Nations Environment Program. "Biomass Fired Fluidized Bed Combustion Boiler Technology." September 2007. http://www.unep.org/climatechange/mitigation/Portals/93/documents/EnergyEfficiency/FBC_30_sep_2007.pdf (accessed April 2016).

[42] U.S. Environmental Protection Agency. "Adapting Boilers to Utilize Landfill Gas: An Environmentally and Economically Beneficial Opportunity." December 2009. https://www3.epa.gov/lmop/documents/pdfs/boilers.pdf (accessed April 2016).

[43] Büttner. "Combination Burners From Büttner." n.d. http://www.buettner-energy-dryer.com/en/dryingsystems-burners-systems/drying-systems-combination-burners-multi-fuel-burners/ (accessed April 2016).

[44] Electrotechnology applications in industrial process heating, Electric Power Research Institute (EPRI), 2012.

[45] See, for example, efforts to improve computational approaches of microwave heating applications by the Industrial Microwave Modeling Group at Worcester Polytechnic Institute (WPI): http://www.wpi.edu/academics/math/CIMS/IMMG/

[46] Brown, J. A. "Intelligent Heat Transfer Management Through Individual Sootblowing Optimization." http://www.babcock.com. June 2014. http://www.babcock.com/library/Documents/BR-1907.pdf (accessed March 2016).

[47] Masoumi , Mir Esmaeil, and Zahra Izakmehri. "Improving of Refinery Furnaces Efficiency Using Mathematical Modeling." International Journal of Modeling and Optimization, 2011: 74-79.

[48] Linde. "CARBOJET®. High-speed gas injection for advanced heat treatment." lindeus.com. n.d. http://www.lindeus.com/internet.lg.lg.usa/en/images/2822_0915_CARBOJET_datasheet_lowres138_176816.pdf (accessed April 2016).

[49] *Improving Process Heating System Performance: A Sourcebook for Industry*, Second Edition, U.S. Department of Energy, Industrial Heating Equipment Association (IHEA), 2007. Available at: http://www.nrel.gov/docs/fy08osti/41589.pdf.

[50] Aerogels as Promising Thermal Insulating Materials: An Overview, Prakash C. Thapliyal and Kirti Singh, Journal of Materials, Volume 2014 (2014), Article ID 127049, 10 pages

[51] *Roadmap for Process Heating Technology – Priority Research & Development Goals and Near-Term Non-Research Goals to Improve Industrial Process Heating*, AHEA and DOE, March 2001. Available at: http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/process_heating_0401.pdf.

[52] National Energy Technology Lab, U.S. Department of Energy. "Crosscutting Technology Research Sensors and Controls Project Portfolio." April 2015. http://www.netl.doe.gov/File%20Library/Research/Coal/crosscutting%20research/CTR-Sensors-and-Controls-Project-Portfolio-2015.pdf (accessed March 2016).

[53] U.S. Department of Energy. "Furnace Pressure Controllers." September 2005. http://energy.gov/sites/prod/files/2014/05/f16/furnace_press_control_process_htgts6.pdf (accessed March 2016).

[54] U.S. Department of Energy. "Advanced Laser-Based Sensors for Industrial Process Control." June 2011. http://energy.gov/sites/prod/files/2013/11/f4/laser-based-sensors.pdf (accessed March 2016).

[55] Emerson Process Management. "Flue Gas Analysis as a Diagnostic Tool for Fired Process Heater Furnaces." http://www2.emersonprocess.com. 2013. http://www2.emersonprocess.com/siteadmincenter/PM%20Rosemount%20Analytical%20Documents/CMB_ADS_O2Analyzer_Refining_Flue_Gas_Analysis.pdf (accessed April 2016).

[56] U.S. Department of Energy. "Waste Heat Recovery: Technology and Opportunities in U.S. Industry." March 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed April 2016).

[57] Ibid

[58] Ibid

[59] Linnhoff March. "Introduction to Pinch Technology." 1998. http://www.ou.edu/class/che-design/adesign/Introduction%20to%20Pinch%20Technology-LinhoffMarch.pdf (accessed April 2016).

[60] *Improving Process Heating System Performance: A Sourcebook for Industry*, Second Edition, U.S. Department of Energy, Industrial Heating Equipment Association (IHEA), 2007. Available at: http://www.nrel.gov/docs/fy08osti/41589.pdf.

[61] U.S. Department of Energy. "Waste Heat Recovery: Technology and Opportunities in U.S. Industry." March 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed April 2016).

[62] Hurley, John P., and Charlene R. Crocker. "Very-High-Temperature Materials and Heat Exchanger Testing in a Pilot-Scale Slagging Furnace." n.d. https://www.netl.doe.gov/File%20Library/Events/2002/materials/hurley.pdf (accessed March 2016).

[63] U.S. Department of Energy. "Demonstration of a High-Temperature Corrosion-Resistant Coating for Recuperators." January 2001. http://www.nrel.gov/docs/fy01osti/27618.pdf (accessed April 2016).

[64] A. Sommers, et al., "Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems: A review", Applied Thermal Engineering (2010).

[65] See, for example, the Process Heating Assessment Survey Tool (PHAST), and the Process Heating Modeler Tool (PHMT), available for download here: https://ecenter.ee.doe.gov/Pages/default.aspx

[66] U.S. Department of Energy. "Waste Heat Recovery: Technology and Opportunities in U.S. Industry." March 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed April 2016).

[67] U.S. Department of Energy. "Oxygen-Enriched Combustion." September 2005. http://energy.gov/sites/prod/files/2014/05/f16/oxygen_enriched_combustion_process_htgts3.pdf (accessed March 2016).

[68] Krishnamurthy, Krish R. "Demonstration of a Novel, Low-Cost Oxygen Supply Process and its Integration with Oxy-Fuel Coal-Fired Boilers." May 2007. http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/42748-BOC-O2-supply-CAR-6th-CCSconference-2007.pdf (accessed March 2016).

[69] Industrial Oxygen: Its generation and use, Prakash Rao et.al., 2007 ACEEE Summer Study on Energy Efficiency in Industry.

[70] *Industrial Combustion Technology Review* – Oak Ridge National Laboratory (ORNL) Report by Arvind Thekdi, Klaus Hemsath, and Richard Martin, March 2007.

[71] U.S. Department of Energy. "Waste Heat Recovery: Technology and Opportunities in U.S. Industry." March 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed April 2016).

[72] *Industrial Combustion Technology Review* – Oak Ridge National Laboratory (ORNL) Report by Arvind Thekdi, Klaus Hemsath, and Richard Martin, March 2007.

[73] *IMPACTS – Industrial Technologies Program: Summary of Program Results for CY2008*, US DOE. August 2010. Available at htpp://www1.eere.energy.gov/manufacturing/about/pdfs/impacts2008_full_report.pdf

[74] See the article "Better Combustion for Power Generation," available at: https://www.ornl.gov/news/bettercombustion-power-generation

[75] *Industrial Combustion Technology Roadmap – A Technology Roadmap by and for the Industrial Combustion Community*. This roadmap document was prepared by Energetics Incorporated based on input provided by participants in an August 2001 facilitated workshop, October 2002.

[76] Ibid

[77] Ibid

[78] Ibid

[79] Ibid

[80] *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; *2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions*, U.S. DOE Office of Energy Efficiency & Renewable Energy, available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf

[81] *Industrial Combustion Technology Roadmap* – A Technology Roadmap by and for the Industrial Combustion Community. This roadmap document was prepared by Energetics Incorporated based on input provided by participants in an August 2001 facilitated workshop, October 2002.

[82] Ibid

[83] Ibid

[84] Ibid

[85] U.S. Department of Energy. "Joint Fuel Cell Technologies and Advanced Manufacturing Office Webinar." November 20, 2012. http://energy.gov/sites/prod/files/2014/03/f11/webinarslides_fct-amo_mfg_112012.pdf (accessed May 2016).

[86] Redox Power Systems. "Affordable, High Performance, Intermediate Temperature, Solid Oxide Fuel Cells." June 11, 2015. https://www.hydrogen.energy.gov/pdfs/review15/fc115_blackburn_2015_o.pdf (accessed May 2016).

[87] University of South Carolina. "Development of Ultra-low Doped-Pt Cathode Catalysts for PEM Fuel Cells ." June 9, 2015. https://www.hydrogen.energy.gov/pdfs/review15/fc088_popov_2015_o.pdf (accessed May 2016).

[88] Pacific Northwest National Laboratory. "Development of 3rd Generation Advanced High Strength Steels (AHSS) with an Integrated Experimental and Simulation Approach." June 16, 2014. http://energy.gov/sites/prod/files/2014/07/f17/lm082_sun_2014_o.pdf (accessed May 2016).

89 Pacific Northwest National Laboratory. "Enhanced Room-Temperature Formability in High-Strength Aluminum Alloys through Pulse-Pressure Forming (PPF)." June 11, 2015. http://energy.gov/sites/prod/files/2015/06/f24/lm079_davies_2015_o.pdf (accessed May 2016).

90 American Iron and Steel Institute. "A Novel Flash Ironmaking Process." energy.gov. May 28, 2015. http://energy.gov/sites/prod/files/2015/06/f22/R8-AMO%20Peer%20Review%20May%2028-29%202015%20_EE0005751%20Flash%20Ironmaking.pdf (accessed May 2016).

91 U.S. Department of Energy. "Energy Intensive Processes Portfolio: Addressing Key Energy Challenges Across U.S. Industry." 2011. http://energy.gov/sites/prod/files/2014/01/f6/eip_report.pdf (accessed 2016).

92 U.S. Department of Energy. "Induction Consolidation/Molding of Thermoplastic Composites Using Smart Susceptors." May 2011. http://www.temperinc.com/images/consolidation_thermoplastic_1_.pdf (accessedMay 2016).

93 "Infrared Billet Heating Technology Enables Production of Low Cost Diesel Engine Rotors," Oak Ridge National Laboratory (ORNL), Fact Sheet. Available at: http://web.ornl.gov/sci/ees/itp/documents/FS_QC_Impellers2010.pdf

94 Enhancement of Aluminum Alloy Forgings through Rapid Billet Heating, US DOE, June 2006. Available at http://www.forging.org/system/files/field_document/Enhancement.pdf.

95 Feher, Lambert E., and Manfred K. Thumm. "Microwave Innovation for Industrial Composite Fabrication—The HEPHAISTOS Technology." IEEE TRANSACTIONS ON PLASMA SCIENCE, 2004: 73-79.

96 Vostch. "HEPHAISTOS VHM - Microwave technology for energy-efficent and fast production." n.d. http://www.voetsch-ovens.com/sixcms/media.php/2323/Flyer%20Mikrowelle%20FLAME%20E.pdf.

97 Kwak, M., P. robinson, A. Bismarck, and R. Wise. "Curing of Composite Materials Using the Recently Developed HEPHAISTOS Microwave." iccm-central.org. 2011. http://www.iccmcentral.org/Proceedings/ICCM18proceedings/data/2.%20Oral%20Presentation/Aug23(Tuesday)/T11%20Processing%20and%20Manufacturing%20Technologies/T11-2-IF1073.pdf (accessed April 2016).

98 Improving Process Heating System Performance: A Sourcebook for Industry, Second Edition, Available at http://www.nrel.gov/docs/fy08osti/41589.pdf

99 North American Combustion Handbook, Volume II, North American Manufacturing Company, Cleveland, Ohio.

100 Glossary of Energy-Related Terms – Office of Energy Efficiency & Renewable Energy, http://energy.gov/eere/energybasics/articles/glossary-energy-related-terms

101 Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities, Arvind Thekdi and Sachin Nimbalkar, ORNL Report 2014 - ORNL/TM-2014/622.

Acronyms

AMO	Advanced Manufacturing Office (of the U.S. Department of Energy)
BERL	Burner Engineering/Research Laboratory
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CMSs	Ceramic Matrix Composites (CMCs)
DOE	Department of Energy
FCC	Federal Communications Commission
GHG	Greenhouse Gas
GRI	Gas Research Institute
HPC	High Performance Computing
IGT	Institute of Gas Technology
MECS	Manufacturing Energy Consumption Survey
MMBtu	Million Btu
NAICS	North American Industry Classification System

ORNL	Oak Ridge National Laboratory
TBtu	Trillion Btu
Tonne	Metric ton (1,000 kilograms)
U.S.	United States
USGS	U.S. Geological Survey
WHR	Waste heat recovery

Glossary

Air/fuel ratio (a/f ratio)	The ratio of the air supply flow rate to the fuel supply flow rate when measured under the same conditions. For gaseous fuels, usually the ratio of volumes in the same units. For liquid and solid fuels, it may be expressed as a ratio of weights in the same units, but it is often given in mixed units such as cubic feet of air per pound of fuel.[98]
Available heat	The gross quantity of heat released within a combustion chamber minus the dry flue gas loss and the moisture loss. It represents the quantity of heat remaining for useful purposes (and to balance losses to walls, openings, and conveyors).[99]
Batch-type furnace	A furnace shut down periodically to remove one load and add a new charge, as opposed to a continuous-type furnace.
Blower	The device in an air conditioner that distributes the filtered air from the return duct over the cooling coil/heat exchanger. This circulated air is cooled/heated and then sent through the supply duct, past dampers, and through supply diffusers to the living/working space.[100]
Burner Capacity	The maximum heat output (e.g., in Btu per hour) released by a burner with a stable flame and satisfactory combustion.[99]
Combustion air	All of the air supplied through a burner other than that used for atomization.[98]
Direct resistance heating	This refers to systems that generate heat by passing an electric current (AC or DC) through a to-be-treated material that is reasonably conductive, causing an increase in temperature.
Emissivity	A measure of the ability of a material to radiate energy electromagnetically at a given wavelength. The ratio (expressed as a decimal fraction) of the radiating ability of a given material to that of a black body (a black body always emits radiation at the maximum possible rate and has an emissivity of 1.0).[98]
Excess air	The air remaining after a fuel has been completely burned; air is supplied in excess of the quantity required for complete stoichiometric combustion. A lean fuel/air ratio contains excess air, whereas a rich fuel/air ratio contains excess fuel.

Flue gas	All gases that leave a combustor (e.g., furnace, recuperator, regenerator) by way of the flue, including gaseous products of combustion, water vapor, excess oxygen, and nitrogen.[98]
Higher heating value (hhv)	Gross heating value—equal to the total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 60°F when combustion starts, and after the combustion products are cooled. See net or lower heating value.[98]
Hybrid process heating systems	Heating systems that utilize a combination of process heating technologies based on different energy sources and/or different heating methods to optimize their energy use and increase overall process thermal efficiency.
Indirect resistance heating and melting	This refers to systems in which an electrical current is passed through a resistor, and energy is transmitted to the work piece through convection and/or radiation.[100]
Induction heating	Induction heating occurs when passing alternating magnetic fields through conductive materials.
Infrared Heating	Heating done by passing an electrical current through a solid resistor, which in turn emits infrared radiation.[98]
Lower heating value (lhv)	Net heating value. The gross heating value minus the latent heat of vaporization of the water vapor formed by the combustion of hydrogen in the fuel. For a fuel with no hydrogen, net and gross heating values are the same.[98]
Preheated air	Air heated prior to combustion, generally transferring energy from the hot flue gases with a recuperator or regenerator.[98]
Recuperator	Equipment that uses hot flue gases to preheat air for combustion. The flue gases and airflow are in adjacent passageways so that heat is transferred from the hot gases, through the separating wall, to the cold air.[98]
Refractories	Highly heat-resistant non-metallic materials used to line furnaces, kilns, incinerators, and boilers.[98]
Regenerator	A cyclic heat interchanger, which alternately receives heat from a thermal source and then transfers that heat to a cold material.
Regenerative heating	The process of using heat that is rejected in one part of a cycle for another function or in another part of the cycle.[100]
Sensible heat	Heat for which the addition to or removal of will result in a temperature change, as opposed to latent heat which is a change in heat content that occurs with a change in phase and without change in temperature.[98, 100]
Smelting	The chemical reduction of a metal from its ore. Smelting separates impurities, allowing for their removal from the metal.[98]
Specific heat	The amount of heat required to raise a unit weight of a substance under a specified temperature and pressure without a change in phase.[98]

Susceptors	A material that absorbs electromagnetic energy at a specified wavelength or range of wavelengths; at sufficient power levels, the absorbed energy can be converted to useful heat. Based on this property, susceptors can be added to materials that are normally electromagnetically transparent (e.g., certain plastics), leading to a heating response.
Thermal efficiency	A measure of the efficiency of converting heat to energy and useful work. For calculating the thermal efficiency from combustion of fuel, useful work and energy output is divided by higher heating value of input fuel times 100 (for percent).[100]
Waste heat	Energy in the form of heat rejected or lost from a process. Some of this waste heat may be recovered or reused in another process providing it is of sufficient quality (i.e., hot enough and there is a use for it).[101]