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Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy

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and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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List of Abbreviations

AI	artificial intelligence
ANL	Argonne National Laboratory
bbl	barrel
BF	blast furnace
BOF	basic oxygen furnace
Btu	British thermal unit
CCUS	carbon capture and utilization system
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
DOE	US Department of Energy
DRI	direct-reduced iron
EAF	electric arc furnace
EIA	US Energy Information Administration
EM	electromagnetic
GHG	greenhouse gas
H_2	hydrogen
HCFC	hydrochlorofluorocarbon
IoT	Internet of Things
IR	infrared
kg	kilogram
kWh	kilowatt-hours
lb	pound
LBNL	Lawrence Berkeley National Laboratory
MECS	Manufacturing Energy Consumption Survey
MMBtu	million British thermal units
MMT	million metric tons
MT	metric tons
MW	microwave
MYPP	Multi-Year Program Plan
N_2O	nitrous oxide
NAICS	North American Industry Classification System
NO_x	nitrogen oxides
NREL	National Renewable National Laboratory
ORC	organic Rankine cycle
ORNL	Oak Ridge National Laboratory
Q&A	questions and answers
R&D	research and development
RAPID	Rapid Advancement in Process Intensification Deployment
RD&D	research, development, and demonstration
RF	radio frequency
RO	reverse osmosis
SCADA	supervisory control and data acquisition

SRNL	Savannah River National Laboratory
TBtu	trillion British thermal units
TES	thermal energy storage
TPI	thermal process intensification
TRL	technology readiness level
US	United States
UV	ultraviolet

Executive Summary

The US Department of Energy's (DOE's) Advanced Manufacturing Office held the virtual workshop entitled "Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy" in November and December 2020. The workshop brought together participants from universities/laboratories, industries, equipment manufacturers, technology vendors, nongovernmental organizations, and subject-matter experts to discuss transformative technologies and strategies to substantially improve the performance (e.g., energy productivity, thermal efficiency, reduced greenhouse gas [GHG] emissions, reduced number of process steps) of thermal processing systems in the industrial sector.

The US industrial sector accounts for 32% of the nation's primary energy use (including feedstocks), and refining, chemicals, pulp and paper, iron and steel, and food products represent the top energy-consuming sectors. Thermal processing or process heating represents the largest energy use category; it accounts for 63% of all energy use in manufacturing.[1] Additionally, thermal processing is the largest contributor of carbon dioxide (CO_2) generation, resulting from combustion of fuels and process related chemical reactions, such as in the case of cement and lime production. The challenge of achieving net-zero industrial GHG emissions is colossal considering the established industrial base that depends mainly on carbon-based processes and energy sources; the time frame and cost to replace carbon-based energy sources and feedstocks; and the long-term outlook for development with large-scale adaptation of alternative non-carbon–based technologies.

The goals of the DOE Advanced Manufacturing Office Thermal Process Intensification Workshop were as follows:

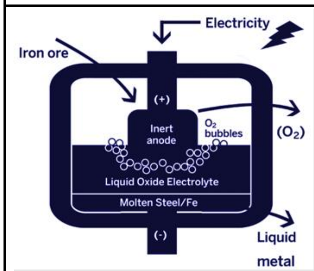
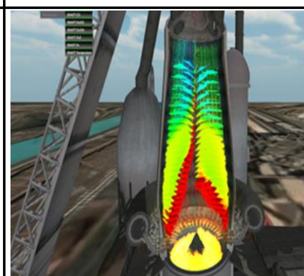
- Identify R&D gaps and opportunities to facilitate transformative improvement in industrial thermal processes beyond current technologies and allow for entirely new methods for processing materials.
- Gain insight into new and innovative approaches to thermally intensify processes, reduce heat demand, harness waste heat, and use fuels and hydrocarbon feedstocks more efficiently.
- Identify the R&D pathways to thermal process intensification (TPI) with the highest potential for impact and adoption by the industrial sector.
- Define areas of research, development, and demonstration (RD&D) activities to accelerate development and application of emerging and transformative technologies to intensify thermal processes in industry.

The scope and focus of the workshop were defined to meet these goals. Based on the available data for energy use and GHG emissions, the industries that collectively use more than 80% of the total process heating energy consumption were selected as primary focus areas. The chosen

[1] DOE (US Department of Energy). 2015. *Improving Process Heating System Performance: A Sourcebook for Industry*. Third Edition.

industries were combined into the following four groups based on similarities in their thermal processes: high-temperature metal processing (iron and steel industry, alumina-aluminum industry); high-temperature nonmetal and mineral processing (cement and glass industry); medium- to low-temperature thermal processing (food processing and pulp and paper industry as part of forest products sector); and hydrocarbon processing (petroleum refining and chemical industry). Furthermore, all potential TPI technologies associated with the processes defined were considered as part of the workshop. Different types of TPI technologies possible in industrial thermal systems were categorized into four TPI pillars, which are laid out as a framework in Table ES1.

Table ES1. Industrial Thermal Process Intensification Technology Pillars (TPI Pillars)

Low–thermal budget transformative technologies (mid- to long-term)	**Alternative thermal processing (near- to mid-term)**	**Transformative supplemental technologies (near-term)**	**Waste heat management technologies (near-term)**
Technologies that may use alternative energy sources while offering disruptive changes in the current production methods (e.g., electrolysis and electrodialysis)	Technologies that use an alternative source of energy while maintaining the current production methods to gain more flexibility/control (e.g., induction and resistance furnaces)	Emerging energy efficiency and supplemental technologies that reduce thermal demand (e.g., smart Internet of Things devices for system optimization)	Emerging waste heat reduction, recycle, and recovery technologies (e.g., thermoelectric devices and heat pipes)
 Metal oxide hydrolysis[2]	 Induction melting furnace[3]	 Virtual blast furnace[4]	 Direct-coupled regenerative burners[5]

The Thermal Process Intensification Workshop was held over seven virtual sessions—a plenary session and six brainstorming breakout sessions—in November and December 2020. More than 120 individuals representing researchers, academia, manufacturers, end-users, government, and other stakeholders attended the plenary session, and an average of 70 individuals participated in the six brainstorming sessions that followed. The sessions leveraged the unique collaboration capabilities of a virtual environment to identify and assess the opportunities for improved thermal efficacy and the R&D needed to overcome barriers to scale up across a wide range of technology maturities and manufacturing scales.

In preparation for the workshop, an in-depth literature review of available TPI technologies was performed by the workshop team. This review, compiled for each industry, served as a starting

[2] Boston Metal. Metal Oxide Hydrolysis (MOE). https://www.bostonmetal.com/moe-technology/
[3] Inductorterm. Steel Frame Furnace. https://www.inductotherm.com/products/steel-frame-furnaces/
[4] Chenn Q. Zhou, Purdue University Northwest. "Simulation and Visualization for steel manufacturing". DOE Thermal Process Intensification Workshop, Session 5.
[5] Dave Schalles, Bloom Engineering. "Industrial Waste Heat Recovery - Advanced and Emerging Technologies". DOE Thermal Process Intensification Workshop, Session 6.

point for the brainstorming discussions and individual follow-up with participants. In addition to identifying TPI technologies and its barriers, the sessions also examined the broader role TPI can play in enhancing the energy efficiency, energy flexibility, productivity, and long-term manufacturing sustainability/resilience of US manufacturing operations. An extensive list of the RD&D activities identified, along with the insights gained on the technology and the industry, is provided in Section 5.

The following list highlights the areas of research with most potential and associated R&D needs identified from the discussions during the workshop; these are grouped under the respective workshop TPI pillars.

Early stage research in low–thermal budget technologies:

- There is a need to develop alternative non-carbon or low-carbon technologies for processing naturally available raw materials (i.e., iron ore, bauxite, calcium carbonite) to produce commodities. These naturally available materials require the reduction (oxygen removal) process, which is traditionally done by using carbon-based reducing agents. Alternative methods include the use of non-carbon–based reducing agents such as hydrogen or the electrolysis process.

- Non-heat–based technologies that rely on mechanical vibrations (contact and non-contact ultrasound), advanced membrane (reverse osmosis [RO] and ultrafiltration), and other non-thermal techniques have shown great results in applications with low/medium-temperature drying and separation processes. Potential exists to expand their usage, leading to a drastic reduction in the thermal demand in these operations.

- Electromagnetic (EM) radiations (microwave [MW] and radio frequency [RF]) interact with materials in fundamentally unique ways, leading to energy and quality improvements. Processing with EM radiations has drastically reduced the heat demand for annealing, sintering, and drying applications in different industries. Many of the technologies discussed in this document under the EM radiation processing category are at the concept stage or in early stages of development and will require extensive RD&D and pilot testing to be deployed.

- Improving crosscutting low–thermal budget technologies (e.g., developing more efficient electrolysis for converting water to hydrogen[H_2]) show great promise and could have a much wider impact.

- Development of alternative manufacturing methods: Innovative methods such as additive manufacturing can play a role in eliminating or reducing thermal processing steps.

Increased use of alternative low-carbon fuels and electric heating applications:

- The use of electrical heating systems (i.e., induction, resistance) can lead to higher productivity and reduce losses given the improved controls and directionality that these systems intrinsically provide compared to traditional fuel-based systems. Furthermore, when driven from clean electricity, these systems can lead to carbon-free operations.

Currently, there is very limited (<5%) use of electric and hybrid-electric systems for thermal operations, which could drastically increase with proper incentives and education.

- Increased use of renewable fuels such as biogas and hydrogen are possible in most industries with the development of innovative processes that produce these fuels in a safe, reliable, and economically acceptable manner.

- Solar thermal applications have been successful in low/medium-temperature processes and can be more broadly adopted in certain regions in the United States.

Wider adoption of smart manufacturing technologies:

- Process simulation development can optimize the process performance, reduce energy use and CO_2 emissions, and achieve other benefits.

- Sensors and systems can be used for online continuous measurement of critical process parameters (i.e., oxygen, moisture, temperature) and system components for process heating equipment.

- Artificial intelligence (AI), deep learning algorithms, and additional tools can be used for improving consistency of performance of process heating equipment.

- Digital twins (virtual replicas of thermal equipment and processes) can be used to optimize operations and improve product quality.

- Tools for flexible manufacturing, including application of additive manufacturing, can be used to supplement or replace current practices.

Improvements to waste heat management technologies

- Design and material improvements that reduce heat loss from thermal processing system (e.g., furnace, oven, boiler) can benefit all industries.

- There is an enormous opportunity to use the waste heat generated from thermal processes.

    - When using the heat within the heat generating system itself (recycling), there is total synchronization between heat supply and heat demand.

    - Waste heat (recovery) outside the heating system can be used directly or may be converted into another form of energy such as steam, electricity, or mechanical power. There is no synchronization between heat (energy) supply and demand in this case. Waste heat can be recovered for use either within the plant boundary (on-site) or be exported outside the plant boundary (off-site).

Cross-cutting research on advanced materials:

- Substitution or reduced use of certain basic materials (i.e., cement, lime, glass) that require very high (>1,600°F) temperatures can reduce thermal demand and cut down on a large amount of the CO_2 emitted by the raw material. Similarly, potential exists to develop processes that use renewable resources such as biomass as raw material to replace fossil fuel–based raw materials in the production of chemicals and other products.

- RD&D in alternative catalysts to enhance performance and reduce energy intensity. Advancements in catalysts will significantly affect the pulping of paper and in the hydrocarbon industry.

- Development of alternative materials is needed to replace or enhance thermally activated processes, such as separation and drying, used in multiple industries.

- RD&D in advanced materials is needed for designing the next generation of thermal systems components (i.e., heat exchangers, insulations), as well as waste heat management systems.

Although these points represent opportunities to help the US manufacturers become technology leaders, improve their competitiveness, and reduce GHG emissions, many challenges and barriers are associated with the RD&D of current, emerging, and transformative TPI technologies and their scale up, as well as whole-system integration. A portfolio of RD&D initiatives, multigenerational plans, agile management, and durable support is recommended to face these challenges and drive progress. Table ES2 lists technical, economic, infrastructural, and institutional challenges and R&D opportunities.

Table ES2. TPI technology challenges, barriers, and R&D opportunities.

Category	Challenge/hurdle	RD&D opportunity
Technical	Applications of low–thermal budget technology and alternative energy sources, such as electricity, for high-temperature thermal processes are challenging and difficult to implement within the near future.	Drive RD&D on solutions; pilot, learn, and improve
Economic	The last 10% to 20% of efficiency improvements are challenging and may require long payback periods.	Improve economics of transformative supporting technologies to improve performance and reduce cost Optimize energy consumption across a broad scope via system- and facility-level application of new tools such as artificial intelligence
	RD&D and starting costs are high with long development and deployment timelines.	Provide investment incentives such as tax breaks and remove institutional and legal hurdles for collaborative RD&D efforts among the companies, institutions, and government research facilities

	Investment costs for rebuilding existing manufacturing clusters can be very expensive.	Strengthen and increase awareness of programs and incentives that foster private investment
Infrastructure	Replacement of current plant layout and infrastructure could be technically challenging and expensive.	Work with industrial clusters to make connections and lower implementation hurdles
	Development costs are too high for any one company; collaborative efforts are needed.	Initiate RD&D partnerships with multiple partners, funders, developers, and vendors
Institutional	Companies may lack in-house technical resources to drive transformative technology changes.	Educate and train workforces to implement and maintain advanced TPI technologies in manufacturing plants
	Industrial and engineering companies lack awareness and may need retraining with emerging and transformative technologies.	Use RD&D at clusters to make benefits and technical solution options more visible

Many projects are underway to address many of these challenges and barriers at national laboratories, research organizations, universities, research and development (R&D) facilities of equipment suppliers, and end-user industries.

A review of literature and feedback from the workshop attendees during brainstorming sessions confirmed the major barriers to implementing the results of many R&D activities. These barriers include time and expenses required for proof of concept or pilot/on-site testing under realistic operating conditions; scale-up to the production scale systems used in the plants; reluctance of the industrial plants to risk potentially disrupting operations; infrastructure modifications in operating plants; extensive testing of the product processed in the alternative process and production facilities; and time associated with regulatory approval requirements in some cases. Some of these barriers can be removed by collaborative efforts by public-private partnerships with DOE, and regulatory actions by government agencies.

1. Industrial Thermal Processes

Industry faces numerous barriers and challenges to reduce its energy and GHG footprint while meeting expanding societal needs and supporting growth of the community. Considering the scale of manufacturing across the United States, achieving lower energy intensity through the deployment of superior manufacturing technologies to reach net-zero industrial GHG emissions is a grand challenge, especially when including deployment of alternative energy sources and feedstocks while maintaining competitiveness of US industries.

Thermal processing of materials, commonly referred to as "process heating operations," involves supplying thermal energy to transform materials such as metal, plastic, rubber, limestone (cement), silica (glass), ceramics, and biomass into a wide variety of industrial and consumer products. Industrial heating processes include melting, drying, heat treating, curing, forming, calcining, and smelting.[1] Examples of common process heating systems include furnaces, ovens, dryers, heaters, kilns, and boiler/steam systems. These equipment systems are operated from 300°F to 3,000°F and require the use of heating systems (e.g., burners, electric heaters) to supply heat, a material handling system to transport materials through the heating system, advanced materials that can withstand high temperatures and challenging environments, controls, and other auxiliary systems. Most heating systems use fossil fuels (increasingly, natural gas is used in the US manufacturing sector and subsectors), which are significant sources of CO_2 emissions. Their thermal efficiencies (i.e., the ratio of energy used for material processing material to the gross energy input) range from 15% to 80%.[1]

TPI targets dramatic improvements in thermal processing (which includes process heating, CHP/cogeneration, and boilers) and associated functions commonly used in manufacturing by making existing thermal operation schemes more precise and efficient. Resulting improvements translate into reductions in energy intensity, GHG emissions, process steps, complexity, and facility footprint, thereby minimizing cost and risk in manufacturing facilities.

Thermal processing technologies can be grouped into four general categories based on the type of fuel consumed:

1. Fuel-fired systems,
2. Steam- or thermal fluid–heated systems,
3. Electrically heated systems using a variety of electro-technologies, and
4. Hybrid systems that use a combination of one or more energy types listed above.

These technologies rely on conduction, convection, or radiative heat transfer mechanisms—or some combination of these mechanisms—to transfer heat from the energy source to the material being processed.

Thermal processing systems are interconnected, and the major technology areas shown in Figure 1.[6] As shown in the figure, five technology areas affect the design and performance of thermal process systems used in the manufacturing sectors. These are as follows:

- **Sustainable manufacturing:** the creation of manufactured products through economically sound processes that minimize negative effects while conserving energy and natural resources
- **Combined heat and power (CHP):** integration of CHP with process heating equipment
- **Waste heat recovery systems:** waste heat recovery from process heating equipment; facility integration to enable reuse of exhaust gases in low-temperature processes
- **Advanced sensors, controls, platforms, and modeling for manufacturing:** sensors for monitoring process conditions, control systems for safe operations, product quality, and thermal system integration with allied manufacturing systems
- **Process intensification:** integrated control systems and process unit operations; replacement of batch operations with continuous operations resulting in increased energy productivity and energy efficiency

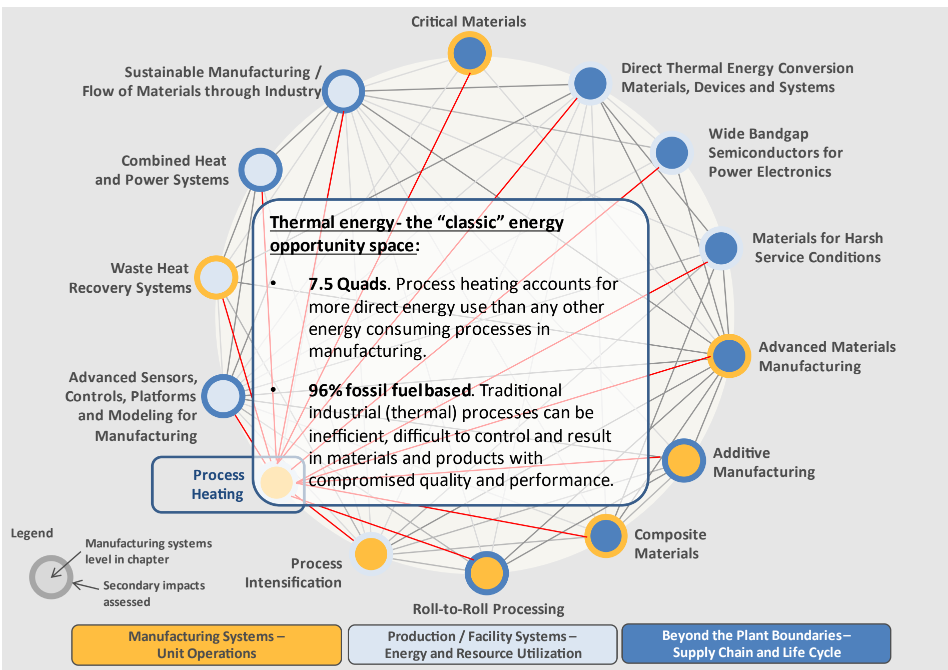


Figure 1. Interconnections among process heating and other important advanced technology areas.[6]

Thermal processing is carried out at different temperatures (Table 1a), and there are wide variations in energy source type and heating values (e.g., natural gas, fuel oil, by-product fuels,

[6] DOE (US Department of Energy). 2015. "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing Technology Assessments: Process Heating." In *Quadrennial Technology Review 2015*. – The figure from the original source has been updated with data for the process heating opportunity space from 2018 EIA's Manufacturing Energy Consumption Survey.

electricity), method of heat transfer from the source to the material processed, production capacity, equipment design (batch vs. continuous), operating temperature range, and method of process energy (heat) supply. These variations can be illustrated by an example of a drying process that involves removal of water or other solvents from a product by evaporating the liquid mixed with solids or powders. The fundamental mechanism of removing the liquid is to raise the temperature of the mixture and bring it to the liquid's boiling or vaporization temperature so that the liquid evaporates and is separated from the mixture. Drying is an important step used by almost all industries at some stage of the manufacturing process. It is a major process step for chemicals manufacturing, pulp and paper, and food manufacturing. However, the drying methods vary considerably depending on the scale or production capacity, product quality specifications and constraints, pressure, final product temperature, amount of moisture present in the mixture, and other considerations. The source of energy for drying depends on the method of drying and product-specific requirements. Drying of food products often requires separation of the heating source from the product itself, whereas drying of coatings on a metal strip or wet paper web can be performed in the presence of combustion products. Some examples of drying processes in the different industries are provided in Table 1b.

Table 1a. Types of thermal processes used for eight large energy consuming industries. Colors indicate upper-bound temperature range for a given application. Blue = low temperature (<800°F); yellow = medium temperature (800°F to 1,400°F); red = high temperature (>1,400°F).

Thermal process step	Iron and steel	Petroleum refining	Chemical industry	Glass	Aluminum	Pulp and paper	Food processing	Cement
Calcining	Red		Red		Red	Red		Red
Curing and forming			Blue	Red				
Drying	Blue	Blue	Yellow	Blue	Blue	Blue	Blue	Blue
Fluid heating		Yellow	Yellow			Blue	Blue	
Heat treating (metal and nonmetal)	Yellow			Yellow	Yellow			
Metal and nonmetal reheating	Red				Yellow			
Metal and nonmetal melting	Red			Red	Yellow			
Other heating: processing			Yellow					
Reactive thermal processing	Red	Yellow	Yellow	Red	Yellow	Blue		
Smelting, agglomeration etc.	Red		Yellow					
Steam generation	Yellow	Yellow	Yellow		Yellow	Yellow	Yellow	

Table 1a lists the most widely used thermal processes across different industries. The table uses color-coding to indicate the higher temperature range for each process in different industries. For example, reactive thermal processing of materials—which includes iron ore reduction, catalytic processes used in the petroleum refining and chemical industries, and the Kraft process in the pulp and paper industry—involves chemical reactions by heating the materials to the required temperature. The temperature can vary from less than 600°F for the pulp and paper industry to as high as 2,000°F for the iron ore reduction process in a blast furnace (BF).

Table 2b. Examples of drying processes in different industries

Industry	Application	Description	Temperature Range (°F)
Pulp and Paper	Drying of Pulp/ Paper	Typically done with heated cylinders where a heated surface in contact with paper causes water removal by evaporation. Can be gas-fired or steam heated.	250 - 800
	Biomass Drying	Drying of biomass fuel makes it appropriate for use in the furnaces. Commonly done using rotary dryers.	250 - 450
	Black Liquor Evaporation	Typically done in a multiple-effect evaporator. This dewatering step helps produce materials suitable for combustion in the recovery furnace.	270 - 500
Food and Beverage	Grain Drying	Depending on the type of grain and its quality, hot air in crossflow, concurrent flow, or mixed flow configuration is used to achieve drying.	212 - 260
	Drying of Fruits and Vegetables	The temperature range and the processing period depend on the fruit/vegetable processed. Air drying and continuous fluidized bed dryers are commonly used.	160 to 360
	Coffee/ Dairy - Spray Drying	Spray dryers achieve moisture removal by spraying the liquid into a hot vapor stream. Solids form as moisture quickly leaves the droplets.	350
Iron and Steel	Iron Ore Drying	Done as part of the ore beneficiation process to remove atmospheric moisture.	150 - 570
	Coal Drying	Can be done at the facility or the mines using steam. Waste heat from the facility or waste coal fines from the mine are typically used as the source of heat.	140
	Drying of Scrap	Drying of the scrap material is done to remove moisture and reduce load on the electric arc furnace. Belt and bucket drying techniques are employed.	220+
	Metal Finishing - Drying Powder Coating	Some steel products require drying and curing of powder coating as part of its finishing. Gas or electric powered IR drying systems are used in these applications.	400
Aluminum	Drying of Bauxite	A directly or indirectly heated rotary dryer, or kiln, is used to dry bauxite (the principal ore of aluminum). Direct-fired rotary dryers are more common.	212 - 300
	Preheat/ Dry Material Feedstock	Drying is achieved at the first stage of the main calcination furnace. The high temperature at the fluidized bed provides instantaneous water removal.	350
Cement	Raw material drying	Removal of moisture from raw materials is required for effective grinding and subsequent handling of raw meal. Typical achieved by exhaust gases from kiln.	600
Glass	Drying of Specialty Coatings and Inks	Infrared systems are used for curing and drying various types of inks and hard coatings. These require a drying oven with a high degree of control flexibility which is typically achieved by using infrared.	225-350
	Cullet Drying	Drying of cullet (recycled glass) is done to achieve the highest efficiencies in the separation process. Drum and vacuum drying are commonly used.	500
Chemicals	Fluidized Bed Evaporation - Salts	A fluid bed dryer is used to dry various bulk chemical products. Hot air at high pressure dries the product via direct contact by suspending it in a stream of air.	500 - 1400
	Plate dryers - Additives, lithium etc.	Stationary, horizontal plates in the dryer are heated while rotating arms with plows transport the product in a spiral pattern across the heated surface of the plates.	570
	Contact Drum Dryers – Viscous materials	In a drum dryer, products are dried by spreading them in a thin and uniform layer onto the heated surface. The heating medium is hot water, steam, or thermal oil.	570
	Spray drying of liquid chemicals	Achieves moisture removal by spraying the liquid into a hot vapor stream. Used in the drying of enzymes, paint pigments and pharmaceutical drugs.	250 to 300
Petro-chemicals	Drying of Product - Natural gas, Ethelene etc.	Typically done via molecular sieves and other desiccants to remove moisture in the final product. The desiccants are regenerated by hot air.	450 - 570
	Pretreatment of Feedstock	Moisture removal from feedstock is necessary for certain applications to protect water-sensitive catalyst in downstream conversion units and to prevent freezing in cryogenic systems.	450 - 570
Textiles	Drying of Fabric and Yawn	The drying of fabric is done using mechanical dewatering followed by hot air blowing. The drying of yarn sheet is commonly done by using drying cylinders and in some cases, it is coupled with hot air drying or infrared drying.	250 - 340

2. Energy and Greenhouse Gas Footprints of Industrial Thermal Processes

Industrial heat makes up two-thirds of industrial energy demand and almost one-fifth of global energy consumption.[7] It also constitutes most of the direct industrial CO_2 and other GHG emitted each year because most industrial heat originates from fossil fuel combustion. In the United States, GHG emissions associated with industrial thermal processes account for 32% of all industrial-sector emissions and 7% of total US emissions.[8] Because of the large contribution to GHG emissions, it is vital to carefully analyze the industrial thermal processes and identify solutions to reduce emissions associated with heat production.

The majority of industrial heat–related GHG emissions are concentrated in six energy-intensive basic material manufacturing sectors—steel, chemicals, cement, pulp and paper, aluminum, and oil refining—that produce more than 77% of global industrial emissions.[9] As more countries and companies are committing to net zero GHG emissions and setting carbon neutrality or deep decarbonization targets (e.g., using science-based targets), it is critical for companies, especially the ones with energy- and carbon-intensive production processes in their supply chain, to address the energy use and GHG emissions associated with process heating. Companies need to set up action plans on how to address the decarbonization of process heating in their supply chains to achieve their deep decarbonization goals.

Decarbonizing heat faces numerous challenges, including a wide range of specific temperature needs for industrial users. The technical applicability and economic viability of different process heating decarbonization pathways—such as end-use heat electrification, waste heat recovery technologies, CHP and waste heat to power, use of hydrogen as fuel, and application of other renewable thermal technologies—can vary significantly by process, plant, industry, and geography. Given the complexity of the industrial sector and dozens of different heterogenous subsectors with substantial differences in the way they use energy for heating, investigating and offering a suite of tools and solutions (instead of focusing on only one solution) is critical.

Energy Use and GHG Emissions

In 2014, thermal processes accounted for 74% of total manufacturing energy use in the United States, process heating for 35%, CHP/cogeneration for 26%, and conventional boilers for 13%[10] (Figure 2). Five industries account for more than 80% of all US manufacturing thermal process energy consumption: petroleum refining, chemicals, pulp and paper, iron and steel, and food and

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[7] International Energy Agency. 2018. Commentary: Clean and efficient heat for industry. Retrieved from https://www.iea.org/newsroom/news/2018/january/commentary-clean-and-efficient-heat-for-industry.html.

[8] Joint Institute for Strategic Energy Analysis. 2016. *Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions*. NREL/TP-6A50-66763. Retrieved from https://www.nrel.gov/docs/fy17osti/66763.pdf.

[9] Imperial College London Grantham Institute for Climate Change. 2012. *Reducing CO_2 emissions from heavy industry: A review of technologies and considerations for policy makers*. Retrieved from https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Reducing-CO2-emissions-from-heavy-industry---Grantham-BP-7.pdf.

[10] DOE (US Department of Energy). 2018. Manufacturing Energy and Carbon Footprints (2014 MECS). Retrieved from https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2014-mecs.

beverage.[11] Process heating, process cooling, machine drives, and other processes may use steam. We only report the energy use for steam under conventional boilers and CHP to avoid double counting.

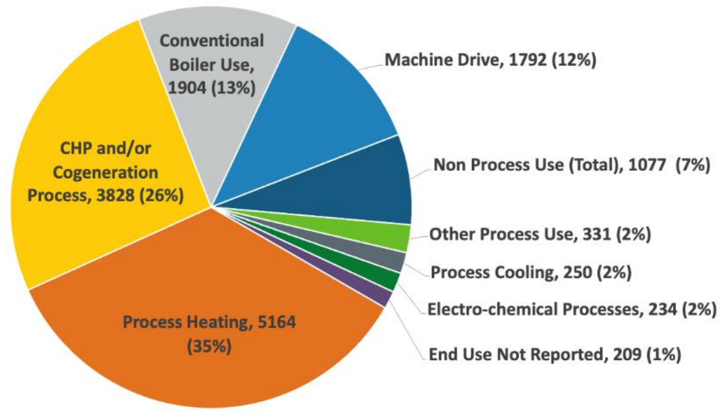


Figure 2. US manufacturing energy use by end uses (TBtu).[10]

Figure 3 shows the total GHG emissions from US manufacturing by end uses in 2014. Thermal processes combined (process heating, CHP/cogeneration, and boilers) still account for a large share of total GHG emissions, whereas the share of machine drive increases because of indirect GHG emissions from power generation associated with electricity used in machine drives.

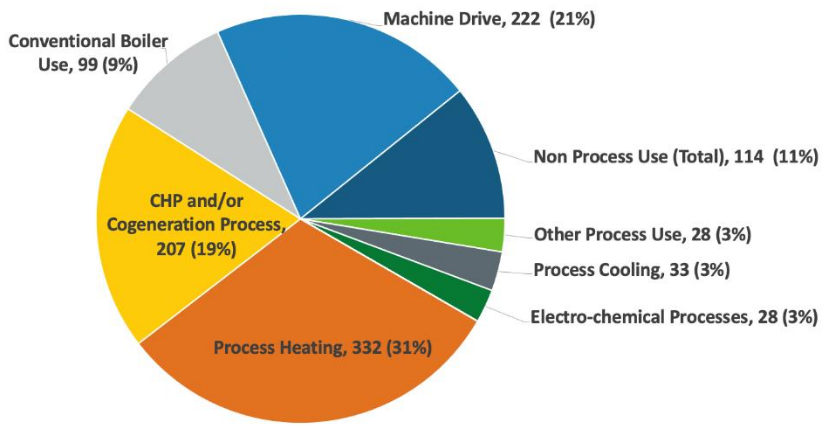


Figure 3. Total GHG emissions from US manufacturing by end uses (MMT CO_2e).[10]

Figure 4 shows energy consumed by industrial process heating systems distributed among the three sources (fuel, steam, and electricity). The process heating energy is mainly from fuel (63.8% of total) and steam (31.3%), and a relatively small percentage is from electricity (4.9%). In manufacturing plants where steam is used for process heating, steam is generated by using fuel or waste heat from fuel-fired systems. Historically, the energy mix for thermal processing in these industries has remained primarily fuel-based (fuel and steam) with very little change over the past century. Only a few new processes and other innovations have been made that changed

[11] EIA (US Energy Information Administration). 2014 MECS Survey Data. Retrieved from https://www.eia.gov/consumption/manufacturing/data/2014/.

the energy source from fossil fuel to electricity. Examples include electric arc furnaces (EAFs), vacuum furnaces, electric boost for glass melting, and plastic injection molding.

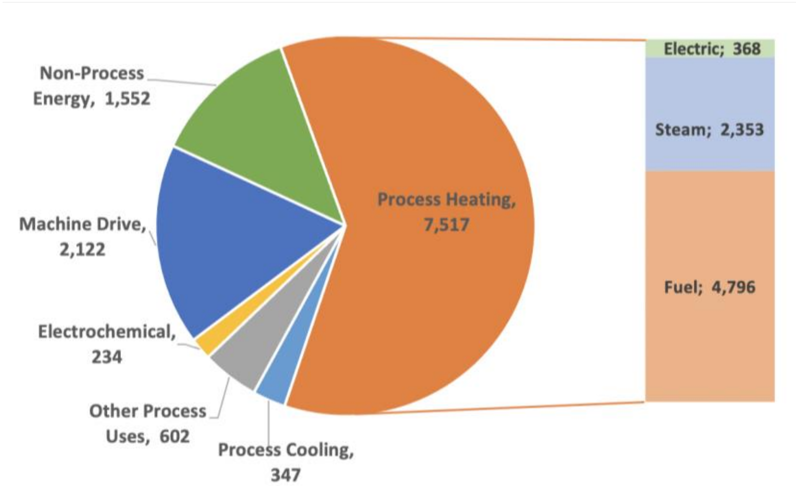


Figure 4. Total energy use in manufacturing (TBtu).[10]

Table 3 shows the onsite energy used for process heating applications (along with electrochemical process energy), associated energy losses, and emissions in the major industry sectors. These energy losses vary by industry; on average, an estimated 36% of process heating energy is lost in the entire manufacturing sector. A portion of these losses can be recovered, but another portion is thermodynamically unrecoverable.

Table 3. Major US manufacturing industries ranked by energy used for process heating (including electrochemical process energy) in 2014.[10]

Industry	NAICS codes	Process heating energy use (onsite) (TBtu/year)*	Percent of total US manufacturing process heating energy use (%)	Process heating energy losses (TBtu/year)*	Percent of total US manufacturing process heating energy loss (%)	Process heating related GHG emissions (onsite)† ($MMTCO_2e$)
Petroleum refining	324110	2,385	30.8%	430	16.1%	133.0
Chemicals	325	1,727	22.3%	410	15.4%	49.1
Forest products	321–322	917	11.8%	632	23.7%	8.9
Iron and steel	3311–3312	740	9.5%	334	12.5%	18.1
Food and beverage	311–312	484	6.2%	266	10.0%	10.8
Cement	327310	257	3.3%	113	4.2%	21
Alumina and aluminum	3313	178	2.3%	95	3.6%	4.0
Glass and glass products	3272, 327993	148	1.9%	82	3.1%	6.7
Fabricated metals	332	146	1.9%	51	1.9%	6.1
Transportation equipment	336	81	1.0%	27	1.0%	3.0
Plastics	326	77	1.0%	18	0.7%	1.3
Foundries	3315	76	1.0%	34	1.3%	2.1
Electronics	334, 335	58	0.7%	21	0.8%	1.4
Textiles	313 - 316	44	0.6%	24	0.9%	1.1
Machinery	333	30	0.4%	10	0.4%	1.0

† The onsite emissions represent the combustion related emission and does not consider offsite emissions

* Includes electrochemical process energy use/losses

The focus of AMO's Thermal Process Intensification Workshop was mainly on the top eight industry sectors with significant process heating energy use—petroleum refining, chemical, pulp and paper, iron and steel, food and beverage, cement, glass, and alumina and aluminum. In the United States, the energy consumed for thermal processing in these industries is roughly 95% the total energy consumed for thermal processing in all US industries.[10]

The total energy use is distributed among various categories such as process heating, electrothermal processes, machine drive, on-site steam and electrical power generation, and facilities. The energy used for thermal processes is supplied by fuel and steam or electricity. Figure 5 shows process heating energy consumption used by the industries distributed among the three sources (fuel, steam, and electricity), and the electrical energy used in the electrochemical process, which contributes to thermal processing in certain industries.

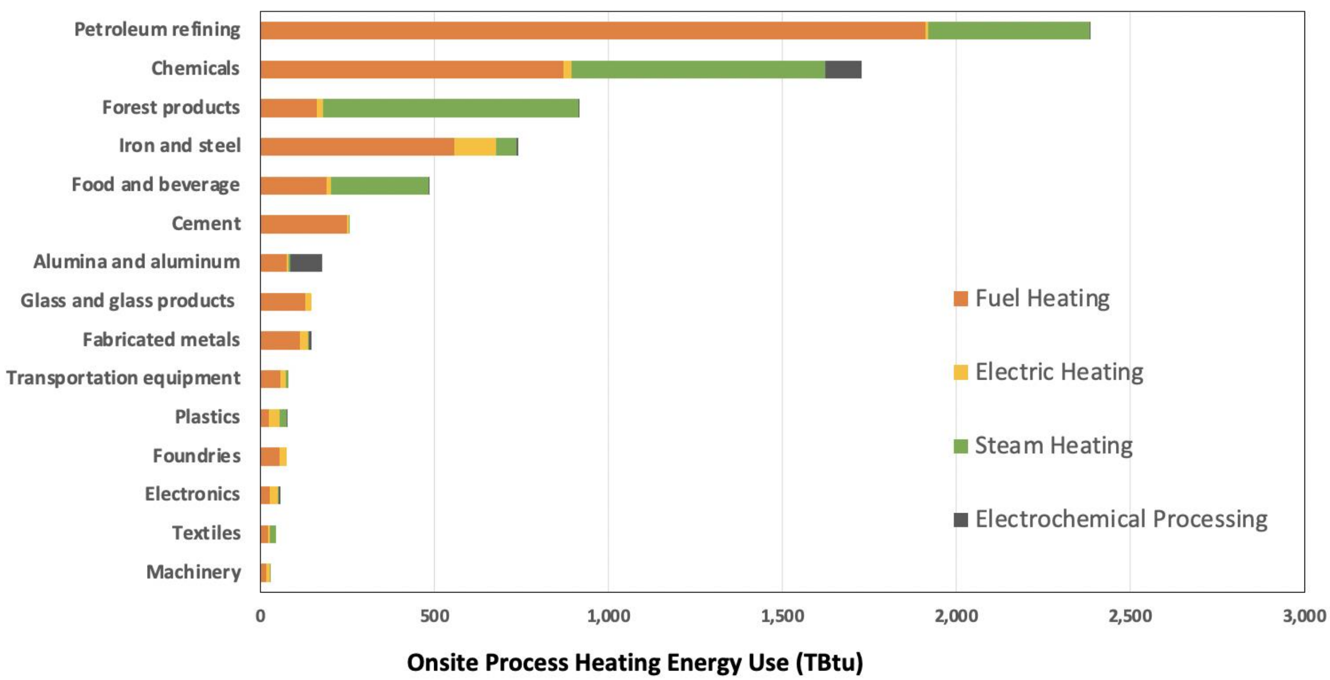


Figure 5. US process heating energy consumption by sectors.[11]

Industrial Processes and Product Emissions

In addition to energy related GHG emissions, some of the thermal processes also have GHG emissions associated with chemical processes and products involved. The industrial processes and product use categories included in this section are presented in Table 4[12]. GHG emissions from industrial processes can be considered in three categories:

1. Heating system with combustion generated GHG emissions
2. Reactive heating system using carbonaceous material for heat and reactions
3. Heating system using carbonaceous fuels and raw materials

[12] Source: Arvind Thekdi, E3M, Inc

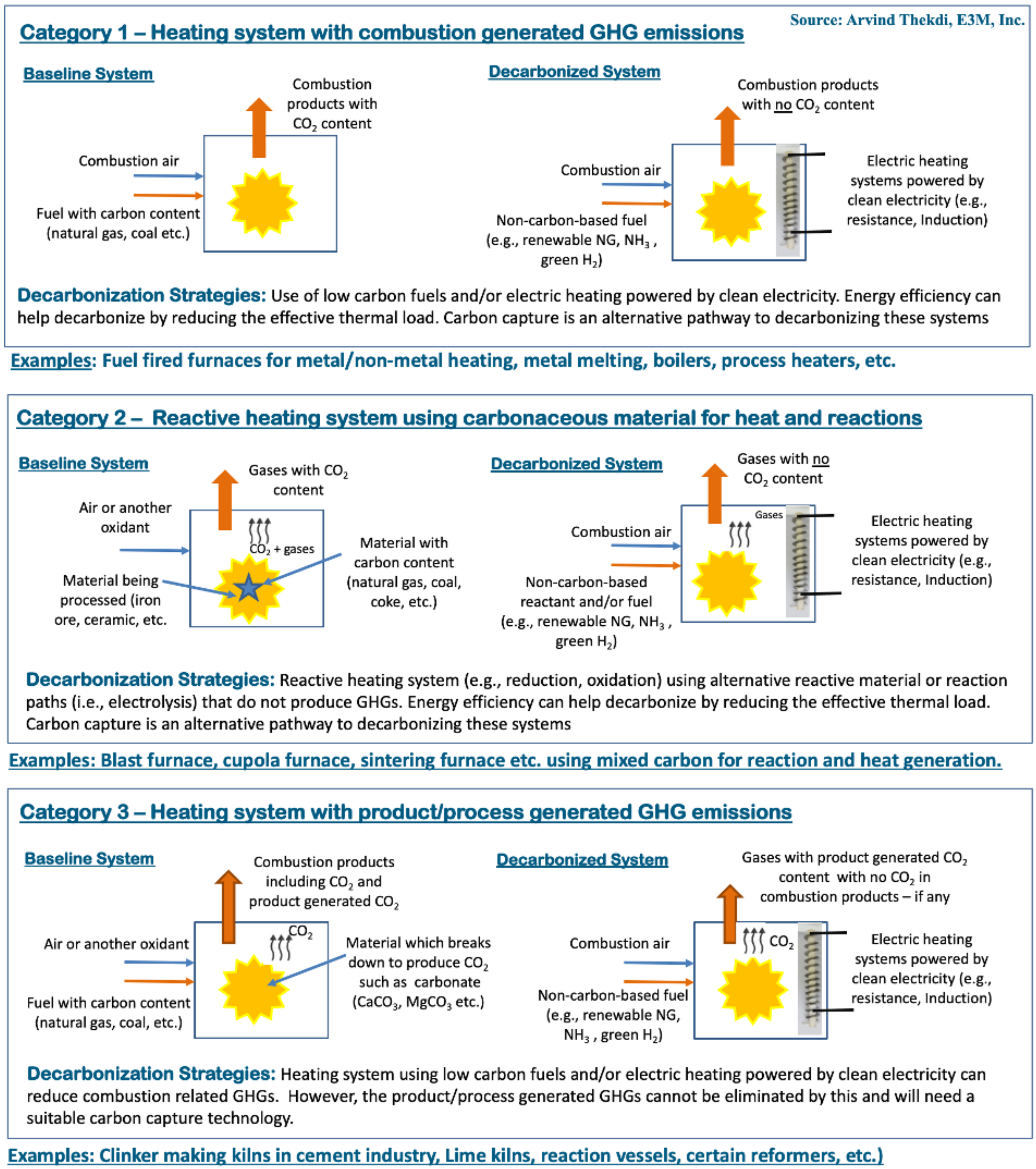


Figure 6. Different categories of GHG emissions from industrial processes.

In the case of categories 2 and 3, the GHG emissions are generated by the industrial processes and are not just a result of energy consumed during the processes. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of GHG emissions such as CO_2, methane (CH_4), nitrous oxide (N_2O), and hydrochlorofluorocarbon (HCFC) gases.[13] Note: The three categories represent the major modes of emissions associated with thermal processes. Some thermal applications could have an overlap between category 2 and category 3 making it difficult to categorize them in a single group, e.g., direct reduction of iron using hydrogen.

Table 4 shows the GHG emissions from major industrial processes and product uses reported by the US Environmental Protection Agency for various years.

Table 4. US GHG emissions from industrial processes and product use (MMT CO_2).[13]

Industrial processes and product use	1990	2005	2015	2019
Iron and steel production, and metallurgical coke production	104.8	70.1	47.9	41.3
Cement production	33.5	46.2	39.9	40.9
Petrochemical production	21.8	27.5	28.2	31.1
Ammonia production	11.7	14.6	13.3	13.0
Lime production	13.0	9.2	10.6	12.3
Adipic acid production	12.1	11.3	11.6	10.0
Other process uses of carbonates	6.3	7.6	12.2	7.5
Nitric acid production	3.8	3.7	4.6	6.6
Electronics industry	15.2	7.1	4.3	5.3
Carbon dioxide consumption	1.5	1.4	4.9	4.9
N_2O from product uses	3.6	4.8	5.0	4.6
Electrical transmission and Distribution	23.2	8.4	3.8	4.2
Urea consumption for non-agricultural purposes	4.2	4.2	4.2	4.2
HCFC-22 production	46.1	20.0	4.3	3.7
Aluminum production	28.3	7.6	4.9	3.6
Ferroalloy production	1.4	1.7	1.7	1.8
Soda ash production	2.2	1.4	2.0	1.6
Titanium dioxide production	1.2	1.8	1.6	1.5
Caprolactam, glyoxal, and glyoxylic acid production	1.7	2.1	1.9	1.4
Glass production	1.5	1.9	1.3	1.3
Magnesium production and processing	5.2	2.7	1.1	1.0
Zinc production	0.6	1.0	0.9	1.0
Phosphoric acid production	1.5	1.3	1.0	0.9
Lead production	0.5	0.6	0.5	0.5
Carbide production and consumption	0.4	0.2	0.2	0.2

Opportunity for Process Heating Market Assessment

As part of the TPI workshop, the ORNL team utilized various datasets to understand the energy consumption, GHG emission and operating efficiency of thermal process heating systems. The total energy used by process heating applications is made available through EIA's Manufacturing Energy Consumption Survey (MECS) and DOE's industry specific energy footprints (presented in section 2.1). The bandwidth studies gave valuable insight into the existing opportunity in different industries and the EPA datasets provided information on the GHG emissions. While these datasets provided valuable insight into the thermal processes in different industries, the team struggled to find energy performance data (thermal efficiency, combustion efficiency,

[13] EPA (US Environmental Protection Agency). 2020. Inventory of U.S. GHG Emissions and Sinks: 2010-2019. EPA 430-R-21-001. https://www.epa.gov/sites/production/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf

waste heat recovery, etc.) on existing process heating systems and equipment. An opportunity exists to develop supporting datasets that help frame a more holistic and deeper understanding of the thermal systems in manufacturing plants. The salient aspects of the recommendation from the workshop team are listed below.

- The TPI workshop identified a need for **conducting a process heating market study or assessment**. The process heating market assessment will involve the development and deployment of a common data collection framework that will allow for characterizing the energy efficiency of process heating equipment used in manufacturing operations.
- The recommended data collection framework will allow process heating equipment characterization using a common and easily understandable data collection and analysis methodology. Presently, the energy performance of heating equipment is expressed using a variety of terms such as thermal efficiency, combustion efficiency, unit energy use, energy intensity, etc. The framework will allow the collection of energy performance data and will express it in a common format for a variety of heating systems such as direct fuel-fired, indirect fuel-fired, electrically heated, hybrid, steam heated, etc.
- Performance analysis could be carried out by classifying the thermal processes into "generic" groups such as melting (metals, non-metals), fluid and solids heating, heat treating, steam generation, drying, etc. For each of this "class" of thermal processes, the proposed framework will identify a method for calculating their theoretical performance and current performance based on the data collected.
- The framework is intended to standardize the data collection to assure consistency across independently conducted surveys. Consistency allows the surveys to be leveraged against each other, enabling comparisons to heating system energy efficiencies across various industries with similar operations. For example, drying operation in one industry group may have the same end objective however they may differ significantly in energy efficiency, emissions, and cost per unit of production. A database using a common framework will enable policymakers and industry to better assess the improvement potential of their installed process heating system with respect to other industries, source of energy (i.e., electrical vs. fuel fired), operations (batch vs. continuous), or geographical locations. The efficiency differences and its causes will provide additional insights that promote improvements to the energy efficiency of process heating systems.
- The framework will be supplemented by exergy-based analysis of industrial process heating systems where applicable. The above-mentioned framework may help identify such processes where exergy-based analysis can justify the use of advancements in heating system configuration or design. The market assessment effort will also include the development and showcase of exergy methodology that efficiently manages fuel supplies for process heating (e.g., added conservation insights for "exergy-water-materials" nexus). The market assessment effort will try to demonstrate versatility of methodology with benchmarks against fuel-based, electric-based, and steam-based process heating systems including calcining, drying, curing and forming, and fluid heating.

3. Industrial Thermal Process Intensification Technology Pillars (TPI Pillars)

In the manufacturing of goods, the actual energy used for each process step is greater than what is theoretically required for the process because of the inefficiencies involved with the heat supply system (i.e., combustion of fuels or electrical power supply system), as well as losses associated with the thermal process equipment (e.g., furnaces, ovens). Changes can be made to the process to significantly reduce energy use by changing the process steps or modifying the process equipment to reduce losses or even recover part of the energy wasted from the process equipment. This can be achieved by four approaches:

- TPI Pillar 1: Low–thermal budget transformative technologies: These may use alternative energy sources while offering disruptive changes in the current production methods.
- TPI Pillar 2: Alternative sources of energy for thermal processing: These use alternative energy sources in manufacturing processes while maintaining the current production methods to gain more flexibility/control and eventually reduce energy/carbon intensities.
- TPI Pillar 3: Transformative supplemental technologies: These include emerging energy efficiency and supplemental technologies that reduce thermal demand use.
- TPI Pillar 4: Waste heat management technologies: These include emerging waste heat reduction, recycle, and recovery technologies, which allow for the use of the heat discharged from thermal processes. Figure 7 shows some examples for each pillar.

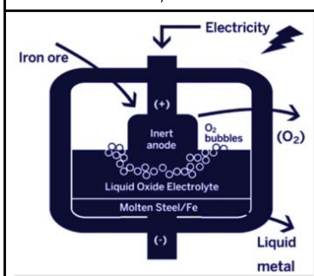
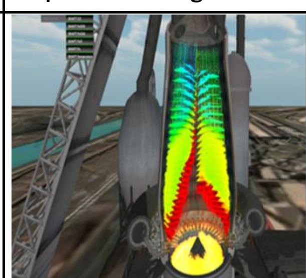
Low–thermal budget transformative technologies (mid- to long-term)	Alternative thermal processing (near- to mid-term)	Transformative supplemental technologies (near-term)	Waste heat management technologies (near-term)
• Electrolysis and electrodialysis • MW and RF processing • Ultrasound processing and membrane separation for drying • Hydrogen-based production of ammonia, methanol etc.	• Induction and resistance furnaces • Electric pre-heaters • Alternative liquid biofuels or biochemicals • Hybrid fuel systems • Solar thermal systems	• Smart IoT devices for system optimization • Smart manufacturing (e.g., digital twin, AI, predictive process controls) • Flexible, modular manufacturing and operations design	• High-temperature heat pumps • Thermal energy storage • Recuperators, regenerators, and economizers for nontraditional applications • Thermoelectric devices, heat pipes etc. • Waste heat to power,
 Metal oxide hydrolysis[14]	 Induction melting furnace[15]	 Virtual blast furnace[16]	 Coupled regenerative burners[17]

Figure 7. Industrial Thermal Process Intensification Technology Pillars (TPI Pillars) with examples.

[14] Boston Metal. Metal Oxide Hydrolysis (MOE). https://www.bostonmetal.com/moe-technology/
[15] Inductorterm. Steel Frame Furnace. https://www.inductotherm.com/products/steel-frame-furnaces/
[16] Chenn Q. Zhou, Purdue University Northwest. Simulation and Visualization for steel manufacturing. DOE Thermal Process Intensification Workshop, Session 5.
[17] Dave Schalles, Bloom Engineering. "Industrial Waste Heat Recovery". DOE TPI Process Intensification Workshop, Session 6.

The following section provides more information on the TPI technology TPI pillars and makes connections with the research targets identified in the AMO Multi-Year Program Plan (MYPP).[18]

TPI Pillar 1: Low–Thermal Budget Transformative Technologies

US Department of Energy's (DOE's) Multi-Year Program Plan Target: Develop low–thermal budget transformative technologies that use alternative process routes or technologies to reduce energy intensity (energy consumed per unit of physical output) by at least 50% compared with current typical technology.

This TPI pillar identifies transformative technologies that may use alternative process routes or technologies to achieve the same end products manufactured by the current processes. These technologies may not use thermal processing, or they may significantly reduce the use of thermal energy in production (i.e., low thermal budget). TPI through application of nonthermal-budget or low–thermal budget methods to replace or supplement currently used processes offers several advantages such as reduced cost, use of alternative raw materials, improved product quality, product yield, reduction in waste by-products, and reduction in GHG (CO_2) emissions.

The primary objective of these developments is to replace or supplement existing thermal processes without sacrificing product yield, sacrificing product quality, or increasing cost.

Current research focuses on using alternative methods that replace conventional fuel-based thermal processing or making changes in currently used processes to eliminate or reduce the use of conventional carbon-based fuels and improve energy intensity. Some examples are provided below.

- Extracting metals by electrolysis: Replacement of fuel-based thermal processing can be achieved in the production of metals (like iron and aluminum) from its ore by developing a suitable electrochemical process. This approach eliminates the use of petroleum coke or other sources of carbon and reduces further production of GHGs, such as CO and CO_2, in downstream combustion processes (metals: iron, steel, and aluminum industries).

- Use of hydrogen as a reductant: Modification of the thermal process to use clean hydrogen and replace carbon-based reductants (mainly CO). Applicable to reduce iron oxide and produce direct-reduced iron (DRI) resulting in reduced energy use and CO_2 (GHG) emissions (iron and steel industry).

- Development of low–thermal budget processes with advanced catalysts: Advanced catalytic processes can reduce reaction temperatures and energy intensity in chemical and petroleum refining industries[19]. Exelus styrene monomer process is one example of a novel catalytic technology that maximizes styrene (used in plastics) production.

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[18] DOE (US Department of Energy). Advanced Manufacturing Office (AMO) Multi-Year Program Plan For Fiscal Years 2017 Through 2021. Retrieved from https://www.energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017.

[19] Hasanbeigi, A., and C. Springer. 2019. *Deep Decarbonization Roadmap for California's Cement and Concrete Industry*. San Francisco, California: Global Efficiency Intelligence. https://www.climateworks.org/wp-content/uploads/2019/09/Decarbonization-Roadmap-CA-Cement-Final.pdf

- Thin strip casting: Applicable to steel and aluminum production, it eliminates heating of ingots or slabs by casting directly from the tundish while producing the required size of metal sheets.

- Additive manufacturing: Eliminates mass metal melting and castings of components. Applicable to all metal industries.

- Innovative heat treatment processes: Advanced heat treatment techniques can eliminate currently used lengthy multi-step processes. The flash bainite process is a good example, it involves induction heating to rapidly increase the temperature of steel and subsequent quench it to produce high-strength steel (iron and steel industry).

- Thermomagnetic processing: Involves processing materials under magnetic fields. In the heat treatment of metallic alloys, the technique improves structural and mechanical properties.

- Application of electromagnetic radiation: The unique material-wave interaction that some materials have with electromagnetic radiation leads to opportunities to significantly reduce thermal demand. Using ultraviolet (UV) radiation to cure paint results in the reduction or elimination of heat. UV also finds application in sterilization processes used in food manufacturing. Microwaves (MF) can reduce the thermal demand in drying applications as volumetric heating accelerates the release of moisture or other liquid vapors without creating a large temperature gradient within the material (multi-industry).

- Acoustic drying: Dries coatings on nonporous materials, films, foils, and papers where high temperatures are not effective. This can be used in industries such as printing, converting, drying of nonwoven fabrics, carpets, textiles, glossy paper, and films, foils, and printed circuit boards (multi-industry).

TPI Pillar 2: Alternative Sources of Energy for Thermal Processing

DOE's Multi-Year Program Plan Target: Develop advanced technologies that use low-carbon alternative sources of energy in manufacturing processes while maintaining the current production methods. DOE is aggressively conducting research, development, demonstration, and deployment of decarbonization technologies in the industrial sector to drive the energy transition needed to achieve net-zero carbon emissions by 2050.

This TPI pillar identifies technologies that use alternative sources of energy in manufacturing processes while maintaining the current production methods. These technologies may require changes in the design of thermal processing equipment (i.e., furnaces, ovens, heaters) and mass (i.e., material) and energy flow through the production line. Application of these technologies may offer reduced energy intensity, reduced manufacturing cost, improved product quality, higher product yield, reduced waste by-products, and reduced GHG (CO_2) emissions.

In this category of transformative technologies, the thermal processes using conventional fuel combustion and heat transfer mechanisms are converted to use fully or partially (hybrid systems) alternative non-fuel–based systems to reduce energy intensity and to achieve several additional advantages. The basic process steps such as melting, drying, and heating of the materials and controlling process parameters such as temperature of the final material may remain unchanged, but the method of supplying heat to the material may change significantly.

Some examples of process heating technologies that fall under this pillar include the following:

- Electrification of thermal processes: An alternative heating method using electricity as an energy source offers several advantages for many heating processes. The heat transfer process to the material and within the material differs from traditional radiation, convection, or conduction and may result in reduced heating time, improved temperature uniformity, lower energy intensity, and reduced GHG emissions. Commonly used electro-technologies are resistance heating, induction heating, MW heating, RF heating, electric arc/plasma heating, and electric infrared (IR) heating.

  - Electric heating of solid materials: While some industries and applications already make use of electric heating extensively, there is room for further adoption. Examples include electric arc melting of ferrous metals, induction melting of ferrous and nonferrous metals, direct contact heating in glass-melting furnaces (glass), plasma melting of hazardous and other types of solid waste, etc.

  - Electric steam generation: Steam generation using electric boilers can improve system efficiency and can impact multiple industries.

  - Electric fluid heating: Fluid heating in the petroleum refining and chemical industry can use induction with susceptors or other heat transfer enhancement devices (petroleum refining, chemical, and other industries).

- Use of hydrogen as a fuel: Modification of the thermal process to use clean hydrogen to replace carbon-based fuel. Applicable to all industrial thermal processes.

- Hybrid heating systems: With optimized use of electrotechnology and fuel firing, hybrid systems can increase productivity, reduce overall energy use and improve product quality. Examples include hybrid induction and radiation/convection heating for metal reheating applications such as forging steel billets (iron and steel industry).

- Industrial solar thermal systems: Solar energy transferred to process via hot water, heated air, steam, or heat exchanger are well-suited dairy, meat processing, and general process applications.

In each case, the material is brought to the required temperature, and the process conditions remain the same as in fuel-fired processes. In most cases, alternative heating methods require major changes in the process equipment and energy supply system, which result in a smaller footprint and production flexibility.

TPI Pillar 3: Transformative Supplemental Technologies

DOE's Multi-Year Program Plan Target: Develop advanced sensors, controls, smart manufacturing, and IoT technologies that enhance the performance of process heating systems, ensure safe and predictable performance of the thermal processes, and reduce energy intensity (energy consumed per unit of physical output) by 15% compared with current typical technology.

This TPI pillar focuses on transformative supplemental technologies that are used in the operation and control of thermal processing systems. These technologies enhance the performance of process heating systems and ensure safe and predictable performance of the thermal processes. They may improve the life of process heating systems (equipment and auxiliary systems), reduce operating and maintenance costs, improve product quality, increase product yield, reduce waste by-products, reduce GHG (CO_2) emissions, and so on. Examples of these technologies include integration of sensors and control system components, deployment of predictive tools-models, improved materials and material handling systems, and enhanced communications.

Performance of thermal processing systems can be enhanced by using supplemental technologies that allow enhancement of process performance, rapid and accurate identification of key parameters controlling the process variables, and functions that enable optimum energy use and product quality. This can result in optimization of energy use while improving productivity, product quality, production flexibility, and often operating cost.

A need exists for the advancement and development of various components that can bring improvements in the performance of the required functions. These include intelligent and advanced material handling systems, materials used in the system components, sensors, intelligent controllers, actuators, and communication to the appropriate personnel. Thermal processes require sensors for online and accurate measurement of key parameters that control the process quality, processing time or schedule, and product quality. The accurate measurements must follow intelligent controllers and accurate functionality of actuators to allow smooth control of heating systems. At this time, for many thermal systems, the quality of the processed material is based on one or two measurements and an empirical relationship between this measurement and the product quality.

Examples of such developments that are applicable to multiple industries include the following:

- Predictive algorithms and machine learning for process control: Development of process models that use deep learning algorithms and/or predictive methods can inform the condition of the product while being heated leading to better control options. Can be used in all industrial heating applications to improve the performance of equipment while delivering consistent product quality, productivity, safety, and reduced downtime.

- Internet of Things (IoT) devices: Development and deployment of higher temperature sensors and IoT devices for process heating system components can lead to real-time monitoring of component's integrity, such as in refinery fluid heater tubes or heat exchangers. Online continuous measurement can also be applied to low and medium-temperature processes like drying to measure surface moisture or moisture profile within or across the material. Application examples include grain drying, coatings drying, paper drying, aggregate drying, and metal scrap drying.

- Application of advanced robotics: Innovative material handling systems can be used for high-temperature and/or hazardous production environments, including the use of intelligent robotics.

- Advanced materials: For components used for material handling and heat containment (insulation), the development of advanced materials can reduce heat losses.

- Innovation in TPI support systems: Some of the innovations discussed in pillars 1 and 2 are greatly supported with advancements in critical support systems. These supporting systems/technologies while not directly related to the thermal process itself, can facilitate innovation by providing the necessary conditions. Some of the technologies and systems that fall under this category are discussed below.

  - Innovative energy storage technologies: Innovation in large-scale energy storage that improves upon the efficiency and output will help support the rapid adoption of industrial electrification.

  - Advanced power conversion technologies: Breakthroughs in photovoltaic power conversion via system design, improved doping materials, optimized concentrators, etc. can lead to higher utilization of solar power for thermal application in industries.

TPI Pillar 4: Waste Heat Management Technologies

DOE's Multi-Year Program Plan Target: Develop transformative/emerging technologies used for reducing, recycling, and recovering waste heat, collectively known as waste heat management, from thermal processing equipment (e.g., furnaces, ovens, heaters).

Develop material and system advancements to enable greater recovery from high-temperature (>1,200°F) and heavily contaminated industrial waste heat streams, and cost-effectively use 30% of available waste heat in this temperature range.

Develop innovative, cost-effective systems to recover heat from low-temperature (<450°F) waste heat sources and successfully use 20% of available waste heat in this temperature range.

This TPI pillar includes transformative/emerging technologies used for reducing, recycling, and recovering waste heat, collectively known as waste heat management, from thermal processing equipment (e.g., furnaces, ovens, heaters). This includes technologies that help reduce energy use (i.e., energy efficiency measures), synchronize and allow the use of waste heat from a heating system within the system, and recover heat for use outside the heating system boundary. These technologies reduce energy intensity for a specific process, reduce overall energy consumption for the plant or community in general, and reduce CO_2 emissions for the plant. Examples of these technologies include heat recovery systems (e.g., recuperators, regenerators) applied in nontraditional systems, high-temperature heat pumps, waste heat to power generation, CHP, and waste heat for district heating and agricultural uses.

Thermal processing of materials or process heating in US manufacturing produces slightly over 2.5 TBtu of waste heat, mostly in the form of hot gases or liquids.[10] Most of this heat is lost because it is discharged into the atmosphere. These losses can be reduced by taking steps that reduce the generation of waste heat, recycling the waste heat within the process, or recovering part of the waste heat outside the process boundary. Figure 8 shows waste heat recovery opportunities in five categories from ultralow to ultrahigh temperatures by waste heat source in various US manufacturing industry sectors. The sources that do not exist in an industry sector or have unknown opportunities are left blank.

Waste Heat Source	Steel	Aluminum	Glass	Paper	Pet. Refining	Mining	Chemical	Food	Cement	Coating	Steam generation	CHP/Gas turbine
1) The Exhaust Gases or Vapors	Low to Ultra-high	High to Ultra-high	High to Ultra-high	Low to Medium	Low to high	Low to high	Low to high	Low to medium	High to ultra-high	Low to medium	Low to medium	Low to medium
2) Heated Water or Liquids	Ultra-low to Low			Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low
3) Hot Products	High to Ultra-high	Low to Medium	High to Ultra-high	Ultra-low to Low	Ultra-low to Low	Low to Medium	Ultra-low to Medium	Ultra-low to Low	High to Ultra-high	Low to Medium		
4) High Temperature Surfaces	Ultra-low to Low	Ultra-low to Low	Ultra-low to Low		Ultra-low to Low				Ultra-low to Low			

Figure 8. Waste heat recovery opportunities in different temperature regimes. Ultrahigh = >1,600°F; high = 1,200°F to 1,600°F; medium = 450°F to 1,200°F; low = 250°F to 450°F; ultralow = <250°F.

Numerous actions have been proposed and implemented by manufacturing plant equipment suppliers to reduce the generation of waste heat, including proper design, operation and maintenance of furnaces, ovens, and heaters.[20] Implementation of these actions would help reduce energy intensity and result in reducing waste heat discharged from the heating system. Energy savings by waste heat reduction can also be achieved by the development, availability, and use of improved materials, sensors and controls, and energy management tools as discussed in the previous section. These steps are also commonly known as energy efficiency improvement actions. However, complete elimination of waste heat discharge from fuel-fired systems is not possible.

Some of the waste heat can be recycled or used within the heating system by transferring heat from flue gases for combustion air preheating, preheating the charge material or load, removing moisture content (drying) of the incoming material, and so on. These actions reduce energy requirement in furnaces, ovens, and heaters. Some of the possible actions and developments are listed later in this section.

[20] Thekdi, A. C., and S. U. Nimbalkar. 2014. *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities*. ORNL/TM-2014/622. Oak Ridge National Laboratory. Retrieved from https://info.ornl.gov/sites/publications/files/Pub52987.pdf.

Even after taking steps to reduce and recycle waste heat, a large quantity of waste heat is still discharged into the atmosphere. Several systems have been used to recover part of the waste heat and use it in the manufacturing operations inside or outside the plant. Selection of a waste heat recovery method depends on the temperature, magnitude (mass flow rate), and quality of waste heat sources. Traditionally, heat recovery from medium- to high-temperature sources (mostly flue gases) has been used for steam generation in waste heat recovery steam generators, steam-based electrical power generation, water heating, and other applications. However, these methods become challenging and often economically unjustifiable when the waste heat is in the form of gases that contain various contaminants such as combustible or noncombustible particles, condensable solids or liquids, and corrosive gases, or vapors. Also, these methods are most suited for relatively clean, high–mass flow, and high-temperature gases above 1,000°F.

A large amount of waste heat contains the presence of contaminants such as corrosive gases, solid particles from the processed material, and combustibles (i.e., soot) at very high temperatures (>1,800°F), such as in the case of EAFs, glass-melting furnaces, and cement kilns. This is also true at low temperatures (<400°F) from the pulp and paper industry, food processing, and others. The recovery of this waste heat is very challenging. These challenges offer opportunities for RD&D activities in this area.

Some of the technologies or systems that can be developed are used by multiple industries, including the following:

- Development of advanced materials: Robust materials for use in high-temperature harsh environments (e.g., iron and steel) can help improve the efficiency of heat exchangers and facilitate heat recovery.
- Additive manufacturing: Innovative and flexible manufacturing can be used for heat exchangers using additive manufacturing.
- High-temperature heat pumps: These allow the temperature of a waste-heat stream to be transferred to a useful process heat stream and increased to a higher, more useful temperature. Industries with low and medium temperature processes like food and beverage stand to benefit the most.
- High-efficiency recuperative and regenerative heat exchangers and burners: Can facilitate implementation of challenging flue gas heat recovery projects in high-temperature applications.
- Thermoelectric systems: Can be used for heat to electricity generation applications in industries with sufficient waste heat.
- Better designs and advanced materials for thermal storage systems (TES): TES can solve the existing supply to demand mismatch by recovering the industrial waste heat and storing it for later use.
- Small and flexible CHP systems: Helps provide dispatchable power and improve resiliency.

This is only a partial list and can be expanded to include other innovative concepts and developments.

The applicability and selection of technologies under each of these TPI pillars will vary for each manufacturing sector. The trade-offs in costs, local energy situation and economics, environmental (GHG reduction) regulations, infrastructure, and other factors will influence the choices. Parallel investment and pursuit of multiple TPI pillars will be vital for sectors to contribute to TPI. The goal of the discussion is to identify and guide RD&D for transformative technologies, lower implementation hurdles, and address scale-up and adoption issues.

Note: While the four pillars are defined in a way to accommodate any type of innovation in the TPI space, it is to be noted that some technologies might not have a straightforward categorization in a single pillar. Further, while the workshop team has tried its best to define the pillars to be encompassing, it is possible that some technologies might not be captured under the pillar definitions. As such, the pillars are proposed to facilitate categorization and communicate effectively on existing and future TPI technologies, the definitions are open to revision as the space evolves.

4. Thermal Process Intensification Workshop Summary

The virtual workshop sessions, brainstorming exercises, and related activities were structured to facilitate discussion, identify opportunities for improved thermal efficacy, and assess the R&D needed to overcome barriers to scale up across a wide range of technology maturities and manufacturing scales.

As discussed earlier (Section 2.1), a few large industries use a significant percentage of the total process heating energy in the United States. The top industries and associated thermal processes—which use more than 55% of the total energy consumption—were considered as the focus of the workshop. These industries were grouped based on the similarity of their thermal process, forming four breakout groups around which the workshop sessions were structured.

Group 1: High-temperature primary metals
Iron, steel, aluminum, and other metal production processes typically conducted at high temperatures

Group 2: High-temperature nonmetallic minerals
Glass, cement, and other nonmetallic production processes typically conducted at high temperatures

Group 3: Low/medium-temperature processing
Food processing, paper mills, and other industries—low/medium-temperature processes, including steam-heating applications

Group 4: Hydrocarbon processing industry
Petroleum-refining and chemical industries with significant steam usage and fuel-based heating systems

Figure 9. Thermal Process Intensification Workshop breakout groups.

The Thermal Process Intensification Workshop was held over seven sessions—a plenary session and six brainstorming breakout sessions—in November and December 2020. All the participants attended the plenary session and subsequently joined the specific brainstorming sessions most relevant to their interest and expertise. A total of 128 participants attended the plenary session, whereas the brainstorming session had an average attendance of 70 participants. The structure and schedule of the workshop is provided in Figure 10.

Industry Groups

Brainstorming Topics	High-Temperature primary metals	High Temperature Non - Metallic Minerals	Low/Medium Temperature Processing	Hydrocarbon Processing Industry
Orientation Session (for online A/V platforms) – November 4th, 2020 (9am -10am and 1pm - 2pm)				
Plenary Session - November 5th ,2020 (12pm – 3pm)				
TPI Pillar 1 & 2 – Transformative Low Thermal Budget and Alternative Thermal Processing	Brainstorming Session 1 November 9th (12pm to 2pm)	Brainstorming Session 2 November 12th (12pm to 2pm)	Brainstorming Session 3 November 16th (12pm to 2pm)	Brainstorming Session 4 November 20th (12pm to 2pm)
TPI Pillar 3 – Transformative Supplemental Technologies	Brainstorming Session 5 - Dec 2nd (12pm to 3pm)			
TPI Pillar 4 – Waste Heat Management Technologies	Brainstorming Session 6 - Dec 9th (12pm to 3pm)			

All in Eastern Time

Figure 10. The structure and schedule of AMO's Thermal Process Intensification Workshop.

Brainstorming sessions 1 through 4 were planned for each industry group separately to discuss the first two TPI pillars (transformative low–thermal budget processing and alternative thermal processing). The remaining brainstorming sessions 5 and 6 were joint sessions for all the industry groups to discuss the corresponding crosscutting TPI pillars (transformative supplemental and waste heat management technologies). The presentations from each workshop session are summarized in Appendix A.

Upon registration, each participant received a framing document that provided a primer to TPI and laid out the structure of the workshop. The content of the framing documents was integrated into the early sections of this report. Also, before the brainstorming sessions, participants received a supplementary document developed by the workshop team. The supplementary document provided an overview of the thermal processes in each sector and identified a list of applicable technologies to significantly improve these processes based on a thorough review of available literature. The technologies identified through literature review were used as a starting point for the discussions during the brainstorming sessions.

The brainstorming sessions leveraged the unique collaboration capabilities of a virtual environment to promote engagement and receive feedback. The online video conferencing platform Zoom was used for audio/visual interactions, whereas MeetingSphere, an online group decision support system, was used for participant engagement. The MeetingSphere platform allows participants to directly provide their comments, ask questions, and provide additional insight, contributing to the materials presented during the sessions. The brainstorming sessions also made use of some of the more advanced interface options of the platform (such as the question cards shown in

Figure 11) to promote discussion and receive feedback.

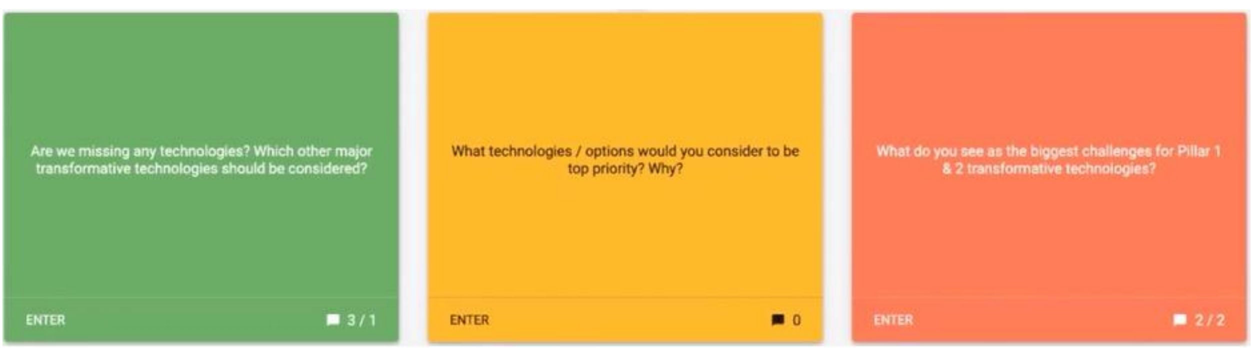

Figure 11. The brainstorming exercise within the MeetingSphere platform listing the questions that participants responded to during the sessions

The technologies identified from literature review, along with the additional insights provided by the workshop participants, are presented in Section 5 of the report.

5. RD&D Opportunities, Challenges, and Barriers

This section details the outcomes from the Thermal Process Intensification Workshop. The energy use, thermal processes, and savings potential are described for each industry considered under the workshop focus areas. The technologies identified during the workshop based on literature review, brainstorming discussions, and follow-up interviews with the participants are tabulated, along with their challenges, barriers, and commercialization status.

As discussed in Section 4, workshop sessions 1–4 focused on the first two TPI pillars (low–thermal budget transformative technologies and alternative sources of energy for thermal processing) for specific industries. The latter two TPI pillars (transformative supplemental technologies and waste heat management technologies), being crosscutting, were discussed in sessions 5 and 6, respectively. This section follows the same chronological order.

5.1 High-Temperature Metals: Iron and Steel Industry

5.1.1 Energy Use

Iron and steel manufacturing is the fifth largest consumer of energy in US manufacturing, accounting for 1,524 TBtu (7.6%) of the 20,008 TBtu of total primary manufacturing energy consumption in 2014.[10] Off-site electricity and steam generation and transmission losses in iron and steel manufacturing totaled 440 TBtu in 2014; on-site energy consumed within the boundaries of US iron and steel mills totaled 1,084 TBtu. Around 70% of steel in the United States is produced by EAFs and the remainder by the BF–basic oxygen furnace (BOF) route.

Figure 12 shows the total on-site energy entering US iron and steel mills; most of the energy entering was in the form of fuel in 2014. About 25% of this fuel is used on site in boilers and CHP to generate additional electricity and steam.[10]

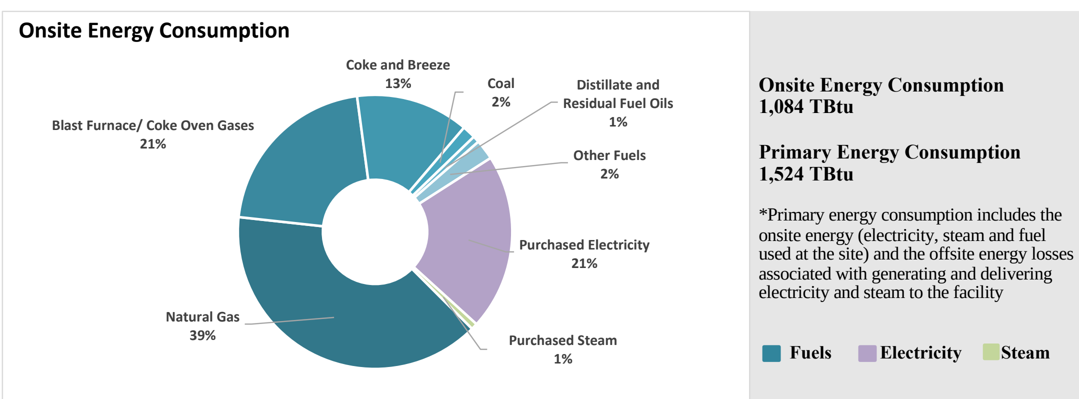

Figure 12. On-site energy consumption at US iron and steel mills in 2014.[10]

Figure 13 provides a simplified process flow diagram for the iron and steel industry. Today, there are two main ways to produce steel: EAF or BOF. The first step in BOF is to produce coke. Coke is made in coke ovens, which purify coal by heating it with the absence of air. The next step is to combine coke, limestone, and iron ore into the BF and inject oxygen to produce pig iron. From there, the pig iron is put into the BOF, which can include up to 30% of recycled steel, and oxygen is blown into the pig iron to reduce carbon and produce steel. EAFs, in contrast, can use up to 100% recycled steel and involve combining recycled steel and molten steel, which is then charged by electric arcs to produce steel. Following this step, in both EAFs and BOFs, the molten steel is poured into a ladle that transports it to the continuous casting stage. Here, the molten steel is poured and is cooled by thinning out the molten steel and spraying water onto it. From there, the steel is dispersed into blooms, billets, and slabs and is stored away until an order comes in for how the customer wants their steel to be finished. When this is determined, the steel is reheated and goes onto a hot rolling furnace and can be shaped and sized to the customer's need. Depending on the use of the steel, some steel is coated with zinc or some other coating to protect the metal and reduce wear and tear. Drying of raw material and product is done at various stages of this process. The coal and iron ore are dried as part of their beneficiation step, scrap metal used in EAF is dried in belt conveyor systems prior to melting it, and the finishing mills employ gas or electric powered IR systems to dry powder coatings.

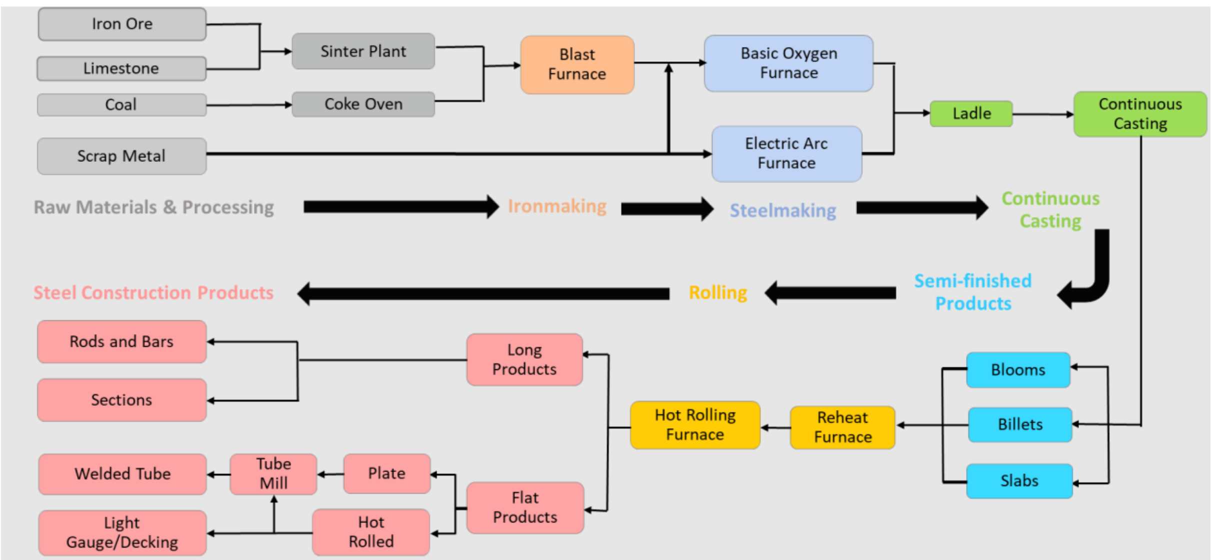

Figure 13. Simplified process flow diagram for the iron and steel industry.

5.1.2 RD&D Needs and Opportunities

US steel production has been relatively stable—between 78 and 90 million metric tons (MMT) produced during the past 10 years—whereas China and other countries have increased their production several fold.[21] In the United States, a significant shift has occurred in the method of steel production. Steel production using EAFs has increased from about 46% in 2000 to as high as 70% in 2019, with the remainder by the BF–BOF route.[2] Production of steel in the raw form and final product form requires several thermal processing steps ranging from iron ore agglomeration to casting of shapes in typical steel plants followed by a number of shaping or forming, heat treating, and other processes that require process heating.

Analysis of energy use for major process steps used by many industries has been carried out and reported in industry-specific energy bandwidth studies prepared for DOE.[22] These reports present

[21] Emerging Technologies for Energy-efficiency and GHG Emissions Reduction in the Iron and Steel Industry, Ali Hasanbeigi, https://www.globalefficiencyintel.com/new-blog/2017/technologies-energy-emissions-steel-industry
[22] DOE (US Department of Energy). "Energy Analysis, Data and Reports." Retrieved from https://www.energy.gov/eere/amo/energy-analysis-data-and-reports.

energy use values in four technology categories: current typical, state-of-the-art, practical minimum (which reflects potential from early–technology readiness level [TRL] technologies), and thermodynamic minimum. As discussed in the iron and steel industry bandwidth analysis,[23] current typical energy intensities of each process step for the iron and steel industry are higher than practical minimum energy intensities. This is because of the inefficiencies involved with the heat supply system (i.e., combustion of fuels or electrical power supply system), as well as losses associated with the thermal process equipment (e.g., furnaces, ovens). Figure 14 shows the estimated current and R&D energy savings opportunities for individual iron and steel manufacturing processes.

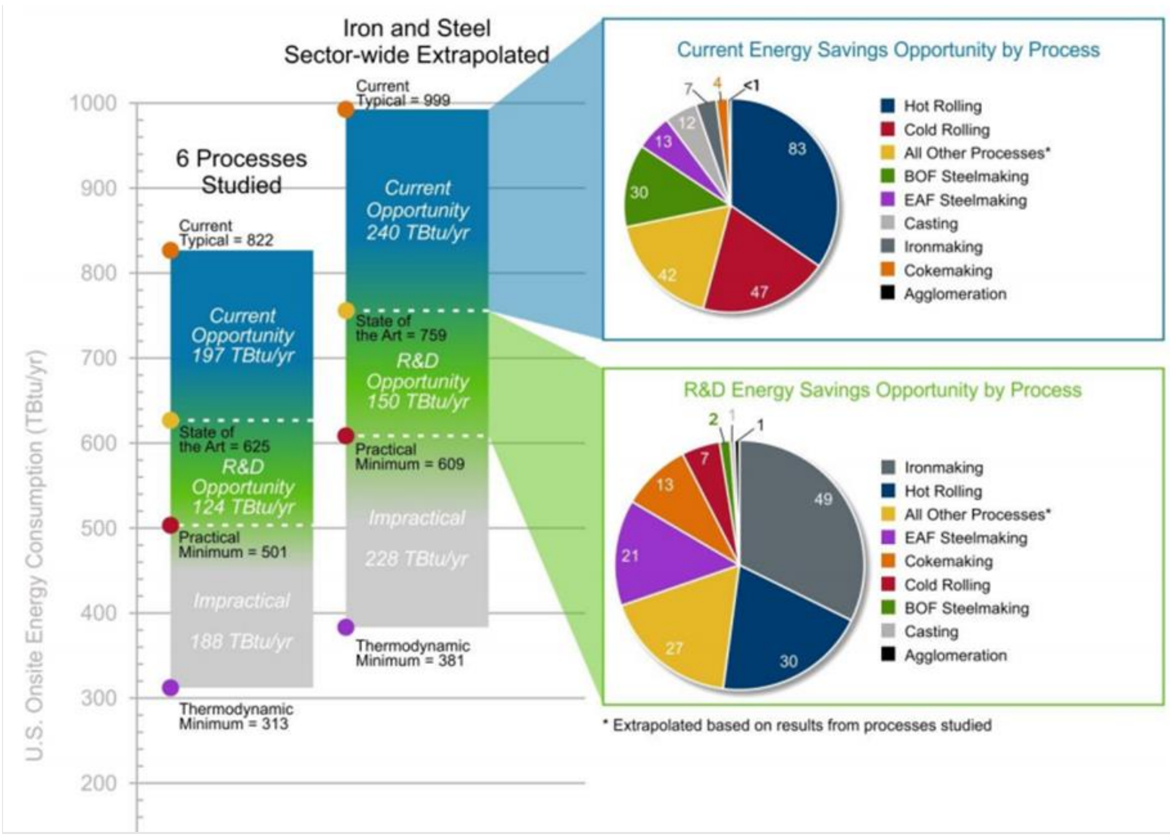

Figure 14. Current and R&D energy savings opportunities in US iron and steel manufacturing for the processes studied and for sector-wide based on extrapolated data.[23]

Table 5 shows the energy intensity estimates for six iron and steel processes in 2010. If we compare current typical energy intensity numbers with practical minimum values, the reduction in energy intensity ranges from 16% to 80%. For example, in the steel industry, the iron reduction step to convert iron oxide by the BF BOF route with current typical technology requires 11.72 million Btu (MMBtu) per ton, whereas the practical minimum value is 9.49 MMBtu/ton and the thermodynamical minimum value is 8.43 MMBtu/ton.[23] Most of this energy

[23] DOE (US Department of Energy). 2015. "Bandwidth Study U.S. Iron and Steel Manufacturing." Retrieved from https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing.

is used for thermal processing using conventional fuels such as coal, by-product fuels, and natural gas.

Table 5. Energy intensity estimates and potential reduction in energy intensity in major iron and steel processes.[23]

Process	On-site energy intensity (MMBtu/t)		Percent reduction
	Current typical	Practical minimum	
Agglomeration			
Pelletizing	0.70	0	100%
Sintering	1.32	1.11	15.9%
Cokemaking	3.83	1.92	49.9%
Ironmaking			
BF	11.72	9.49	19%
Direct reduction	9.17	0	100%
Steelmaking			
BOF	0.58	−0.36	162.1%
EAF	1.86	1.24	33.3%
Casting	0.19	0.04	78.9%
Rolling			
Hot	2.58	1.25	51.6%
Cold	3.48	1.15	67%

5.1.3 TPI Technologies

Several developments under each TPI pillar were identified through literature searches and discussions held during the workshop. The following subsections and tables show and discuss technologies for each of these TPI pillars for the iron and steel industry.

TPI pillar 1: Low–thermal budget transformative technologies

The current energy use can be reduced, and alternative energy sources can be used by developing alternative processes and use of energy sources that significantly reduce GHG (mostly CO_2) emissions. The steel industry has taken steps in this direction by developing alternative methods of iron production, such as the following:

- Natural gas–based DRI with transfer of hot DRI products (e.g., pellets, briquettes) to an EAF, which uses electricity as the main source of energy. This route of steel production eliminates the use of coal and coke, BF and BOF, which are major sources of CO_2 production for an integrated steel plant. The energy consumption in natural gas–based DRI production is well known and established to be 8.8 MMBtu/ton. Natural gas–based DRI production also leads to lower CO_2 emissions, with emission ranging from 0.77 to 0.92 ton of CO_2 per ton of steel produced depending on the source of electricity.[24]

- Use of renewable energy sources to produce hydrogen from water to enable reduction of iron oxide in the DRI process.[23]

[24] Institute for Industrial Productivity. Direct Reduced Iron. Retrieved from http://www.iipinetwork.org/wp-content/Ietd/content/direct-reduced-iron.html.

- Transfer of hot DRI (e.g., pellets, briquettes) for hot charging in an EAF results in significant reduction in energy use in an EAF.[25]

In addition to the production of liquid steel, a steel plant includes downstream thermal processing for casting and hot rolling, batch, or continuous annealing of steel sheets or coils, and wire/rod coils and heat treatment of finished products either at the manufacturing plants or end-user locations. RD&D and new developments enable greatly reducing or eliminating the use of traditional thermal processing. For example, during the past 40 years, conventional ingot casting with the use of soaking pits has been almost completely replaced by slab or ingot casting, thin slab casting, or even strip casting. These developments are replacing the use of a large amount of energy for steel reheating, which is the second largest energy user for many steel mills. Further RD&D may lead to truly continuous operation of a steel manufacturing process that involves iron ore reduction, steelmaking, and net shape casting in one streamlined operation. This will lead to reduced energy use and CO_2 emissions in steelmaking.

Table 6 shows the low–thermal budget transformative technologies for the iron steel industry.

Table 6. Low–thermal budget transformative technologies for the iron and steel industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.1.1	Hydrogen DRI†	Use of hydrogen instead of natural gas or coal syngas in DRI process: If hydrogen is produced from renewable energy, it will significantly reduce CO_2 emission from steel production. BFs could be replaced with hydrogen DRI facilities. • HYBRIT pilot in Lulea, Sweden • ArcelorMittal building a pilot in its Hamburg DRI plant • SALCOS—partial hydrogen replacement of natural gas in a standard DRI (not implemented yet)	HYBRIT: Pilot ArcelorMittal: Pilot being planned SALCOS: R&D	• Different type of iron ore and quality; scale-up issues; H_2 supply and infrastructure issues
1.1.2	Producing iron by electrolysis of iron ore (electrowinning and molten oxide)†[26]	Electrolysis of iron ore allows the transformation of iron ore into metal and gaseous oxygen using only electrical energy. It would eliminate coke-making and BFs and emissions associated with them. • The low-temperature electrolysis of iron ore in alkaline solution at 230°F, so-called "electrowinning," which is currently being developed by ArcelorMittal in the SIDERWIN project • The high-temperature reduction of iron ore in molten oxide environment at 2,910°C, pioneered at the Massachusetts Institute of Technology and currently	Development	• Scale-up issues

[25] Midrex Technologies. "Midrex: The World Leader in Direct Reduction Technology." From https://www.midrex.com/.
[26] Cavaliere, P. 2019. "Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement." In: *Clean Ironmaking and Steelmaking Processes*. Springer, Cham.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
		developed by the start-up Boston Metal		
1.1.3	Novel flash ironmaking process†[27]	The conventional coke oven/BF process that produces pig iron for steelmaking requires additional energy to prepare the raw iron ore as sinter and pellets. This new process uses natural gas and/or hydrogen to both heat the iron ore concentrates in the furnace and remove oxygen, converting the ore to iron metal. When fully scaled up, this novel ironmaking technology has the potential to provide steel plants with significantly more energy efficient and customized iron production facilities over state-of-the-art BFs. • Reduces energy consumption up to 15% over competitive processes by eliminating pelletizing, briquetting, or sintering • Improves competitiveness by reducing operating time and capital costs	American Iron and Steel Institute with University of Utah, Berry Metal Co., ArcelorMittal USA, Timkensteel, and US Steel Corp.	• Scale-up and industrial pilot
1.1.4	Thin strip casting with in-line heat treating†[28,29]	Strip casting is a form of near-net-shape production that reduces the amount of reheating and rolling required to meet final specifications. Traditional slab casting usually produces sheets that are a minimum of 20–30 millimeters thick. To produce thin strips, the slabs are reheated and hot rolled before being coiled. Thin strip casting produces thin strips directly from the tundish and eliminates the need for reheating. • Locations that perform thin strip casting include Crawfordsville, Indiana and Blytheville, Alaska	Commercialized: Castrip and poStrip Development: Baostrip, MAINSTRIP, and others Technology has been around for decades. It fell out of favor because thin slab casting can produce thin strips with less reheat	• Drop in yield and tensile strength in the belt cast-produced material[30]
1.1.5	Cold tundish*[31,32]	The tundish sits between the ladle and the molds for the continuous castors. To prevent destruction of the tundish's permanent brick	Commercialized Case study for a cold tundish	• Advanced refractories and insulating lining system

[27] Sortwell, M. 2018. "A Novel Flash Ironmaking Process." American Iron and Steel Institution. Retrieved from https://www.osti.gov/servlets/purl/1485414.
[28] ASM International. 2014. Castrip to build steel plant for thin-strip casting process. Retrieved from https://www.asminternational.org/web/hts/news/newswire/-/journal_content/56/10180/18520589/NEWS.
[29] Ge, S. et al. 2012. "Progress of Strip Casting Technology for Steel; Historical Developments," *ISIJ International* 52, 12.
[30] Carl Slater and Claire Davis. 2020. "Near Net Shape Casting: Is It Possible to Cast Too Thin?" Metallurgical and Materials Transactions B volume 51, pages 2532–2541.
[31] Materikin, Y. V., and V. A. Molochkov. 1983. "Refractory linings of the tundishes of continuous billet casting machines (a review)." *Refractories* 24, 108–114.
[32] K. Beraldo Andrade, D. B. Moreira, J. Chiabi Duarte, M. F. Matos, and Z. D. Nascimento. 2003. "Implementation of a cold tundish at the CST continuous casting plant," *Metallurgical Research & Technology* 100, 10, 955–960.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
		linings, a temporary lining is used that can be removed and replaced. Certain thermal insulation linings allow for significantly reduced or elimination of preheating, allowing for a "cold" casting start. • Has shown reduced energy consumption and improved working conditions	installed at a plant in Brazil	
1.1.6	Next-generation system for scale-free steel reheating†[33]	Development of a new scale-free heating mode for reheat furnaces: This is a heating and combustion process that can heat steel to rolling temperatures while forming little or no scale. In the scale-free heating mode, burners in the soak and heat zones are operated at only 50%–60% of stoichiometric. Air is added into the front end of the furnace to burn down combustibles. • Has the potential to reduce energy consumption by 0.375 MMBtu/ton or 28.5 TBtu nationwide Application in new furnaces and retrofits	In development: testing (2010) at a rebar mill and upgrading a rotary furnace in a piecing operation	• Further research in preheated steel (e.g., slabs, billets), thin slab casting, and direct strip casting processes • Study of possible methods of using and justifying scale free application for the forging industry • Measurement & Verification activities to monitor performance of one or more scale-free heating applications
1.1.7	Thermo-magnetic processing†[34]	• Reducing material processing energy by replacing conventional energy-intensive heat treatment and concomitant post-processing methods such as carburization, tempering, and surface finishing with thermomagnetic processing, a new, transformational energy-efficient heat treatment and forging technology.[34] • Thermomagnetic processing could be hybridized with inductive high-frequency heat treatment to achieve the required bulk and surface properties of components at greatly reduced energy use.[34]	In development	• Demonstration of the utility of industrial thermo-magnetic processing technology for manufacturing applications • Development and employment of multi-scale modeling and simulation tools to drive performance and optimize design and operation of industrial thermo-magnetic processing • Industrially relevant, system-scale demonstration

*Included in DOE's iron and steel bandwidth study, 2015
†Not included in DOE's iron and steel bandwidth study, 2015

[33] Thekdi, A. C. 2011. Development of Next Generation Heating System for Scale Free Steel Reheating. E3M Inc. Retrieved from https://www.osti.gov/servlets/purl/1004059.
[34] DOE (US Department of Energy). 2011. Energy-Efficient Thermomagnetic and Induction Hardening. Retrieved from https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/thermomagnetic_induction_hardening.pdf.

TPI pillar 2: Alternative thermal processing

TPI pillar 2 technologies achieve TPI by using alternative energy sources while maintaining the current production methods. Table 7 shows alternative thermal processing technologies identified for the iron and steel industry.

Table 7. Alternative thermal processing for the iron and steel industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.2.1	DRI and increased use of EAFs†	DRI is a solid-state process that reduces iron oxides to metallic iron at temperatures below the melting point using a reducing gas or carbon. Steel made with DRI uses significantly less fuel than BOF-produced steel. EAFs use an electric arc to heat the iron. The charge material is in direct contact with the arc, which displaces the need for gas consumption.	Widely available	DRI steel requires additional protection to avoid oxidation because of its porous structure and because it is pyrophoric. EAFs have extremely high electrical demands.
1.2.2	Electric annealing†[35,36,37]	Annealing furnaces hold specific temperature profiles to change the microstructure of metals to achieve certain strength properties. Most annealing furnaces in the United States are gas-powered because of the relatively low cost of natural gas and its widespread availability. Electric annealing furnaces, however, have certain advantages over gas powered furnaces: • Even temperature distribution depending on the placement of heating elements • Efficiency touching 90% compared with ~60%–80% for gas powered furnaces • Safer operation because of less combustible gas Electric heating would apply to batch-style furnaces and continuous annealing furnaces, which could either be with radiant or inductive heating.	Commercially available (multi-batch annealing furnace with electric heating elements)	• Increased electric demand and availability of low-carbon electricity

[35] Edwards, B. 2012. "Electric Furnaces Complement Heat Treat Requirements for Gears," GEARSolutions.
[36] Eurotherm 2006, "Single and Multi-stack Batch Annealing," Retrieved from - https://www.eurotherm.com/us/metals-processing-applications-us/single-and-multi-stack-batch-annealing/
[37] ANDRITZ, "Continuous Annealing Line Furnaces for All Applications," Retrieved from - https://www.andritz.com/products-en/metals/metals/furnaces/continuous-strip-processing/annealing-line-furnaces

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.2.3	Solar thermal systems†[38,39]	Solar energy is captured and focused to produce environments that can reach temperatures higher than 1,000°F. This is accomplished with advanced mirror and solar tracking technology. • Heliogen in California looking to use solar heat to power furnaces directly • Research being conducted for using concentrated solar power for agglomeration of iron ore and smelting	In development: 2019 article from Heliogen and 2018 research paper on concentrated solar power	• Industry-level scale-up and demonstration
1.2.4	Molten oxide electrolysis†[26]	Iron ore is dissolved in a mixed oxide solvent, such as silicon oxide or calcium oxide, at 2900°F. An inert anode is dipped in the solution and electrical current causes the formation of oxygen gas. Iron is produced as a liquid metal at the cathode and will collect at the bottom of the cell. The O_2 can be collected and sold as a by-product. • Active research in identifying an appropriate inert anode • Estimated to be 30%–40% more efficient than BF	The first semi-industrial molten oxide electrolysis cell was commissioned in 2014. Boston Metal is conducting research to bring the molten oxide electrolysis technology to market for ferro-alloys, steel, and a variety of other metals[40]	• Demonstration of iron and chromium anode material, industry-level scale-up, and once deployed, availability of low-carbon electricity
1.2.5	Inductive heating of tundish†[41]	Instead of burning fuels for maintaining the temperature of the tundish, inductive heating is used. Inductive heating shows improved cleanliness of the tundish steel and up to 90% heating efficiency for the total tundish. • Used at Yawata steelmaking plant • Muroran Works has used this technology since 1993	Commercially available	The coupling effect of electromagnetic force and Joule heating is still not demonstrated in the study of liquid metal flow behavior and inclusion migration characteristics. The mechanism of aggregation of inclusions in the inductive heating and adhesion to the wall surface remains to be studied in high-temperature experiments.[42]

*Included in DOE's iron and steel bandwidth study, 2015
†Not included in DOE's iron and steel bandwidth study, 2015

[38] Stone, M. 2019. "This company wants to make steel and cement with solar power. Here's how," Grist.
[39] Fernández-González, D., J. Prażuch, I. Ruiz-Bustinza, C. González-Gasca, J. Piñuela-Noval, and L. F. Verdeja González. 2018. "Iron Metallurgy via Concentrated Solar Energy," *MDPI* 8, 11, 873.
[40] Metal Oxide Electrolysis – Boston Metal. Retrieved from https://www.bostonmetal.com/moe-technology/
[41] Kimura, H., A. Uehara, M. Mori, Tanaka, R. Miura, T. Shirai, and K. Sugawara. 1994. *Innovative Technologies in Continuous Casting Tundish*, Nippon Steel.
[42] Dou, W. X., et al. 2020. "State of the art in tundish with induction heating for clean steel casting." Metalurgija 59 (1), 125–128.

5.2 High-Temperature Metals: Aluminum Industry

5.2.1 Energy Use

The aluminum industry can be broadly divided into two categories: the primary sector, where aluminum is extracted from bauxite, and the secondary sector, where aluminum is produced using scrap collected from various sources. Both primary and secondary (recycled) aluminum are important manufactured products in the United States. The share of each of these sectors has changed from year to year depending on the market conditions; however, over the years, the percentage of the US aluminum production by the primary sector has declined.[43] For example, the annual primary aluminum production has steadily declined from 1.71 to 1.1 MMT from 2014 to 2019, whereas the secondary production has fluctuated around 3.3 to 3.6 MMT. A large amount (4.29 to 6.22 MMT) of aluminum consumed in the United States is imported, and the share of imports changes with the international price of aluminum.[43]

Energy use for the aluminum industry processes reported in the 2014 EIA MECS report is about 242 TBtu/year and consists of fuel (96% of the fuel use and 48% of total energy is natural gas), electricity (mostly off-site generated), and steam (mostly on-site generated).[10] The share of each of these energy types for 2014 is given in Figure 15. This share will change depending on the production method (i.e., primary vs. secondary) because the use of electricity mainly relates to the primary aluminum production whereas the secondary production (using scrap) uses fuel as the main energy source.

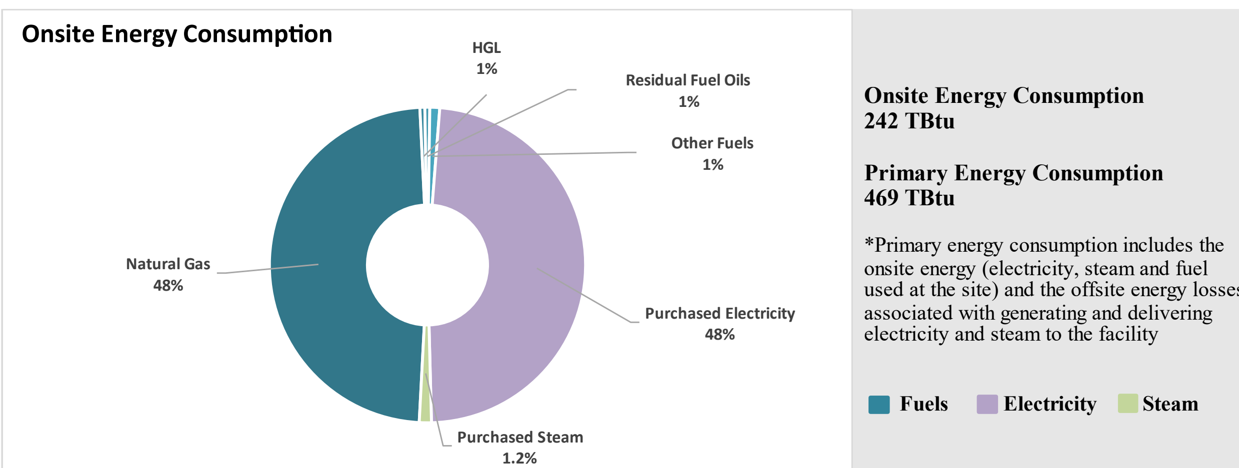

Figure 15. Process and non-process energy sources for the US aluminum industry.[10]

Energy consumption in aluminum manufacturing can be classified into five energy-intensive process subareas. For primary aluminum production, there are three main subareas: production of alumina, production of carbon anodes, and the Hall-Héroult process, involving both electrolysis and the casting of primary ingots. Secondary production involves the production of aluminum ingot from a combination of mostly recycled and processed aluminum scrap, as well as some

[43] US Geological Survey. 2020. "Aluminum Statistics and Information." National Minerals Information Center. Retrieved from https://www.usgs.gov/centers/nmic/aluminum-statistics-and-information.

primary aluminum. Figure 16 shows the aluminum manufacturing process flow diagram addressing the subareas discussed in this document.

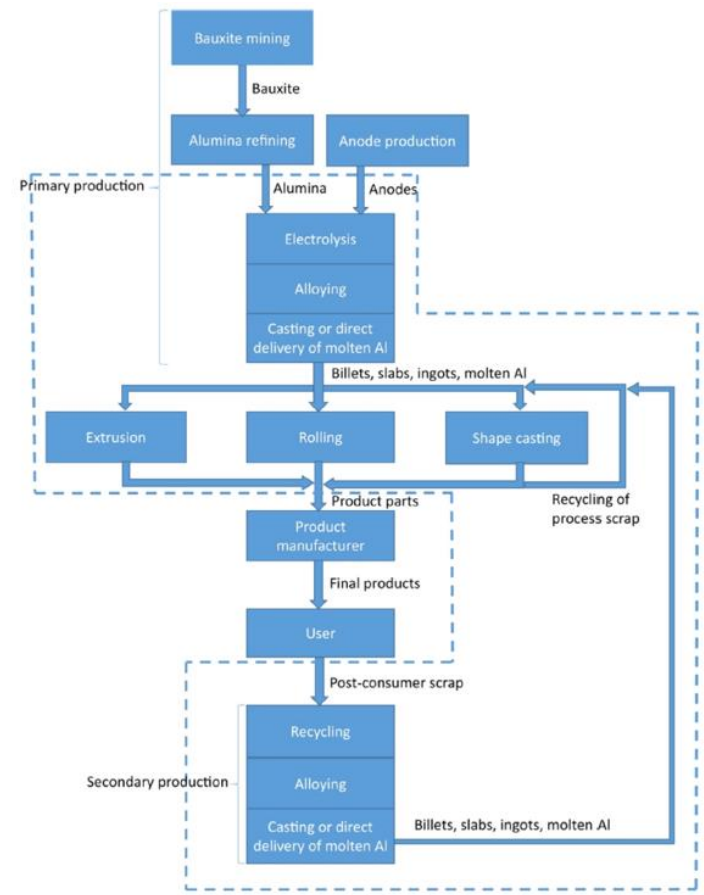

Figure 16. Simplified process flow diagram for the alumina and aluminum industry.

For primary aluminum production, there are three main subareas: raw material preparation or beneficiation (the production of alumina), reductant production (the production of carbon anodes), and primary aluminum production (the Hall-Héroult process, involving both electrolysis and the casting of primary ingots). Secondary production involves the production of aluminum ingots from a combination of mostly recycled and processed aluminum scrap, as well as some primary aluminum. Minor drying operations are carried out in both primary and secondary processing. It is a common practice to dry the washed and filtered raw materials prior to the main calcination furnace (final step in the production of alumina). Both primary and secondary cast aluminum ingots are then shipped to be further processed or used to produce rolled and extruded aluminum products in semi-finished shape production.

These process subareas are further identified in Table 8, along with some of the major subprocesses. These subareas and subprocesses fall within North American Industry Classification System (NAICS) code 3313, alumina and aluminum production and processing. Further steps, such as the production of aluminum parts (e.g., those for automobiles) and the die casting of aluminum, are not discussed.

Table 8. Aluminum manufacturing process areas considered in this report.

Subareas	Subprocesses
Raw material beneficiation (alumina production)	—
Reductant production (carbon anode production)	—
Primary metal production	Electrolysis primary ingot casting
Secondary metal production	Scrap processing secondary melting and ingot casting
Semi-finished shape production	Hot rolling/cold rolling extrusion

5.2.2 RD&D Needs and Opportunities

The bandwidth analysis represented in Figure 17 shows the estimated current and R&D energy savings opportunities for individual manufacturing processes in the aluminum industry.[44]

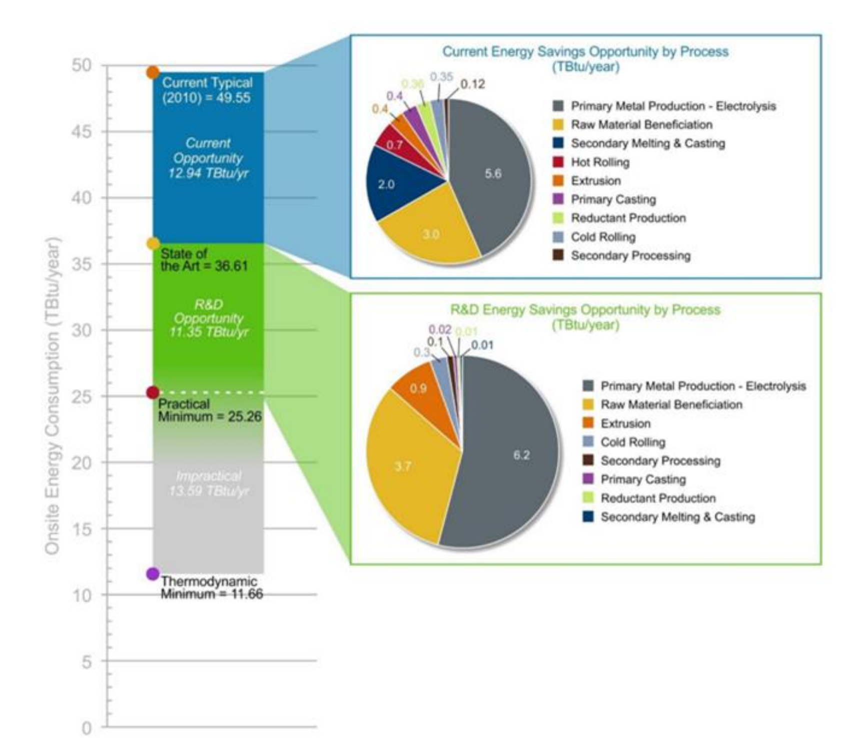

Figure 17. Current and R&D energy savings opportunities in US aluminum manufacturing for the processes studied and sector-wide based on extrapolated data.[44]

Aluminum is used in many applications that differ substantially in product use, performance requirements, and relevance to energy use. Aluminum is produced from bauxite by the electrolysis process and by recovering scrap aluminum metal in secondary aluminum industry. The US primary aluminum production in 2019 was about 1.1 MMT whereas the secondary aluminum production was about 3.6 MMT.[43]

The primary aluminum production process is very energy-intensive, and a large percentage of this energy in the form of electricity is used in the electrolysis process. Major energy savings are

[44] DOE (US Department of Energy). 2015. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Aluminum Manufacturing.

achieved through recycling of aluminum scrap. Reusing aluminum by remelting and casting requires only 5% to 8% of the original energy input of aluminum produced from bauxite. In the United States, the secondary aluminum production uses mainly natural gas–fired melting furnaces.

The melting process is usually preceded by scrap treatment steps such as delacquering and drying of consumer scrap such as used beverage cans, removal of water or moisture, and drying/preheating of the charge material. These steps involve thermal treatment and become a major source of GHG emissions. Commonly used aluminum-melting reverberator furnaces have thermal efficiencies ranging from approximately 20% to 45%. Rotary kilns and conveyor furnaces operate in essentially the same efficiency range. Induction melting is more thermally efficient at approximately 90%, but furnace capacities are limited, and additional steps are required to address oxide concentrations created by EM stirring.

Because of the quality of exhaust gases, which contain contaminants such as particles, soot, and corrosive gases such as chlorine, heat recovery from the exhaust gases has been very limited. The downstream processes of casting, homogenizing, annealing, and so on also use natural gas–fired furnaces and ovens. Because of relatively low temperatures (<1,000°F), this equipment is fairly efficient (>70%), and some may use heat recovery systems. Main sources of CO_2 emission from the aluminum industry are combustion of fuel in furnaces for secondary aluminum and boiler fuel, as well as the calcining process for the primary sector.

The energy use and CO_2 emissions in the aluminum industry can be reduced by using alternative energy sources such as electricity. The use of induction furnaces is common for small furnaces, and in a few cases, electric resistance heating has been used to replace gas-fired burners. However, there is no revolutionary breakthrough in the use of electricity. The use of electrotechnology will result in improved efficiency and reduced emissions.

Table 9 shows potential energy intensity reduction through development and application of advanced technologies for the aluminum industry. The reduction in energy intensity ranges from 13% to 78%. The energy intensity reductions can be achieved by pursuing developments in many different areas. These areas can be broadly classified into four categories. These areas are identified as four TPI pillars, which are described in the next section.

Table 9. Energy intensity estimates and potential reduction in energy intensity for select manufacturing areas in the aluminum industry.[44]

Process	On-site energy intensity (Btu/lb)		Percent reduction
	Current typical	Practical minimum	
Raw material beneficiation	8,660	2,334	73%
Reductant production	744	394	47%
Primary metal production			
Electrolysis	23,388	12,248	47.6%
Primary casting	503	110	78.1%
Secondary metal production			
Secondary processing	567	409	27.9%
Secondary melting and casting	2,229	850	61.9%
Semi-finished shape production			
Hot rolling	1,814	1,572	13.3%
Cold rolling	1,511	1,092	27.7%
Extrusion	2,948	1,474	50%

5.2.3 TPI Technologies

Several developments under each TPI pillar have been identified through literature searches and other investigations by the workshop technical team. The following subsections and tables show and discuss the technologies for each of these TPI pillars for the aluminum industry.

TPI pillar 1: Low–thermal budget transformative technologies

Most aluminum operations are batch or semi-continuous operations, and technology developments leading to continuous material flow would improve energy efficiency and reduction in GHG emissions. Improvements to existing anode and cathode technologies show promise to substantially reduce the use of carbon, and correspondingly, reduce CO_2 emissions. This includes the use of inert anodes, novel physical designs for anodes, use of alternative material/design for cathodes, development of carbon-free or reduced-carbon anodes, and use of multipolar cells with multiple electrodes in a single reaction area. Advancement in bauxite purification or beneficiation processes, Kaolinite reduction (Kaolin to aluminum chloride to aluminum and chlorine), and aluminum integrated mini mills are also promising pathways to optimized aluminum production.[45]

Table 10 shows some key low–thermal budget transformative technologies for the aluminum industry.

Table 10. Low–thermal budget transformative technologies for the aluminum industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.1.1	Inert anode smelting[†46,47,48]	Chemically nonreactive anodes are not consumed by the electrolysis reaction. It produces pure oxygen instead of releasing carbon dioxide Potential materials for inert anodes metals, ceramics, and cermet material (a ceramic-metal composite) Could help to reduce anode-cathode distance	Demonstration/ development: large-scale production trials, retrofit expected to be available in 2024 Elysis (consortium) is made up of Alcoa, Rio Tinto, Apple, and the Canadian authorities. Russian company RUSAL is currently operating with pilot cells based on the use of metal anodes. In Europe, Arctus Metals in Iceland is conducting R&D into inert anodes.[49]	A major barrier is finding cost-efficient anode materials that do not corrode significantly in the reaction solvent. Corrosion adds impurities to the aluminum produced. Advantages: Increases anode life expectancy by 30 times, a 15% decrease in operating costs, and a 15% increase in productivity Energy savings of 3%–4% within a modified Hall-Héroult cell

[45] Based on discussions and feedback from workshop participants
[46] Heimgartner, J. 2018. "Revolutionary Aluminum Process Eliminates Emissions, Produces Oxygen," Engineering.com. Retrieved from https://www.engineering.com/story/revolutionary-aluminum-process-eliminates-emissions-produces-oxygen.
[47] Nelson, B. 2003. "Pass the Smelting Salts," Forbes. Retrieved from https://www.forbes.com/global/2003/1110/032.html?sh=7f26c41151e7.
[48] Springer, C., and A. Hasanbeigi. 2016. "Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for Industrial Production of Aluminum," Lawrence Berkeley National Laboratory.
[49] Solhein, A. 2019. "Is aluminum electrolysis using inert anodes a blind alley?" Sintef. Retrieved from https://blog.sintef.com/sintefenergy/energy-efficiency/aluminium-electrolysis-using-inert-anodes/.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.1.2	Vertical flotation melter in place of a gas reverberatory furnace*[50,51]	Decoats without oxidizing under layer of metal and melts shredded scrap in single component Can be used as preheater, which leads to lower fuel usage Scrap is fed into a cone where hot gases are routed. When drag force and scrap weight become equal, the scrap “floats” or is suspended. The liquid metal is then gravity-fed into a holding furnace.	Demonstration/ development	Thermal efficiency about 2 times greater than a conventional melting furnace (nearly 60% efficiency)[52]
2.1.3	Ultra-high-efficiency aluminum production cell*[53]	This production cell is a combination of several technologies to optimize the production process. Technology used in the optimized cell includes the following: • Inert anode, wetted cathode, and a novel low-temperature electrolyte, as well as numerous advanced sensors and controls	Demonstration/ commercialization	• Impact of sodium fluoride accumulation in the electrolyte melt on cell efficiency, cell performance, and anode stability • Scaling successful 100 hour, 100 Amp trials of a novel low-temperature electrolyte and metallic inert anode to a new, larger 1–3 kiloAmp test cell
2.1.4	Multi-chamber remelting furnace†[54]	• Light or contaminated scrap indirectly melted away from burner flames • Contaminated scrap preheated on dry hearth to burn off paints/lacquers/ combustibles • Cleaned scrap, then pushed into bath for submersed melting • Clean swarf and chips, delacquered shredded light scrap melted in vortex • Molten metal pumped from fired “clean chamber” to circulate through contaminated	Commercially available	• Only suited for the melting of loose scrap with moderate organic content

[50] DOE (US Department of Energy). 2000. *Innovative Vertical Flotation Melter (VFM) and Scrap Dryer*. Retrieved from https://p2infohouse.org/ref/08/07497.pdf.
[51] DeSaro, R. 2004. *The Development of an Innovative Vertical Floatation Melter and Scrap Dryer for Use in the Aluminum Processing Industry*, Energy Research Co. Retrieved from https://www.osti.gov/servlets/purl/828752.
[52] Gas Technology Advisor. “Vertical Flotation Melter,” Equipment. Retrieved from http://gta.gastechnology.org/primary_metals/pm_eq_b4.
[53] Strahs, G. 2011. “Ultrahigh-Efficiency Aluminum Production Cells,” US Department of Energy. Retrieved from https://www.energy.gov/sites/prod/files/2013/11/f4/ultrahi-eff_aluminum.pdf.
[54] Emes, C. 2014. “Innovations in Secondary Smelting and Recycling Furnace Technology,” *22nd International Recycled Aluminum Conference*.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.1.5	WetTable ceramic–based drained cathode technology*	Cathodes made from ceramic material Traditionally, because of the molten aluminum, the anode and cathode must sit far apart to prevent shorting. This technology will allow for smaller interelectrode distances. Savings estimated to be around 7,200 kWh/ton	Commercialization	• Large-scale industry demonstrations
2.1.6	Carbothermic process*[53]	Oxygen forced to react with carbon by reacting alumina at high temperatures, similar to iron smelting Energy consumption estimated at 8.5 kilowatt-hours/kilogram (kWh/kg)	Commercialization	• Slag and scale formation, metal and carbon quality issues, mini-mill operation, and so on[55]
2.1.7	Lower electrolysis temperature*[53]	Currently, processing is conducted at a temperature much higher than aluminum's melting point, indicating high heat loss. By lowering the temperature, excessive heat loss can be avoided. Estimated to reduce energy consumption by 1.5 kWh/kg	Demonstration/ development	• Different electrolyte additives being investigated to allow lower-temperature processing
2.1.8	Tilting rotary furnace†[56,57]	Replacement for a fixed axis rotary furnace The furnace lifts and tilts to pour the aluminum; dry slag remains in the furnace and is later removed via the same tap hole Results in better separation of slag, faster melting, saved energy Studies have shown 15% energy savings, 3%–5% increase in metal recovery, and 50% reduction in cycle time and reduction of manual labor	Commercialization	• Optimizing energy productivity using smart manufacturing and IoT

[55] Choate W., Green J. (2016) Technoeconomic Assessment of the Carbothermic Reduction Process for Aluminum Production. In: Bearne G., Dupuis M., Tarcy G. (eds) Essential Readings in Light Metals. Springer, Cham. https://doi.org/10.1007/978-3-319-48156-2_156
[56] Melting Solutions USA. 2014. "Tilting Rotary Furnace: World Class Melting Technology."
[57] Brough, D. and H. Jouhara. 2020. "The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery," *International Journal of Thermofluids* 1–2.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.1.9	Thermo-magnetic processing†	Magnetic processing could create significant savings in the manufacturing of aluminum castings, especially through heat treatment energy savings of up to 80% based on reductions in heat treatment times.[46] This technology will contribute to transportation fuel savings by enabling lighter weight vehicles with enhanced performance.[46]	Development[58]	• Industrially relevant, system-scale demonstration • Development and employment of multi-scale modeling and simulation tools to drive performance and optimize design and operation of induction-coupled thermo-magnetic-processing

*Included in DOE's Aluminum bandwidth study, 2017
†Not included in DOE's Aluminum bandwidth study, 2017

TPI pillar 2: Alternative thermal processing

TPI pillar 2 technologies achieve TPI by using alternative energy sources while maintaining the current production methods. Alternative energy sources for steam generation and calcination that typical use conventional fuels (coal and natural gas) have been explored by the aluminum industry. Use of electricity in secondary melting plants for melting, casting, rolling, and heat treating is also a promising area of development. Table 11 shows the alternative thermal processing technologies identified for the aluminum industry.

Table 11. Alternative thermal processing for the aluminum industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.2.1	Inductive/ immersion heater†[59,60]	• Resistance heating element placed inside a ceramic tube • Best if constructed from SiAlON ceramic material. SiAlONs are ceramics based on the elements silicon (Si), aluminium (Al), oxygen (O) and nitrogen (N). • Allows for precise control of the temperature and continuous monitoring of the heating element • Electric heating technology	Commercialization: can be found for small holding furnaces	• Scale-up and large-scale industrial demonstration • Energy intensity optimization • Availability of low-carbon electricity
2.2.2	Plasma heating/ MW†[61]	• Coupling of thermal treatment and melting process • Used for preheating, paint stripping, melting of aluminum scrap, and being tested for powder metallurgy sintering • Faster than natural gas counter parts and considered green technologies	Demonstration: plasma heating Commercialization: MW heating	• Large-scale industrial demonstration

[58] Weiss, D., et al. 2020. "Thermomagnetic Processing of Aluminum Alloys During Heat Treatment," *Inter Metalcast*.
[59] Thermocoax. 2016. "Immersion heater for maintaining aluminum bath temperature and for pre-heating of foundry ovens." Retrieved from https://www.thermocoax.com/immersion-heater-maintaining-aluminum-bath-temperature-pre-heating-foundry-ovens/.
[60] Friedmann, S. J., Z. Fan and K. Tang, 2019. "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," The Earth Institute.
[61] Allan, S., R. Sisson, and D. Apelian. 2008. "Microwave Heating Technologies," *Heat Treating Progress* 39–42.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.2.3	Solid-phase processing†[62]	• Eliminates several steps in traditional extrusion processing of aluminum alloy powders while achieving a significant increase in product ductility • Uses Pacific Northwest National Laboratory's shear-assisted processing and extrusion technology • Processed wires, rods, and tubes directly from aluminum alloy powder in one step	Development: mechanical testing being conducted to validate the resulting material's performance	• Rotating die causes friction against the powder, causing it to heat and be extruded in one motion
2.2.4	Electric furnaces†[57]	• Efficiency is much higher, at roughly 90% • Removes combustion gas and saves energy • Leads to much lower metal loss of 0.5%–3% compared with 5%–8% in fossil fuel furnaces	Commercialization	• Because of the higher cost of electricity, only applicable in small operations
2.2.5	High-capacity induction melting in secondary aluminum production†	• Crucible induction furnace: max capacity 8–10 metric ton (MT) • Channel induction furnaces: up to 40 MT. These furnaces operate with a constant "swamp"—that is, ready to metal—that is not completely drained, and part of it remains in the furnace for the next melting. This complicates the use of such furnaces as smelters, mixers, and holding furnaces.	Commercially available	• Crucible induction furnace: large capital investment and high maintenance costs and labor[63] • Barriers to channel induction furnaces include cost

*Included in DOE's Aluminum bandwidth study, 2017
†Not included in DOE's Aluminum bandwidth study, 2017

While the iron & steel and aluminum sectors were chosen as the focus for the workshop given their large energy footprint, production of other metals (copper, zinc, magnesium, manganese etc.) with similar high-temperature process heating applications were also discussed along with the relevant TPI technologies. TPI technologies discussed under pillars 1 and 2 of this section find relevance in the production of other non-ferrous metals as well. While the level of adoption of these technologies in each sector varies, some of the barriers are common and use of the technology in one sector can help drive implementation in others.

In addition to the technologies discussed above (TPI pillar 1 and TPI pillar 2), transformative supplemental technologies such as AI-based process controls could significantly improve the thermal processes. These technologies show great promise to improve productivity, product yield, and product quality in aluminum manufacturing. Also, waste heat management technologies for the aluminum industry, such as heat recovery from harsh environments present in furnace exhaust gases, can help reduce thermal energy use in this sector. These additional technologies are discussed in Sections 5.9 and 5.10.

[62] DOE/Pacific Northwest National Laboratory. 2019. "New manufacturing process for aluminum alloys: Process eliminates multiple steps typical in conventional extrusion."
[63] Aluminium Guide. "Furnaces for production of secondary aluminum." Retrieved from https://aluminium-guide.com/en/pechi-vtorichnogo-alyuminiya/.

5.3 High-Temperature Nonmetallic Mineral: Cement Industry

5.3.1 Energy Use

The United States produced 86 million tons of Portland cement and 2.4 million tons of masonry cement in 2019. Cement was produced at 96 plants in 34 states. Among these, 86 have a dry kiln process and 9 have a wet kiln process. The sales of cement in 2019 were around $12.5 billion. Texas, California, Missouri, Florida, Alabama, Michigan, and Pennsylvania have the highest cement production, in that order, and accounted for about 60% of US cement production.[64]

Energy use for the cement industry reported in the 2014 EIA MECS report is about 298 TBtu/year and consists of fuel (61% of the fuel use is coal) and electricity (mostly off-site generated).[10] The share of each of these energy types for 2014 is given in Figure 18. Coal is the primary fuel in the US cement industry. Figure 18 shows the share of different energy types used in the US cement industry. Heat from fuel combustion accounts for 87% of total final energy consumption, and electricity use accounts for the remaining 13%.

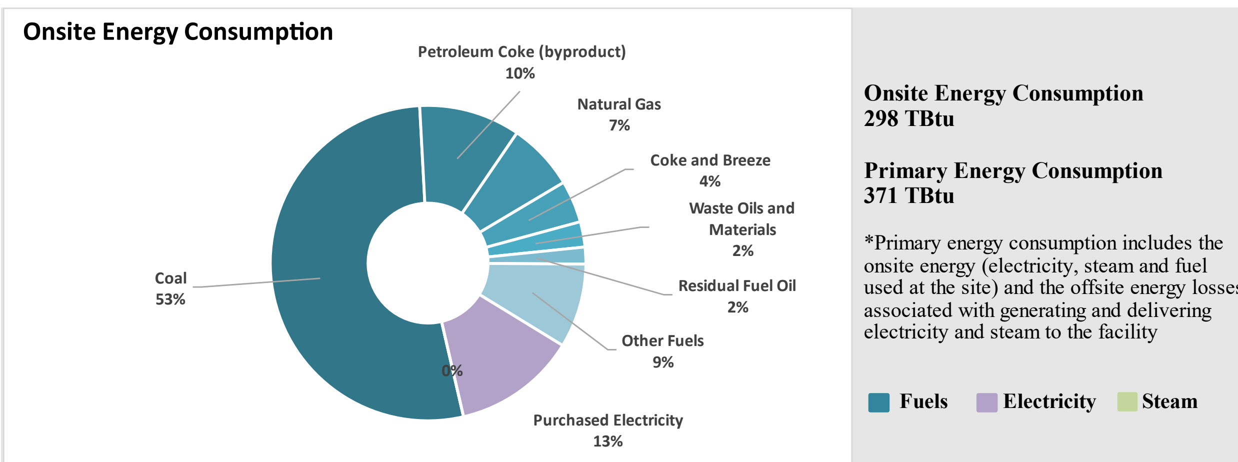

Figure 18. Energy mix in the US cement industry in 2014.

The actual energy used for each process step for the cement industry is higher than the practical minimum required for each of the processes. This is because of inefficiencies involved with the heat supply system (i.e., combustion of fuels or electrical power supply system), as well losses associated with the thermal process equipment (e.g., furnaces, ovens). Approximately 60% of the heat release from fuel is consumed in the chemical reactions, 10% is lost through radiation from equipment, and the remainder is lost in exit gases and hot clinker. Some of the heat in the exit gases is used for raw material drying (Figure 18). Waste heat is being used in many countries for waste heat recovery (where energy prices warrant).

[64] US Geological Survey. 2020. Cement Mineral Yearbook 2016.

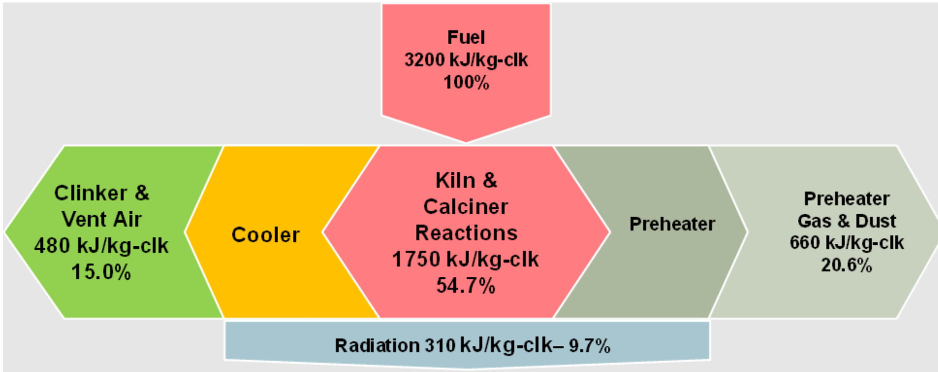

Figure 19. Distribution of heat use and losses in a typical cement plant.[65,66]

Fuel is consumed in two main areas of the modern cement plant. The first area, which requires about 60% of the fuel, is the highly endothermic reaction of limestone calcination (2,141 Btu/kg-clinker or 2,259 kilojoules/kg-clinker), which takes place between 1,562°F and 1,652°F. The second area, requiring 40% of the fuel, is the fusion of the calcium silicates, which takes place between 2,552°F and 2,732°F; this reaction is slightly exothermic. The fused calcium silicates are collectively termed "clinker" in the industry. The fusion takes place as a portion of the raw materials are melted, which catalyzes the fusion reaction and allows agglomeration of the materials into a viscous combination of liquids and solids. A portion of the viscous material adheres to the refractory in the rotary kiln, reducing heat loss and protecting the refractory from the 3,632°F flame temperature.

Cement production is capital-intensive, and cement plants are built to run for 50 or more years. Plants are almost always located adjacent to their limestone reserves. The trend in the industry is to build larger plants to gain economies of scale. The newest greenfield cement plant in the United States produces 12,000 tons per day of cement, or over 4 million tons per year, in a single thermal processing line.

Cement is an intermediate product, and concrete is the final product. Cement makes up between 10% and 20% of the ingredients in concrete. Cement efficiency and cement substitutes represent perhaps the largest area for GHG reduction in concrete use.

5.3.2 RD&D Needs and Opportunities

DOE's bandwidth report for the cement industry[67] shows two energy savings opportunity bandwidths—current opportunity and R&D opportunity (Figure 20). The current opportunity is the difference between the 2010 current typical technology energy consumption and the state-of-the-art energy consumption; the R&D opportunity is the difference between the state-of-the-art energy consumption and the practical minimum energy consumption.

Figure 20 shows 238 TBtu was consumed in 2010 to manufacture US cement in the four subprocesses. Total sector-wide energy consumption in 2010 was 245 TBtu to manufacture all cement in the United States according to EIA.

[65] Kline. J. 2020. Oxy Combustion technology. Presented at Global Cement Live event.
[66] 1 kJ is 0.9478 Btu ; 1kj/kg is 0.4299 Btu/lb

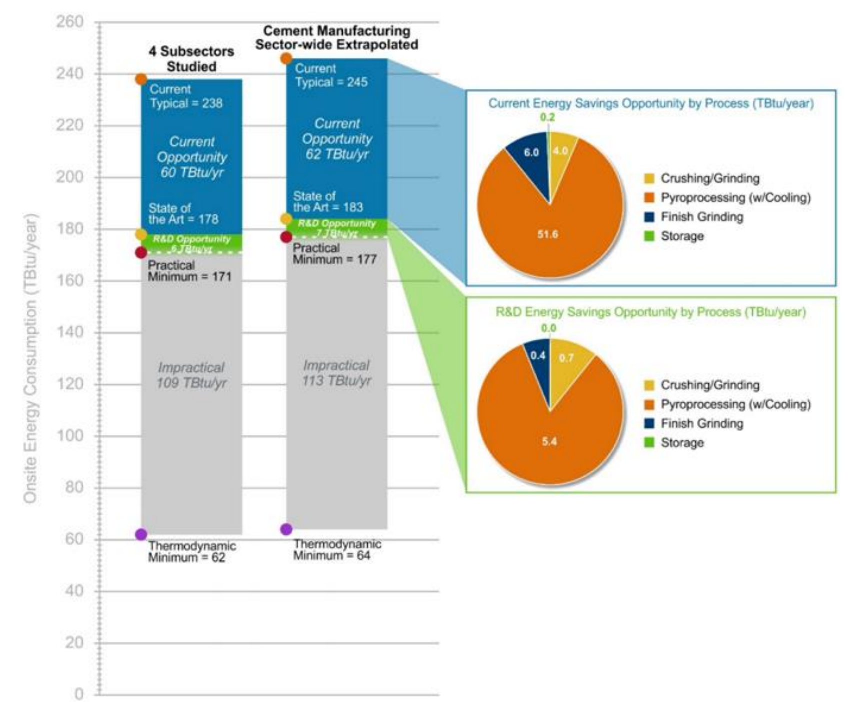

Figure 20. Current and R&D energy savings opportunities in US cement product manufacturing for the processes studied and sector-wide based on extrapolated data.[67]

DOE's bandwidth study looked at the opportunity for energy reduction and estimated that 59.9 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade the cement manufacturing subprocesses studied; an additional 6.4 TBtu could be saved through the adoption of applied R&D technologies under development worldwide. The opportunity quantified in the bandwidth report is tabulated in Table 12, which shows the breakdown of the energy intensity estimates for major processes in cement manufacturing. Although the opportunity to cut energy using best available technology is high across the board, 80% of the R&D energy saving opportunities is in pyroprocessing.

Table 12. Energy intensity estimates and potential reduction in energy intensity in major cement processes.[67]

Process	On-site energy intensity (MMBtu/ton)		Percent reduction
	Current typical	Practical minimum	
Dry process			
Kiln preparation	55	36	34.5%
Fuel preparation	54	28	48.1%
Pyroprocessing with cooling	1,554	1,206	22.4%
Finish grinding	92	48	47.8%
Wet process			
Kiln preparation	48	39	18.8%
Fuel preparation	54	28	48.1%
Pyroprocessing with cooling	2,750	1,612	41.4%
Finish grinding	105	27	74.3%

[67] DOE (US Department of Energy). Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing. Retrieved from https://www.energy.gov/sites/prod/files/2017/12/f46/Cement_bandwidth_study_2017.pdf.

The workshop focused on thermal processes and explored the opportunity in pyroprocessing and other heating applications within the cement manufacturing in more detail. The technologies identified in the bandwidth report were used as a starting point for the workshop.

5.3.3 TPI Technologies

The following subsections and tables show and discuss the technologies for each TPI pillar for the cement industry. The technologies identified within the bandwidth study, along with the ones identified during the workshop, are detailed here.

TPI pillar 1: Low–thermal budget transformative technologies

Table 13 shows some key examples for low–thermal budget transformative technologies for the cement industry. Fluidized bed kilns are one such transformative technology proposed to replace traditional rotary kilns. The advantages of fluidized bed kilns are anticipated to be lower capital costs, lower operating temperatures, lower NO_x emissions, lower overall energy use (10%–15%), and the ability to accept a wide variety of fuels. However, it is difficult to scale up the current fluidized bed kiln demonstrations to the required 5,000 to 6,000 ton/day clinker capacity.

Table 13. Low–thermal budget transformative technologies for the cement industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.1.1	Fluidized bed kiln*	A fluidized bed kiln replaces the traditional rotary kiln with a stationary vertical cylindrical vessel (reactor) where the raw materials are calcined in a fluidized bed. An overflow at the top of the reactor regulates the transfer of clinker to the cooling zone. Fluidized bed kilns have improved heat recovery rates compared with conventional rotary kilns (burn to 2,550°F and cool to 212°F in a two-stage cooler)	Demonstration	• RD&D is needed to scale up • The efficiency needs to be further improved • Integration with carbon capture and storage should be investigated
3.1.2	Oxy-combustion technology†	Oxy-combustion (oxy-fuel) technology replaces the air with an oxygen stream, using pure oxygen instead of air for fuel burning. Because this eliminates the nitrogen that would normally be in the air that is traditionally used for fuel burning, fuel requirements and flue gas volumes are reduced. When the oxygen stream is fed to the kiln, the resulting kiln exhaust gas contains up to 80% of the CO_2 concentration from the fuel burning. This can also increase kiln production capacity. Three configuration can be considered for oxy-combustion in a cement plant: • Kiln oxy-combustion: Using oxy-combustion technology only in the kiln • Calciner oxy-combustion (oxy-calcination): Using oxy-combustion technology only in the precalciner • Total oxy-combustion: Using oxy-combustion technology in both the kiln and precalciner	Pilot or development	Challenges that need to be addressed by further RD&D: • Clinker quality impact • Burner impact • Refractory impact • Kiln seals • Cooler sealing issues • Heat recuperation to the kiln system from cooler

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.1.3	Electrolysis of limestone†	• The process uses an electrochemical reactor that first breaks $CaCO_3$ into a $Ca(OH)_2$ (slaked lime) powder. • This process releases a stream of pure CO_2 that would make it easy to capture and sequester or use in industry, as well as streams of oxygen and hydrogen. • O_2 may be used as a component of oxyfuel in the cement kiln to improve efficiency and lower CO_2 emissions, or the output gases may be used for other value-added processes such as liquid fuel production. • The scalability may be a big challenge.	Development	• RD&D is needed to scale up this system • Availability of clean electricity • Integration with carbon capture and storage

*Included in DOE's cement bandwidth study, 2017
†Not included in DOE's cement bandwidth study, 2017

Although full kiln oxy-combustion will need to address issues related to leakage, quality impact, efficiency impact, and refractory impact, the calciner oxy-combustion will have no or limited issues related to these impacts. As mentioned earlier, around 60% of fuel is used in the calciner and around 80% of emissions is from the calciner. Therefore, oxy-combustion will provide most of energy and emissions benefits while avoiding most of technological challenges. Another challenge to oxy-fuel combustion is the high cost of oxygen. RD&D is needed to produce oxygen at a lower cost.

Electrolysis of limestone is another emerging technology that uses an electrochemical reactor that breaks $CaCO_3$ into $Ca(OH)_2$ (slaked lime) powder. This process releases a stream of pure CO_2 that would make it easy to capture and sequester or use in industry, as well as streams of oxygen and hydrogen that can be used whether in the cement plant or for other uses. The proof-of-concept experiment at the Massachusetts Institute of Technology produced lime from calcium carbonate on a small scale, but scaling up to produce cement at commercial scale is challenging and requires substantial RD&D efforts.

5.3.3.1 TPI pillar 2: Alternative thermal processing

Table 14 shows some key examples for alternative thermal processing technologies for the cement industry. They can be categorized into indirect calcination, use of alternative fuels, and alternative raw materials.

Table 14. Alternative thermal processing for the cement industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.2.1	Indirect calcination†	A breakthrough calciner that can directly separate and capture the CO_2 released from limestone when being transformed into clinker: What makes this direct separation reactor different is that the heat for calcination is not directly brought into contact with the limestone.	Demonstration: Calix technology demo at Heidelberg Cement's Lixhe cement plant in Belgium (LEILAC project)	• Integration into existing plants requires further R&D • High cost of retrofit • Integration with carbon capture and storage

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
		The heat is introduced indirectly via the hot surface of super-high-grade steel at 1,920°F or more. This allows stripping of CO_2 from the limestone without mixing it with other combustion gases. The result is a high CO_2 concentration of more than 95%.		
3.2.2	Electrification of kiln†	Use of electricity instead of fuel in a kiln (challenging): A CemZero project study found that using electricity to supply heat during the clinker production process is possible using plasma technology, although this needs to be tested on a larger scale. Induction and MW heating technologies are also being considered.	Development CemZero project: Vattenfall and Cementa	• Attaining high temperature (>3,270°F) in large-scale kiln suitable for cement production is a challenge • Availability of large amount of green/renewable electricity • Does not address process-related emissions
3.2.3	Electrification of precalciner†	Use of electricity instead of fuel in a precalciner (better possibility than electrification of kiln, especially with indirect calcination): Applying electrification and CO_2 capture to the precalciner only is attractive because of the following reasons: • A relatively high CO_2 reduction rate (around 70%) may be achieved. • The precalciner requires a temperature of ~1,652°F, which can be achieved by electrified technologies; the very high temperature required in the rotary kiln itself is not needed in this case. • Only one of the main equipment units in the kiln system (the precalciner) needs to be modified and the kiln itself does not need any major modification.	Development	• Availability of large amount of green/ renewable electricity • Does not address process-related emissions • Integration into existing plants requires further R&D
3.2.4	Concentrated solar power technology for cement production†	Concentrated solar power technology can be used to achieve temperature around 1,830°F. This is significant but does not go high enough. Clinker production requires temperatures of up to around 2,642°F in the sintering phase to form the clumps of clinker. However, this temperature range by concentrated solar power is sufficient for the	Pilot by Heliogen and SOLPART project	• Location-specific and only suitable for locations with high solar radiation • Does not address process-related emissions • R&D in needed for integration into industrial-scale plants

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
		calcination stage of clinker production and can be the focus of this technology in the near term.		
3.2.5	Use of hydrogen in the fuel mix†	Use of hydrogen in the fuel mix for the use in kiln or precalciner	Development Pilot project to use a mix of hydrogen and biomass fuels at Hanson Cement's Ribblesdale integrated plant in UK being planned	• Availability of clean/green electricity for hydrogen production • High cost of hydrogen • Does not address process-related emissions • Hydrogen use may affect the physical aspects of the kiln system, the fuel mass flows, temperature profile, heat transfer and the safety considerations for the plant
3.2.6	Alternative raw materials that reduce heat demand in a cement plant*	Innovative chemistries and use of alternative materials can help to lower the temperature need and heat demand in the production process while using conventional kiln systems. An example of this is Solidia cement.	Some early commercial and some demonstration or development	• Demonstrating technical performance, especially durability under different ambient conditions, and long-term safety of cements based on alternative binding materials to meet construction standards • Production at large scale • Availability of raw materials

*Included in DOE's cement bandwidth study, 2017
†Not included in DOE's cement bandwidth study, 2017

Indirect calcination

In an indirect calciner, the heat for calcination is not directly brought into contact with the limestone. The heat is introduced indirectly via the hot surface of super-high-grade steel at 1,922°F or more. This allows stripping of CO_2 from the limestone without mixing it with other combustion gases. The result is a high CO_2 concentration of more than 95% that is easier to capture at lower cost. The Calix technology is being demonstrated at Heidelberg Cement's Lixhe cement plant in Belgium. RD&D is needed to identify issues and mitigation options for retrofitting of indirect calciners in existing cement plants. If indirect calcination were combined with electric heating (see next section), it would provide a great opportunity to substantially reduce energy-related emissions (by using renewable energy as electricity source) and process-related emissions by capturing high-purity CO_2 inexpensively from the indirect calciner.

Cement process electrification

Process electrification is in the early stages of development and still faces challenges in meeting the requirements for the high temperature and heat transfer required in cement production. Direct and indirect calcination using electric heating each have different challenges.

For modern precalciner kilns, 40% of the fuel is fired in the kiln itself with flame temperatures reaching higher than 3,600°F. Clinker formation is made in a combination of viscous liquids and solids. This forms the clinker nodules and a coating on the inside of the kiln, which protects the refractory. Attempts to produce Portland cement clinker in stationary (electric) vessels has often failed in the past because of the “sticky” nature of the clinker. Electrification is possible, but because the full reaction of the clinker currently takes place in the combination of liquid and solids, new methods face technological challenges.

However, around 60% of the fuel is fired in the precalciner with temperature around 1,560°F–1,650°F. Not all kilns have precalciners, but all new kilns built in the past two or even three decades have precalciners. Indirect calcination, driving the calcination reaction through indirect heating, provides a relatively pure CO_2 stream from the calcination reaction, which accounts for more than half of the emissions of a modern precalciner plant. Indirect heating can be performed in many fashions, and many suggestions have been made in the past, including using heating oils, indirect firing, electric induction coils, and concentrated solar power. Indirect calcination should be relatively easy to design and incorporate in new cement plants and may be retrofittable (with a loss of thermal efficiency) in existing precalciner kiln systems.

Although electric furnace technology for temperatures up to 1,830°F is in the early stages of commercialization for industrial-scale applications, much more RD&D is needed for temperatures above that.[68] Given the technological challenges, more basic RD&D is needed for electrification of the full kiln via plasma arc or other electrification technologies. The use of electric heating for indirect calcination can also be studied in combination with carbon capture and storage, given the concentrated process CO_2 emissions associated with this route. Other electrification options also exist. Initial lab tests have shown that sintering of cement can occur at a lower temperature in a MW environment, and additional studies have investigated a hybrid method combining conventional kilns and an electric furnace, which indicated lower energy use compared to the fully conventional route.

Use of hydrogen in the fuel mix

Hydrogen is another potentially transformative technology still in the research stage for application in cement kilns. Like other alternative fuels, high levels of hydrogen in the fuel mix could affect physical aspects of the kiln, such as the fuel mass flows, temperature profiles, heat transfer, exhaust gas moisture content, and safety considerations for the plant in ways that are not yet completely understood. For example, acidification is a potential problem: as the gas is cooled, nitrogen oxides (NO_x), sulfur oxides, and chlorine gases may form, and higher moisture content in the exhaust gases going to the main baghouse may cause damage. The potential impact on refractory from high levels of hydrogen in the fuel mix is still unknown. However, there is the possibility of using low proportions of hydrogen in the fuel mix without the need for substantial changes in operation. Hydrogen also faces economic challenges. It is expensive and has little current infrastructure for transport and storage. Safety is also a major concern for transport and storage.

To address technological issues, RD&D should investigate how to optimize kilns and burners for low, medium, and high levels of hydrogen use, especially with regard to safe, efficient and effective combustion in the kiln fuel mix. Research is needed to better understand the impact of

[68] de Pee, A., D. Pinner, O. Roelofsen, K. Somers, E. Speelman, and M. Witteveen. 2018. *Decarbonization of Industrial Sectors: The Next Frontier.* McKinsey & Company. Retrieved from https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/How%20industry%20can%20move%20toward%20a%20low%20carbon%20future/Decarbonization-of-industrial-sectors-The-next-frontier.ashx.

high levels of hydrogen and increased exhaust moisture on refractory and other materials in the kiln.

To address economic challenges, RD&D is needed to bring down the cost of manufacturing hydrogen, including transport and storage issues. A Columbia University study found that blue hydrogen (natural gas steam methane reforming in addition to carbon capture and storage [CCUS]) could be cost competitive with CCUSs with conventional fuels. However, additional analysis is needed to understand when and how hydrogen options could become cost-competitive with current practices. In addition, research should focus on the potential for green or clean hydrogen. RD&D should investigate the comparative life cycle impact of hydrogen fuel switching for hydrogen produced via different routes.

Alternative raw materials

Innovative chemistries and use of alternative materials can help to lower the temperature need and heat demand in the production process while using conventional kiln systems. An example of this is Solidia cement. Solidia cement is composed primarily of low-lime-containing silicate phases. In total, Solidia cement clinker contains between 42% to 48% lime by weight. Portland cement clinker typically contains approximately 65–70% lime by weight.

Alternative binding materials, which use different raw materials besides Portland cement, have a series of challenges and opportunities. The technical performance of alternative binding materials is still not well characterized, especially with respect to durability under different ambient conditions and long-term safety. Low-carbon chemistries can only be used for certain applications. The engineering standards and building codes in relation with the use of these alternative products should be investigated.

Economic challenges are also significant. Many such materials are also expensive and not yet produced at a large scale. Raw material availability is often limited, and some types of alternative binding materials would compete for raw materials with other industries, such as the aluminum industry. Some alternative binding cement materials are already commercially available, such as belite clinker, calcium sulphoaluminate clinker, and alkali-activated binders. In the demonstration and pilot phases are materials such as belite calcium sulphoaluminate clinker, cements based on carbonation of calcium silicates, and pre-hydrated calcium silicates. Magnesium oxides derived from magnesium silicates are still in the R&D phase and face challenges in acquiring funding.[69] However, raw materials such as calcinated clays and limestone fillers being readily available does not mean they are economically or logistically available as alternative binding materials for cement products.

RD&D can address challenges with technical performance and seek to demonstrate the long-term safety of cement with alternative binding materials under different ambient conditions. In addition, RD&D should assess the comparative CO_2 intensity of different cement binding materials (Figure 21) to demonstrate their benefits for decarbonization to decisionmakers.

[69] DEEDS (Dialogue on European Decarbonization Strategies). 2020. Industry - Cement. Retrieved from https://deeds.eu/wp-content/uploads/2020/05/Cement_web.pdf

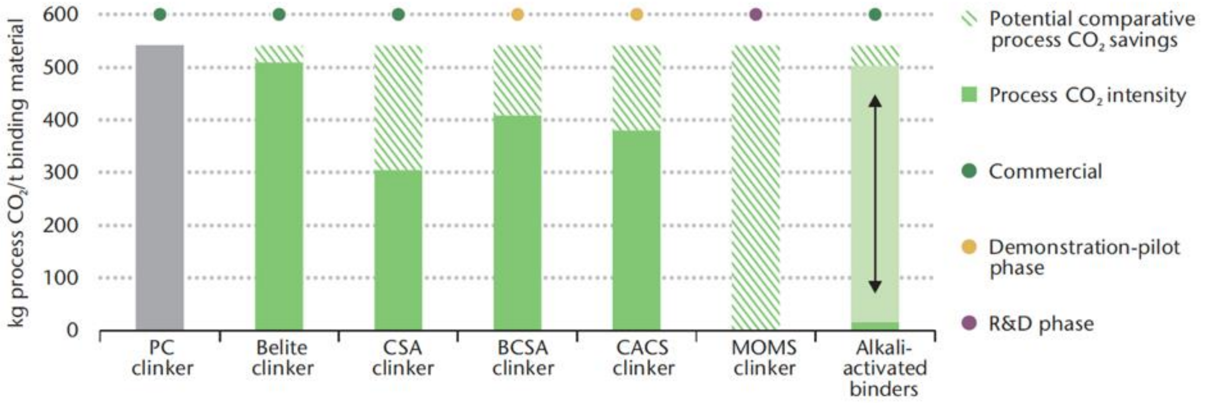

Figure 21. Process CO_2 emissions intensity for cement binding materials.[7]

RD&D should also develop lower-cost production processes, given the economic challenges for alternative binding materials. Techno-economic analysis can identify regional cost and availability of raw materials and look at life cycle impact scenarios for different applications. There should also be educational programs and testing, pilot, and demonstration programs to promote acceptance and uptake.

In addition to the technologies discussed, there are also transformative supplemental technologies for the cement industry such as digital twin, smart IoT for system optimization, AI, and predictive models for plant optimization. Also, waste heat management technologies for the cement industry—such as waste heat recovery for power generation and optimization of preheater design and clinker cooler heat recovery—can help reduce thermal energy use in this sector. These additional technologies are discussed in the transformative supplemental technologies and waste heat management technologies sections.

5.4 High-Temperature Nonmetallic Mineral: Glass Industry

5.4.1 Energy Use

The major five glass subproducts are flat glass, container glass, glass fiber wool, glass fiber textiles, and pressed and blown glass[6]. In 2017, the United States produced around 20 million tons of glass. Figure 22 shows the share of each glass type from the total glass industry energy use in the United States in 2014. Flat glass has the largest share followed by container glass. Figure 22 shows that 71% of the on-site energy use in the glass industry is natural gas and 23% is electricity.[11]

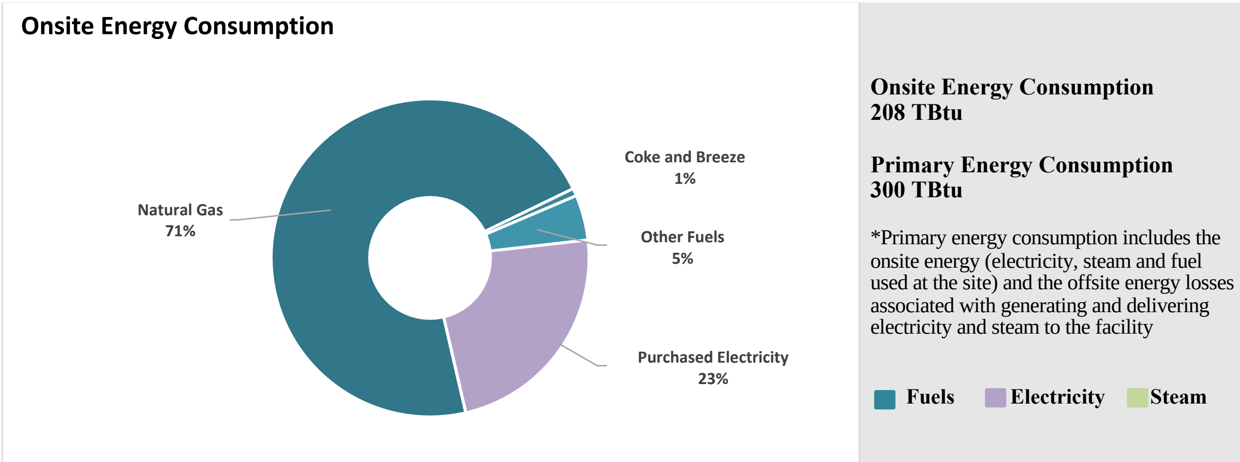

Figure 22. Energy mix in the US glass industry in 2014.[11]

The production of glass can be generally split into four main stages. The first stage is raw materials preparation. The production process starts with the preparation of raw material (generally sand). These processes include crushing, hammering, batching, mixing and grinding, screening, atomization, separation, and filtering. When glass cullets (recycled glass that is crushed and ready to be remelted) are used as the raw material, drum and vacuum systems are used to dry it prior to separation. The second stage is smelting and refining. Melting, refining, and homogenization occur simultaneously during the smelting process. Raw materials are heated to 2,730 °F in a furnace to produce molten glass. This step takes 75% of the energy of the entire process. The third stage is forming. The forming process varies according to the type of products produced: flat glass forming, molded glass forming, and tube glass forming. The fourth stage is downstream processing. A variety of downstream processes follows the forming process.[70] Figure 23 shows the share of each glass type from total glass industry energy use in the United States in 2014. Flat glass has the largest share followed by container glass. Around 74% of the energy used in the glass industry is natural gas and 21% is electricity.[70] Figure 24 shows a simple schematic of the float glass (flat glass) production process.

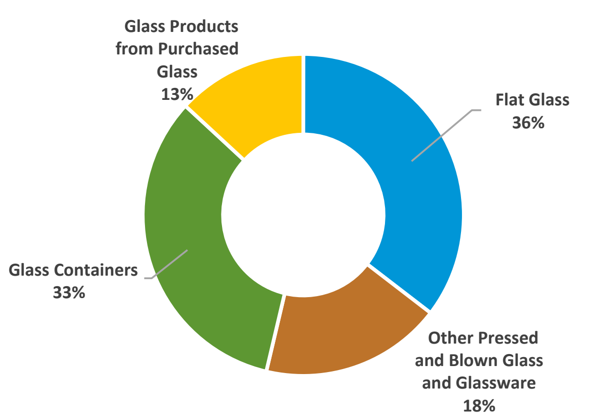

Figure 23. Share of each glass type from total glass industry energy use in the United States in 2014.[11]

[70] DEEDS (Dialogue on European Decarbonization Strategies). 2020. *Industry - Glass*. Retrieved from https://deeds.eu/wp-content/uploads/2020/05/Glass_web.pdf.

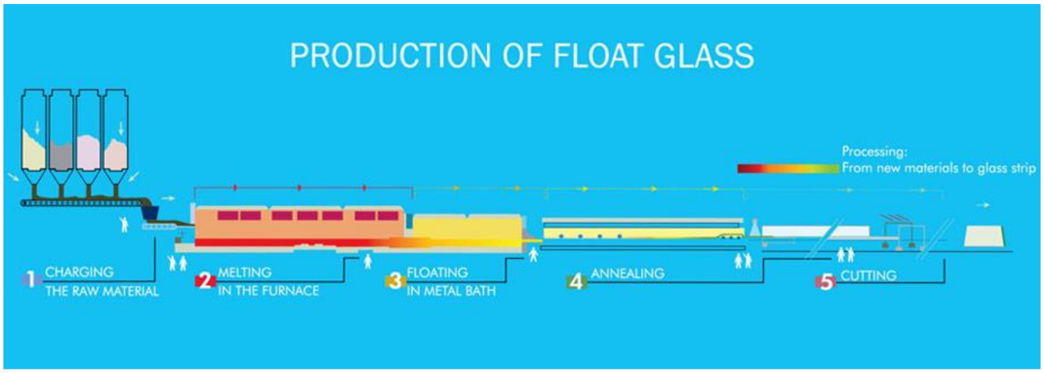

Figure 24. Float glass (flat glass) production process.[71]

5.4.2 RD&D Needs and Opportunities

The bandwidth analysis represented in Figure 25 shows the estimated current and R&D energy savings opportunities for individual manufacturing processes in the glass industry.[72]

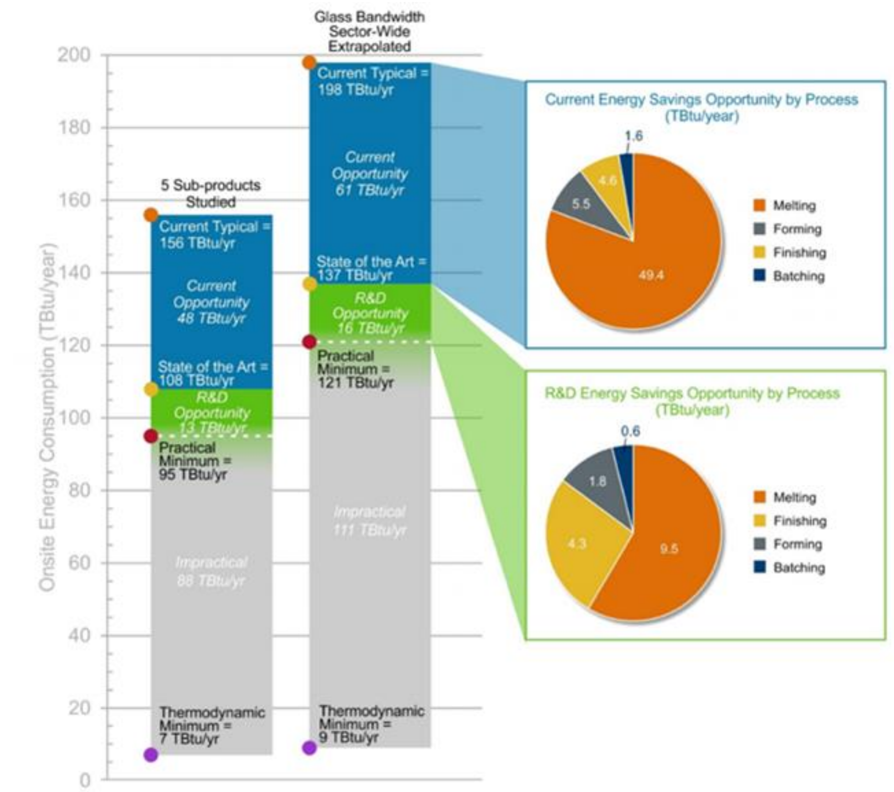

Figure 25. Current and R&D energy savings opportunities in US glass product manufacturing.[72]

The savings opportunities by process are different for each glass sub-product, and the above estimates correspond to the total energy savings opportunities for all sub-products included in this study. Based on the bandwidth analysis, the greatest current and R&D opportunities for glass

[71] AIS. 2020. Glass manufacturing process. Retrieved from https://www.aisglass.com/glass-manufacturing-process.
[72] DOE (US Department of Energy). 2017. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing.

manufacturing involve more efficient glass melting/refining. On-site energy savings in glass melting/refining account for 81% of the current opportunity and 58% of the R&D opportunity. Energy savings opportunities that do not involve glass melting/refining represent about 19% of the current opportunity and 42% of the R&D opportunity.

The opportunity quantified in the bandwidth report for flat glass and container glass operations is tabulated in Table 15. The workshop focused on thermal processes and explores the opportunity in pyroprocessing and other heating applications within glass manufacturing in more detail.

Table 15. Energy intensity estimates and potential reduction in energy intensity for select manufacturing areas in the glass industry.[72]

Process	On-site energy intensity (MMBtu/ton)		Percent reduction
	Current typical	Practical minimum	
Flat glass			
Batching	0.68	0.57	16.2%
Melting/refining	6.19	3.84	38%
Forming	1.50	1.23	18%
Finishing	2.20	1.66	24.5%
Container glass			
Batching	0.68	0.57	16.2%
Melting/refining	5.55	2.46	55.7%
Forming	0.12	0.09	25%
Finishing	0.56	0.35	37.5%

The technologies identified in the bandwidth report were used as a starting point for the workshop. Furthermore, the barriers associated with these technologies and their research needs were reviewed and discussed in more detail during the workshop. The results from these discussions are presented in the next section.

5.4.3 TPI Technologies

The following subsections and tables lay out the technologies discussed within glass manufacturing for each TPI pillar of TPI. The technologies identified in the bandwidth study and the ones identified during the workshop are appropriately distinguished for reference.

TPI pillar 1: Low–thermal budget transformative technologies

Table 16 shows the low–thermal budget transformative technologies for the glass industry. Most past work using plasma melting has focused on the melting of metals and scrap/waste in which the material was highly conductive. However, R&D in the past decade has investigated the use of plasma melting to produce high quality glass. Past plasma melting efforts have highlighted several technical barriers that must successfully be resolved before plasma melting can take its place as a viable commercial process: short torch lives, instability in the process, poor glass quality, metals contamination from process hardware, and low maximum throughput of the melter. RD&D efforts should focus on addressing all these technical barriers to further advance the plasma technology for glass production.

Table 16. Low–thermal budget transformative technologies for the glass industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.1.1	Plasma melter†	Plasma arc melting of glass has an energy density 2.5 times higher than conventional glass melting, allowing melting to occur more rapidly and efficiently Improvement in energy intensity of 50%–70%	TRL 6 Pilot	The main challenges which should be addressed by RD&D are • Enclosures to reduce high sound levels • Dust collector for furnace off-gas • Reducing slag production • Reducing cooling water demand • Reducing heavy truck traffic for scrap and materials handling • Environmental effects of electricity generation • Flicker and harmonic distortion, which are common power system side-effects of arc furnace operation • Design of an industrial-scale plant
4.1.2	Segmented melter*	Segmented melters separate the melting processes for the main materials in glass, the batch and the cullet, which have different melting temperatures and residence times. Segmentation of the melting process allows optimization of each stage since each stage requires special conditions 25% improvement in thermal efficiency	TRL 3 Research	• Further R&D on the possible melting rate and the usage of the melting zone should be carried out. • More R&D is needed for the intersection between the melting zone and the rest quartz dissolution zone. The flowing down of the primary melt with unresolved rest quartz could increase the corrosion in this region. • New concepts of the batch supply for the melting zone and new refractory materials should be investigated. • More R&D is needed for scale-up.
4.1.3	FLOX flameless burner†	"FLOX" refers to a flameless burner in which the combustion gas and air go into the combustion chamber at a high flow rate. Mixing is delayed, preventing a large, visible flame from forming. The combustion chamber can achieve very high and homogenous temperatures. This leads to improved energy transfer to the melting glass. The reduced flame temperatures at the burner nozzles also reduce generation of thermal NO_x, an undesired by-product.	TRL 7 Pilot	• More R&D is needed for design of both the new burner system as well as their positions in the furnace to avoid high gas velocities immediately above the glass bath. • Because there are considerable temperature differences between hot and cold streams, optimization of the glass melting process is a bottleneck. More R&D is needed to address this. • Integrating this technology with existing plants should be investigated.

*Included in DOE's glass bandwidth study, 2017
†Not included in DOE's glass bandwidth study, 2017

Segmentation of the melting process in a segmented melter allows optimization of each stage since each stage requires special conditions. RD&D efforts on the possible melting rate and the usage of the melting zone should be carried out. A problem of the segmented thin film melter might be the intersection between the melting zone and the rest quartz dissolution zone. The flowing down of the primary melt with unresolved rest quartz could increase the corrosion in this region. Furthermore, new concepts of the batch supply for the melting zone and new refractory materials should be investigated.[73]

TPI pillar 2: Alternative thermal processing

Glass-making process electrification: The three main applications of electric heating in glass production are (1) electric boosting of fuel fired furnaces, (2) all-electric melting and refining, and (3) electrically heated temperature conditioning.

The transition to an electrified glass container manufacturing process is quite viable because of the commercial availability of electric melting, forming, and finishing equipment for container glass production. This transition can result in a substantial energy saving and GHG emissions reduction in the glass industry as shown in a recent study by the Global Efficiency Intelligence.[74] Electric furnaces are typically able to achieve high melt rates per surface area of the furnace, and the thermal efficiency of these furnaces (on an energy delivered to the furnace basis) is almost twice or three times that of fossil fuel-fired furnaces.[75] Numerous glass makers have already transitioned to using electric forehearths and annealing lehrs. Major manufacturers of these equipment include Electroglass (for electric forehearths), and CNUD and Pennekamp (for electric annealing lehrs).[76]

The all-electric furnace for float glass production still requires further RD&D. The quality requirement for most float glass is significantly higher than that for container glass. In fuel-fired container glass furnaces and all-electric container glass furnaces, melting and refining are achieved in one tank. In contrast, in float glass production, it is generally considered that melting and a certain degree of refining takes place in the main melting chamber, with a secondary refining chamber completing the process, resulting in a comparatively long residence time. Electric boosting in a fuel-fired float glass furnace can and has been applied, although not nearly as widely as in container glass production.

Theoretically, an electric melter could be used for the main melting, with the glass being further refined in a designated secondary refining chamber. The chamber could be heated electrically, either by electric radiant elements in its superstructure, over the molten glass surface, and/or by immersed electrodes in the glass. RD&D is needed to investigate the viability of these electrification options for float glass. Table 17 shows the alternative thermal processing technologies for the glass industry.

[73] Hessenkemper, H. R. Weigand, and A. Wiltzsch. 2010. “A View in the Future of the Melting Technology and Refractory Materials for the Glass Industry,” *Refractories Worldforum* 2, 69–74.
[74] Hasanbeigi, Ali; Collison, B., Kirshbaum, L., Gardiner, D. (2021). Electrifying U.S. Industry: Technology and Process -Based Approach to Decarbonization. Global Efficiency Intelligence, LLC. U.S.
[75] Scalet, B. M., M. Garcia Muñoz, A. Q. Sissa, S. Roudier, and L. Delgado Sancho. 2013. “Best available techniques (BAT) reference document for the manufacture of glass.” Sevilla: Joint Research Centre of the European Commission.
[76] Beyond Zero Emissions. 2019. Zero Carbon Industry Plan: Electrifying Industry. Melboume, Australia.

Table 17. Alternative thermal processing technologies for the glass industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.2.1	Electric melting/ electric furnace*	Fuel switching: fuel switch to electricity (electric melting and electrification or boosting) 55% energy savings on furnace heating	TRL 8	• The economic viability of electric furnaces is a major barrier. More research is needed for more efficient large industrial melters. • An all-electric furnace needs a stable, reliable power grid • Electrodes need to be maintained by advancing them in case wear leads to higher resistance. The new methods to counter electrode wear would need to be investigated. • Especially for the container industry, how this kind of furnace would handle extremely high amounts of cullet, which may result in different ways cullet and batch are managed
4.2.2	Fuel switching: hydrogen†	Fuel switching to hydrogen	TRL 4	• More R&D is needed for matching hydrogen burners with glass melters. • More research is needed to design an industrial-scale plant.
4.2.3	MW melting*	MW energy is used to selectively heat and melt the glass.	TRL 3	• A major challenge to MW heating is controlling the temperature distribution in heated glass, which is less uniform when heating via MW. • More research is needed to design an industrial-scale plant. • Simulation of MW heating to predict heat transfer patterns. • Emerging research on operations control can help improve the efficiency of glass MW heating.
4.2.4	RF laminating in autoclaves*	RF lamination can reduce the energy intensity of conventional autoclave lamination by reducing the processing time and energy needs of the process Applicable to flat glass production Can achieve 45% energy savings		• The effect of pre-heating on quality and efficiency should be investigated. • More pilot plants are needed for investigating industrial scale operation.

*Included in DOE's glass bandwidth study, 2017
†Not included in DOE's glass bandwidth study, 2017

Hydrogen can also be used as alternative fuel in glass manufacturing. The RD&D challenges and opportunities are mainly similar to those mentioned in previous sections for the cement industry.

One way to accelerate glass melting is directly heating the foam and incoming batch. A good heating source for that is MW. Millimeter wave MWs interact with the glass batch so efficiently that the batch can be melted within seconds. This gives opportunity for the new design of glass melting tanks, and any capacity melting tanks (including small) can be designed.[77]

A major challenge to MW heating is controlling the temperature distribution in heated glass, which is less uniform when heating via MW. Researchers are working on a simulation of MW heating to predict heat transfer patterns and how to design an industrial MW oven. Scientists have used numerical models to study the physics of MW heating applied to biomass, water, and alumina. Emerging research on operations control can help improve efficiency of glass MW heating. Researchers also developed a numerical methodology implemented using COMSOL software and automated controls to optimize energy efficiency in MW heating.[78] Because MW heating is an emerging technology, this control method faces challenges in obtaining adequate data for validation of the software.[79]

While the cement and glass sectors were chosen as the focus for the workshop given their large energy footprint, production of other non-metallic minerals (ceramics, gypsum, etc.) with similar high-temperature process heating applications were also discussed along with the relevant TPI technologies. TPI technologies discussed under pillars 1 and 2 of this section find relevance in the production of other non-metallic minerals as well. While the level of adoption of these technologies in each sector varies, some of the barriers are common and use of the technology in one sector can help drive implementation in others.

In addition to the technologies discussed, there are also transformative supplemental technologies for the glass industry such as new fault detection technology, process heating control systems, process controls in forehearths, more efficient forehearths or oxy-fuel-fired forehearths, improved fiber drying and curing, and the use of IoT for plant monitoring. Also, waste heat management technologies for the glass industry—such as batch preheating/raw materials preheating, raining bed batch and cullet preheater, and oscillating combustion—can help reduce thermal energy use in this sector. These additional technologies are discussed in the transformative supplemental technologies and waste heat management technologies sections.

5.5 Low- and Medium-Temperature Processing: Pulp and Paper Industry

5.5.1 Energy Use

Pulp, paper, and wood product manufacturing (NAICS 321 and 322) is the third largest consumer of energy in the US manufacturing sector (after chemical manufacturing and petroleum refining), accounting for 13% (2,473 TBtu) of the total primary manufacturing energy

[77] Gyrotron Technology. 2020. Microwave Glass Melting is a Unique Processing Technology.
[78] Mimoso, Ricardo M. C., Duarte M. S. Albuquerque, José M. C. Pereira, and José C. F. Pereira. 2017. “Simulation and Control of Continuous Glass Melting by Microwave Heating in a Single-Mode Cavity with Energy Efficiency Optimization.” International Journal of Thermal Sciences
[79] Springer, C., and A. Hasanbeigi. 2017. *Emerging Energy Efficiency and Carbon Dioxide Emission Reduction Technologies for the Glass Industry*. Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory.

consumption in 2014.[80] The on-site energy use and a breakdown of its different sources is provided in Figure 26.[10]

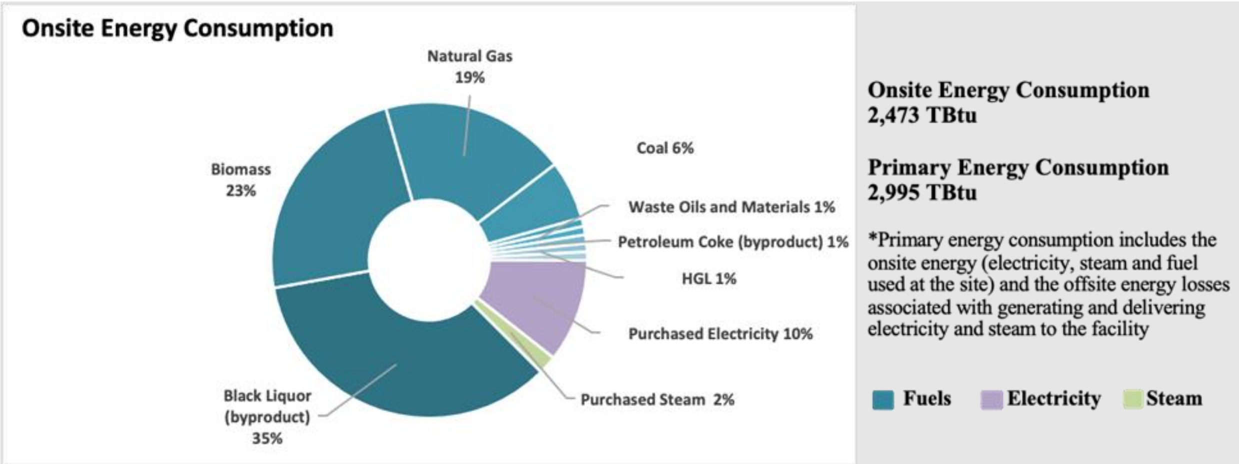

Figure 26. Onsite energy consumption in the US pulp and paper sector by energy source in 2014.

The production of paper from wood can be generally split into raw material preparation, pulping, and paper-making. The pulping and paper-making steps can be done at separate facilities or concurrently in an integrated pulp and paper mill. Recycled paper processing mills, which are a significant portion of the industry, utilize used paper as their feedstock instead of wood chips.

The major consumers of thermal energy within the pulp and paper sector are liquor evaporation, pulping chemical preparation, wood cooking and bleaching in pulp manufacturing, and paper drying and paper machine wet end in paper manufacturing. Recycled papermaking does not have the typical steps associated with Kraft pulping process (digesters, liquor recycling) seen in a virgin pulp mill, but there is significant thermal energy use associated with heating the pulp slurry and dry paper. Some mills make use of both recycled and virgin fiber to make paper.

Liquor evaporation involves using steam to concentrate the weak liquor solids generated during washing of chemical pulp to that required for firing in a recovery boiler. Pulping chemical preparation is the energy used in the pulp mill for chemical preparation, such as white liquor, and includes energy consumed in the lime kiln. Wood cooking is the energy consumed in the cooking of chemical pulps in the digester.

Paper drying is predominately done using multicylinder designs, and the main part of the supplied energy comes from low-pressure steam. The low-pressure steam is produced by burning lignin and hemicelluloses in the recovery boiler followed by electricity production in the back-pressure turbine. Paper machine wet end (current typical: 2.07 MMBtu/ton) is the stock preparation ahead of the paper machine and includes refining, cleaning and screening, forming, and pressing.

[80] DOE (US Department of Energy). 2015. Bandwidth Study U.S. Pulp and Paper Manufacturing. Retrieved from https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing.

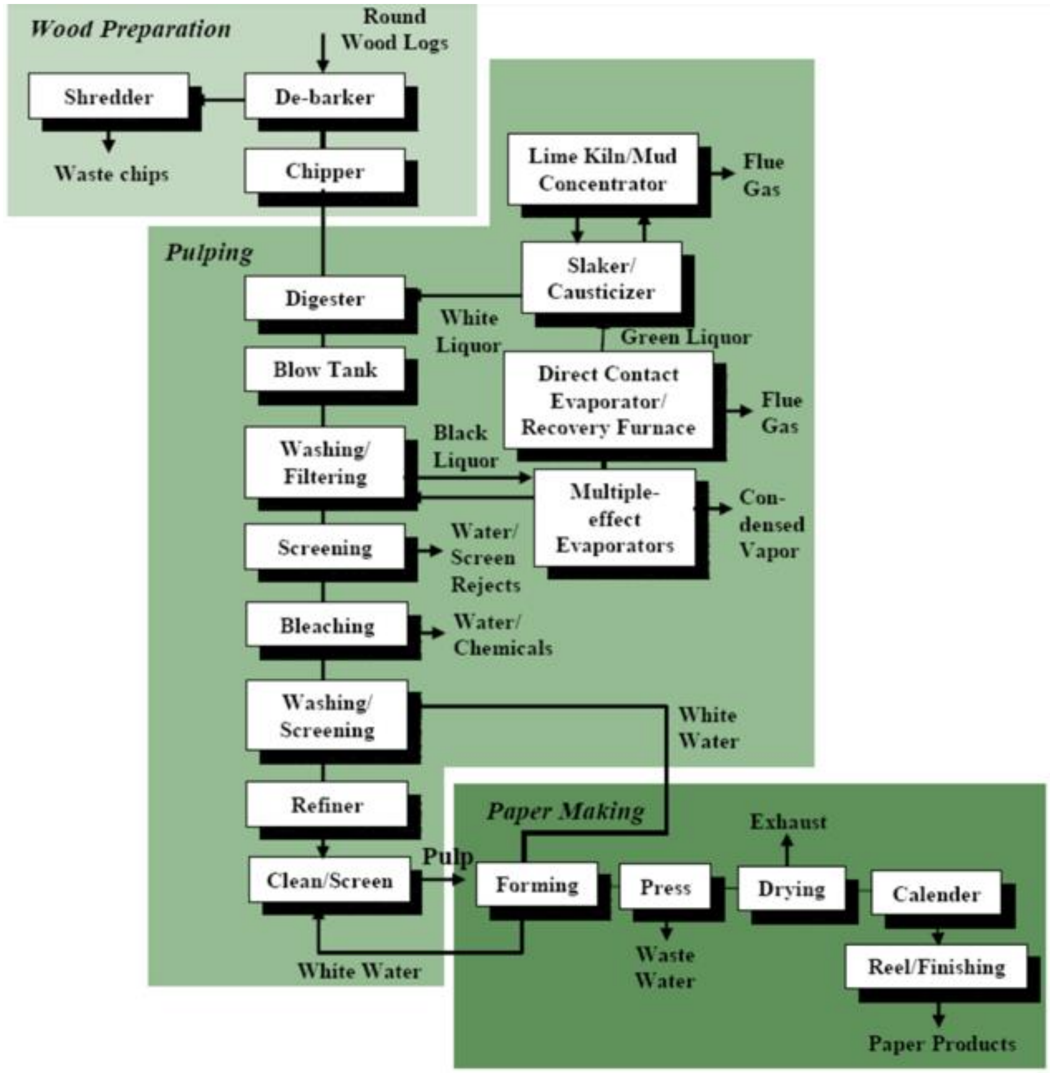

Figure 27. Process flow in a typical integrated pulp and paper mill.[80]

5.5.2 RD&D Needs and Opportunities

DOE's bandwidth study[80] describes the opportunity space for energy intensity reduction in the pulp and paper sector. The bandwidth report includes current energy intensity, state-of-the-art, practical minimum, and theoretically minimum energy intensities for each of the areas studied. Figure 28 shows the estimated current and R&D energy savings opportunities in the pulp and paper sector, extrapolated from select processes studied in detail.

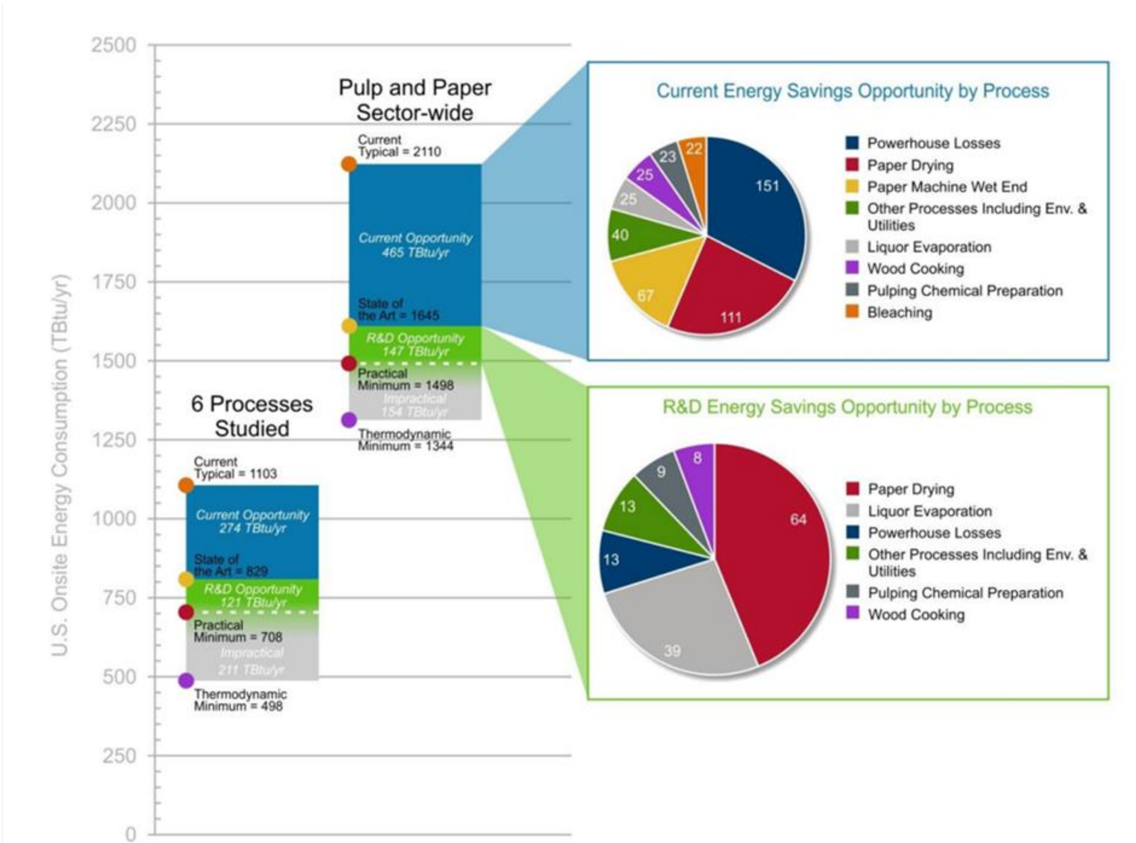

Figure 28. Current and R&D energy savings opportunities in US pulp and paper manufacturing.[80]

The bandwidth analysis determined the potential on-site energy savings opportunities to be 24% (465 TBtu) from upgrading to the best available technologies and practices available in US pulp and paper manufacturing (based on the 274 TBtu in the six processes studied in the bandwidth analysis). Integrating R&D technologies under development would yield an additional 7% (147 TBtu) energy savings (based on the 121 TBtu saved in the six processes studied in the bandwidth analysis).

The top R&D energy saving opportunities from the six processes identified in the reports were in paper drying (64 TBtu or 44% of the R&D opportunity), liquor evaporation (39 TBtu or 27% of the R&D opportunity), and pulping chemical preparation (9 TBtu or 6% of the R&D opportunity). The opportunity quantified in the bandwidth report is tabulated in Table 18. The workshop focused on thermal processes and explored the opportunity in pyroprocessing and other heating applications within glass manufacturing in more detail.

Table 18. Energy intensity estimates and potential reduction in energy intensity for select manufacturing areas in the pulp and paper industry.

Process	On-site energy intensity (MMBtu/ton)		Percent reduction
	Current typical	Practical minimum	
Liquor evaporation	3.55	2.27	36.1%
Pulping chemical prep	2.07	1.43	30.9%
Wood cooking	2.56	1.89	26.2%
Bleaching	1.32	0.91	31.1%
Paper drying	4.68	2.77	40.8%
Paper machine wet end	2.07	1.35	34.8%

5.5.3 TPI Technologies

Through the workshop, additional insights into the R&D opportunity were explored with participants and were expanded to identify new and innovative TPI technologies, as well as barriers to their wide-scale adoption. The following subsections discuss these technologies in the context of the TPI pillars.

TPI pillar 1: Low–thermal budget transformative technologies

The Kraft process is the most common method for producing paper and has a typical pulp yield of around 50%. Given that a major viable alternative to Kraft processing has not been developed in decades of research, it is agreed that the logical approach is to focus resources to improve the process instead of working to replace it. Most recent research efforts have focused on developing new pulping catalyst and pretreatment techniques. By improving the yield, these improvements promise to significantly reduce the energy use and emissions per unit of pulp. Catalytic pulping using anthraquinone has been applied commercially over the years. There is an opportunity to identify alternatives to anthraquinone that offer a sufficient reaction rate, sufficient turnover, and recovery to be economical at scale. Plant-based deep eutectic solvents are a pulping aid that have also seen increased interest and were identified as a top-priority technology challenge by the European pulp and paper industry.[81] Other improvements to the Kraft process, such as the replacement of the Tomlinson recover boiler to black liquor gasification, are commercially available, but the uptake has been slow, given that life extension has kept the existing boilers operating for three decades.

Pretreating wood chips can significantly improve process efficiency, and developing improved chip activation processes for the initial stages of delignification (removal of lignin from wood) is a viable area of research. There is an opportunity to improve the cost effectiveness of sodium borohydride (most commonly used pretreatment chemical) or develop entirely new alternative pretreatment chemistry that is more efficient. Although the reuse of green liquor (from the recovery boiler in the Kraft process) and other biological compounds to pretreat woodchips have been explored and are available at a commercial level, they have not been widely adopted.

Membrane technologies that replace a portion of the multi-effect evaporators used in black liquor concentration provide the possibility of replacing the energy-intensive separation process with a nonthermal method. To this end, a number of membrane technologies are being developed; these are further discussed in Table 19, along with their challenges and potential.

[81] CEPI, 2050 Roadmap to a low-carbon bioeconomy.

Table 19. Low–thermal budget transformative technologies for the pulp and paper industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.1.1	Biological pulping†[82]	• Uses a lignin-degrading fungus as a pretreatment to pulping that can break down the unwanted lignin but not the cellulose fibers • Requires a decontamination of the wood chip surface and maintaining a hospitable environment for the fungus to be effective, and the overall process economics Benefits: • Reduced electrical energy consumption (at least 30%) during mechanical pulping • Potential 30% increase in mill throughput for mechanical pulping • Improved paper strength properties and reduced pitch content	Was scaled up to 40 t/day of chips in pilot studies in the 2000s Has been licensed for commercialization but has not seen deployment in scale to the best of our knowledge	• Limited to the temperature range • Produces a fair amount of aerial hyphae
5.1.2	Catalytic-assisted Kraft pulping†[83]	• The catalytic chemicals aim to improve the Kraft process by controlling and directing the reactions. • The catalyst can oxidize, reduce, or hydrolyze lignin to improve the reaction. • Examples: anthraquinone, rhodium compounds, cobalt salcomine Because a major viable alternative to Kraft processing has not been developed in decades of research, this could be the logical approach to improve on both cost and pulp quality.	Anthraquinone (commercial)	• Anthraquinone accelerates pulping but has very low turnover. • Anthraquinone's reaction rate is low; catalyst degradation and concerns over its carcinogenic properties pose as barriers. • Inherent cost of the catalyst • Loss of effectiveness after relatively few cycles R&D opportunity: Evaluate transition metals or main group metals that can perform two-electron oxidation and/or serve as a delignifying chemical system.
5.1.3	Membrane separation of black liquor*[84]	Black liquor concentration is performed by multi-effect evaporators and is one of the most energy-intensive industrial separation processes. Several membrane technologies are being developed, including the following: • Membranes with sacrificial protective coatings (Teledyne)	Teledyne has demonstrated success of concentrating weak black liquor in a laboratory setup using actual black liquor from a mill and heating it to 185°F.	• The membranes must be capable of withstanding the high pH (>12), high temperature (175°F–200°F), and different fouling species in black liquor. • Teledyne coating resists fouling by black liquor and, as a result, the membrane system maintains higher average flux. The coating has to be periodically reapplied, but this can be automated.

[82] Scott, G. M., M. Akhtar, M. J. Lentz, T. K. Kirk, and R. Swaney. 1997. "Commercialization of Biopulping: A New Technology for Papermaking," In: *Proceedings of the 1997 Mechanical Pulping Conference, SPCI*, Stockholm, Sweden, 271–280.
[83] Agenda 2020 Technology Alliance. 2016. Next Generation Pulping - Research Roadmap.
[84] Agenda 2020 Technology Alliance. 2016. Black Liquor Concentration - Research Roadmap.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
		• Robust membranes specifically for harsh environments (graphene oxide, Carbon molecular sieve, and zeolite membranes) • High-performance architectured system membrane technology	Graphene oxide–based membrane system: benchtop scale	• Carbon molecular sieve membranes are the more viable candidate based upon its excellent pH and temperature stability. The impurities are presently too high for this stream to be readily integrated into an existing pulp mill.
5.1.4	Chip pretreatment *[83]	Develop improved chip activation processes for the initial stages of delignification (removal of lignin from wood) • Directed green liquor utilization pulping is based on the reuse part of green liquor (20% to 30%) for pretreatment of wood chips prior to Kraft pulping. Green liquor is naturally rich in hydrosulfide ions, which can accelerate pulping and provide a high-value product. • Develop an alternative pretreatment chemistry that is more efficient than sodium borohydride.	Implementation of chip pretreatment pulping is straightforward and requires minimal capital investment. Commercial-scale trials have been reported in literature for directed green liquor utilization (Evadale, Texas).	Barrier: Among the potential negative impacts are that green liquor pulping might reduce the heat value of black liquor. R&D opportunities: • Develop new pretreatments chemicals or in-situ pulping additives that reduce the impact of the peeling reaction on the Kraft pulping yield • Increase the processing or cost-effectiveness of sodium borohydride • Find alternative methods for producing polysulfide that do not generate corrosive sulfur oxides
5.1.5	Solvent pulping methods†[83] 1. Alkaline sulfite methanol process 2. Ammonium sulfide ethanol and water pulping 3. Deep eutectic solvents	1. The alkaline sulfite methanol process is in the presence of anthraquinone and methanol and is suitable for all sorts of hardwood and softwood species. 2. Pulping is done with 21% ammonium sulfide (19% Na_2O) in a 50:50 ethanol-water solvent at 350°F. 3. Deep eutectic solvents, produced by plants, can replace mechanical and chemical pulping to produce pulp at low temperatures and at atmospheric pressure.	1. Extensive studies were done on a pilot scale, but the process was never commercialized. 3. EU-funded PROVIDES, a public-private partnership, is developing and testing deep eutectic solvents in pilot plants.	1. Alkaline sulfite methanol process pulps have approximately 20% higher breaking length and higher yields compared with Kraft pulps. Complex and expensive solvent recovery processes higher pressure rated digesters and explosion proof motors and controls. 2. Pulp yield is approximately 14% higher than conventional Kraft pulp and is easier to bleach. This process is suitable for both hardwoods and softwoods. 3. Deep eutectic solvents are expensive, and solvent decomposition can be high (depending on the chemical structure); a very high degree of recovery (99.9%) will be essential for these chemicals to be economically viable.
5.1.6	Drying in electrostatic/EM fields†	Drying moist porous media such as paper in the presence of a nonuniform, static, electric field has shown to enhance moisture removal.	Lab scale Lab results have shown 5% to 18% increase in the drying rates	The higher temperature gradient can cause a pressure buildup between the sheets from the vaporized liquid, leading to failure by delamination.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.1.7	Ultrasound in paper drying†	Using ultrasound to assist with the drying of paper Can be coupled with EM fields	Very early development	Applied successfully to dry cloth in small scales. Achieving uniform drying in large scale application can be challenging.
5.1.8	Cavitation-jet deinking†[85]	Conventional deinking processes impose mechanical load onto the entire fiber. Using cavitation-jet as a selective deinking force, which acts only on the fiber surface, the fiber damage can be minimized.	Lab scale	Cavitation can be generated using a liquid jet, ultrasonic transducer, laser irradiation, or mechanical mixing, each with its associated capital cost.
5.1.9	Dry sheet forming*	The principle is to produce paper without adding water. It relies on high levels of turbulence in the air stream to produce paper products. Fibers can be dispersed either mechanically or using air-laying techniques. It estimated that 50% of drying energy consumption could be eliminated with 150 to 250 kWh/t	Commercial: The worldwide installed capacity of this technology is about 350,000 ton/year and growing rapidly.	Increased electric demand, potentially higher capital and installation costs
5.1.10	Foam forming†[86]	In foam-forming technology, aqueous foam is used in place of water as a carrier medium. This fundamentally changes the properties of the carrier fluid radically widening the product property window and allowing a wider variety of raw materials to be used in the manufacturing process.	Piloted for unpressed products, such as insulation materials, filters, and technical textiles Foam forming is a significant topic among European paper industry.	Product applications are unknown. More research is needed to find a technology product fit.
5.1.12	Enhanced oxygen delignification†	Develop methods to delignify higher-yield (higher-Kappa) pulps to conventional residual lignin levels through enhanced oxygen delignification without sacrificing strength, viscosity, and other pulp qualities.	Commercial	The use of oxygen-based systems to remove lignin from pulp can be beneficial for selectivity, pulp quality, and environmental impact. However, significant energy savings are not realized.

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

Paper drying is another significant energy user in the paper mill and has been the subject of many research advancements in the past decade. Most innovations to the dryer section have tried to improve upon the inherent low heating rates, one of the biggest limitations of the existing steam based multi-cylinder designs. New technologies try to improve heating rates using a larger temperature gradient, higher pressure, vacuum, and other factors. Although gas-fired cylinder designs that produce improved heating rates are commercially available, they have not been widely adopted, given the fuel cost and common issues associated with product delamination. The higher temperature gradient produced by gas-fired systems causes a pressure buildup

[85] S. Goto, H. Tsuji, I. Onodera, K. Watanabe, and K. Ono. 2014. "Cavitation-jet deinking: A new technology for deinking of recovered paper." *TAPPI Journal*.
[86] Poranen, J., H. Kiiskinen, J. Salmela, J. Asikainen, J. Keranen, and E. Paakkonen. 2013. "Breakthrough in papermaking resource efficiency with foam forming," *TAPPI PaperCon*.

between the sheets from the vaporized liquid, leading to failure by delamination. Researchers that seek to improve heating rates by increasing the temperature gradients should be aware of this potential barrier and design systems accordingly. Using EM radiations shows promise in paper drying; they heat the product volumetrically and have better directionality and control compared with traditional steam driers.

MW radiation–based systems that enhance moisture removal have been studied and have shown good results with respect to heating rates. An issue noted with MW systems is the difficulty to get consistent heating across a sheet with varying levels of moisture. RF is positioned to solve this, given its better absorption properties. RF as part of hybrid drying systems may be attractive because it can improve product quality by avoiding over-drying with fiber degradation, given its unique interaction with the materials. Leveraging ultrasonic along with RF is also being considered; these systems are in early experimental phases and will need significant advances to be commercially available.

Increasing the dryness of paper webs entering the paper machine dryer section by approximately 30% (to 65% solids from the current level of 45%–55% solids) can lead to increased efficiency of the dryer section. Approaches to achieve this include the following:

- Exploring novel ways to develop an advanced fiber matrix to facilitate water release without negative impacts to sheet strength/uniformity
- Studying the relationship between equilibrium moisture and the bound water located inside the fiber and fiber wall
- Identifying strategies to lower the minimum pressed moisture (e.g., surface tension, fraction of open pores on the fiber wall surface, effect of temperature and ionic species)
- Developing alternative press fabrics to avoid/minimize rewetting following the nip roller in the press section

TPI pillar 2: Alternative thermal processing

Alternative thermal processes represent technologies that use alternative sources of energy while maintaining the current production methods. The pulp and paper industry has a wide scope for a varied use of alternative energy sources; multiple facilities have integrated a concentrated solar power into their processes. Furthermore, the industry is transitioning and looking into alternative revenue streams from its by-products; this transition could make alternative energy sources more attractive for the industry. The paper industry has long used by-product from the process as an energy source in its thermal processes. If these by-products were processed for biofuels/biochemicals and sold in the open market, which is the vision for biorefineries, it could potentially change the energy balance within a pulp and paper mill. This change, in addition to adding value to the traditional pulp and paper industry, could also make electrification of the thermal processes more viable in the future, given the reduced availability of biomass waste for energy. Table 20 shows the alternative thermal processing technologies for the pulp and paper industry.

Table 20. Alternative thermal processing technologies for the pulp and paper industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.2.1	Electrification of digestion and liquor recovery process†	• Resistance/induction systems that can heat the slurry directly or indirectly using a susceptor could be built to significantly improve the thermal efficiency of these processes. • Chemical recovery involves evaporating the black liquor to a solid constancy and burning it to recover the molten salts that are dissolved in process water and recausticized to get white liquor; resistance or induction heating to dry black liquor can be used to achieve a higher concentration of smelt.	Electric digesters are used mainly in lab settings to study the pulping process.	• Scaling to commercial level could be a challenge • Significant improvements to their efficiency and productivity would be necessary for them to be viable in an industrial environment because these electricity-based systems would need to compete with low-cost fuel systems to be economically viable • A switch from using existing sources of waste for fuel to producing higher valuer products can pave the way for the reconsideration of electrification of pulp and paper process
5.2.2	Displacement pressing†	This technology combines mechanical and air pressure, pressing web lightly while forcing air through it.	A pilot-scale displacement press with a four-roll press (Beck cluster press) showed promising early results. • Reduces drying energy consumption • Increases web solids content before dryer • Improves paper strength properties • Reduces raw material costs	Increased electric demand, potentially higher capital and installation costs
5.2.3	Gas-fired dryer*[87]	Gas-fired dryers offer a high-efficiency alternative to traditional steam-heated dryers and are expected to exceed the performance of existing paper drying systems.	Commercial	The higher temperature gradient can cause a pressure buildup, leading to delamination.
5.2.4	Impulse drying*[87]	The technique uses temperatures in the range of 450°F–850°F, 20–100 bar pressures, and a very short residence time.	Pilot machine built that could operate at industrial machine speeds on a 300 millimeter wide paper web	• One main challenge has been to avoid delamination of the paper sheets • Using electricity for heating to high temperatures is more expensive than the traditional low-pressure steam

[87] Kong, L., A. Hasanbeigi, and L. Price. 2012. *Emerging Energy-Efficiency and Greenhouse Gas Mitigation Technologies for the Pulp and Paper Industry*, Lawrence Berkeley National Laboratory.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.2.5	EM induction for paper drying†	Contact drying with heated cylinders is the predominant method of drying in paper and paperboard machines. The rolls and cylinders are heated using steam. EM induction can be used to directly heat the rolls and cylinders.	Commercial	• Helps phasing out fuel-fired systems without changing the process • Use of more expensive energy sources (electricity and gas) and a lower energy efficiency for the units
5.2.6	Electric IR for paper drying†	Electrically and gas-heated IR dryers are already used for drying of coated papers, profiling of the paper web, and increased capacity in limited dryers.	Gas-fired IR to dry the paper has been adopted widely. The fuel-fired equipment could be replaced with electric IR, which provides much better control.	• The advantages compared with the multicylinder design are high heat fluxes, absorption of radiation inside the wet web, and profiling possibility • Use of more expensive energy sources (electricity and gas) and a lower energy efficiency for the units
5.2.7	MW/RF paper drying†[87]	Hybrid technologies could use MW/RF as preheating to build an optimized drying operation. Feasibility studies have shown an increase in paper machine speeds by 30% and reduced paper drying energy by 20%	Development: Studies have reported MW dryers tested on the pilot scale.	• Challenges to be addressed are the energy efficiency of the MW generator and the high power levels required
5.2.8	Alternative fuels: liquid biofuels or biochemicals*	Various thermochemical and biochemical paths exist to produce said products, each with its capability and challenges. 1. Gasification: biomethane and other biosynthetic gaseous fuels, synthetic liquid fuels, and/or hydrocarbons 2. Pyrolysis and torrefaction: intermediate bioenergy carriers 3. Chemical and biological processes: ethanol and higher alcohols from lignocellulosic feedstock, hydrocarbons (e.g., diesel and jet fuel) from biomass	Commercial: biogas production Semi-commercial and demonstration for thermal gasification Research and pilot for pyrolysis Some pre-commercial, industrial-scale demonstration plants are producing cellulosic ethanol.	The following benefits and costs have been identified for the mentioned biorefinery concepts: • Improve energy efficiency for the pulp and paper industry • Potentially lower the GHG emissions • Provide significant added value to the traditional pulp and paper industry • Reduce raw materials use in other industrial sectors Barriers: capital Investments
5.2.9	Solar thermal applications†	Solar radiation is either absorbed directly (non-concentrating collectors) or concentrated onto a receiver where it is converted into heat that is used to produce hot water or steam.	Commercial	• Displacement of fossil fuel use with heat from concentrating and non-concentrating solar collectors Barriers: capital Investments

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

Challenges and barriers: When evaluating the benefits of alternative thermal technologies, evaluators should consider that an integrated mill uses CHP technologies to generate electricity and steam. The value of the low-pressure steam used in paper drying is low, which could make it economically difficult to replace. The need to dispose of the waste biomass creates a challenge for shifting to electrification in the primary paper industry. The power to heat balance makes thermal energy in the form of steam more attractive because it can always be sold as excess electricity to the market. Although this is less of a driver in recycled paper production, primary paper has a waste stream disposal cost issue that combustion addresses. As discussed earlier, the pulp and paper industry is in a transitional phase, and the facilities are looking at alternative revenue streams from these waste stream with the development of biorefineries and creating secondary product markets. The successful implementation of these biorefineries could lead to an uptake of electrification with lesser by-products available as fuel.

The common approach from the industry has been to focus more on decarbonizing existing processes; it is very difficult to completely change existing processes (e.g., steam rollers for drying). For this reason, facilities are looking increasingly at electrification, solar thermal, bioenergy, and other technologies that could be used to retrofit existing processes. Although completely changing existing processes would have a larger impact (e.g., EM radiation–based drying), it is considered difficult to change those processes without impacting product attributes or qualities.

With the digitization of the many uses of paper, much of the industry is on a decline. The return on investment on transformative energy savings technology often is not attractive without revenue growth, and this poses an additional barrier for transformative technology.

***Supplemental and waste heat technologies*:** In addition to the technologies discussed earlier, there are transformative supplemental technologies for the pulp and paper industry such as new fault-detection technology, process heating control systems, and the use of IoT for plant monitoring. Also, waste heat management technologies for the pulp and paper industry such as raw materials preheating and water and heat recovery from the paper drying section hood for pocket ventilation can help reduce thermal energy use in this sector. These additional technologies are discussed in the transformative supplemental technologies and waste heat management technologies sections.

5.6 Low- and Medium-Temperature Processing: Food and Beverage Industry

5.6.1 Energy Use

The food and beverage processing industries in the United States consumed a total of 1,209 TBtu (on-site) of energy in 2014, representing approximately 7% of energy consumption of all manufacturing sectors. Fuel energy is supplied predominantly by natural gas in the food processing industry, and coal is rarely used, except in wet corn milling and sugar manufacturing. The on-site energy use and a breakdown of the different sources for the food and beverage sector are provided in Figure 29.[11]

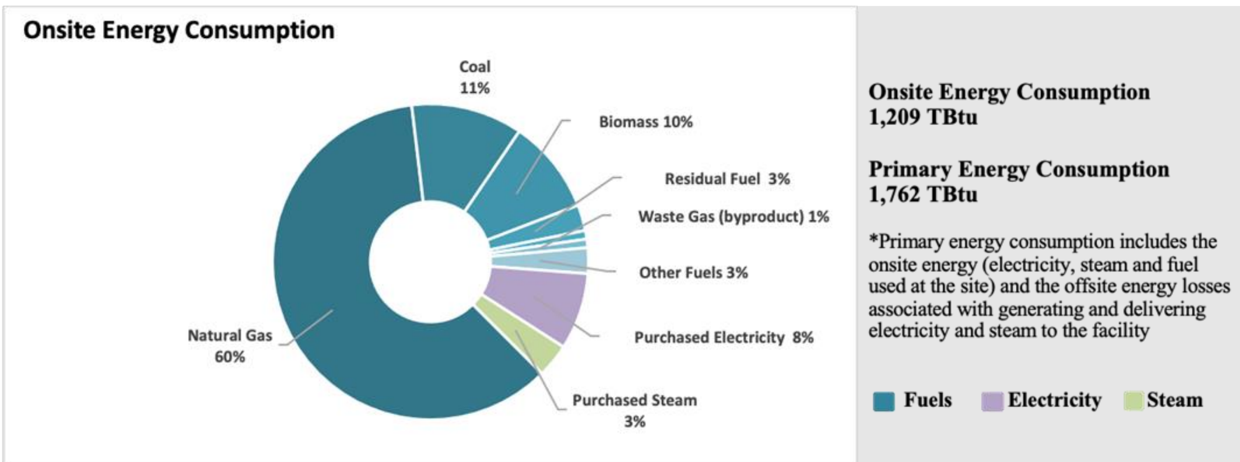

Figure 29. On-site energy consumption in the US food and beverage sector by energy source in 2014.[11]

The US food and beverage sector tends to have more smaller, specialized facilities as opposed to large centralized facilities producing multiple products. Additionally, the industry produces many diverse products that are consumed both domestically and exported to international markets. According to the US Census Bureau, in 2010 there were 24,773 establishments involved in food manufacturing and 4,527 establishments involved in beverage manufacturing. Given the diversity of products produced, a variety of thermal and nonthermal processing steps are employed by the food and beverage sector. Overall, the main sources of energy consumption include on-site steam, general process heating, process cooling and refrigeration, and machine drive. Sectors that consume the most energy in terms of natural gas and electricity are shown in Figure 30 and Figure 31, respectively.[88]

[88] Compton, M., S. Willis, B. Rezaie, and K. Humes. 2018. "Food processing industry energy and water consumption in the Pacific northwest," *Innovative Food Science & Emerging Technologies* 47, 371–383.

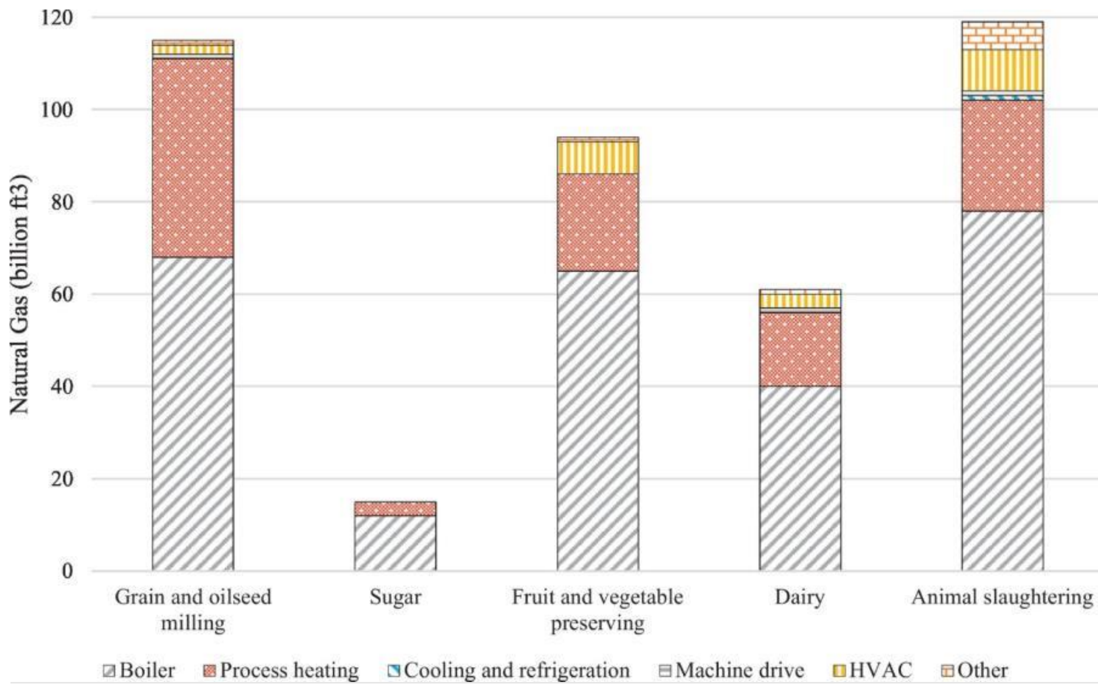

Figure 30. US natural gas consumption in different sectors of the food processing industry.[89]

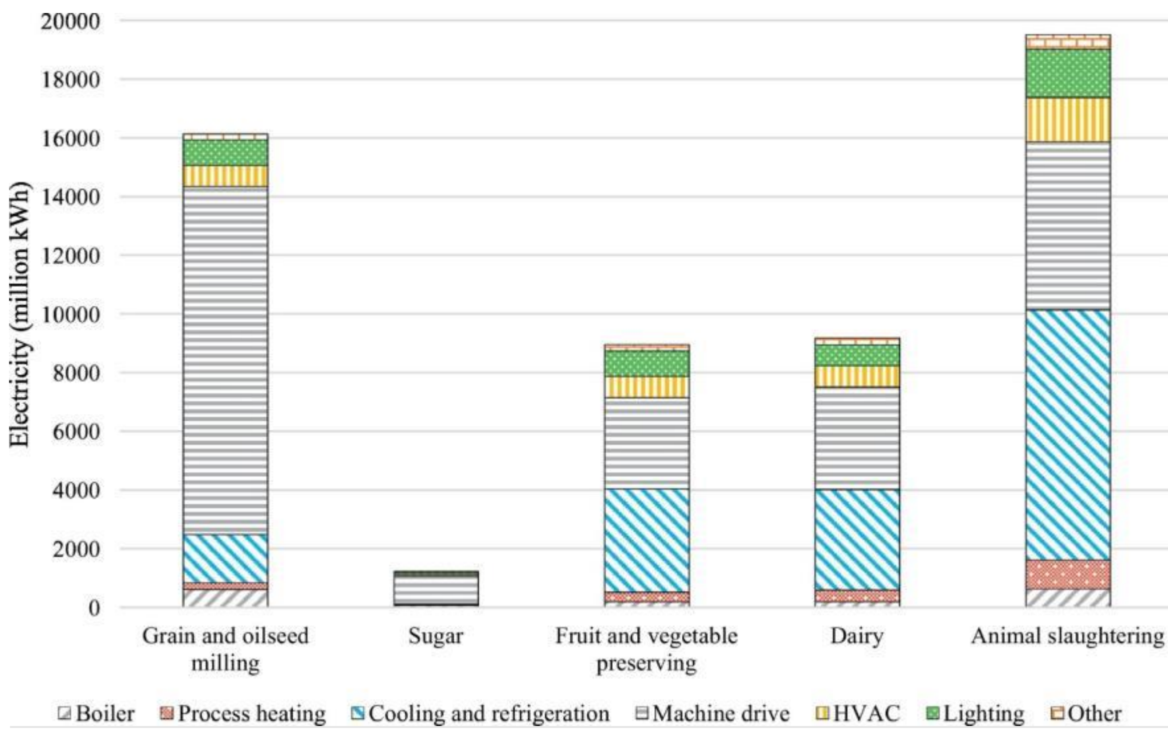

Figure 31. US electricity consumption in different sectors of the food processing industry.[89]

[89] Compton, M., Willis, S., Rezaie, B., & Humes, K. (2018). Food processing industry energy and water consumption in the Pacific northwest. Innovative food science & emerging technologies, 47, 371-383.

The major thermal processes associated with the highest energy-consuming subsectors in the food and beverage industry are listed in Table 21 and subsequently discussed in this section.

Table 21. Major thermal processes in energy-intensive subsectors.

Grain milling (wet corn milling: 311221)	Fruit and vegetable preserving (3114)	Dairy products (3115)	Animal slaughtering and processing (3116)	Beverages (3121)
• Evaporation (steep-water) • Drying (germ, starch, feed) • Refining • Steeping • Dewatering	• Pasteurization • Sterilization • Blanching cooking/frying • Brine heating • Evaporation • Drying/dehydration	• Pasteurization • Sterilization • Concentration • Evaporation • Spray drying	• Curing, smoking, cooking • Blood processing • Drying • Pasteurization scalding • Cleaning	• Fermentation • Drying (malt) • Mashing (wort) • Boiling (wort) • Pasteurizing

Grain milling, especially wet milling, is an energy-intensive industry because it is a wet process that produces dry products. In wet corn milling, corn is soaked in water to loosen the corn component materials (protein, gluten, and fiber) and throughout the process, water is used as a medium for separating these components. For many of the products, dewatering, evaporating, and drying are required, and these often entail the use of large amounts of thermal energy. Fuel is used either to make steam or for direct drying. Steam is used for evaporation, drying, and maintaining process temperatures, as well as fermentation, extraction, ethanol recovery, and jet conversion of starch in refineries. Flue gas is used for drying and stillage processing.[90]

In fruit and vegetable processing, in addition to blanching and sterilization, there are several other important unit processes employed in fruit and vegetable processing that are based on the application of heat. Among the most common thermal processes are evaporation, pasteurization, drying and dehydration, and frying. In evaporation, heat is used to remove water contained in fruit and vegetable pulps and juices to produce a more concentrated product; falling film evaporators and forced circulation evaporators are common. Drying and dehydrating processes preserve fruits and vegetables by removing moisture to retard or prevent the growth of microorganisms. Most fruits and vegetables are currently dried using heated drying equipment. Direct (using fuel) and indirect (using steam) heated hot air continuous belt dryers are among the most common dryers used in fruit and vegetable processing.

For dairy products, milk is typically heat treated by pasteurization and/or sterilization after being standardized (to ensure proper fat content). These are relatively gentle heat treatment processes performed at temperatures near the boiling point of water. Both traditional sterilization and pasteurization methods use saturated steam or pressurized hot water. Several dairy products need a cooking or fermentation step to allow the desired biological/chemical changes to occur to the product. Evaporation is also commonly used to remove water from dairy products. Falling film evaporation, in which the liquid falls by gravity down the inside surfaces of tubes arranged in a shell-and-tube heat exchanger configuration, is most common, and steam is generally used as the heating medium.

[90] Christina Galitsky, Ernst Worrell and Michael Ruth." Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry". An ENERGY STAR® Guide for Energy and Plant Managers

5.6.2 RD&D Needs and Opportunities

DOE's bandwidth study[91] describes the opportunity space for energy intensity reduction in the food and beverage sector. The bandwidth report includes current energy intensity, state-of-the-art, practical minimum, and theoretically minimum energy intensities for each of areas studied. Figure 32 shows the estimated current and R&D energy savings opportunities in the food and beverage sector, extrapolated from select subsectors studied in detail.

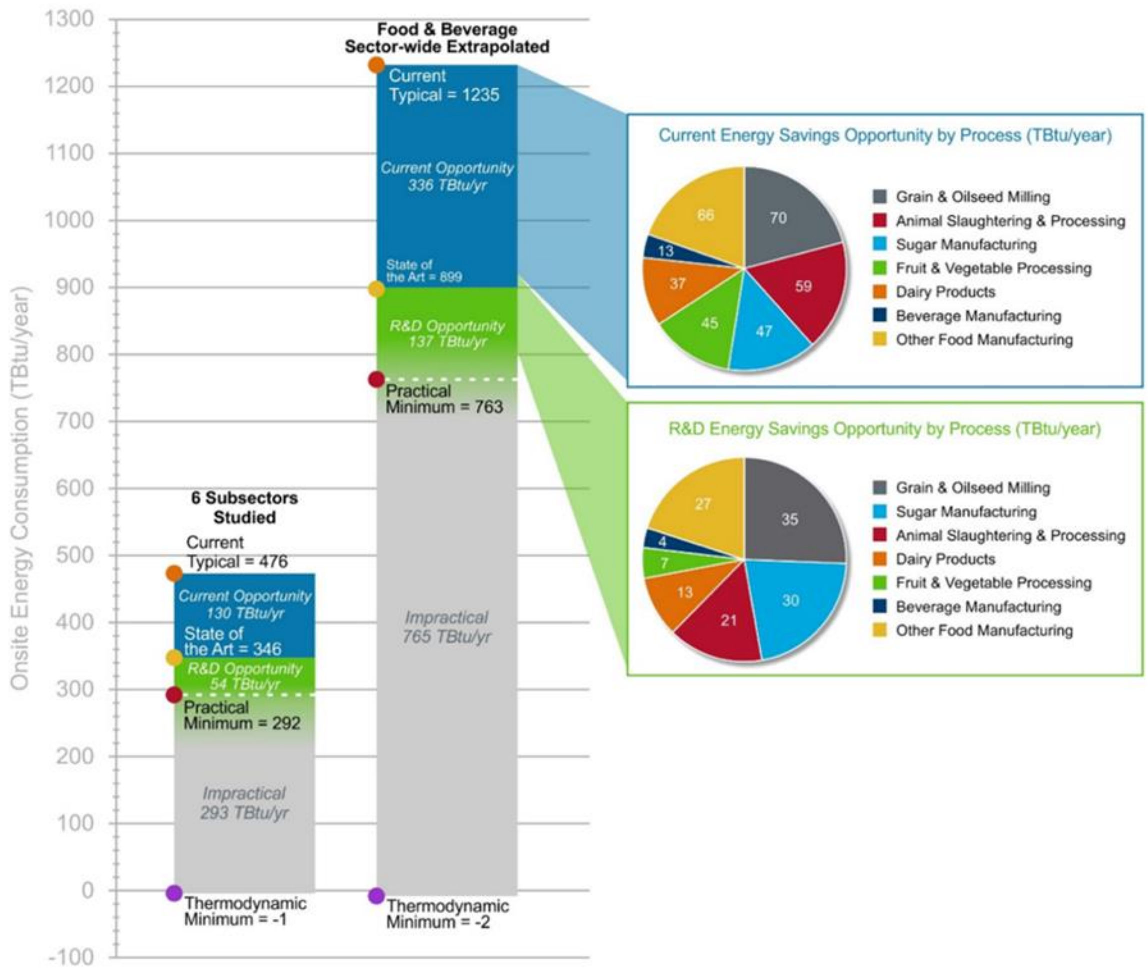

Figure 32. Current and R&D energy savings opportunities in US food and beverage product manufacturing for the subsectors studied and industry-wide extrapolation.[91]

The bandwidth analysis determined the potential on-site energy savings opportunities to be 27% (336 TBtu) from upgrading to the best available technologies and practices available in the US food and beverage product manufacturing (based on the 130 TBtu energy saving in the six subsectors studied). Integrating R&D technologies under development would yield an additional

[91] DOE (US Department of Energy). 2017. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Food and Beverage Manufacturing. Retrieved from https://www.energy.gov/sites/prod/files/2017/12/f46/Food_and_beverage_bandwidth_study_2017.pdf.

11% (137 TBtu) energy savings (based on the 54 TBtu saved in the six subsectors studied in the bandwidth analysis).

The savings opportunities by process are different for each subsector, and the above estimates correspond to the total energy savings opportunities for six subproducts included in this study. These opportunities quantified in the bandwidth report for these subsectors are tabulated in Table 22. While this subset of the larger food and beverage industry was used as a starting point to drive discussions during the workshop, technologies related to the thermal processes in other sectors were also encouraged.

Table 22. On-site energy consumption at US food and beverage plants in 2014.

Process	On-site energy intensity (Btu/lb; Btu/barrel for beverages)		Percent reduction
	Current typical	Practical minimum	
Grain and oil seed milling: corn oil			
Steep water evaporation	358	29	91.9%
Germ dewatering and drying	129	76	41.1%
Starch dewatering and drying	530	507	4.3%
Gluten feed dryer	418	400	4.3%
Fruits and vegetables			
Fruit juice: pasteurization (heat treatment)	133	34	74.4%
Heat sterilization (retorting)	100	42	58%
Canned fruits/vegetables: heat sterilization (retorting)	217	92	57.6%
Frozen vegetables: frying	325	305	6.2%
Dairy			
Fluid milk: pasteurizing	92	16	82.6%
Powdered dry milk: concentration	172	138	19.8%
Powdered dry milk: spray drying	115	69	40%
Animal slaughtering			
Red meat: processing (curing, miking, cooking)	320	276	13.8%
Red meat: blood processing	80	64	20%
Pork: scalding	149	36	75.8%
Beverage manufacturing			
Beer: brewhouse	67,045	63,671	5%
Wine: alcoholic fermentation	38,749	30,999	20%
Sugar manufacturing			
Cane Sugar	2,526	671	73.4%
Beet Sugar	3,682	1,063	71.1%

The technologies identified in the bandwidth report were used as a starting point for the workshop. Furthermore, the barriers associated with these technologies and their research needs were reviewed and discussed in more detail during the workshop. The results from these discussions are presented in the next section.

5.6.3 TPI Technologies

The following subsection discusses the TPI technologies for the food and beverage industry.

TPI pillar 1: Low–thermal budget transformative technologies

Table 23 shows some key low–thermal budget transformative technologies for the food and beverage industry. The applications area is categorized by technology; various technologies have applications across the food and beverage applications, which is expected since the fundamental processes used across the sector are similar and make use of low- to medium-temperature heating.

Table 23. Low–thermal budget transformative technologies for the food and beverage industry.

Technologies	Application/ processes	Description	Commercialization status	Challenges and barriers/R&D needs
6.1.1 Supercritical fluid processing† (CO_2)	Supercritical fluid drying (vegetables and fruits)[92]	Works similarly to air drying, the most used drying operation. Above their critical point, supercritical fluids have liquid-like solvating properties and densities, as well as gas-like diffusivity and viscosity, allowing them to easily permeate and readily evaporate the water from products.	Commercially used for the drying in production of aerogel R&D, laboratory scale for food drying	The drying process can be conducted at relatively low temperatures (e.g., 100°F). • Primary energy saving of up to 20% • Solid structure of the product is maintained Barriers: Cost. Economic justification is required for the industrial application at a large scale.
6.1.2 No-heat spray drying*[93]	Spray drying (spray drying of milk powder, flavor industry)[94]	Spray drying produces dry powders from a fluid material by atomization through an atomizer into a heated drying gas medium, usually air. By starting with more viscous emulsions, atomizing the emulsion into finer droplets, and keeping the droplets suspended longer, spray drying is achieved at ambient temperature.	Emulsion preparation now a commercial process Reduces energy use by 40% or more	R&D opportunities: • Development of atomizers with increased throughput and the desired particle size • Commercializing technology for different powder (e.g., milk) drying operations

[92] Tomic, N., et al. 2020. "Comparison of Supercritical CO2-Drying, Freeze-Drying and Frying on Sensory Properties of Beetroot," *Foods*.

[93] Charles Beetz, ZoomEssence, Inc." No Heat Spray Drying Technology". Final Technical Report. DOE Award Number DE-EE0005774

[94] Brush, A. E. Masanet, and E. Worrell. 2011. *Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industries*, Lawrence Berkeley National Laboratory.

Technologies	Application/ processes	Description	Commercialization status	Challenges and barriers/R&D needs
6.1.3 Membrane technologies*	1.3.1 Forward osmosis and reverse osmosis (RO)[94] (steep evaporators in wet corn milling, concentration of milk, concentration of thin juice and liquid food)	RO is the tightest possible membrane process in liquid separation; only water can pass through the membrane. RO can be used to partially remove steep water prior to the evaporation phase. Forward osmosis to achieve concentration of various products without the membrane fouling problems that tend to affect operations that would just use RO are being explored.[95]	Commercial with potential for further adoption Reported savings of 67% in primary energy (electricity and fuel) with a hybrid approach; increased product recovery and reduced carbon requirements	Barriers: • Biofouling or fragility of the membrane surface • High capital costs • As solutions become more concentrated, the effectiveness of RO diminishes • Limits on operating pressures prevent implementation in certain processes • Regulations can cause potential delays
	1.3.2 Ultafilters and microfiltrations Nanofilters: fruit juice clarification, purification Ultafilters: concentration of caffeine, corn syrup, and animal gelatin Microfiltrations: Microbial removal, ultra-pasteurizing of dairy, filtration of oil	Ultafilter membranes allow water, dissolved salts, lactose, and acids to pass through the filter in either direction, while retaining (and thereby concentrating) proteins, carbohydrates, and enzymes. Ultafilter operating pressure falls between nanofilters and microfilters with a pore size range of 0.01 to 0.1 µm. Microfiltrations are used to separate bacteria, spores, and fat globules from the stream.	Commercial (R&D for new materials and techniques) Promising new technologies: crossflow membrane ultafilters, hybrid membrane process, selective membranes	Reported energy savings of 90% were observed by replacing evaporation with membrane filtration. Using hybrid microfiltration process with heating (only the retentate is heat treated) for pasteurizing milk extends shelf life, reduces energy consumption, and preserves chemical properties and sensory quality. Barriers: membrane fouling
	1.3.3 Modern molecular sieves (wet corn milling) **Error! Bookmark not defined.**	Instead of evaporation, molecular sieves can be used in dehydrating ethanol. Most modern molecular sieve dehydrators use pressure swing adsorption to remove water from a vaporized feed stream.	Commercial (R&D for new absorbent)	For the same feed and product, a rectification and solvent extraction (evaporation) system requires 8 times the energy of the molecular sieve technique.
6.1.4 Biological and chemical processing†	Catalytic enzymes (corn steeping)	Using enzymes during steeping can reduce steep time. Steeping is the first step in corn milling and involves soaking the corn in a low-temperature mixture of water and chemicals for an extended period of time.	Development	Research indicates a two-stage steeping process using proteases (an enzyme that breaks down proteins and peptides) may reduce conventional steep time by 67% to 83%. Barriers: additional use of chemicals

[95] California Energy Commission. 2018. Demonstration of Forward Osmosis to Produce Juice Concentrate, Purify and Reuse Wastewater and Reduce Energy Use.

Technologies	Application/ processes	Description	Commercialization status	Challenges and barriers/R&D needs
6.1.5 UV processing†	Pasteurization: sterilization: enzyme inactivation (dairy)[96]	UV pasteurization delivers a high intensity beam of UV light the flowing liquid to kill microorganisms.	R&D in dairy industries; commercial in some others	• The energy-intensive requirement of heating and cooling the fluid is eliminated • Regulations can cause potential delays •
6.1.6 Electron beam processing†	Pasteurizing and sterilization (beverages)[97]	Irradiation with aseptic packaging uses an electron beam, or a radiation source is used to sterilize food products after packaging. Extends shelf life and reduced waste	Commercial	• Increased cost • Regulations can cause potential delays
6.1.7 High-pressure processing†	Pasteurization and sterilization (dairy, meat, fruit and vegetables juices)[98]	High-pressure processing is a technology that uses water as a medium to transmit pressures between 100 and 900 MPa to inactivate vegetative microorganisms and quality-related enzymes to preserve food. The high pressure, and subsequent high pressure drop, kills microorganism by bursting cell membranes and inactivating several essential enzymes.	TRL 3–4 (laboratory research)	• Although energy must be expended to create the high pressure, the energy-intensive heating and cooling steps of traditional pasteurization are eliminated. • Increased cost
6. 1.8 Ultrasound processing*	Pasteurization and sterilization (liquid food, beverage, and solid food)[99]	High-power ultrasound causes microbial inactivation by physical (cavitation, mechanical effects, and micromechanical shocks) Higher product yields, shorter processing times, reduced operating and maintenance costs, reduced pathogens at lower temperatures, and improved tastes, texture, flavor, and color	TRL 4 (laboratory research)	• Limited information available on the effects of ultrasound on the nutritional and sensorial quality posing a regulatory barrier

[96] Koutchma, T. 2008. "UV Light for Processing Foods," *Ozone: Science & Engineering* 30, 1, 93–98.
[97] H.-M. Lung, et al. 2015. "Microbial decontamination of food by electron beam irradiation," *Trends in Food Science & Technology* 44, 1, 66–78.
[98] Hogan, E., A. Kelly, and D.-W. Sun. 2005. "High Pressure Processing of Foods: An Overview," *Emerging Technologies for Food Processing*, 3–32.
[99] Jayathunge, K. G. L. R., A. C. Stratakos, G. Delgado-Pando, and A. Koidis. 2019. "Thermal and non-thermal processing technologies on intrinsic and extrinsic quality factors of tomato products: A review." *Journal of Food Processing and Preservation* 43, 3, e13901.

Technologies	Application/ processes	Description	Commercialization status	Challenges and barriers/R&D needs
	Grape maceration process	A low-frequency high power ultrasound equipment (ULTRAWINE) is used to extract the phenolic compounds from grape skins during the first stages of winemaking. • Optimizing the extraction helps in completing the grape maceration process in 6 hours (conventional systems take approximately 4 days)	Commercial	• Increased cost • Regulations can cause potential delays
	Cleaning/blanching (vegetables, fruits, eggs)	Ultrasound can be used to replace the cleaning and blanching process of vegetables and eggs that use low temperature hot water.	Used in Europe for the cleaning of eggs	• Offsets the thermal energy needed • Regulatory barriers
6.1.9 Pulsed electric field processing*	Pasteurization and sterilization (liquid food, beverage, and solid food)[99]	Pulsed electric field processing technology involves delivery of short, high-power electrical pulses (milliseconds or microseconds) to a product placed in a treatment chamber confined between electrodes to inactivate harmful microorganisms.	TRL 7 (pilot)	• Maintains the nutritional quality, antioxidant content, and freshness of liquid foods. The process operates at lower temperatures than conventional heat-based methods and thus uses less energy.
6.1.10	Thermovacuum drying[100] (bulk food product drying technology)	The technology combines a traditional rotary dryer with a thermal driven ejector system and heat pump.	TRL 7 (pilot)	• High exergy efficiency, waste heat–driven

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

The food processing industry is exploring different approaches to shift away from legacy central natural gas steam systems by moving to electric thermal technologies. Whereas electric boilers and heat pumps are more readily implemented within existing plants and processes, shifting to technologies such as RF and UV is more challenging to integrate and needs to be studied and supported.

TPI pillar 2: Alternative thermal processing

Alternative thermal processes represent technologies that use alternative sources of energy while maintaining the current production methods. Multiple facilities have integrated concentrated solar power into their processes. Furthermore, the use of electric means of heating is rapidly being adopted in place of fuel by the sector. Sorption, chemical, and thermally activated heat pump systems with high lift and high temperature will become more important as we start to

[100] California Energy Commission. 2020. Direct Gas-Fired Dryer with Thermal Driven Ejector System for Bulk Food Processing. Retrieved from https://ww2.energy.ca.gov/2020publications/CEC-500-2020-018/CEC-500-2020-018.pdf.

look at plant-wide thermal integration because many different qualities of heating and cooling exist at plants.[101] Table 24 shows the alternative thermal processing technologies for the food and beverage industry.

Table 24. Alternative thermal processing technologies for the food and beverage industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.2.1 RF and hybrid RF processing[†]	RF drying (e.g., grains, nuts) Cooking (fresh meat) Pasteurization and sterilization (liquid food) Thawing (e.g., frozen meat, fish) Enzyme inactivation (blanching: vegetables and fruits)[102]	RF processing uses dielectric heating to thermally process foods using EM waves (longer wavelength than MW). RF processing can be used to process any dielectric material and most food products are dielectric. RF rapidly generates heat volumetrically within the product minimizes product deterioration.	Commercially available for thawing applications, pasteurizing, and baking (TRL 7) TRL 3–5 for most other applications RF pasteurization is used in meat processing. Liquid pasteurization applications are also being explored.	• Shorter processing times • Equipment footprint is reduced • Construction of large RF heating systems is simpler than MW • Application to continuous processes more straightforward compared to MW. Thawing: RF can reduce the thawing time by up to 95%. It can also be performed directly inside packaging. Common barriers: nonuniform temperature distribution, dielectric breakdown (arching) and thermal runaway heating from hot spots, high capital cost of the equipment
	Hot-air–assisted RF (e.g., roasting nuts) [102]	A hybrid approach that uses RF processing to supplement traditional hot-air systems has shown promise.	TRL 5 (laboratory research)	Has high roasting efficiency and improves the product quality and shelf life
6.2.2 Ohmic heating*	Blanching (fruits and vegetables) Cooking (fresh meat) Thawing (meat processing) Fermentation (dairy; growth of lactobacillus acidophilus and whey proteins) [103, 104]	Ohmic heating is based on the “Joule effect,” which is the principle that the passage of electricity through a semiconductive material will allow generation of internal heat.	TRL 3–5 (laboratory research)	• Shorter processing times, higher yields, and less power consumption • Hot spots and the interaction of electric fields with food at the molecular, cellular, and tissue levels • Reduce lag time • Still many unknowns on the best combinations of electric field and frequency to be applied

[101] From discussion with experts from the workshop
[102] Jiao, Y., J. Tang, Y. Wang, and T. L. Koral. 2018. “Radio-frequency applications for food processing and safety.” *Annual Review of Food Science and Technology* 9, 105–127.
[103] Sun, D. W. 2014. “Emerging technologies for food processing”. Elsevier. Chicago.
[104] Pereira, R. N., J. A. Teixeira, A. A. Vicente, L. P. Cappato, M. V. da Silva Ferreira, R. da Silva Rocha, and A. G. da Cruz. 2018. “Ohmic heating for the dairy industry: a potential technology to develop probiotic dairy foods in association with modifications of whey protein structure,” *Current Opinion in Food Science* 22, 95–101.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.2.3 IR processing/IR hybrid processing*	IR drying (fruits, vegetables, grains, spices)[103]	IR radiation uses an electric or ceramic heating element that gives off EM energy waves.	Commercial	Differential energy absorption by fats, proteins, and water may also influence the performance of IR drying.
	Hybrid IR and hot air drying (fruits, vegetables, grains, spices)[103]	A drying process that combines IR and hot air has a more synergistic effect than processes that use only IR or hot air.	Commercial	• Shorter processing times, higher yields, and less power consumption • Significantly reduce lag time
6.2.4 MW and hybrid MW processing†	Evaporation (milk, vegetable and fruit processing) Drying: dehydration/ microbial reduction/ thawing[103]	MW provides uniform material temperature (no scorching), and the flexibility to operate under pressure, vacuum and/or nitrogen blanket.	TRL 5 (laboratory research)	• Shorter processing time • High total efficiency of energy • Eliminates burning • Material heated and dried directly • Instant power control
6.2.5 Concentrating and non-concentrating solar thermal collectors†	Dairy, meat processing (drying, roasting, boiler preheating, general process heat use)[105]	Solar energy transferred to process via hot water, heated air, steam, or heat exchanger	TRL 9 (pilot)	Displacement of combustion fuels, off-grid applications. Barriers: process integration, unfamiliarity with technology, need for storage for higher solar fractions
	Solar thermal with TES (baking)[105]	Concrete based TES with food-grade oil heat transfer fluid as part of linear Fresnel collector for durum wheat pasta production	TRL 4 (laboratory research)	• Solar contribution of ~40% for total thermal energy requirement • Expected payback period of 8 years Barriers: cost
	Solar-driven evaporation for concentration of liquids (dairy, milling)[106]	Solar-driven evaporator designs are widely being explored for desalination and wastewater treatment. Similar systems can potentially be applied in the food and beverage industry to replace or complement fuel-driven concentration systems	TRL 9 (pilot)	Barriers: The material components and structure will affect the absorption and needs to be optimized. Scaling needs to be addressed by tailoring surface properties and structure.

[105] Schoeneberger, C. A., et al. 2020. "Solar for industrial process heat: A review of technologies, analysis approaches, and potential applications in the United States," *Energy* 206, 118083.
[106] Wu, S.-L., et al. 2021. "Solar-driven evaporators for water treatment: challenges and opportunities," *Environmental Science: Water Research & Technology* 1, 1.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.2.6 Electric steam generation†	Cooking, drying, and any place steam is used	Producing steam by electric boilers for traditional steam-heated system: Decentralized (local) steam units that use electricity to produce steam could also be a route for electrification.	Commercial	Potential offset emissions with a cleaner grid Barriers: cost
6.2.7 Use of biomass†	Sector-wide application	Biogas could be generated from the waste stream in certain segments of the food and beverage industry.	Commercial	The waste stream could be a high value product (e.g., animal feed) and the economics may not work for it to be used for energy production.
6.2.8 Electric heat pumps†	Cooking, drying, pasteurizing (can be applied to any thermal process with steam) Used for the cold side in dairy plants	Generation of process heating and cooling with centralized and decentralized heat pumps • Energy savings up to 65%	Commercial	• Lack of awareness • Needs accommodating process changes R&D opportunities: • Developing detailed enthalpy versus temperature curves (pinch technology composite curves) for all key food processing industries and processes available to the public • Characterization of heat pump contributions to cooling streams

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

In addition to the technologies discussed earlier, exemplar case studies may help drive adoption. Specifically, an end-to-end mapping of the thermal budget and analysis of alternative thermal processes and associated energy reduction (or reducing process steps, intensification) for typical processes in the industry were agreed to be useful.

Challenges: The current low cost of natural gas in the United States (national average for industrial use: $3.29–$5.74 per thousand cubic feet[107]) is considered a significant barrier for most of these transformative technologies, and changes in the economics will drive companies to consider the alternatives. Presently, electrification is hindered by utility cost and the need to upgrade existing electrical infrastructure to handle increased loads. Grid reliability, demand charges, and carbon intensity of grid-supplied electricity make investments in electrification questionable from cost, reliability, and sustainability perspectives. Also, the low profit margins and potential seasonality in food and beverage operations, along with a resistance to technology that has not been demonstrated to work effectively, lower the likelihood of moving to new processes.

[107] EIA (Energy Information Administration). 2021. Natural Gas Monthly Report. Table 3. Selected national average natural gas prices, 2016-2021.

Opportunity: Given that the regulatory barrier is common across the sector, DOE/AMO creating a subprogram to work with regulators to approve new processes could be a step to drive rapid adoption. Some DOE technology programs have had success in breaking this barrier by working directly with the appropriate regulators. For example, nuclear energy has a subprogram to help the Nuclear Regulatory Commission develop licensing processes for advanced reactors. Furthermore, the Hydrogen and Fuel Cells Technology Office has a subprogram called "Safety, Codes, and Standards" that conducts research to inform regulatory standards and codes (e.g., safety codes for hydrogen pipelines in coordination with the Pipeline and Hazardous Materials Safety Administration).

While the food, beverage, pulp, and paper sectors were chosen as the focus for the workshop given their large energy footprint, industries with similar low and medium temperature process heating applications were also discussed along with the relevant TPI technologies. TPI technologies discussed under pillars 1 and 2 of this section find relevance in all sectors with processes in the low to medium temperature range. While the level of adoption of these technologies in each sector varies, some of the barriers are common and use of the technology in one sector can help drive implementation in others.

In addition to the technologies considered under TPI pillars 1 and 2, transformative supplemental technologies and waste heat management technologies for food and beverage sector can help reduce thermal energy use in this sector. Biofuel generators and microturbines are potential applications to reuse the waste product from the mills. Many food (especially meat) processing and manufacturing plants have a dual need of cold water for production and hot water/steam for plant cleaning. This demand represents various waste heat recovery opportunities. These opportunities could offset electrical cost but could interfere with utility contracts if the load factor is reduced below contract threshold. These additional technologies are discussed in Section 5.10.

5.7 Hydrocarbon Processing: Petroleum Refining Industry

5.7.1 Energy Use

The US petroleum refineries are one of the largest producers of liquid transportation fuels and refined petroleum products in the world and the second largest consumer of energy in US manufacturing. This industry accounted for 3,744 TBtu (19%) of the 20,008 TBtu of total US primary manufacturing energy consumption in 2014. A total of 3,373 TBtu of energy was consumed on-site— within facility boundaries of US petroleum refineries—whereas off-site electricity and steam generation and associated transmission losses accounted for the remaining 371 TBtu. Figure 33 shows the distribution of energy use by fuel source type in the petroleum refining sector. For each type of energy source shown in this figure, the description includes the type of energy source and its percentage of the 100% total energy use.[11]

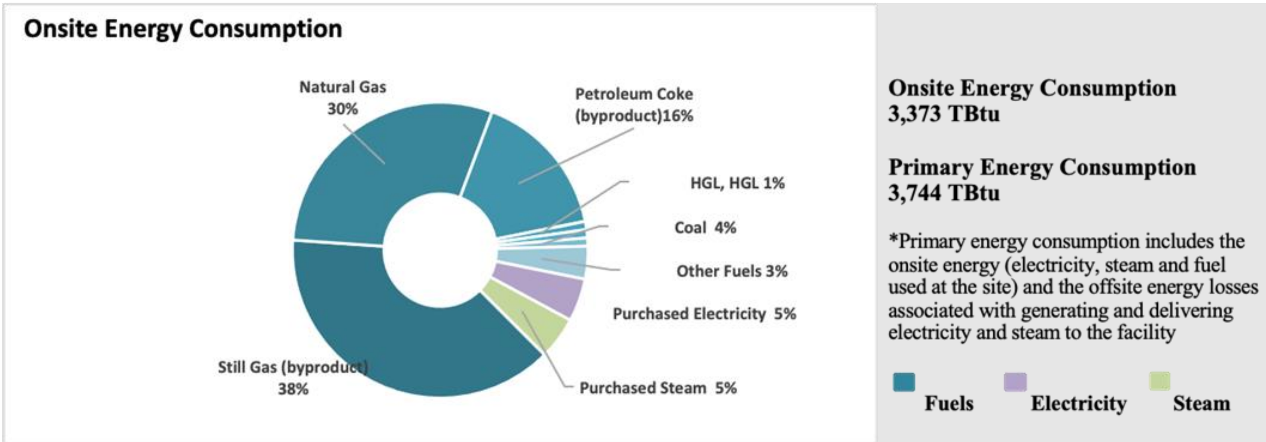

Figure 33. On-site energy consumption at point of use in US petroleum refineries in 2014.[11]

Petroleum refining is a complex industry that generates a diverse slate of fuel and chemical products, including gasoline and heating oil. Numerous outputs are produced by petroleum refineries each year in the United States. Some of the processes used in a typical refinery are shown in a simplified flow diagram (Figure 34). The flow of intermediates between the processes vary by refinery, and it depends on the structure of the refinery, type of crude processes, and product mix.

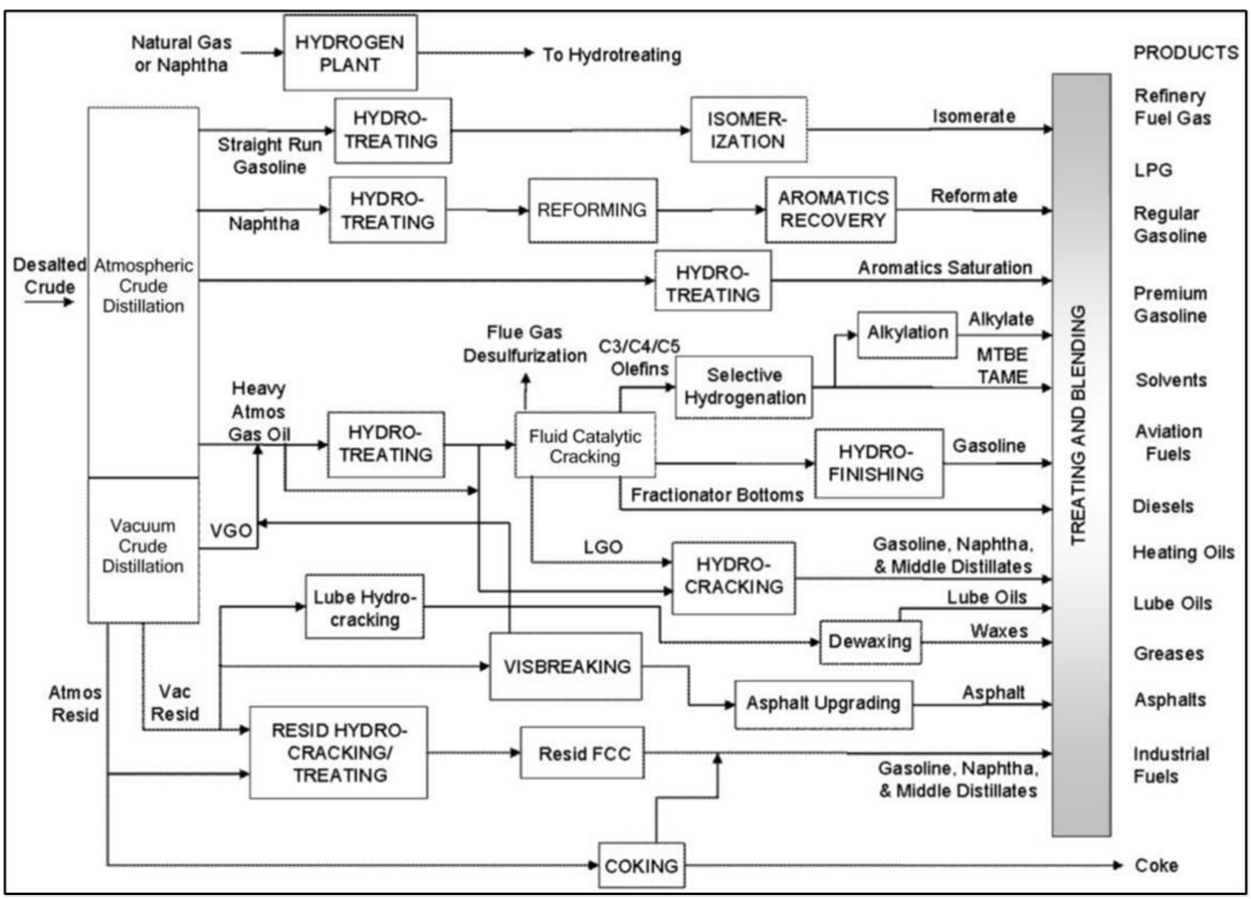

Figure 34. Simplified flow diagram of a typical petroleum refinery.[108]

The first process unit in nearly all refineries is the crude oil or "atmospheric" distillation unit. Different downstream conversions are possible using thermal or catalytic processes (e.g., delayed coking, catalytic cracking, catalytic reforming) to produce the desired mix of products from the crude oil. The products may be treated to upgrade the product quality (e.g., sulfur removal using a hydrotreater). Side processes that are used to condition inputs or produce hydrogen or by-products include crude conditioning (e.g., desalting), hydrogen production, power and steam production, and asphalt production. Drying processes that remove moisture from the product (Natural Gas. Ethylene etc.) and/or the feedstock material are common across the sector and are typically achieved using desiccant systems. Lubricants and other specialized products may be produced at special locations. More detailed descriptions of petroleum refining processes are available in other references.[108,109]

The majority of the fuel (64%) is used directly for process heating; some examples of process heating equipment include fired heaters, heated reactors, and heat exchangers. A significant portion of fuel (30%) is used indirectly in boilers and CHP to generate additional on-site electricity and steam. Figure 35 shows estimated energy consumption by the major specific petroleum refining unit processes. The top five energy-consuming refinery processes account for 85% of refinery energy consumption and associated CO_2 emissions.

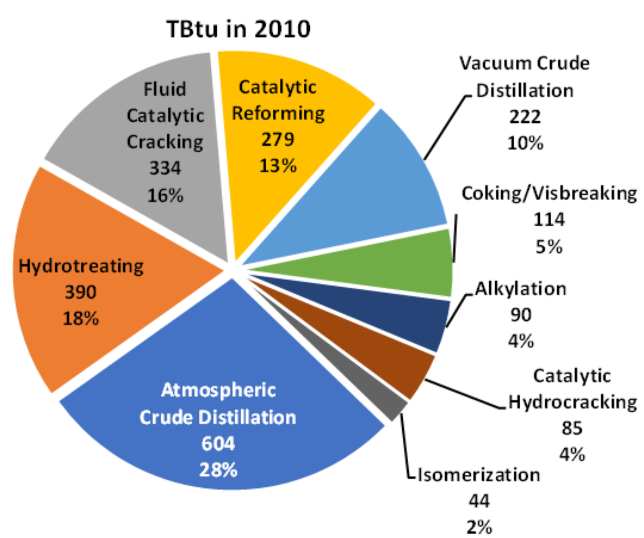

Figure 35. Estimated energy consumption by the largest energy consuming petroleum refining unit processes.

5.7.2 RD&D Needs and Opportunities

Each refinery and its use of technologies for various thermal processes are unique, and the refineries are constantly improving the processes to reduce the process energy intensity. Energy efficiency measures and advancements in technologies have the potential to reduce fuel use by

[108] DOE (US Department of Energy) 2015. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Petroleum Refining. Retrieved from https://www.energy.gov/sites/prod/files/2015/08/f26/petroleum_refining_bandwidth_report.pdf.
[109] EPA (US Environmental Protection Agency), AP 42, Fifth Edition, Volume I Chapter 5: Petroleum Industry.

50%.[110] The bandwidth study[111] carried out by DOE's AMO analyzed energy use at four different levels of energy consumption (Figure 36) for major energy-consuming manufacturing processes.

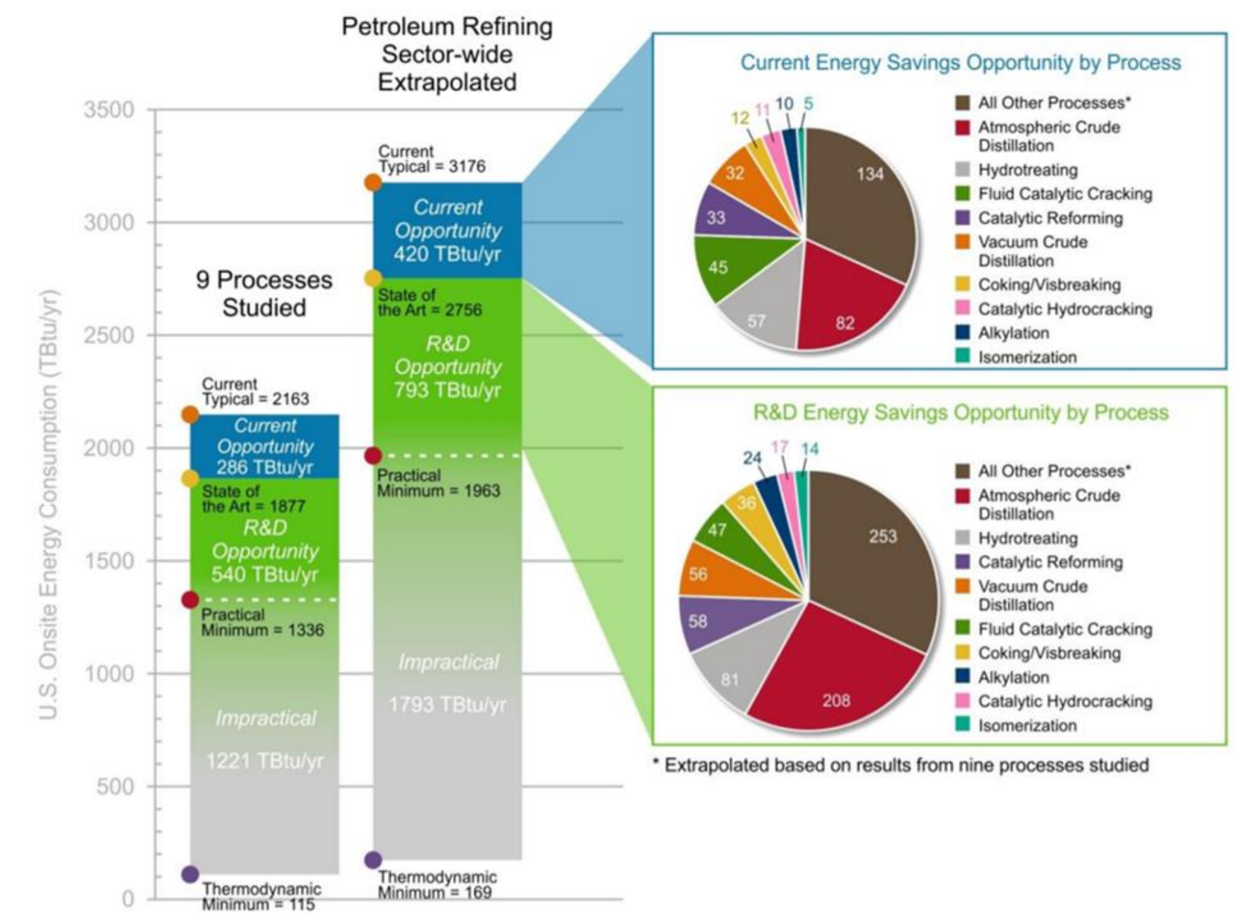

Figure 36. Current and R&D energy savings opportunities in US petroleum for the subprocesses studied and industry-wide extrapolation.[111]

The bandwidth analysis report for the petroleum refining sector analyzed eight major processes. The five largest energy-consuming refinery processes account for 85% of refinery energy consumption and associated CO_2 emissions. These include atmospheric crude distillation, hydro treating, fluid catalytic cracking, and catalytic reforming, in which achieving practically minimum energy use can result in energy reduction by 40% or more.

The bandwidth analysis results indicate that there are several opportunities to develop and apply new technologies or modify existing process operations through further R&D to reduce energy consumption in all major refinery processes. Table 25 shows the energy intensity of the studied

[110] Morrow, W. R. III, J. Marano, A. Hasanbeigi, E. Masanet, and J. Sathaye. 2015. "Efficiency improvement and CO_2 emission reduction potentials in the United States petroleum refining industry," *Energy* 93, 95–105.
[111] DOE (US Department of Energy). 2015. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Petroleum Refining.

petroleum refining process operations. The values of practical minimum energy consumption were obtained in the bandwidth study by applying current opportunities and R&D opportunity to current typical energy consumption.

Table 25. Energy intensity estimates and potential reduction in energy intensity for select petroleum refining processes in 2010.

Process	Energy intensity (Btu/barrel)*		
	Current typical	Practical minimum	**Percent reduction‡**
Alkylation†	246,700	154,400	37.4%
Atmospheric crude distillation	109,100	56,700	48.0%
Catalytic hydrocracking	158,900	107,400	32.4%
Catalytic reforming	263,900	178,400	32.4%
Coking/visbreaking	147,700	85,100	42.4%
Fluid catalytic cracking	182,800	132,700	27.4%
Hydrotreating	80,800	52,200	35.4%
Isomerization†	216,000	122,300	43.4%
Vacuum crude distillation	89,100	54,000	39.4%

*1 barrel of crude (bbl) = 42 US gallons.
†Values for alkylation and isomerization are production; all other process values are throughput
‡Based on difference (current typical – practical minimum lower limit)

Table 25 shows the relative improvement opportunity in the basic operations of a petroleum refinery. The highest relative opportunity is noted in atmospheric crude distillation, followed by isomerization and then coking/visbreaking.

5.7.3 TPI Technologies

The following subsections discuss technologies under each TPI pillar covered during the brainstorming session for the petroleum refining industry.

TPI pillar 1: Low–thermal budget transformative technologies

Modular chemical process intensification has been a long-standing concept when it comes to improving energy efficiency in the hydrocarbon processing industries. Many promising transformative technologies in the petroleum and chemical sectors can commonly be categorized by this approach. In fact, modular chemical process intensification has been the framework for DOE-funded RAPID[112] initiative and is supported by numerous industrial companies and research institutes.

Process intensification entails

- Rethinking processes to dramatically improve performance,
- Shifting from a unit operations paradigm to an integrative paradigm, and
- Removing bottlenecks.

Modular processing entails

- Rethinking systems to enable flexible, distributed manufacturing,
- Shifting from a bigger-is-better paradigm to a small, modular paradigm, and
- Transitioning from volume to number scaling.

[112] The Rapid Advancement in Process Intensification Deployment Initiative. Retrieved from https://www.aiche.org/rapid.

Several low–thermal budget R&D projects selected from the pre-workshop research and identified during the workshop are discussed in Table 26.

Table 26. Low–thermal budget transformative technologies for the petroleum refining industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.1.1	Thermal cracking (crude distillation/ separation)*	Replacement for crude distillation; alternative to primary separation: Innovative processes are developed and patented that separate heavy crude oil into fractions by cracking large hydrocarbon molecules into smaller ones, thereby lowering their boiling points and increasing yields.	Commercial, R&D	• Repurposing of existing equipment • High temperature and pressure requirements • Catalyst material availabilities
7.1.2	Bio-desulfurization, hydro-desulfurization/ hydrotreating (certain fuels)*	Biological removal of sulfur from gasoline is an alternative to hydrodesulfurization/ hydrotreating. The use of the biological agent results in lower temperatures and atmospheric pressure and eliminates the need for hydrogen as a feed and combustion of fuel gas.	R&D 1. Pilot by Energy Bio Systems, 1999	• Biological process limits and environmental regulations • Waste management and new controls engineering
7.1.3	Advanced synthetic fuel synthesis, refinery, chemicals†	The technology combines CO_2 and hydrogen to create hydrocarbons. Electricity is provided to enable the reaction.	R&D 1. Demonstration plant in Dresden, Germany	• Technoeconomic feasibility • Safety with H_2 and exothermic reaction • Fuel quality/regulation
7.1.4	Selective membrane separation, distillation†	Selective membranes have been developed for many years in many fields. Currently, separation in industrial chemical systems is done mainly by distillation and fractioning techniques, which can be quite heat-intensive. Using selective membranes would allow for chemical separation to be done at lower energy costs.	R&D; commercial for simple applications	• Membrane regeneration • Production throughput requirements • Costs
7.1.5	Hydrogen fuel cell, hydrogen generation, electricity†	Fuel cells are efficient electricity generators, especially when coupled with H_2 gas production; they have an 80%–83% theoretical limit, closer to 50%–60% for actual cells. Polymer electrolyte membrane electrolyzers are a promising technology.	R&D	• High capital cost • Some fuel cell technologies that involve high temperatures
7.1.6	Biomass hydrothermal liquefaction and biocrude oil refinery feedstock†	Technology to create synthetic crude is in development as a substitute to petroleum using a pyrolysis process. Organic matter is heated in the absence of oxygen, which causes the biomass to decompose into base hydrocarbon material, which can be used as a refinery feedstock.	R&D	• High cost to benefit ratio • Local raw material supply chain • Meeting fuel specification standards

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

TPI pillar 2: Alternative thermal processing

During the petroleum refining process, the petroleum refining industry—being a producer of carbon-based fuel and raw materials for other industries—generates and consumes ~30% of the total by-product fuel used by the sector. The remaining fuel use is in the form of natural gas and coke used in the refining processes; use of alternative non-carbon energy sources is considered a very low priority. In addition to the energy-related issues, conversion of large energy-consuming equipment such as fluid heaters and reactors is very capital-intensive and comes with high risks. Therefore, very few examples of RD&D work exist in this sector. The future requirements of decarbonization may lead the industry to convert some of the processes, particularly those producing raw materials, such as chemical feedstock for chemical and other industries. A few examples found in the literature are described in Table 27. There was very little discussion on this area of RD&D activity in the workshop.

The available information from the literature is provided in Table 27.

Table 27. Alternative thermal processing technologies for the petroleum refining industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.2.1	Progressive distillation, new distillation plants*	Integrates atmospheric and vacuum distillation columns; atmospheric distillation, vacuum distillation, gasoline fractionation, and naphtha stabilizer	RD&D; commercial demonstration	• Initial high cost of adoption
7.2.2	Electrification, distillation, utilities†	Applies electricity to turbine-driven pumps, electric heating for heating systems at the production scale, use of mechanical vapor recompression to reduce steam load	Commercial for smaller systems; R&D	• Low fossil fuel costs • High-temperature applications • Corrosion maintenance costs • RE availability • Commercial availability of complex systems such as mechanical vapor recompression
7.2.3	Fuel switching†	Switches conventional heavy fuels to lighter and cleaner fuels such as natural gas, hydrogen, and liquified coal with greater heat recovery technologies and efficient burners	R&D; commercial	• Redesign of equipment • High cost of hydrogen plant construction • Ease/availability of alternative fuels

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

A summary of the feedback received from the workshop participants is provided here. The topics that received the most interest include the following:

1. RD&D related to separation processes, such as selectivity in membranes with fouling-resistant/anti-fouling properties and alternative separation processes for heavier products. Existing membranes are not ideal for heavy products because these membranes are

defined not by their chemical composition but by their properties (volatility, density, chemical type).

2. Energy generation cycles and fluids for petrochemical/refinery applications

3. Application of electrical energy and alternative energy sources for thermal processes in the petroleum refining industry, as demonstrated in European countries

4. Research and technology development for processes that can use the heat at low temperature level (175°F–300°F), including adsorbent processes such as CO_2 adsorption

5. New and advanced heat exchanger concepts for large and frequent use in petro-chemical industries

General barriers: The feedback on challenges to R&D in the petroleum refining sector included three major issues:

1. Price of available types of crude oil (heavy vs. light) and related technical issues such as condensers for crude distillation units and deemphasizing research on use of heavy crude (i.e., better coker, process and equipment upgrading)

2. Regulatory issues such as environmental regulations, demand for oil (e.g., gasoline, jet fuel)

3. Return on investments for capital projects

The refining industry is very conservative and wary of taking risks in new operating technologies if the savings potential is not significant. Helping to lower the risk of applicability and prove potential would be a hugely beneficial to the industry. Some key discussions and responses from the workshop participants are summarized as follows.

5.7.3.1 TPI pillar 3: Transformative supplemental technologies

Integration technologies (better optimization and modeling) are critical to improve the operational efficiency of refineries. Current research related to transformative supplemental technologies mostly involves development of special sensors for temperature and temperature profiles for materials, and models for thermal processes. This development includes heating and cooling of materials, heat transfer to and within the materials being processed, predictive models based on feedback from sensors, chemical reactions including catalytic reactions, and several other processes such as separation. Efforts are also made in the areas of control of material handling systems, continuous monitoring of equipment conditions, and preventive maintenance of heating systems. The expected result is safe, efficient, and cost-effective operation of the systems. Many petroleum companies, control system companies, and institutions, including national laboratories, are working collaboratively to achieve the goal of highly integrated autonomous plants for safety, consistent product quality, and improved productivity.

5.7.3.2 TPI pillar 4: Waste heat management technologies

The thermal processes in the petroleum refining industry mostly discharge waste heat in the form of exhaust gases or discharge from process operation as flared gases, which contain a substantial amount of energy. The industry recovers a large part of the waste heat from the heating systems such as process heaters and discharges exhaust gases at relatively low temperatures, often less than 600°F. Much of this heat is not recovered because of economics (long payback periods) and maintenance issues related to the contaminants (presence of acid gases). Many of these issues are discussed in Section 5.10.

The current research activities address the issues of materials required to handle corrosive gases and condensation of acid gases during the heat recovery. The other issues related to maintenance and life of the equipment are also being addressed.

5.8 Hydrocarbon Processing: Chemical Industry

5.8.1 Energy Use

The US chemical industry is highly complex and supplies over 70,000 different chemical products. The processes used to manufacture these chemicals vary widely, and some are more energy-intensive and inefficient compared with others. Out of the overall energy use in the manufacturing sector (20,008 TBtu), the chemical sector accounted for 24% (4,542 TBtu) of that use in 2014. Off-site energy generation and losses (generation and transmission) in the chemical sector totaled 1,015 TBtu. Figure 37 shows the on-site energy in chemical manufacturing plants at the point of end use. The total on-site energy use for chemical manufacturing was estimated to be 3,527 TBtu in 2014.[11]

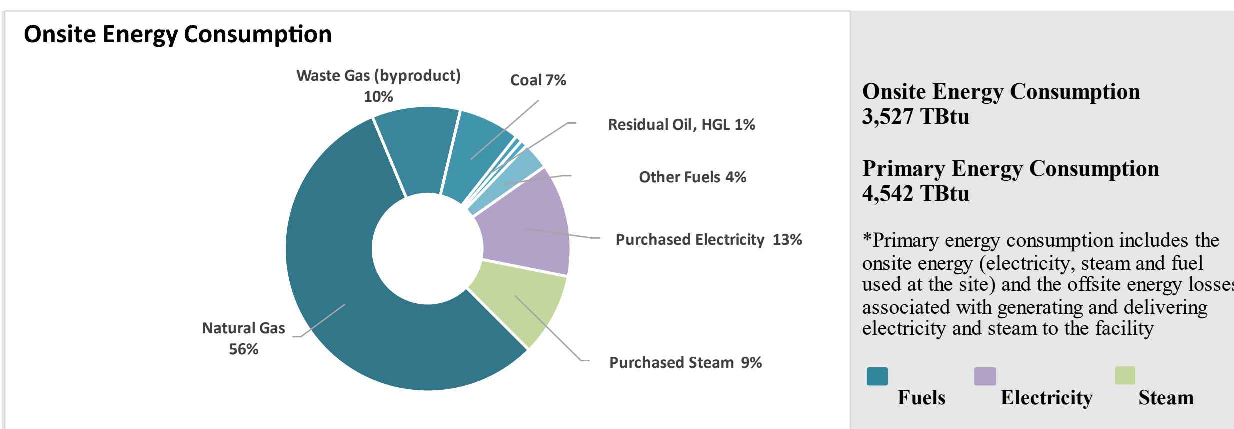

Figure 37. On-site energy consumption at the point of use in the US chemical industry in 2014.[11]

At US chemical facilities, most used on-site energy is in the form of fuel. This fuel is mostly used in on-site boilers and CHP systems to generate additional electricity and steam in addition to other uses, such as direct-fired process heaters. A total of 45% of the on-site energy consumption—primarily natural gas—was accounted for by on-site steam and electricity generation and associated losses. The next highest user of fuel is process heating category that accounts for 32% of the total energy use. Thermal processes in the chemical sector include direct-fired heaters, heated reactors, dryers, heat exchangers etc. Drying of product is a common thermal process achieved using different methods depending on the chemical processed. Fluid bed dryers, that heat the material via direct contact by suspending it in a stream of air, are commonly used to dry various bulk chemical products. Contact drum dryers are used for viscous materials while spray dryers that atomize the liquid feedstock into a heated air stream to achieve rapid drying is used for enzymes, paint pigments and pharmaceutical drugs.

5.8.2 RD&D Needs and Opportunities

The manufacturing processes for 70,000 chemicals currently produced in the United States are wide-ranging. Out of these chemicals, 64 of the most energy-intensive manufacturing processes were studied in the bandwidth study of the chemical sector. As shown in Figure 38, energy efficiency potential that exists based on the application of existing commercial and R&D level technologies exceeds 50%.[113]

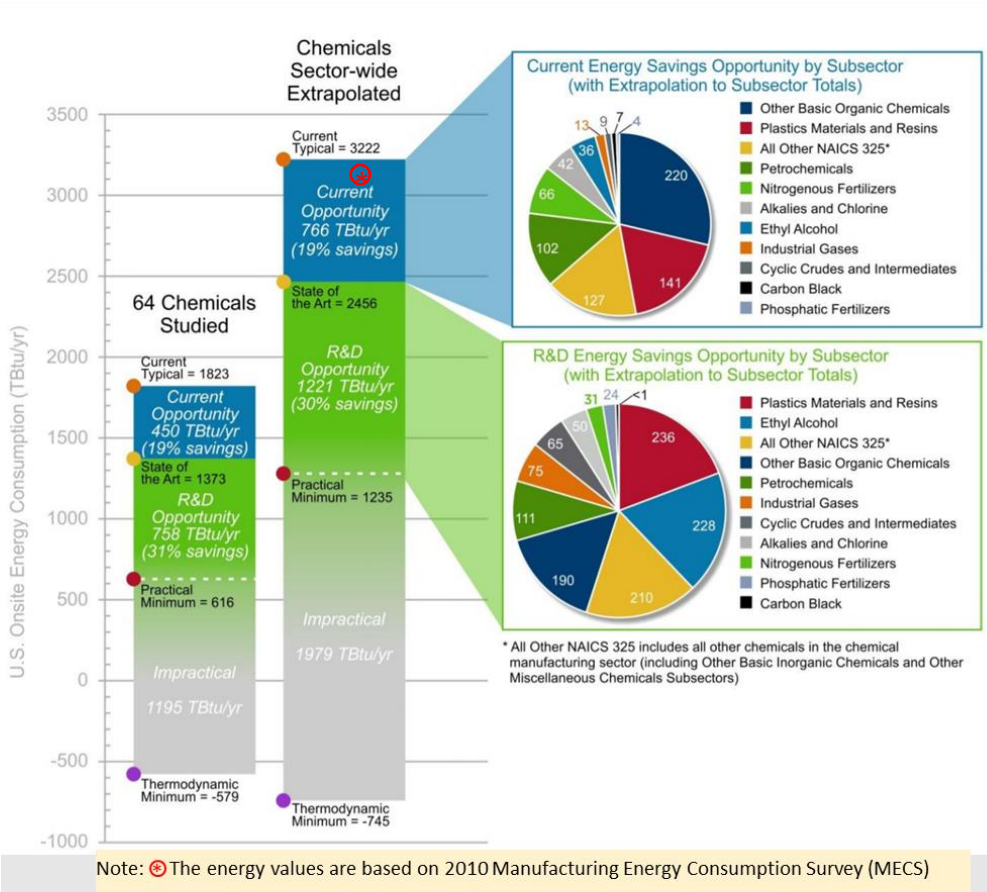

Figure 38. Definition of terms used for bandwidth analysis and graphical representation of opportunities for reducing energy use (opportunity bandwidth).[113]

The bandwidth study also quantified the practical minimum energy consumption for each of the studied chemicals. The chemicals were sorted into chemical products (e.g., ethylene, propylene,

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113 DOE (US Department of Energy). 2015. "Bandwidth Study U.S. Chemical Manufacturing." Retrieved from https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing.

other olefins) that would be classified into chemicals subsectors. The chemicals data were then extrapolated to estimate the energy savings achievable with practically minimum energy use technologies deployed across all US manufacturers in the subsector. The highest calculated available opportunity was found to be in other basic organic chemicals followed by the petrochemicals subsector and then the plastics and resins subsector. The found opportunity is quantified as 1,204 TBtu per year from the selected subsectors, out of which 54.7% (659 TBtu) exists in the aforementioned subsectors (i.e., other basic organic chemicals, plastics and resins, and petrochemicals). Further details on specific commercial and R&D technologies that are considered for this analysis are discussed in the bandwidth study report.[113]

The potential savings indicated show the maximum possible subsector-wide savings based on calculated current typical energy values compared with estimated energy values after the deployment of all technologies, as listed in Table 28. The highest absolute opportunity in trillion Btu is noted in ethyl alcohol followed by petrochemicals and then other basic organic chemicals subsectors. The highest relative improvement opportunity is found in other basic organic chemicals followed by cyclic crudes and then industrial gases.

Table 28. Energy intensity estimates and potential reduction in energy intensity for selected chemical industry subsectors in 2010.[6]

Categories	Energy intensity (Btu/lb)		Percent reduction
	Current typical	Practical minimum	
Petrochemicals (NAICS 325110)	4,239	2,436	42.5%
Industrial gases (NAICS 325120)	730	279	61.8%
Alkalies and chlorine (NAICS 325181)	4,444	2,200	50.5%
Carbon black (NAICS 325182)	3,845	1,861	51.6%
Other basic inorg. chem. (NAICS 325188)	−225	−708	214.7%
Cyclic crudes and interm. (NAICS 325192)	1,649	−677	141.1%
Ethyl alcohol (NAICS 325193)	4,646	652	86.0%
Other basic org. chem. (NAICS 325199)	3,099	1,123	63.8%
Plastics mat. and resins (NAICS 325211)	1,562	286	81.7%
Nitrogenous fertilizers (NAICS 325311)	2,485	985	60.4%
Phosphatic fertilizers (NAICS 325312)	388	73	81.2%
All other misc. chem. prod. (NAICS 325998)	1,871	1,073	42.7%

*Negative energy intensity represents processes that are net producers or potential net producers of energy

5.8.3 TPI Technologies

The basic research efforts in the chemical industry are focused on novel energy transfer methods, electrochemistry, hybrid membranes, new catalysts/processes, and embodied carbon methodology. Other projects/areas of research in development, demonstration, and deployment stages include,

- Catalyst/process conditions, such as in catalytic cracking.
- Low-carbon precursors, such as methanol, ammonia, biomaterials, and the incorporation of H_2 from renewables.
- Multi-energy source reactions.
- Bioreactors.
- Separations.
- Energy cascade
- Drying.

Based on the pre-workshop literature search and feedback from the workshop participants, a list of RD&D programs was developed and is presented in the following sections. These projects do not indicate any significant RD&D work related to steam production and/or CHP activities.

TPI pillar 1: Low–thermal budget transformative technologies

Table 29 summarizes the low–thermal budget transformative technologies for the chemical industry.

Table 29. Low–thermal budget transformative technologies for the chemical industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.1.1	Autothermal oxidative dehydrogenation of alkanes*	A process for the production of propylene and other olefins using alkanes in a catalytic autothermal oxidative dehydrogenation. This process reduces reaction times in short contact time reactors and increases yield.	R&D	• New unit designs • Frequent regeneration unit
8.1.2	Oxidative dehydrogenation using vanadium-based catalyst†	Ethane and propane are dehydrogenated in the presence of vanadium-based catalyst that supplied oxygen at 750°F–1,020°F. This produces low carbon oxides.	R&D	• Yield compared conventional processes • Capital-intensive redesign and training
8.1.3	Oxidative methylation of toluene†	Alternative oxidative technology, autothermal styrene monomer manufacturing process that results in net export of energy.	R&D	• Rapid catalyst deactivation • Yield improvement • Redesign of upstream/ downstream processes
8.1.4	High-temperature Shilov-like catalytic system for methyl chloride*	Newer process of partial methane oxidation in high-temperature Shilov-like catalytic system to produce methyl chloride	R&D	• Precipitation issue • Platinum catalyst stability
8.1.5	Exelus styrene monomer†	Exelus styrene monomer process is a novel catalytic technology to maximize styrene monomer production using toluene and methanol feedstocks in a single step.	R&D/ demonstration	• Capital-intensive redesign
8.1.6	Hydrogen fuel cell*	Fuel cells are efficient electricity generators, especially when coupled with H_2 gas production; they have an 80%–83% theoretical limit, closer to 50%–60% for actual cells. Polymer electrolyte membrane electrolyzers are a promising technology.	R&D	• High capital cost • Some fuel cell technologies involve high temperatures

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.1.7	Reactive distillation*	Reactive distillation or catalytic distillation is reaction and distillation combined into one unit operation. The reactions can be catalytic or thermal and can occur in liquid or gaseous phase.	Mostly commercial; R&D	• Newer processes need scale-up and model development and validation • Control details for optimization of process
8.1.8	Advanced nanostructured molecular sieves for energy-efficient industrial separations*	Porous material beds that adsorb the molecules in a mixture are used. Other molecules with a larger diameter cannot be adsorbed and hence separated.	Commercialized, implementation subjective to process feed/parameters	• Generic designs for specific feeds • Regeneration of sieve
8.1.9	Biomass as feedstock: olefins and polyethylene synthesis from biomass†	One common pathway is the fermentation of sugar-or starch-rich biomass (e.g., sugarcane, sugar beet, maize) to ethanol as secondary feedstock, which is then converted by dehydration into ethylene. Alternatively, biomass can be gasified into a synthetic gas, which is used for methanol production (secondary feedstock). Olefins are then made using the methanol to olefin process	R&D	• Waste wood and forest management regulations • Local availability of alternative fuels • Social acceptability
8.1.10	Alternative separation process for industrial gases*	Adsorption separation processes and gas separation membrane processes could be used for some separations instead of distillation process by using new materials and methods to reach the same enrichment.	R&D/pilot with some commercial	• Availability of a large amount of adsorbent/absorbent • Environmental issues for storage and regeneration • Performance maintenance
8.1.11	Artificial photosynthesis†	Artificial photosynthesis uses sunlight to create high-value chemicals. The method has shown promise for direct hydrolysis producing H_2 gas, which can be converted to methanol and subsequently ethylene. It can also directly produce synthetic organic molecules, such as ethylene.	R&D	• Local availability of enough sunlight • CO_2 availability • Capital-intensive
8.1.12	CAMOL (catalyst-assisted manufacture of olefins)*	This is a coking mitigation technology. It involves novel chemistry to anchor catalytic coating to furnace tubes. This prevents delamination from thermal shock. The technology produces a 6% reduction in energy per cracker.	R&D/pilot	• Applicability to high-severity cracking in industrial use • Thermal stress and life

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.1.13	Advanced distillation microchannel process technology*	A breakthrough distillation process using microchannel process technology to integrate heat transfer and separation into a single unit operation. The project focuses on the application of microchannel process technology in a fractionation section of an ethylene plant, the C-2 splitter.	R&D/pilot with some commercial	• Capital-intensive application • Prohibitive return on investment

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

TPI pillar 2: Alternative thermal processing

The chemical industry is one of the largest consumers of fuels to produce high pressure steam that is used to generate electricity and low-pressure stream used for process heating as well as feedstock for many processes and products within a chemical plant. The second largest user of fuels is process heating where combustion generated heat is used for various processes carried out in a broad range (<400°F to as high as 1,600°F). Due to use of conventional steam generating equipment which is almost exclusively fuel fired and use of by-product fuel generated within the plant (all being hydrocarbons), use of alternative non-carbon energy sources is considered a very low priority. In addition to the energy related issues, conversion of large energy consuming equipment such as heaters and reactors are very capital-intensive with high risks. Outside of integrated heat pumps and electric boilers, there are very few examples of RD&D work carried out to use alternative non-GHG generating thermal systems in this sector. The future requirements of decarbonization may lead the industry to convert some of the processes to use alternative heating methods such as induction, RF heating, and UV processing. However, there are very few examples of RD&D activities in this direction. A few examples found in the literature are given below. There was very little discussion in this area of RD&D activity in this workshop.

The available information from the literature and the discussions from the workshop are compiled in Table 30 for alternative thermal processing technologies in the chemical industry.

Table 30. Alternative thermal processing technologies for the chemical industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.2.1	Hollow fiber column packing*	The technology replaces the conventional packing materials used in distillation columns for olefin/paraffin separations with hollow fibers, which have a high specific area and separated channels for both liquid and vapor phases resulting gains in separation as well as energy efficiency	R&D/Los Alamos National Laboratory–Chevron partnership for commercialization	• Effects of reflux ratio • Temperature and Pressure stability ranges • Optimal separation efficiency Membrane mechanical integrity at high temperatures
8.2.2	Elongating the reactor to increase the residency time of the feed stream*	BOP Furnace Energy Improvement in Steam Cracking	Commercial	• Frequent run length changes • Maintenance procedures

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.2.3	MW enhanced direct cracking of hydrocarbon*	MW enhanced cracking of the hydrocarbon feed material was demonstrated by Ceralink. The operation takes place below atmospheric pressure 15-55 Torr and with carrier gas Argon.	R&D	• Slightly lower yield rates
8.2.4	New drying technologies*	Different drying technologies are used to reduce moisture. Bulk Solids Cooler, Plate Bank Cooler, Rotary cooler are few examples.	Commercial	• Condensation on plates and caking of product • Maintenance of critical relative humidity of product
8.2.5	Hybrid distillation*	It is a combination technique that can involve extraction, distillation, reactive distillation, adsorption distillation, and others in a single unit process to minimize energy consumption.	R&D	• Limited modeling capabilities • Computationally intensive models
8.2.6	Distributive distillation*	Improving efficiency of the distillation process by replacing a single distillation column with several smaller ones using microchannel processing.	Commercial	• Low benefit to cost ratio • Complex modeling • Scale up • Separation efficiency has been verified, but economic viability of commercial scale microchannel distillation units needs to be examined.

*Included in DOE's bandwidth study, 2017
†Not included in DOE's bandwidth study, 2017

While petroleum refining and chemical sectors were chosen as the focus for the workshop given their large energy footprint, production of other hydrocarbons with similar process heating applications were also discussed along with the relevant TPI technologies. TPI technologies discussed under pillars 1 and 2 of this section find relevance in the production of other hydrocarbons as well. While the level of adoption of these technologies in each sector varies, some of the barriers are common and use of the technology in one sector can help drive implementation in others.

TPI pillar 3 and TPI pillar 4: Transformative supplemental and waste heat management technologies

In addition to TPI pillar 1 and TPI pillar 2 technologies, development of advanced sensors and process simulation software for process performance predictions can be used to enhance the performance of process heating system and safety of the thermal processes. Current research related to transformative technologies includes development of special sensors for heating and cooling of materials, heat transfer to and within the materials being processed, predictive models based on feedback from sensors, chemical reactions including catalytic reactions, and several other processes such as separation. Many transformative technologies in advanced materials and improved manufacturing technologies such as additive manufacturing are also used to allow design and manufacturing of equipment used by the chemical industry. Some examples include heat exchangers, reactors, better insulation, and higher-temperature capabilities. The expected result is safe, efficient, and cost-effective operation of the systems.

Many chemical companies, control system companies, and institutions (including national laboratories) are working collaboratively to achieve the goal of highly integrated autonomous plants for safety, consistent product quality, and improved productivity.

The chemical industry thermal processes discharge waste heat mostly in the form of exhaust gases from process furnaces, heaters, and reactors, and others which contain substantial amount of sensible and, in some cases, chemical energy. The industry recovers a significant part of the waste heat from the heating systems such as process heaters and discharges exhaust gases at relatively low temperatures, often lower than 600°F. Much of this heat is not recovered because of economics (long payback periods) and maintenance issues related to the contaminants (presence of acid gases). Many of these issues, along with potential solutions such as TES, are discussed in Section 5.10.

5.8.4 Applicable Crosscutting RD&D Activities

Thermal processes used by the petroleum refining and chemical industries use very similar basic operations or processes (e.g., distillation, reforming, catalysis) and can benefit from adaptation of many RD&D activities from either industry. This section provides a summary of commonly applicable RD&D activities by researchers in this field. The RD&D programs are applicable to and overlap in the petroleum refining and chemicals sectors. Many projects address the basic issues of reduction in energy intensity, CO_2 and GHG reduction, increased productivity, recycling of by-products or other materials, and overall production cost reduction.

The RD&D includes separation processes used for specific process steps such as gas separation, liquid separation, and distillation; improvements in catalysts to reduce process temperature; acceleration of chemical or bio-chemical reactions applicable to currently used non-catalytic reaction; enhancement of reactions through the use of catalysts or other techniques; use of alternative sources such as biomass of feedstock to reduce fuel usage; and use of waste heat-energy produced from thermal processes to optimize energy expenditure. DOE has initiated and/or supported several R&D programs through formation of consortiums. One of them associated with the American Institute of Chemical Engineers, RAPID, conducts RD&D for the petroleum refining and chemical industries. Several similar public and private organizations conduct RD&D in these areas.

As part of the workshop, RAPID shared information on numerous R&D projects that it manages in collaboration with the industry, academic institutions and research organizations. Most of these projects include process-specific activities for which detail information is not available due to confidentiality but RAPID has shared information on these projects and published summary on their website.[114]

[114] RAPID Funded Projects | RAPID Manufacturing Institute for Process Intensification (aiche.org). https://www.aiche.org/rapid/projects/list

A few examples of the projects underway at RAPID are listed as follows. These projects are applicable to entire spectrum of hydrocarbon processes used in petroleum refining and chemical industry.

Separation Process: Membranes

1. Compact membrane systems to seek alternatives to distillation
2. Para-xylene selective membrane reactor
3. Energy-efficient separation of olefins and paraffins through a membrane
4. Advanced nanocomposite membranes for natural gas purification
5. Robust membranes for black liquor concentration
6. High purity ethanol without distillation: carbon nanotube–enabled ethanol dewatering
7. Multiphase microchannel separator
8. Thermoneutral propane dehydrogenation via a solid oxide membrane reactor
9. Energy efficient technology for metals separation
10. Modular mechanical vapor compression; membrane distillation for treatment of high total dissolved solids produced water
11. On-demand treatment of wastewater using 3D printed membranes

Other Separation Methods

1. Adsorptive nitrogen from natural gas
2. Microfibrous entrapped sorbents for high-throughput modular process-intensified gas separation and ion exchange

Alternative Feedstock

1. Autothermal pyrolysis of lignocellulosic wastes to sugars and other biobased products
2. Sugars-to-bioproducts scalable platform technology

Process Intensification

1. Dynamic intensification of chemical processes
2. Modular conversion of stranded ethane to liquid fuels
3. Intensified commercial-scale manufacture of dispersants
4. Efficient chemicals production via chemical looping
5. Three-way catalytic distillation to renewable surfactants via triglycerides
6. Modular catalytic partial oxidation reactors using microstructured catalyst structures with combined high thermal conductivity and flame extinction capacity to enhance process safety margins and enable high per-pass conversion and high selectivity
7. Synthesis of operable process intensification systems
8. Modular catalytic desulfurization units for sour gas sweetening
9. Deploying intensified, automated, mobile, operable, and novel designs "DIAMOND" for treating shale gas wastewater

Alternative Energy Source

1. MW catalysis for process intensified modular production of value-added chemicals from natural gas
2. Use of power ultrasound for nonthermal, non-equilibrium separation of ethanol/water solutions
3. Intensified MW reactor technology
4. MW heating for direct natural gas conversion

The subject of waste heat recovery was extensively covered in session 6 of the workshop.

5.9 Supplemental Technologies for TPI: All Industries

5.9.1 Introduction

This section focuses on transformative supplemental technologies that are used in the operation and control of thermal processing systems. These technologies enhance the performance of process heating systems and ensure safe and predictable performance of the thermal processes. They may improve the life of process heating systems (equipment and auxiliary systems), reduce operating and maintenance costs, offer improved product quality, offer higher product yield, reduce waste by-products, reduce GHG (CO_2) emissions, and so on. Examples of these technologies include integration of sensors and control system components, predictive tools-models, smart manufacturing, IoT, AI, digital twin, improved materials and material handling systems, and enhanced communications. Figure 39 provides a schematic of this integration.

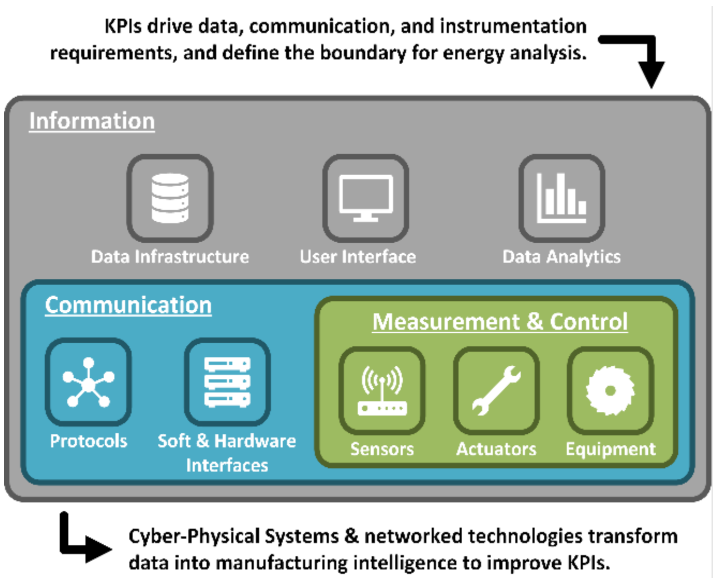

Figure 39. Smart manufacturing and IoT could integrate the thermal processing systems with digital systems, creating a cyber-physical system that can leverage information to improve efficiency, productivity, and safety.

Performance of thermal processing systems can be enhanced by using supplemental technologies that allow enhancement of process performance, rapid and accurate identification of key parameters controlling the process variables, and functions that enable optimum energy use and product quality. These enhancements can result in optimization of energy use and improve productivity, product quality, production flexibility, and often operating cost.

A need exists for the advancement and development of various components that can improve the performance of the required functions, including intelligent and advanced material handling systems, materials used in the system components, sensors, intelligent controllers, actuators, and communication to the appropriate personnel. Thermal processes require sensors for online and accurate measurement of key parameters that control the process quality, processing time or schedule, and product quality. The accurate measurements must follow intelligent controllers and accurate functionality of actuators to allow smooth control of heating systems. At this time, for many thermal systems, the quality of the processed material is based on one or two measurements and an empirical relationship between this measurement and the product quality.

Examples of such developments that are applicable to multiple industries include the following:

- Development of process models or use of predictive algorithms that can provide information on conditions of the product while being heated
- Use of AI and deep learning algorithms and additional tools for improving consistency of performance of process heating equipment while delivering consistent product quality, productivity, safety, reduced downtime, and so on
- Digital twins of real plants, processes, and products
- Development and deployment of IoT devices for the process heating system components
- Automatic control of combustion air-fuel ratios—flue gas oxygen sensing and automated control valves
- Online continuous measurement of moisture content of various products during drying/heating processes: The measurements could be surface moisture or moisture profiles within or across the material. Application examples include grain drying, coatings drying, paper drying, aggregate drying, and metal scrap drying.
- High-temperature sensors to monitor product (metals and nonmetals) temperature profiles within the material being heated
- Online instantaneous fuel composition measurement in cases in which the fuel consists of a mix of process by-product fuels as in the case of refineries and chemical plants
- Real-time monitoring of components integrity as in the case of refinery fluid heater tubes or heat exchangers
- Presence of flammable gases or vapors in heating systems
- Tools for flexible manufacturing, including application of additive manufacturing to supplement or replace current practices
- Innovative material handling systems for high-temperature and/or hazardous production environments, including intelligent robots
- Use of advanced materials for components such as material handling and heat containment (insulation) for a thermal processing system

Development and deployment of these critical components and associated systems can continue leadership of the US manufacturing sector.

5.9.2 RD&D Needs and Opportunities

Crosscutting supplemental technologies can be used across all industries to decrease the use of raw materials, decrease equipment size, decrease energy intensity, improve quality, and so on while promoting the use of alternative energy sources with low CO_2 footprints. Deployment of supplemental technologies such as CHP, materials efficiency, circular economy, smart manufacturing, and IoT approaches can help lessen energy demand and GHG emissions and provide up to 30% of targeted emissions reductions for cement, steel, and aluminum.[115] The magnitude of possible energy intensity reduction requires considerations for the details of the process itself and can be estimated for each process. However, the application of innovative technologies and advancements in processes still require considerations for many factors related to the thermal equipment design and operations. In turn, thermally efficient and reliable equipment requires availability and application of many transformative supporting technologies. Examples of some of these are as follows:

a. Advanced sensor technology or "smart" sensors for monitoring and controlling thermal systems. Standard sensors are used for measuring, monitoring, and controlling process variables in thermal equipment for all industries. These sensors, together with control systems, are critical for safe product quality control and other functions. However, these sensors and controls make measurements of the process environment with implied information of the product conditions and rarely the conditions within the materials. An urgent need exists for sensors that can measure the distribution or profile of critical process parameters such as temperature, moisture, and density within the material while being heated or cooled. Use of such sensors together with advanced and fast-acting control systems would result in improved product quality and productivity with reduction in plant waste.

b. Smart and digital manufacturing technologies (e.g., modeling and simulation, sensors, process intensification, automation and robotics, IoT) have the potential to improve the energy efficiency and reduce energy costs in thermal processing systems used in manufacturing.

c. Advanced materials (metals and nonmetals) can be used in harsh environments. The presence of certain components in harsh environments may result in unpredictable and shortened life with premature failure of the equipment. Advancement in materials can also be used to replace energy-inefficient methods, such as water cooling or air cooling, that result in significant energy losses and in some cases decrease productivity.

d. Process models and control algorithms should be developed to predict the process performance under a variety of production conditions (e.g., production rate, variations in feed material, adaptation for changes in upstream/downstream production conditions) and optimize the energy intensity for the production line.

[115] International Energy Agency. 2019. Tracking Industry 2020. Retrieved from https://www.iea.org/reports/tracking-industry-2020.

e. Flexible and modular manufacturing should be implemented with the use of production cells with efficient operation of the cell components. Such systems can replace many continuous high-capacity production lines.

f. Alternative production methods such as additive manufacturing can replace current production methods to achieve production flexibility, accelerated production, and on-demand delivery of a variety of products without maintaining a large inventory. For example, additive manufacturing can be used to replace casting, machining, and multiple heat-treating steps for components used to reduce energy intensity and GHG footprint in many industries.

This list represents some examples for supplemental technologies identified from literature; the workshop provided a forum for discussion on the industry-specific technologies and generated additional ideas for R&D, which are captured in the following section.

5.9.3 Supplemental TPI Technologies

5.9.3.1 Supplemental Technologies for Iron and Steel Industry

Smart manufacturing, IoT, and other supplemental technologies will be very important to iron and steel producers as they look to reduce costs and remain profitable. Smart manufacturing has the potential to affect every aspect of the iron and steel industry, including energy efficiency, product yield, sales, purchasing, maintenance, and safety.

The following list provides a few example supplemental technologies discussed during the virtual workshop, and Table 31 discusses the major technologies for the iron and steel sector in more detail.

- Intelligent control of air-fuel ratios in the coke oven
- 3D radar technology measures and broadcasts the distribution of BF burden in real-time
- Intelligent control system regulates slag foaming in the EAF
- Deep learning detects stickers and reduces false alarms to prevent breakouts and slowdowns in continuous casting
- Predictive models of slab reheating furnace
- Digital twin for BOF, BF, 3D caster and others
- Smart IoT for system optimization with smart sensors:
    - Smart sensors for wear condition monitoring of copper staves
    - Laser-based combustion diagnostic equipment
    - Augmented reality for safety and maintenance
- Flexible modular furnace that allows for different modules to be installed as different raw material mixes are used
- Modular manufacturing: mini and micro mills to produce iron and steel

- Zero-defect slabs through the implementation of smart manufacturing technologies in steel continuous casting
- Smart Ladle: AI-based tool for optimizing caster temperature

Table 31. Major transformative supplemental technologies in the iron and steel industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.3.1	Predictive models of slab reheating furnace[116,117]	A combination of smart/IoT devices can be used to improve the operation of a reheating furnace. Information about stock materials entering the furnace and production schedules is used to determine feed rates, zone temperatures, excess oxygen, and so on. 3D models of the steel slabs and furnace are used to find the optimal setpoints and zone temperatures to ensure core exit temperatures.	In development Several papers from the Association of Iron and Steel Technology on test implementation at facilities	• Availability of standardized commercially available solutions • Different competing priorities when running these furnaces • Large-scale industrial demonstrations
1.3.2	Digital twin	A digital twin is a computational model of a physical system. The digital representation of the system allows for optimization and maintenance of the systems to improve energy efficiency and productivity. The twin can also predict the responses of a system to changes in operating conditions and discover new, more efficient modes of operation. • Digital twin for BOF • Digital twin for BF	In development but some with solutions available: HATCH, LuxDEM	• Large-scale industrial demonstrations • R&D to create standardized solutions to reduce cost
1.3.3	Smart IoT for system optimization[117,118,119]	Smart devices and IoT allow for real-time measurements in the ironmaking process. There are new smart sensors for iron and steel to use for optimizing their production processes: • Smart sensors for wear condition monitoring of copper staves • Laser-based combustion diagnostic equipment to measure combustion parameters inside of high-temperature furnaces • Augmented reality for safety and maintenance with smart safety helmets	Some IoT solutions are in development but others are commercially available	• Availability of standardized commercially available solutions • Large-scale industrial demonstrations

[116] Hurd, G., E. Rodriguez, J. Kaufman, J. Ward, and H. Wu. 2011. "Process Control and Automation Systems Advancements for Reheat Furnaces," in *2011 AISTech Conference Proceedings*.
[117] Giltner, D. M., and K. Grieshaber. 2015. "Next-Generation Advanced Level 1 Reheat Furnace Control Using ZoloSCAN Laser Technology," in *2015 AISTech Conference Proceedings*.
[118] Weyer, S., J. Simoes, Y. Reuter, F. Hansen, Solver, C. Meisch, and A. Schmitz. 2020. "Digital Solutions for Modern and Efficient Ironmaking," *Iron & Steel Technology* 44–52.
[119] POSCO Newsroom. 2017. "How Factories Produce Steel- the Smart Way."

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.3.4	Flexible manufacturing[120, 121]	New furnace technology allows iron and steel producers more flexibility in the composition of their raw materials. For example, more pig iron and scrap can be added when prices are low. New furnace technology can also handle the additional CO_2 emissions generated by using these materials. • Siemens jet process uses a bottom-blowing converter. Oxygen is blown into the molten mass from below while lime and other materials are added to prevent slag formation • The flexible modular furnace from Tenova allows for different modules to be installed as different raw material mixes are used	Commercially available: Siemens jet process, Tenova flexible modular furnace	• Need to collect real-world performance data and conduct further R&D to improve performance
1.3.5	Modular manufacturing[122, 123]	Mini mills have allowed iron and steel production in areas without significant coal reserves and in smaller batch sizes than traditional integrated steel mills. Micro-mills could push this technology further, allowing for point of use iron and steel production at lower costs. Benefits of miniaturized steel production include • Greater flexibility of production according to demand • Less required heat to melt small batch steel/rebar production • Lower cost of construction	Commercial	• Need to collect real-world performance data and conduct further R&D to improve performance
1.3.6	Advanced materials for thermal systems	New materials (alloys and refractories) and insulation technologies are becoming available that can increase the thermal retention of crucibles, tundishes, ladles, and so on. Incorporating these advanced materials can reduce wasted heat and save energy. • Thermal ceramics • Silica-alumina refractories		• Large-scale testing and demonstrations • Development of more material options for different harsh environments

120 Siemens. 2014. "More flexibility for steel production," Phys.org.
121 Tenova. "Flexible Modular Furnace (FMF)."
122 Anderton, J. 2015. "New Micro Steel Mill is Competitive Despite Low Steel Prices," Engineering.com.
123 Smith, R. 2020. "The minimill cost advantage," Recycling Today.

5.9.3.2 Supplemental Technologies for Aluminum Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 32, along with their applicability to aluminum sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 32. Major transformative supplemental technologies in the aluminum industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.3.1	Digital twin for aluminum melting furnaces[124]	• Produces a virtual representation of the process, which can be used to predict future performance and adapt practices to improve sustainability • Used to optimize processing times to reduce wasted resources and energy	Demonstration/ development: recent implementation, still being researched	• Large-scale industrial demonstrations • Lack of publicly available performance data
2.3.2	Upgrading various types of aluminum scrap using the latest sensor technologies[125]	• Sensor-based sorting technologies (e.g., x-ray transmission, high-resolution sensors, 3D laser scanning, laser-induced breakdown spectroscopy) • Increased post-consumer scrap, reduced energy consumption (~6%), increased production capacity (~2%)		• Application of smart manufacturing and IoT solutions to reduce operational cost and improve scrap sorting productivity
2.3.3	Smart metal forming with digital process and IoT[126]	• Use of servo press as a digital manufacturing system • Die-embedded sensors used for data gathering and analysis • Precision forging with pulse motion • General use of IoT throughout process	Commercialization/ demonstration[126]	• R&D in process visualization using die-embedded sensors and data management with the IoT

5.9.3.3 Supplemental Technologies for Cement Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 33, along with their applicability to cement sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

[124] Lawrence, M., and R. Hendershot. 2020. "Harnessing Industry 4.0 to Optimize Performance in the Aluminum Industry," *Light Metal Age* 10–14.
[125] Jansen, T. 2019. "Upgrading various types of aluminum scrap using the latest sensor technologies," In: *2019 International Recycled Aluminum Conference*.
[126] Yang, M. 2018. "Smart metal forming with digital process and IoT," *International Journal of Lightweight Materials and Manufacture* 1, 4, 207–217.

Table 33. Major transformative supplemental technologies in the cement industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.3.1	Digital twin	A digital twin is a computational model of a physical system. The digital representation of the system allows for optimization and maintenance of the systems to improve energy efficiency and productivity. The twin can also predict the responses of a system to changes in operating conditions and discover new, more efficient modes of operation.	Pilot and demonstration with some commercial solutions available	• How digital twins can contribute to the value propositions and digital business models of a company • What technologies are required to build digital twins • How digital twins can interoperate • Whether digital twins are exclusively bound to IoT solutions • Need for open-source platforms and ecosystems • More pilot and demonstration needed
3.3.2	Smart IoT for system optimization	Smart devices and IoT allow for real-time measurements in the cement making process. There are some new smart sensors for the cement plants to use for optimizing their production processes.	Pilot and demonstration with some commercial solutions available	• R&D needed to reduce capital cost • More pilot and demonstration needed • Need for open-source platforms and ecosystems
3.3.3	AI and predictive models for plant optimization	AI and predictive models deliver real-time forecasts for key process variables, prescriptions for critical control variables, and supervised autosteer aligned with business objectives for a cement plant operation, including clinker cooler, preheater, rotary kiln, pyro process, ball mill, and vertical mill processes to achieve lowered energy consumption, optimized fuel mix, and increased throughput while maintaining stable operation and high product quality.	Pilot and demonstration	Some of the challenges that RD&D can address are • Accurate fusion of heterogeneous data from various sources • Effective learning for dynamic risk assessment and aided decision-making • Capital cost • More real-world pilot and demonstration needed

5.9.3.4 Supplemental Technologies for Glass Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 34, along with their applicability to glass sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 34. Major transformative supplemental technologies in the glass industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.3.1	New fault detection technology	Approximately 15%–20% of the glass from each batch has faults and must be returned to melter. Because smelting requires 75% of the energy in the glass manufacturing process, a process to minimize the recasting could save up to 15% of the energy costs of a plant. It relies on spectroscopy while the glass is crystallizing. Therefore, it would not require major refurbishment of the production line. 15% energy savings	TRL 2 and 3	Investigation of new spectroscopy methods needed Scale up and industrial pilot needed
4.3.2	Process heating control systems	Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings. • Glass wool and glass fiber finishing (drying) 3% energy savings	Pilot and demonstration	Dynamic simulation could be provided to optimize the operation of the control system.
4.3.3	Process controls in forehearths	Process controls in forehearths, such as gob weight in container glass, tin bath temperature in float glass, and quality controls reduce the number of rejects while increasing productivity and saving energy. 3.5% energy savings	Pilot and demonstration	Dynamic simulation could be provided to optimize the operation of the control system. More R&D to predict faults and errors could save more material and energy.
4.3.4	Optimization of annealing process	Energy savings could be achieved by changing the technological annealing process, investing in adjustments of the annealing lehr, conveyors, receivers, burners, control systems, product loaders, insulation, and so on for flat glass, container glass, and other pressed and blown glass. Energy savings: 2.5% for flat glass; 38% for container glass; 34% for specialty glass	Included in the practical minimum technologies	A precise simulator could be provided for energy-saving calculation. Matching new methods and technology with existing equipment is a major barrier. Availability of new equipment and design is a problem in some regions.
4.3.5	Laser-induced breakdown spectroscopy for improved control of glass feedstocks	Laser-induced breakdown spectroscopy probes can measure the chemical makeup of glass feedstock in real time, detecting potential contaminants and preventing low-quality mixtures from entering the furnace. Energy savings of around ~51,000 MMBtu or $358,000 per year for a single-furnace glass factory producing 225 MT per day.	TRL 7 (pilot)	Proper feedstock selection and separation is expensive, especially in large-scale industries. Matching technology with the existing factory is a problem while a new process section is needed between the feedstock warehouse and furnace.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.3.6	Image-based control of glass melting furnaces	Images of the melting glass surface are often analyzed manually for quality control. Some automated imaging systems have been commercially developed, such as the SIGLAS optical melt control system by Siemens. These optical control systems use automated video analysis to control energy transfer in the furnace, improving efficiency by maintaining optimal temperatures for batch melting. 2%–8% energy savings	TRL 7 (pilot)	More R&D needed on image processing Because there are few systems for the automatic control of the melting process, more development is needed in industry scale. New control system and its actuators are costly
4.3.7	Use of IoT for plant monitoring	By interfacing sensors with data acquisition devices and a software overlay, specific key performance indicators can be monitored in real time. Facilities have reported real-time data analytics to result in a 2%–3% improvement in production efficiency with a payback period of less than a year.	Commercial, developing	Supplying the IoT and related actuators is costly. More R&D is needed for customize the IoT for glass industry.

5.9.3.5 Supplemental Technologies for Pulp and Paper Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 35, along with their applicability to pulp & paper sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 35. Major transformative supplemental technologies in the pulp and paper industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.3.1	OptiCell flotation for deinking	OptiCell uses computational fluid dynamics and image analysis methods to provide smooth flow velocities that allow unobstructed transfer of bubbles to the surface of the pulp mixture or froth. Effectively removes ink at lower energy consumption	Semi-commercial	• More R&D needed for optimized design of injector
5.3.2	Laser ultrasonic stiffness sensor [6]	Can measure paper bending stiffness and shear strength in real time (instead of offline like currently practiced), allowing manufacturers to optimize the amount of raw material used by running closer to specifications	Demonstration	• Initial investments can be quiet high
5.3.3	Measuring dissolved lignin [7]	New sensors that can directly measure the dissolved lignin content continuously give pulp mills the opportunity to control the chlorine dioxide stage based on the total chemical demand	Early research	• Initial investments can be quiet high • Will need measurement at multiple location based on system configuration

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.3.4	Advanced controls for paper machines	Smart drying enabled by multi-source data and machine learning	Early research	• Managing appropriate data and building the initial machine learning algorithms can be tedious. • Cyber-security risks become pronounced with higher automation
5.3.5	Industry 4.0: decision-making model	A model that integrates green manufacturing technologies, activity-based costing, and the theory of constraint to assist in preparing the best production plans Helps achieve the optimal profitable product mix, production planning, and control, including machine maintenance and quality control	Proof of concept	• Supplying the IoT and related actuators is costly.

5.9.3.6 Supplemental Technologies for Food Processing Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 36, along with their applicability to food sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 36. Major transformative supplemental technologies in the food processing industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.3.1	IoT sensors and controls	Cooking/baking [14] Fermentation (malt beverages) [15] Control and regulation of baking temperature with real-time visualization Control of environmental conditions for malting process	TRL 3–5 (laboratory research)	• Network security, cost
6.3.2	Wireless sensor network	Bakery [16] Wireless sensor network developed for a bakery with sensors for environmental condition monitoring, image capture and processing, and machine speed	TRL 6 (prototype)	• Improved product quality, reduced stoppage, and reduced waste Barriers: network security, standardization
6.3.3	IoT: image processing	Fruits and vegetables [17] Camera with convolutional neural network to identify damaged, unusable raw materials	TRL 6 (prototype)	• Identification accuracy of 83.3%; potential production output increase of 31%

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.3.4	Manufacturing execution system	Sector-wide application [18] The manufacturing execution system is a production management system serving as the information center in the enterprise to improve manufacturing transparency. Manages data from manufacturing processes	TRL 5 (laboratory research)	• Quality improvement and reduction in energy use Barriers: Software heterogeneity (interoperability), cost, fragmentation of industries
6.3.5	Electrochemical DNA-based sensors	Molecular quality control (dairy) [19] Molecular sensor for real-time detection of melamine in whole milk	TRL 4 (laboratory research)	Sensors needs routine calibration and maintenance to have long life.

5.9.3.7 Supplemental Technologies for Petroleum Refining Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 37, along with their applicability to petroleum refining sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 37. Major transformative supplemental technologies in the petroleum refining industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.3.1	Predictive fouling minimization Application: heat exchangers	Crude preheat train in a petroleum refinery consists of a set of large heat exchangers. The overall heat transfer coefficient reduces significantly during operation due to fouling. The rate of fouling is highly dependent on the properties of the crude blends being processed, as well as the operating temperature and flow conditions. AI and machine learning technologies (artificial neural networks) are used for predicting fouling threshold, and a preventive maintenance tool is used for controlling heat exchanger fouling.	R&D	• Threshold calculation based on input and output stream compositions • Pressure and temperature effects • Appropriate process sensor R&D • Corrective actions and maintenance schedule • Integrated/new SCADA equipment
7.3.2	Advanced sensors Application: process heaters, reactors	Development of advanced sensors for internal temperature and detection of hot spots on heater components; or multivariate spectroscopic composition sensors	Mostly commercial; some R&D	• High-temperature hostile environment materials • Sophistication in hot spot data collection and transfer • Complex data analysis and maintenance actions

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.3.3	AI to optimize crude distillation units with uncertain feed composition Application: crude distillation/ separation	Crude distillation units are one of the most energy-intensive processes in a refining plant. With varying feed compositions, figuring temperature cut points is often time-consuming and wasteful. By using machine learning with artificial neural networks on data comprising different feed compositions, these cut points can be predicted to reduce energy consumption and time required to figure cut points.	R&D	• Applicability to all crude types and blends • Process parameters uncertainty • Robust predictability and validation of the framework
7.3.4	Energy performance monitoring and real-time optimization technologies Application: petroleum refineries, petrochemicals, alcohols, pulp and paper, others	Key performance indicators monitoring through energy information systems is enabled by advancement in industrial IoT technologies. AI has enabled many optimization technologies deployable specific manufacturing. Yokogawa's VisualMESA Energy Performance Real-Time Optimization tool is one such technology that can enable real-time optimization of interacting utility and process demands. VisualMESA optimizes steam production, electricity production and export, and chilled water and refrigeration demands in real time and simultaneously by recommending actionable insights for operators.	Commercial	• Complex data acquisition and analysis for implementation • Capital intensive

5.9.3.8 Supplemental Technologies for Chemical Industry

Major supplemental technologies identified through literature search and virtual workshop discussions are presented in Table 38, along with their applicability to chemical sector. This list is not intended to be exhaustive; only major developments with published literature are presented.

Table 38. Major transformative supplemental technologies in the chemical industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.3.1	Model-based predictive control for process Application: butadiene	Model-based predictive control can be used to control reactions in styrene butadiene polymerization	R&D/commercial (proprietary AI algorithms are highly application-specific	• Complex data acquisition and analysis for implementation • Capital intensive and low return on investment

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
8.3.2	Database monitoring index method for developing adaptive soft sensors for process control Application: process industries, others	Chemical manufacturing industry has a high degree of automation. Process variables such as temperature, flow, pressures, and tank levels are widely monitored across all plants. Soft sensors augment these data points to enable greater control and energy efficiency through neural network–based inferential estimators. These virtual data points are stored in an indexed database that is used to compared real-time process data to minimize errors and enable controls based on nonstandard process measurements.	R&D/demonstration	• Predictability accuracy for applicable process and applicable range • In situ data processing and cleaning techniques for applied processes • Complexities and operator understanding of applied techniques • Availability of appropriate data to minimize errors
8.3.3	Energy performance monitoring and real-time optimization technologies Application: alcohol, petroleum refineries, pulp and paper industry	Key performance indicators monitoring through energy information systems is enabled by advancement in industrial IoT technologies. AI has enabled many technologies deployable to specific manufacturing. Yokogawa's VisualMESA Energy Performance Real-Time Optimization tool is one such technology that can enable real-time optimization of interacting utility and process demands. VisualMESA optimizes steam production, electricity production and export, and chilled water and refrigeration demands in real time and simultaneously by recommending actionable insights for operators.	Fully commercial	• Complex data acquisition and analysis for implementation • Capital intensive
8.3.4	Advanced process control platform for methane chloride plant Application: generic, applied to methyl chloride and petrochemicals	A platform for advanced control and estimation combines multi-variable control, quality estimation, complex calculation, and user interface definition all in one application to reduce waste and energy consumption while dramatically reducing deployment time and simplifying maintenance for robust performance.	Commercial	• End user training • Capital intensive
8.3.5	Smart manufacturing platform to enable energy efficiency and waste heat reduction Application: steam methane reformers, forging, others	A smart manufacturing platform developed by the University of Texas, Austin and partners combines IT virtualization, operation, sensor data, modeling and actuation in the real world to achieve productivity and energy efficiency gains. The system optimizes plant operation for energy efficiency, waste heat, and simultaneously optimizes production. The technology is demonstrated in the steam methane reformer process.	Demonstration, R&D	• Cross-industry standards development and collaboration • Smart manufacturing platform savings determination • Market changes • End-user training

5.10 Waste Heat Management Technologies for TPI: All Industries

5.10.1 Introduction

The RD&D opportunities for waste heat management for the manufacturing sector were identified using three major sources: research carried out by the workshop team, guest speakers, and feedback from the workshop attendees. Many of the R&D programs are applicable across a broad range of industries covered by the workshop with appropriate modifications for applications to meet industry-specific requirements. Therefore, they are also discussed under subsections for each of the industries covered in the workshop, which are iron and steel, aluminum, cement, glass, food processing, pulp and paper, and hydrocarbon processing (petroleum refining and chemical) industries.

5.10.2 RD&D Needs and Opportunities

Waste heat management activities require consideration of many different subject areas and RD&D in each of these areas, such as advanced materials, fabrication manufacturing technologies, performance enhancement through basic sciences, and application technologies. Numerous R&D projects are underway in each of these and other allied technologies. The primary purpose of many projects is to reduce or recover heat in thermal processing of materials, which results in energy intensity reduction, CO_2 and GHG emission reduction, increased productivity, and production cost reduction.

Advancements in waste heat management in major industries offer many opportunities related to TPI in all industries. The advancements in certain critical areas of waste heat management technologies not only reduce energy intensity (energy use per unit of production) but also significantly reduce carbon emissions. Implementation of large-scale waste heat management in many thermal processes requires developments on many fronts that include understanding of basic principles for areas such as heat transfer, fluid mechanics, design, developments in materials and their application through innovative designs, manufacturing technologies, and application of advanced waste heat recovery methods.

Session 6 of the Thermal Process Intensification Workshop provided an opportunity to investigate many common areas of R&D, as well as industry-specific RD&D projects. The guest speakers and workshop attendees discussed current needs for the industry and many RD&D activities at national laboratories, research organizations, and industries in many parts of the world.

Major areas of R&D include the following:

1. Basic research in heat transfer, fluid flow and combustion reactions
    - Heat transfer: Enhancement of convection and radiative heat transfer, (e.g., re-radiation surfaces, geometric modification)
    - Research into fluid flow, pressure drop and particulate attachment
    - Low-temperature corrosion-resistant coatings and lamination technology
    - Advanced concepts and design of heat recovery systems
    - Achieving higher heat recovery efficiency

- Thermal storage and conversion of waste heat to other forms of energy (e.g., electricity, fuel, feedstock)
- Improved component design and performance

2. Development of advanced heat transfer equipment:
    - Heat exchangers (recuperators or regenerators) with custom heat transfer surfaces using innovative, concepts, materials, and manufacturing methods
    - Compact heat exchangers or micro-channel configuration for heat recovery from clean gases with small footprints for space-constrained retrofit applications
    - Advanced concepts for liquid-to-liquid heat exchangers for heat recovery from wastewater containing particulates and other contaminants
    - Condensing heat exchangers for gases containing high moisture levels with particulates as discharged from paper machines, food drying ovens, or other sources
    - Dry coolers for cooling liquids to reduce or eliminate water use in heat exchangers; development of innovative air to liquid heat exchangers to eliminate the need for cooling towers and cooling loops
    - Integrated heat recovery, including micro-channel heat exchangers with burners, and reactors, eliminating the need for hot air: gas piping and space for external heat recovery systems
    - Innovative regenerator designs using high–surface area and high–thermal capacity materials that are easy to clean and reduce the footprint
    - Innovative noncontact (preferably) seal system for stationary and rotary units

3. Advanced materials for clean, corrosive, and contaminated heat sources
    - Materials (e.g., metallic, ceramics) for
        - Harsh environments at high temperatures (>1,200°F) and chemical reactions
        - The cyclic nature of waste heat stream (mass flow rates, temperature, or composition)
        - Polymers or composite materials with improved thermal conductivity for low-temperature corrosive environments (e.g., combustion products of fossil fuels)
    - Heat storage system materials
        - Engineered materials with high heat capacity and density
        - High-temperature phase-change materials: metallic or nonmetallic materials (polymers)
    - Selective coatings or laminations compatible with base materials to withstand specific contaminants and combustibles in the waste gas streams
    - Catalysts for reforming fuel gases or liquid fuel vapors for use in endothermic heat recovery units

4. Particulate removal and high-temperature gas cleaning
    - Use of nonintrusive gas cleaning or particulate separation methods in all temperature ranges; advancements may include
        - Gravity settling chambers for large particles as used in drop-out boxes

            - Mechanical/inertial collectors using aerodynamic separation such as high efficiency cyclones/multi-cyclones
            - Ultrasonic techniques
            - Warm gas cleanup methods[127] used for syngas particulate removal
    - Innovative methods of avoiding or reducing particulate deposition on heat transfer surfaces, including
        - Retarding or removing deposits of organic materials (e.g., oil vapors) or inorganic materials (e.g., Boron vapors) present in glass melting furnaces, ash in coal-fired boilers, and oxides in steel or aluminum melting furnaces
    - Particulate removal methods such as gas filtering (internal or external) for high-temperature gases, including
        - Continuous (in-line), recuperative, or regenerative filtering with low pressure drop and low maintenance
        - Anti-fouling and anti-clogging capabilities with corrosion-resistant materials
    - Reactive systems (i.e., controlled combustion for organic vapors) to remove or collect organic vapors and combustible gases or vapors with controlled reaction rates and temperature increases, including developments in regenerative thermal oxidizers, catalytic oxidizers, and direct thermal oxidizers

5. Electrical power generation systems integrated with high- and medium-temperature waste heat sources
    - Innovative Rankine cycle systems (steam and other working fluids)
    - High-turndown systems for applications in which the waste heat stream heat content (Btu/hour) changes significantly (because of mass flow or temperature fluctuations)
    - Development of advanced thermoelectric materials (with figure of merit of 2 or higher) with the high-performance heat exchange surfaces, high–heat-flux interface materials, and cost-effective manufacturing techniques
    - Advancement in thermo-mechanical systems such as Sterling engine
    - Other advanced concepts
    - Innovative and efficient designs of components (e.g., compressor, expanders, heat exchangers, control)

6. Advanced supporting technologies (e.g., burners, sensors, controls, thermal system simulation communications)
    - Reliable sensors and controls for high-temperature (>400°F) applications:
        - Measurement and monitoring humidity in dryers
        - Monitoring online measurement of temperature and humidity profile within a product
        - Combustible vapor concentration profile in dryers and ovens to allow for recycling of exhaust gases and reduce the amount of makeup air
        - Reliable remote temperature sensing (e.g., surface emissivity, flue gas interference)

[127] National Energy Technology Laboratory. Developmental Syngas Cleanup Technology. Retrieved from https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/rd-syngas-cleanup.

- Systems for monitoring heat exchangers to detect performance degradation and maintenance issues
- Predictive process simulation with real-time process monitoring and online control integration
- Continuous monitoring of energy intensity (Btu or kWh/unit of production) to identify equipment performance issues

7. Application technologies (e.g., design, manufacturing, system integration, miniaturization)
   - Advanced high-temperature heat pumps, thermal compressors, heat pipes, and other thermally activated systems
   - Efficient and packaged absorption cooling systems using low- to medium-temperature heat sources (e.g., steam, water, gases)
   - Integrated heating systems using small to medium (i.e., 100 kilowatts to a few megawatts) capacity combustion (gas) turbine exhaust gases
   - Advanced concepts and systems for off-site district heating or other applications and similar low-temperature heat demand systems

These crosscutting opportunities as they apply to the industries addressed during the workshop are provided in the following sections. Each area is a potential R&D opportunity being addressed at this time or being considered as a future area of further R&D.

5.10.3 Waste Heat Management TPI Technologies

5.10.3.1 Waste Heat Management Technologies for Iron and Steel Industry

Table 39 provides a list of RD&D activities for key production steps or processes used by the integrated and/or EAF steelmaking facilities. It provides the name of the waste heat management technology, its brief description, and commercial status as we are aware of. There may be many more activities being carried out by private companies or being supported by the research sponsoring agencies, but information on them is not publicly available.

Table 39. RD&D activities for waste heat management in the iron and steel industry.

No.	Thermal Intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.4.1	BF: top pressure recovery	Recovering pressure of top gases from a BF to generate electrical power	Demonstrated and semi-commercial mostly in Japanese steel plants	• Integration in existing facilities and overall economics
1.4.2	BF: top gas enrichment	Separation of combustible gases from inert gases (nitrogen) by using an advanced membrane system	Under development	• Development required for membranes
1.4.3	Recycling of blast furnace gas and reforming treatment	Use of thermo-chemical reactions with catalyst to reform BF off-gases and recycle them as energy source	R&D	• Life of membrane
1.4.4	Heat recovery from molten slag	Heat recovery of molten slag discharged from a BF and EAF	Demonstrated at least at one plant in Japan. No activity in the United States	• Overall economics in US steel plants

No.	Thermal Intensification	Description	Commercialization status	Challenges and barriers/R&D needs
1.4.5	Heat recovery from BOF exhaust gases	Steam generation using hot gases from a BOF in a steel plant	Demonstrated in plants. No wide-scale use because of intermittent nature of hot gases and presence of combustibles	• Integration in existing facilities and overall economics
1.4.6	Dry quenching of coke	Using heat of hot coke by cooling it with recycled gases and heat recovery from these gases	Commercial: may use optimization	• Development of commercial-scale units
1.4.7	Ladle: tundish heating	Use of alternative energy (electricity) supply methods to heat metal transfer ladles and tundishes in a steel plant	Concept: further R&D, refinement, and economic analysis required	• Overall economics in US market for the installation and operation of facilities
1.4.8	Hot gas waste heat recovery	Sensible and chemical heat recovery from EAF off-gases	Partially commercialized. Need R&D and advanced concepts to overcome several hurdles	• No wide-scale use because of intermittent nature of hot gases and variations in combustible content
1.4.9	Cooling water heat recovery	Heat recovery from cooling water used for EAF walls and other areas	Need R&D and technology to address safety issues and on-site demonstration	• Few (if any) new plants being built in the United States
1.4.10	Cooling water heat recovery	Heat recovery from cooling water used in steel reheating furnaces (mostly walking beam and walking hearth furnaces)	Demonstrated outside the United States. Not used in US steel mills	• International economics dictate use of this technology
1.4.11	Replacing water-cooled rolls	Use of advanced materials and/or air-cooled rolls for thin slabs	Demonstration phase waiting for mass application	• Operating cost (natural gas vs. electricity in the United States)
1.4.12	Secondary heat recovery	Heat recovery from gases discharged from primary heat recuperative systems using low-medium temperature heat recovery systems (i.e., Rankine cycle)	Technology proven. Field application in steel plants lacking	• Need pilot unit: demonstration in steel melt shops
1.4.13	Heat recovery from hot surfaces	Use of thermoelectric generation system to use radiation heat losses from off-gas, exhaust gas ducts, surfaces	R&D	• Issues related to batch operation with wide variations in off-gas characteristics
1.4.14	Advanced sensors and controls	Development of sensors and associated systems for online analysis of hot gases containing combustibles present in contaminated environment as in EAF off-gases	Under development with field testing in limited applications	• Development and pilot testing of a system

5.10.3.2 Waste Heat Management Technologies for Aluminum Industry

The primary aluminum production includes several processes that discharge heat at relatively low (<600°F) temperatures and use steam system that is fairly efficient in heat recovery. However, the amount of heat is significant—often more than 20% of the energy use. The industry offers opportunities to recycle or recover heat that can be used within the plant. However, most processes (e.g., melting, homogenizing, heat treating) are operated in batch mode and have cycle times that vary considerably. These factors make "matching" the heat supply and demand difficult. Numerous RD&D projects have been proposed and carried out by the industry. Table 40 provides a summary of these projects as we found in the literature and during plant energy assessments.

Table 40. RD&D activities for waste heat management in the aluminum industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.4.1	Heat recovery from electrolysis cell (pot): exhaust gas and radiation from the cell walls	Recovery of sensible heat of exhaust gases (at ~220°F) to heat water or air; use of radiation heat from outer surfaces (at up to 600°F) of electrolytic cells used for aluminum reduction	No commercial application because of low temperature and presence of contaminants in the gases. No practically applicable technology for recovery of radiation heat	• No practically applicable technology for recovery of radiation heat
2.4.2	Heat recovery from heated alumina (medium temperature)	Alumina discharged at about 570°F from the kiln; heat recovered in a fluidized bed system to preheat air	No wide-scale commercial use	• Cannot be justified economically
2.4.3	Heat recovery from (sensible and chemical) anode baking (ring) furnaces	Recovery of sensible and chemical heat from the ring furnace exhaust gases	Experimental; no commercial application	• No wide-scale commercial use
2.4.4	Anode preheating or "hot" anode transfer	Transfer of hot anodes directly to the electrolytic furnace to reduce electricity consumption in reduction cell	Experimental; no commercial application	• Cannot be justified; overall economics
2.4.5	Use of organic Rankine cycle (ORC) and other electricity generation methods from clean exhaust gases	Electrical power generation from use of heat of clean exhaust gases from furnace	Commercial applications installed by Turbodyne Corporation (Italy)	• Availability of proper materials and design for practical and economically justifiable industrial application
2.4.6	Combustion air preheating using furnace flue gases: advanced recuperator/ regenerator design	Heat recovery from exhaust gases to preheat combustion air using regenerative burner system or recuperator	Commercial: current trend is to use regenerative burner systems, which offer several advantages. Commercial applications installed by Turbodyne Corporation (Italy)	• System integration issues
2.4.7	Charge (scrap and other) drying: preheating using heat exhaust gas heat	Use of furnace exhaust gases to dry, remove organic materials/clean, and preheat charge material	Commercial applications, particularly oily: paint coated scrap processing prior to melting	• Economic justification
2.4.8	Improved control of molten aluminum bath and combustion system to avoid over-firing	Use of "smart" control systems that monitors molten aluminum temperature, furnace gas temperature, and other parameters to reduce energy consumption	RD&D Not fully commercialized	• Current pricing of energy (natural gas) payback periods too long

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
2.4.9	Improved controls to allow heat cascading: use of heat from furnace exhaust other furnaces	Development of control system based on monitoring and use of key parameters (i.e., temperature, pressure, flow) to allow use of heat cascade system	Partially commercialized; need systems that monitor and control all required parameters	• Commercially available and used where economics are justified
2.4.10	Use of predictive models and AI for coil annealing furnaces	Development of heat transfer model with feedback to predict temperature profile and optimum heating/cooling time for coils during annealing	Partially commercial; need additional development and field testing	• Commercially available and used where charge material is mostly coated scrap such as used beverage cans and sidings

5.10.3.3 Waste Heat Management Technologies for Cement Industry

During the past decade, several new cement plants were built mostly in Asian countries. These new plants have included many energy-saving and heat recovery options that have been justified by relatively high energy cost and anticipated GHG emission reduction. These steps have reduced the exhaust gas temperature to as low as 400°F in some plants built in China[128]. The overall heat recovery system uses raw meal (charge material) preheating using several preheaters, heat recovery from hot clinkers, steam and electricity generation using the heat of clinker cooling air and exhaust gases, and the use of air–exhaust gases from raw meal drying or fuel (mostly coal). These techniques implemented across the board make the cement industry a leader in waste heat management. Additional opportunities relate to cleaning of gases prior to their use in boilers, lower-temperature heat recovery, and use of CO_2 from exhaust gases to reform it to usable fuel (CO and H_2 gases) while reducing CO_2 emission. Numerous R&D projects are underway; however, the exact status of their commercial application is difficult to know because of confidentiality concerns. Table 41 contains several areas of research and their status as available. Application of many waste heat recovery methods cannot be economically justified in the United States because of relatively low energy prices compared with other countries. However, concerns about decarbonization may affect decision-making for US plant operations.

Table 41. RD&D activities for waste heat management in the cement industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.4.1	Low-temperature (<300°F) exhaust gas heat recovery	Heat recovery using ORC or other systems	Partially commercialized by Turbodyne Corporation (Italy)	• Cannot be economically justified at current energy prices (fuel and electricity)
3.4.2	Use of exhaust gases for fuel (coal and biomass) drying	Use of heat of low-temperature exhaust gases to dry fuel, particularly biomass with high moisture content	Experimental; no commercial yet.	• System integration and economic justification
3.4.3	Hot gas/air cleaning: filter design and material	Use of high-temperature (>1,000°F) material filters to remove particulates from kiln exhaust gases and clinker cooling air	Experimental; pressure drop is a main concern	• Availability of proper material for the temperature level • Pressure drop across the filters

[128] International Finance Corporation: Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis, 2014.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
3.4.4	Heat (thermal radiation, convection) recovery from clinker kiln surface	Use of cooling air or thermoelectric generation devices to capture heat from the kiln surface	Air cooling partially commercialized: use of thermoelectric generation experimental but not tried on rotary kiln	• Pressure drop in exhaust gas line makes it difficult to integrate in existing plants
3.4.5	Electricity generation from (~400°F–600°F) particulate-laden gases using ORC and other systems	Use of specially designed heat recovery systems (recuperators or regenerators) of heat from particulate-laden gases from kiln preheaters	Conceptually feasible; has not been attempted in large-scale applications	• Difficult installation of the system
3.4.6	CO_2 separation, storage, conversion to CO and H_2 (reforming) concepts and system development	Use of CO_2 storage facilities and/or reforming of CO_2 to produce mixture of CO and H_2	Several concepts and laboratory-scale system proposed; no results reported; no commercial application	• Availability of systems with high efficiency
3.4.7	Optimization of preheater design and clinker cooler heat recovery	Improving management of the preheating process using simulation models to optimize preheater design through parameters such as the number of stages, cyclone and duct design, and particle distribution in the gas stream; simulation models can also be used to assess different designs for clinker cooling and how to achieve optimal waste heat recovery	Development	• Particulate removal from hot gases to obtain acceptable system performance

5.10.3.4 Waste Heat Management Technologies for Glass Industry

A large percentage of the total energy used for thermal processes used in manufacturing of glass in various forms is used in glass meting furnaces, commonly known as “melters.” The melters are fuel-fired (mostly gaseous fuel and fuel oil in some cases) and discharge exhaust gases from a furnace at temperature exceeding 2,800°F. Almost all modern plants use heat recovery systems (regenerator systems) to recover heat of exhaust gases to preheat combustion air. The exhaust gas temperature at the exit end of a regenerator varies from 1,200°F to 900°F and still contains a significant amount of heat. A modern furnace fired with oxy-fuel burners does not use a regenerator, so the exhaust gases are at temperatures higher than 2,800°F. Several heat recovery systems, including preheating of glass batch before charging, have been proposed, but only a few (<10 or so) use such a system. Heat recovery from the regenerator exit gases is rarely used. In a few cases, the heat has been used to produce electricity by use of organic Rankine cycle or Kalina cycle system. The industry can benefit from the development of advanced materials for the regenerator, and improved design to avoid performance degradation during a typical “campaign,” which lasts several years. Table 42 provides the R&D requirements for the glass industry as discussed in the workshop session.

Table 42. RD&D activities for waste heat management in the glass industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.4.1	Use of advanced technology, materials, and design of the regenerators	Use of advanced materials that can reduce size and life of the regenerators with improved heat storage and better uniformity of combustion air for burners during a cycle	Incremental improvement; no breakthrough in commercial applications	• Lack of alternative concept
4.4.2	Secondary heat recovery from regenerator exhaust gases	Use of organic Rankine cycle, Kalina cycle, or other systems to recover heat from exhaust gases leaving the regenerator	A few systems installed in furnaces in Europe; none known in the United States; long-term performance data unavailable	• Availability of alternative materials/system that can withstand the operating conditions and provide better performance • Long-term performance data unavailable
4.4.3	Hot gas cleaning: filter design and materials	Use of organic Rankine cycle, Kalina cycle, or other systems to recover heat from exhaust gases leaving the regenerator	Ongoing R&D work at some R&D organizations; details unknown	• System cost: economic justification
4.4.4	Batch drying and preheating with sensors and controls for bulk temperature and humidity	Use of furnace exhaust gases, particularly in the oxy-fuel–fired furnaces, to dry and preheat batch material without over drying of material	A few commercial applications, including in the United States and Europe; information not available for other parts of the world	• Long-term performance data unavailable
4.4.5	Heat recovery from furnace exhaust gases using oxy-fuel burners	Attempts to preheat oxygen used for burners using heat of exhaust gases Use of exhaust gases to dry and preheat batch	Use of oxygen preheat systems at laboratory and pilot scale but no known commercial installation	• Availability of proper materials and filter concepts
4.4.6	Electric melter design for large–production rate furnaces: container and flat glass sectors	Use of electrical heating system for large furnaces is very limited; need to overcome issues with location of electrodes and overall cost of infrastructure and design	No known commercial installation	• System integration in existing plants • Need to overcome issues with location of electrodes and overall cost of infrastructure and design
4.4.7	Recovery of furnace and regenerator wall surface heat loss using devices such as thermoelectric generators	Installation of noncontact heat recovery system such as recovery of thermal radiation from relatively hot (>400°F) outside wall surface temperature Use of thermoelectric generation systems	No commercial installation for glass melters	• Not many new plants being built with fuel-fired systems
4.4.8	Heat cascading: use of recovered furnace exhaust gas heat for lower-temperature processes (i.e., annealing furnaces)	Use of hot air (from air heaters using exhaust gas heat) or direct injection of hot (cleaned) gases in annealing furnaces, which require a relatively small amount of heat	No commercial application	• Materials availability for high-temperature materials

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
4.4.9	Thermal oxidizer design and heat recovery within the plant for the fiberglass sector	Use of recovered heat (from thermal oxidizer exhaust gases) to meet facility heating and cooling requirements using thermal absorption systems	No commercial application	• Challenges of handling hot and particulate-laden gases
4.4.10	Use of predictive models and AI for glass melting furnaces	Use of simulation software that simulates glass melter performance and predicts several parameters (e.g., temperature uniformity, regenerator cycle time)	Work in progress at some of national laboratories and private companies	• Design, construction, and energy distribution challenges for large furnaces
4.4.11	Raining bed batch and cullet preheater	The raining bed batch and cullet preheater technology use a heat exchanger to re-capture heat energy from hot combustion gases. The batch and cullet fall through the heat exchanger and come in direct contact with the rising flue gases resulting in preheating of the batch.	Development	• Availability of high-efficiency energy recovery thermoelectric generation system
4.4.12	Oscillating combustion	Refers to forcing oscillations in the fuel flow rate to a furnace, creating successive fuel-rich and fuel-lean areas in the furnace. Fuel-rich areas increase the heat applied to the batch materials, whereas fuel-lean areas reduce the production of NO_x and undesirable by-products of the reaction by operating closer to the ideal stoichiometric ratio. Overall, oscillating combustion can reduce the peak temperature of the furnace, thus saving energy.	Pilot	• System integration and control of downstream furnace operations

5.10.3.5 Waste Heat Management Technologies for Pulp and Paper Industry

Waste heat discharge from the pulp and paper industry is in the form of solid waste produced from splitting and crushing wood, black and white liquor produced during pulp making process, hot air with moisture and solid particulate content from pulp and paper drying processes, and commonly recognized gases, vented steam, condensate, and other materials from steam generation plants, which are an integral part of a paper mill. The range of temperatures for these discharges is approximately 140°F to 400°F. The most common opportunities and equipment used for waste heat management are given in Table 43.

Table 43. RD&D activities for waste heat management in the pulp and paper industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.4.1	Development of heat recovery from low-temperature (<140°F) heat sources such as exhaust gases with water vapor and other contaminants: small amount of fiber and particulates	Use of improved heat exchanger designs with heat transfer enhancement to heat air or use of condensing heat exchanger or direct contact condensing heat exchanger to heat water	Systems for clean gases are commercialized	Presence of fibers and other contaminants that prevent use of membrane-based systems Need to develop and test heat exchangers for gases containing particles and fibers
5.4.2	A system for dehumidifying medium-temperature (≥250°F) air containing fibers or particulates	Development of self-cleaning selective membrane or other system to separate gases from water vapor and use of latent heat of condensation	Units for clean gases commercialized for boiler flue gases; need to develop similar system for system that integrates membrane cleaning system	Conventional heat exchanger too large and economically unjustifiable
5.4.3	Development of heat recovery from clean low-temperature (<140°F) exhaust gases and liquids	Use of direct contact water heater or efficient regenerative (aluminum heat wheel) systems	Both commercially available; lack of use of recovered heat within the plant	Development of similar system to meet requirement in pulp and paper industry: a system that integrates membrane with cleaning system
5.4.4	Development of drying system using waste heat from exhaust gases	Use of hot exhaust gases or exhaust air to dry solids such as logs, wood chips, and pulp	Commercially possible and used where the higher-temperature (~>300°F) gases are available in proximity of the materials to be dried; transport of gases a major issue	Barriers: cost of the system and lack of use of recovered low grade heat source
5.4.5	Decentralizing steam systems where possible when external (purchased) fuel is used for steam generation	Use of modular water heater to replace steam used for water/air heating or use of small steam generating units using fuel or electricity to avoid steam supply infrastructure and associated energy losses	Equipment available; no in-plant commercial use because of existing infrastructure	System integration and related technical issues in existing and even new plants
5.4.6	Black liquor gasification: bio treatment	Bio treatment methods for gasification of black liquor to replace liquid injection in boilers	Experimental; no known commercial or pilot demonstration	Transport of large volume of gases could be a hurdle
5.4.7	Gas-fired paper dryer to replace steam-heated systems	Heating of paper dryer cylinders by alternative heating system and energy source (i.e., natural gas); examples include use of combustion products (jet impingement) or gas/electric IR, induction	Pilot scale and commercial demonstration of some versions of such a system	Replacement of existing infrastructure with centralized steam supply
5.4.8	Use of alternative boiler design for waste heat boilers	Use of dual-pressure boiler design to increase heat transfer, overall heat recovery, and boiler efficiency	Commercially available for use where economically justified	Affects electrical power generation with existing CHP system

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
5.4.9	Steam cycle washer using multiport dryer technology	Use of steam cycle wash to treat unbleached pulp using multiport dryer	Pilot studies: partial commercial application	Technology not developed for use in plants
5.4.10	High-temperature heat pumps for heat recovery	Use of electric heat pumps to elevate gas temperature by 50°F or higher in paper dryers	Commercially available; higher temperatures up to 350°F under development in Europe	No major issues other than replacement of existing systems and associated cost
5.4.11	Use of solid waste material as boiler fuel	Drying and gasification of solid waste (e.g., wood bark, chips, plant waste) for use in boilers or other heating systems	Commercialized practice where coal or other solid fuel is used. Logistics of collecting, sizing, drying, and so on are a major hurdle	Economic justification for replacement of existing units

5.10.3.6 Waste Heat Management Technologies for Food Processing Industry

The food processing industry uses thermal processes to heat many products in a variety of heating equipment pieces that operate from approximately 200°F to 600°F. The processes include frying, drying, and boiling. Many of these processes use steam as a heating medium, and steam generation is a major energy-consuming step in large food processing plants. Waste heat is generated in the form of hot air with moisture or other liquid vapor content, flue products from heating equipment including boilers, hot water including steam condensate, vented steam, heated products that are discharged at the process temperature, and more. Heat recovery from steam and condensate are well established and used in many steam plants, but heat recovery systems from other discharges are still lacking because of relatively low temperature (often lower than 400°F) and unacceptable economics (long payback periods) for the heat recovery projects. These unattractive economic conditions associated with recovering heat from low-temperature sources have resulted in very slow progress in RD&D for innovative concepts and design. Some of the current and future RD&D activities for development of heat recovery systems are listed in Table 44. Some of these are based on energy assessment carried out at several food processing plants under DOE and other state energy conservation offices.

Table 44. RD&D activities for waste heat management in the food processing industry.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.4.1	Heat recovery from low-temperature (<200°F) moisture-laden flue gases from ovens, fryers, and boilers	A system such as a condensing heat exchanger with coatings and heat transfer enhancement to allow recovery of latent heat of moisture in exhaust gases	Systems for boilers commercialized; no known equipment developed for indirect heat exchanger for oven/dryer flue gases	Presence of fibers and other contaminants that prevent use of membrane-based systems
6.4.2	Low-temperature heat storage using exhaust gases for air/water heating	Development and application of high–heat capacity or phase-change heat storage materials for application in low-temperature (<300°F) environments	Materials available; system design and application lacking	Conventional heat exchanger too large and economically unjustifiable

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
6.4.3	Air-water vapor separation from dryer exhaust gases	Use of selective membranes to condense water vapor and separate them from air or combustion products, thus allowing recovery of latent heat of water vapor	Development work completed and field demonstration at a few plants; installations mostly for boiler flue gases	Lack of availability of appropriate high–heat capacity and/or phase-change material to keep the size and cost justifiable
6.4.4	Modular heating systems to replace steam supply from centralized boilers	Use of modular water heaters to replace steam used for water/air heating or use of small steam generating units using fuel or electricity to avoid steam supply infrastructure and associated energy losses	No commercial demonstration	Presence of fibers and other contaminants that prevent use of membrane-based systems
6.4.5	Use of organic waste material (solid or gasified) as boiler fuel	Use of dried biomass produced as waste material in food processing plants as fuel	No commercial application in the United States; a few existing in Asian countries, particularly for coal-fired boilers	Conventional heat exchanger too large and economically unjustifiable
6.4.6	Use of multiple effect evaporators with thermal vapor compression where applicable	Use of multiple-effect evaporators with recompression and use of low-pressure steam using high-pressure steam to reduce steam use resulting in energy savings	Several commercial applications in food and other related (e.g., pulp and paper, chemical) industries	Replacement of existing infrastructure with centralized steam supply
6.4.7	Development and use of high-temperature heat pumps	Use of high-temperature (~300°F) heat pumps to elevate temperature of lower temperature water/gas stream Development of innovative fluids for absorption cycle	Systems used for up to 200°F; higher-temperature systems under development	Affects electrical power generation with existing CHP systems
6.4.8	Use of electro-technologies to replace fuel or steam heating	Use of MW, RF, ultrasonic, and others for drying and other heating processes For higher temperature, use of induction with susceptors if needed	Commercialized for selected processes; Issues related to economics, regulatory approvals, product quality and so on can be deterrents in wide-scale use	Integration with existing facilities
6.4.9	Advanced sensors for process/ product quality monitoring and control	Remote temperature sensors for measurement of temperature and moisture profile in bulk or individual product for quality control and optimization	Under development but not widely used in commercial applications	Relatively low cost for "clean" energy

5.10.3.7 Waste Heat Management Technologies for Hydrocarbon Processing Industries (Chemical and Petroleum Refining)

The hydrocarbon processing industry includes two high-energy user industries: petroleum refining and chemical industries. Both industries process basic hydrocarbons such as crude oil and natural gas, as well as semi-finished products from the basic raw materials. Thermal processing of these materials includes a variety of thermal processing techniques that are carried out at temperatures ranging from 400°F to 1,600°F. Most of these processes use conventional heating (by flame radiation and convection) or heating in the presence of reaction enhancement by catalysts and other means. The thermal processing equipment discharge waste heat in the form of combustion products at relatively moderate temperature (400°F to 1000°F) containing sensible heat. However, a few processes release gases with the presence of combustible gases, and they are used as fuel within the plant or flared. Both industrial sectors produce and consume a large amount of steam, which is used as feedstock in processes such as reformers and as source of heat. The steam system generates a large amount of waste heat in the form of boiler flue gases, steam vents, condensate, and so on. Waste heat management from steam system is not addressed in this section since most of the waste heat management methods for steam systems are well known and established.

Table 45 provides known RD&D activities in waste heat management for the hydrocarbon processing industries. These activities were collected from the available literature, feedback from the workshop attendees, and other sources (mostly the industry experts).

Table 45. RD&D activities for waste heat management in hydrocarbon processing (petroleum refining and chemical) industries.

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.4.1	Heat recovery from low-temperature (<400°F) flue products from refinery fuel-fired heaters and boilers	Use of high-efficiency heat exchangers, including condensing heat exchangers, with coatings to avoid corrosion	Limited commercial application	Further development needed to solve corrosion issues
7.4.2	Treatment of high-temperature still gases containing corrosive components (e.g., hydrochloric acid) prior to their use	Use of membrane or other separation process to remove of sulfur- and chlorine-based components	No activity	Very limited use for low-temperature heat
7.4.3	Development of micro-channel heat exchangers for gases with minor presence of solids or other materials	Nano-porous membrane heat exchangers for low grade waste heat recovery that helps separate moisture from flue gases	R&D activities by national laboratories (e.g., ORNL) and private companies; no commercial unit in operation	Availability of materials that offer long life and do not require frequent maintenance or replacement Use of advanced manufacturing technologies such as additive manufacturing to fabricate special geometries at reasonable costs
7.4.4	Use of combustion turbine exhaust gas as vitiated preheated air in heaters and boilers	Use low–oxygen content (~16%) high-temperature (~900°F) gases from combustion turbine exhaust as an oxidant for combustion to replace fuel-fired burners	A few units operating in refineries for fired heater application; requires additional analysis and application engineering	No pilot demonstration

No.	Thermal intensification	Description	Commercialization status	Challenges and barriers/R&D needs
7.4.5	Economically justifiable energy recovery from flared gases	Use of TES or other heat recovery method to recover heat from intermittently operating flare system	Research	Concern for plugging of heat exchanger passages Overall economics not favorable because of low energy prices in the United States
7.4.6	Heat exchangers for latent heat recovery from moisture-laden gases	A system such as a condensing heat exchanger with coatings and heat transfer enhancement to allow recovery of latent heat of moisture in exhaust gases	Systems for boilers commercialized; no known equipment developed for indirect heat exchanger for oven/dryer flue gases	System integration within an existing plant
7.4.7	Heat recovery from exothermic processes to produce high-pressure steam or other uses	Redesign of thermal systems to recover all or part of the heat from hot gases or liquid to produce steam or other uses; examples include several processes in the chemical industry (and in refinery operations) such as hydrogen production, sulfuric, and other acid productions	Partially commercial; economics and modification of existing process equipment are main deterrents	Very few new refineries built in the United States Economics and modification of existing process equipment are main deterrents
7.4.8	Alternative to cooling towers to reduce water usage and other utilities	Use of air-cooled units to replace entire or part of water-based cooling towers	Commercially available for small units; development of optimum system is required	Development of optimum system is required
7.4.9	Use of advanced catalyst for chemical processes in the chemical industry and petroleum refineries	Development of novel catalyst materials, coating technologies, and testing to reduce process temperature and exhaust gas temperature	Several projects are underway at national laboratories and other research organizations in collaboration with the industry	Needs further RD&D

6 Vision of the Future

A vision for a highly efficient and low-carbon manufacturing future via TPI can be examined in terms of near-, mid-, and long-term opportunities.

The **near-term vision** for TPI is to reduce energy use and carbon emissions by supporting the adoption of technologies that are commercially available or close to commercialization. Many low- and no-carbon thermal processing technologies are available under each of the four pillars discussed during the DOE workshop; these technologies can replace existing practices or be integrated within the plant infrastructure with relatively low effort and cost. These projects reduce energy losses and intensify existing processes via redesign of equipment, use of waste heat recovery technologies, adoption of innovative smart and IoT strategies, and upgrading or replacement of traditional thermal systems. During the past few decades, DOE and other organizations have conducted significant research to develop and demonstrate energy-efficient process heating technologies that are now commercially available or close to commercialization. These technologies can be integrated in existing plants as a near-term measure to decarbonize process heating systems.

To support this near-term vision, workshop participants noted that DOE could play an important role in commercialization, deployment, and adoption of these economically viable technologies by raising awareness, conducting technology field validations, and funding demonstration projects. Development of cost modeling tools to compare technologies for effective decision-making, incentivizing the use of state-of-the-art technologies via rebates, adding costs to carbon emissions, and setting up financing programs were also identified as appropriate pathways toward facilitating the rapid adoption of commercially available TPI technologies. Furthermore, workshop participants identified education and workforce development activities as vital strategies for the adoption of commercially available energy- and carbon-efficient TPI technologies.

The workshop participants also participated in developing DOE's **mid-term vision**. This vision includes strategies such as replacement of existing fuel-fired systems with scaled up technologies that use alternative fuel/energy sources (e.g., electricity, hydrogen). Broader application of these technologies will require changes to existing infrastructure within and outside the manufacturing facilities. For example, a transition to a modern cleaner electric grid and access to reliable renewable fuels (e.g., biogas, hydrogen) are vital for the adoption of these alternative energy source process heating technologies (TPI pillar 2). Workshop participants identified that although the technologies exist to achieve electrification of many industrial applications, a national effort is required to build and implement supporting infrastructure at a larger scale. Building a clean electric grid infrastructure is expected to be a top priority for DOE, given the nation's goal to reach 100% carbon pollution–free electricity by 2035.[129] In addition, some alternative technologies also require improvements to material handling systems, effective coupling between charge material and energy sources, innovation in materials used, smart controls, high-performance modeling, life-cycle impacts analysis, and so on to improve energy performance and reduce GHG emissions. Many of these factors relate to market demand, engineering, and economics (capital and operating costs) and may need low-level efforts in basic research.

The **long-term vision** for TPI is to increase process efficiency and achieve deep decarbonization via the development of completely new low- and no-carbon transformative technologies. Research efforts are underway to develop new and innovative processing equipment, use alternative raw materials that reduce

[129] The White House. 2021. "FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." April 22, 2021. Retrieved from https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

energy use or eliminate thermal processing, and use alternative replacement products. The complexity of thermal processes and nuances within each industry pose a difficult but surmountable challenge to these new innovations. Past examples have shown that these barriers can be overcome with sufficient research and breakthroughs in technology. The rapid adoption of the scrap-based EAF method for steelmaking and the evolution of electric vehicles over the past decade are prime examples that show that the rapid adoption of clean technology is possible with breakthrough innovations, economic advantages, and valuable incentive structures. For cases in which the adoption of low-carbon technologies seems unviable, CCUS technologies represent another possible approach to substantially reduce CO_2 emissions.

To support this long-term vision, workshop participants identified the need for industry-level scale-up along with basic research of new thermal processing technologies. These efforts will improve the mass market adoption rate of these TPI technologies. This step is critical because commercialization is a key concern for many promising new technologies, and laboratory-scale testing alone cannot bridge the gap between proof of concept and deployment. Workshop participants suggested that coordinated public-private partnerships at a national level to pilot new technologies in real-world environments are vital to achieve widespread adoption efforts.

Highly efficient thermal processes with minimal energy and carbon intensities will provide US manufacturing with global leadership and recognition. These technologies and associated manufactured products are set to be the norm for the global industries in the future. Adopting these technologies early will help the US manufacturing sector accrue the most benefit from the transition. US technology companies will also have a great opportunity to create a global market for their energy-efficient and low-carbon technologies. The transition may also create new value streams which would provide additional opportunities for economic growth. As industrial sectors find new ways to integrate across solutions and lower economic costs, businesses will rapidly develop minimal–energy use and low-carbon products, thus providing multiple benefits and improving competitiveness to shape future industries.

7 Additional References and Resources for Further Information

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Other Resources

Category	Resource	Links
Tools	Process Heating Assessment and Survey Tool	https://www.energy.gov/eere/amo/articles/process-heating-assessment-and-survey-tool
	Process Heating Assessment and Survey Tool (Excel Version)	https://www.energy.gov/eere/amo/downloads/process-heating-assessment-and-survey-tool-excel-version-phastex-v101
	MEASUR	https://www.energy.gov/eere/amo/measur
Guidance documents	Improving Process Heating System Performance: A Sourcebook for Industry, Third edition	https://www.energy.gov/sites/prod/files/2016/04/f30/Improving%20Process%20Heating%20System%20Performance%20A%20Sourcebook%20for%20Industry%20Third%20Edition_0.pdf
	Process Heating Tip Sheets	https://www.energy.gov/eere/amo/process-heating-systems
	Process Heating Technology Assessment, Quadrennial Technology Review 2015	https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf
Assessments and trainings	Process Heating Training	https://www.energy.gov/eere/amo/process-heating-systems
	DOE Better Plants In-Plant Trainings	https://betterbuildingssolutioncenter.energy.gov/better-plants/activity/plant-trainings
	DOE Energy Treasure Hunt Exchange Toolkit	https://betterbuildingssolutioncenter.energy.gov/energy-treasure-hunt-exchange-toolkit

Appendix A. Workshop Session Summary

The Thermal Process Intensification Workshop was held over seven sessions, a plenary session and six brainstorming breakout sessions. The appendix provides a summary of the content discussed during each workshop session.

Plenary Session

The plenary session, held on November 5, 2020, provided the participants with an overview of the workshop and its goals. The 3-hour session was attended by more than 120 participants from various research organizations, federal and state agencies, original equipment manufacturers (OEMs), and manufacturing companies in the sector.

The presentations provided by the workshop team and guest speakers helped brief participants on DOE's vision for TPI and ongoing research activities in the area. The agenda for the meeting and an overview of the presentations are provided in Table A1.

Table A1. Plenary Session – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Opening remarks, workshop objectives, and overview of DOE's AMO (30 min) -Joe Cresko (DOE) and Valri Lightner (Deputy Director, AMO)	Valri Lightner and Joe Cresko welcomed the participants to the workshop and laid out the objectives and expected outcomes for the event. The presentation provided an overview of DOE AMO's goals and how TPI fits into its future vision. The need for TPI was expounded, and related initiatives set up by DOE were introduced, along with examples of ongoing research.
Thermal Process Intensification Workshop overview and objectives (60 min) -Joe Cresko (DOE) and Arvind Thekdi (E3M Inc.)	The presentation explored the opportunity for TPI in manufacturing, drawing estimates from the bandwidth studies published by DOE. The impact of TPI on the carbon emissions and material circularity were discussed with prime participants on its importance. An overview of the workshop structure and schedule was provided, and the four technology TPI pillars were explained in detail with relevant examples.
Transforming the process industries through modular chemical process intensification (45 min) -Paul Yelvington (CTO, RAPID Manufacturing Institute)	The presentation provided an overview of the work being done at Rapid Advancement in Process Intensification Deployment (RAPID) Institute, one of the manufacturing institutes setups by DOE. Research projects funded by RAPID to address the barriers to wider adoption of modular chemical process intensification were discussed. These research projects spanned various industries, including oil and gas, pulp and paper, and chemical manufacturers, and aimed at developing breakthrough technologies to boost energy productivity and energy efficiency.
Q&A and panel discussion (35 min) -All participants and speakers	Participants shared their feedback on the workshop structure, and the speakers addressed questions solicited from the participants. The session ended with a briefing of the brainstorming sessions that followed the plenary session.

Brainstorming Session 1: High-Temperature Metals

The first session, held on November 9, 2020, examined TPI technologies for the high-temperature metals industry. The 2-hour session was attended by more than 90 participants from various research organizations, federal and state agencies, OEMs, and manufacturing companies in the metals industry.

Technologies related to the first two TPI pillars—low–thermal budget transformative technologies (TPI pillar 1) and alternative thermal processing (TPI pillar 2)—were discussed during the session. The presentations delivered by the workshop team members and guest speakers helped orient the participants to the workshop goals and prepare them for the brainstorming discussions that followed. The agenda for session 1 and an overview of the presentations is provided in Table A2.

Table A2. Brainstorming Session 1 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Part 1: Virtual workshop to collect feedback on low–thermal budget transformative and alternative thermal processing technologies: iron and steel sector (30 min) Session moderator: Sachin Nimbalkar (ORNL)	Moderator discussed the goals of session 1, such as identifying R&D opportunities to significantly improve current thermal processing technologies used in the high-temperature metals industry. Moderator also provided an overview on the process heating energy use in the iron and steel sector and described the opportunities for significant improvement with low–thermal budget transformative (TPI pillar 1) and alternative thermal processing (TPI pillar 2) technologies. The technologies identified under each TPI pillar based on the literature review were presented, along with some detailed discussion on specific examples, such as producing iron by electrolysis and electricity based annealing processes (e.g., flash bainite). These examples set the stage for participants to contribute their ideas and provide additional insights on technologies for TPI.
Development of high energy density thermomagnetic processing technology for intensification of industrial heat-treatment and increased material performance (15 min) Guest speaker: Michael Kesler (ORNL)	The guest speaker provided an overview on processing materials under magnetic fields to improve structure and mechanical properties in metals and alloys. Magnetic fields can alter phase stability, modify diffusion characteristics, and alter material flow substantially. In castings, magnetic fields can be used during melting of the alloy, during solidification, or during post-processing operations such as heat treatment to achieve structural changes. Thermomagnetic processing of metals and alloys improves mechanical properties and reduces required heat treatment times.
Part 2: Virtual workshop to collect feedback on low–thermal budget transformative and alternative thermal processing technologies: aluminum sector (20 min) Session moderator: Sachin Nimbalkar (ORNL)	Moderator provided an overview on the process heating energy use in the alumina and aluminum sector and described the opportunities for significant improvement with low–thermal budget transformative and alternative thermal processing technologies. The technologies identified under each TPI pillar based on the literature review were presented, along with some detailed discussion on specific examples, such as inert anode smelting and rapid IR heating for aluminum hot forging. These examples set the stage for participants to contribute their ideas and provide additional insights on technologies for TPI.
Brainstorming exercise in MeetingSphere: iron and steel and aluminum industries (40 min) -All participants	The presentations delivered during the first half of the session helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A3.

Table A3 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A3. Brainstorming Session 1 – List of TPI technologies.

Low–thermal budget transformative technologies	Alternative thermal processing
Iron and steel industry	
• Hydrogen-based DRI • Electrolysis-based steel production (low-temperature electrowinning) • Novel flash ironmaking process • Thin strip casting with in-line heat treating to eliminate hot mill, reheating, and annealing furnace • Replacing ladle metallurgy furnace with a continuous series of vessels • Using cold tundish or heating inductively and not by combustion • Next-generation system for scale-free steel reheating • Thermomagnetic processing	• DRI and increased use of EAFs • Electric annealing (e.g., flash bainite) • Hydrogen-based DRI and EAFs • Fuel switching to lower-carbon fuels (e.g., H_2) in traditional processes • Solar thermal systems • Molten oxide electrolysis • Induction-based heat treating (e.g., reheating)
Alumina and aluminum industry	
• Inert anode smelting • Vertical flotation melter • Ultrahigh-efficiency aluminum production cell • Multi-chamber remelting furnace • Wettable ceramic-based drained cathode technology • Carbothermic process by reacting alumina at high temperatures • Lower electrolysis temperature • Tilting rotary furnace • Thermomagnetic processing	• Inductive/immersion heater • Plasma heating/MWs • Solid phase processing • Electric furnaces • High-capacity induction melting in secondary aluminum production • Solar thermal systems

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative TPI technologies for improved efficiency. A dynamic conversation followed in which various crosscutting and sector/system specific barriers were identified. The brainstorming discussions explored various topics, including the use of electric ladle preheaters that offer flameless heating, under-use of efficient coreless induction and channel induction melting furnaces, and integration of TES.

Challenges associated with return on investment when competing with installed equipment and established processes were also discussed, as well as the need to align various risk factors associated with uncertainties in demand, environmental requirements, offshore competition, cost of energy based on locale, tax consequences, and financing to implement a new technology.

The key takeaways from these discussions, informed by follow-up research done by the workshop team in correspondence with individual participants, are summarized in Sections 5.1 and 5.2.

Brainstorming Session 2: High-Temperature Nonmetallic Minerals

The second session, held on November 12, 2020, examined technologies for high-temperature nonmetallic minerals with a focus on the cement and glass sectors. The 2-hour session was attended by more than 50 participants from various research organizations, federal and state agencies, nongovernmental organizations, and manufacturing companies in the sector.

Technologies related to the first two TPI pillars—low–thermal budget transformative technologies (TPI pillar 1) and alternative thermal processing (TPI pillar 2)—were discussed during the session. The presentations provided by the workshop team and guest speakers helped orient the participants to the workshop goals and invigorate them for the brainstorming discussions that followed. The agenda for the meeting and an overview of the presentations are provided in Table A4.

Table A4. Brainstorming Session 2 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Introduction to Session 2 (10 min) By: Ali Hasanbeigi (Global Efficiency Intelligence)	The goals of the workshop, definition of TPI, profile of heat demand in industry and thermal processing energy use by industry subsectors in the United States, and profile of energy use and emissions in the nonmetallic sector in the United States were presented.
Guest-speaker 1: Decarbonizing concrete technology pathways for the US cement and concrete cycle (15 min) By: Eric Masanet (University of California, Santa Barbara)	The first guest speaker presented a recent study his team conducted to develop a deep decarbonization pathway for the United States cement and concrete industry. In this study, they assessed the combined effect of all available low-carbon levers using an integrated modeling framework capable of analyzing the underlying technology characteristics of each lever and the nexus between materials flows, energy use, CO_2 emissions, and CO_2 uptake across the entire cement and concrete cycle in the United States.
Part 1: Virtual workshop on low–thermal budget transformative and alternative thermal processing technologies: cement industry (20 min) By: Ali Hasanbeigi (Global Efficiency Intelligence)	This presentation provided an overview of the energy used by thermal processes in the cement industry and described the opportunity for significant improvement with low–thermal budget transformative (TPI pillar 1) and alternative thermal processing (TPI pillar 2) technologies. The technologies identified under each TPI pillar by the workshop team from literature review were presented and a few examples were explored in detail for each TPI pillar. For TPI pillar 1, a fluidized bed kiln was presented. For TPI pillar 2, electrification of a pre-calciner was presented. These examples set the stage for participants to contribute their ideas and insights on technologies for TPI.
Guest-speaker 2: Potential for oxy-combustion in the US cement industry (15 min) By: John Kline (Kline Consulting)	The second guest speaker presented how energy is used in the cement production process and the source locations of GHG emissions. Then, the speaker proposed several approaches to use oxy-combustion in the US cement industry: kiln oxy-combustion, oxy-calcination, and total oxy-combustion. The speaker presented the pros and cons of each option.
Part 2: Virtual workshop on low–thermal budget transformative and alternative thermal processing technologies: glass industry (20 min) By: Ali Hasanbeigi (Global Efficiency Intelligence)	This presentation provided an overview of the energy used by thermal processes in the glass industry and described the opportunity for significant improvement with low–thermal budget transformative (TPI pillar 1) and alternative thermal processing (TPI pillar 2) technologies. The technologies identified under each TPI pillar by the workshop team from literature review were presented and a few examples were explored in detail for each TPI pillar. For TPI pillar 1, a plasma melter was presented. For TPI pillar 2, electrification of glass-making processes was presented.
Brainstorming exercise in MeetingSphere: cement and glass industries (35 min) -All participants/moderated by Ali Hasanbeigi (Global Efficiency Intelligence)	The presentations delivered during the first half of the session helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and the research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A5.

Table A5 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A5. Brainstorming Session 2 – List of TPI technologies.

Low–thermal budget transformative technologies	Alternative thermal processing
Cement industry	
• Fluidized bed kiln • Oxy-combustion technology • Electrolysis of limestone	• Indirect calcination • Electrification of kiln • Electrification of precalciner • Concentrated solar power technology for cement production • Use of hydrogen in the fuel mix • Alternative raw materials that reduce heat demand in a cement plant
Glass industry	
• Plasma melter • Segmented melters • FLOX flameless burners	• Electric melting/electric furnace • Fuel switching: hydrogen • MW melting • RF laminating in autoclaves • Submerged combustion melting

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative TPI technologies for improved efficiency. A dynamic conversation followed in which various crosscutting and sector/system-specific barriers were identified. Issues related to waste material as alternative fuel, alternative cement binding materials, taking advantage of industrial symbiosis, commercialization challenges of new technologies and products, process-related emissions, and the use of MW in cement industry along with other technical issues were discussed. The key takeaways from these discussions, informed by follow-up research done by the workshop team in correspondence with individual participants, are summarized in Sections 5.3 and 5.4.

Brainstorming Session 3: Low- and Medium-Temperature Processing

The third session, held on November 16, 2020, examined technologies for low- and medium-temperature processing with a focus on the food and beverage sector and pulp and paper sectors. The 2-h session was attended by more than 90 participants from various research organizations, federal and state agencies, OEMs, and manufacturing companies in the sector.

Technologies related to the first two TPI pillars—low–thermal budget transformative technologies (TPI pillar 1) and alternative thermal processing (TPI pillar 2)—were discussed during the session. The presentations provided by the workshop team and guest speakers helped orient the participants to the workshop goals and invigorate them for the brainstorming discussions that followed. The agenda for the meeting and an overview of the presentations are provided in Table A6.

Table A6. Brainstorming Session 3 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Part 1: Overview of sector and TPI technologies: food and beverage (20 min) -Kiran Thirumaran (ORNL) and Colin McMillan (NREL)	The presentation provided an overview of the energy used by thermal processes in the food and beverage sector and described the opportunity for significant improvement with low–thermal budget transformative (TPI pillar 1) and alternative thermal processing (TPI pillar 2) technologies. The technologies identified under each TPI pillar by the workshop team from literature review were presented, and a few examples were explored in detail for each TPI pillar. DOE-funded “no-heat spray dryer” technology being piloted to dry-spray flavor

Topics	Presentation summary
	extracts was discussed, and its potential application in other drying applications (e.g., milk powder) was explored. Similarly, for TPI pillar 2, the potential integration of concentrated solar power into various applications within the sector was discussed. These examples set the stage for participants to contribute their ideas and provide additional insights on technologies for TPI.
Value, challenges, and role of RD&D in adopting TPI technologies for food processing (15 min) -Neal Elliott (American Council for an Energy Efficient Economy)	The presentation explored the value, challenges, and role of research in the food and beverage sectors with multiple technological examples. The presentation encouraged participants to rethink research opportunities in the sector—not to solve just technological barriers but also regulatory hurdles via rigorous testing and data collection to validate quality and safety parameters with empirical evidence.
Part 2: Overview of sector and TPI technologies: pulp and paper (20 min) -Kiran Thirumaran (ORNL) and Ali Hasanbeigi (Global Efficiency Intel).	This presentation, like Part 1, provided details related to the opportunity for TPI in the pulp and paper industry. The different technologies for TPI identified by the workshop team were presented, and a few examples were explored in depth. Paper drying, which has the most significant R&D opportunity according to DOE's bandwidth studies, was examined in more detail, along with membrane technologies, which have crosscutting applications in pulp making (liquor concentration) and in the food sector (concentration and evaporation applications).
Brainstorming exercise in MeetingSphere: pulp and paper and food and beverage industries (40 min) -All participants	The presentations delivered during the first half of the session helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and the research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A7.

Table A7 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A7. Brainstorming Session 3 – List of TPI technologies.

Low–thermal budget transformative technologies	Alternative thermal processing
Food and beverage industry	
• Supercritical fluid processing - Fruits and vegetables drying • No heat spray drying technology - Milk powder, essence extraction • Membrane technologies - Corn milling (replace steep evaporators) - Milk concentrations • Biological processing - Enzymes to reduce steep time • UV processing: pasteurization (dairy) • Electron beam processing - Pasteurizing/sterilization • High-pressure processing - Pasteurization (dairy and meat) • Ultrasound processing • Pulsed electric field processing - Pasteurization (dairy)	• RF and hybrid RF applications - Cooking, drying, thawing, baking • Ohmic heating - Blanching, cooking, thawing, fermentation • IR processing/IR hybrid processing - Drying of fruits, vegetables, grains • MW and hybrid MW applications - Drying/dehydration, microbial reduction, thawing • Solar thermal systems - Drying, roasting, boiler preheating - Steam generation • Electric boilers (steam generation) • Bio-waste for direct-fired/CHP applications • Electric heat pumps -Hot water, low-temperature steam applications
Pulp and paper industry	
• Biological pulping using lignin-degrading fungus • Catalytic assisted Kraft pulping (e.g., anthraquinone, rhodium compounds, cobalt salcomine) • Membrane separation of black liquor • Chip pretreatment	• Electrification of digestion and liquor recovery process • Displacement pressing • Gas-fired drying • Impulse drying • EM induction for paper drying

Low–thermal budget transformative technologies	Alternative thermal processing
- Directed green liquor utilization pulping • Solvent pulping methods (e.g., alkaline sulfite methanol process, deep eutectic solvents) • Ultrasound - RF in paper drying • Cavitation-jet deinking • Dry sheet forming	• Electric IR for paper drying • MW/RF paper drying • Alternative fuels: liquid biofuels or biochemicals • IR and MW paper drying of coated paper • Solar thermal applications

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative TPI technologies for improved efficiency. A dynamic conversation followed in which various crosscutting and sector/system-specific barriers were identified. The importance of grid reliability for successful electrification, unique challenges in pulp and paper mills related to the availability of by-product fuels, and cost effectiveness were some of common concerns expressed by participants. Multiple new technologies and their applications were proposed for consideration, as well, including broader application of pulsed electric field processing and thermally driven heat pumps. RO for evaporation application was one of the opportunities proposed. The key takeaways from these discussions, informed by follow-up research done by the workshop team in correspondence with individual participants, are summarized in Sections 5.5 and 5.6.

Brainstorming Session 4: Hydrocarbon Processing

The fourth session, held on November 20, 2020, examined technologies for hydrocarbon processing industries and focused on the petroleum refining and chemical sectors. The 2-hour session was attended by more than 90 participants from various research organizations, federal and state agencies, OEMs, and manufacturing companies in the sector.

Technologies related to the first two TPI pillars—low–thermal budget transformative technologies (TPI pillar 1) and alternative thermal processing (TPI pillar 2)—were discussed during the session. The presentations provided by the workshop team and guest speakers helped orient the participants to the workshop goals and invigorate them for the brainstorming discussions that followed. The agenda for the meeting and an overview of the presentations are provided in Table A8.

Table A8. Brainstorming Session 4 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Part 1: Overview of sector and TPI technologies: petroleum refining (20 min) -Arvind Thekdi (E3M Inc.), Bill Morrow (LBNL), and Subodh Chaudhari (ORNL)	The presentation provided an overview of the energy used by thermal processes in the petroleum refining sector and described the opportunity for significant improvement with low–thermal budget transformative (TPI pillar 1) and alternative thermal processing (TPI pillar 2) technologies. The technologies identified under each TPI pillar by the workshop team from literature review were presented, and a few examples were explored in detail for each TPI pillar. An example of transformative technology, "bio-desulfurization of crude oils," which meets criteria for TPI pillar 1, was discussed. This technology proposes to use specific types of bacteria for desulfurization, denitrogenation, and heavy metal removal. For TPI pillar 2, an example of progressive distillation was discussed. This technology represents integration of distillations, gasoline fractionation, and naphtha stabilization.
Modular chemical process intensification for petroleum	The presentation discussed modular chemical process intensification–related activities. This included process intensification through rethinking processes,

Topics	Presentation summary
refining and petrochemicals (15 min) -Paul Yelvington (RAPID Manufacturing Institute)	shifting from unit operations paradigm to integrative paradigm, and removing bottlenecks. The speaker mentioned modular processing to enable flexible distributed manufacturing and several associated concepts. The presentation discussed RAPID projects that met requirements for TPI pillar 1 and TPI pillar 2. Many of these projects represent industry-government and academia collaboration.
US petroleum refining industry R&D (15 min) -Bill Morrow (LBNL)	The presentation discussed current and future investment drivers for petroleum refining and several AMO projects across development and deployment stages to enable success. Several project ideas across the spectrum of basic research to deployment were presented. They covered crude processing efficiency, energy efficiency, fuel switching, and crosscutting technologies with time horizons ranging from 2020 to 2040. Several areas of modeling were also discussed.
Part 2: Overview of sector and TPI technologies: chemical (20 min) -Arvind Thekdi (E3M Inc.) and Subodh Chaudhari (ORNL)	This presentation, like Part 1, provided details related to the opportunity for TPI in the chemical industry. Many different technologies for TPI for TPI pillar 1 and TPI pillar 2 identified by the workshop team were presented, and a few examples were explored in depth. An example of a project that represents transformative technology for the chemical industry was discussed in the presentation—oxidative dehydrogenation of propane with a vanadium-based catalyst. The results are applicable to ethylene, propylene, and olefin processes. A second example discussed the application of alternative technologies of hollow fiber column packing, which replaces conventional packing materials and offers improvements in energy efficiency, as well as productivity. The application areas include ethylene, propylene, and olefin processes.
Thermal intensification opportunities in the chemical industry -Ed Rightor (American Council for an Energy Efficient Economy)	The presentation discussed energy input/uses, change drivers, process heat as a crosscutting opportunity, and future technology horizons. The change drivers mentioned climate change, energy system electrification and related supply chain, decarbonization and science-based goals, stakeholder expectations, and technology analytics. Several transformational issues and technology readiness steps related to chemical industry were pointed out. A graph of the time horizon (2020 to 2050) vs. low-carbon fuels and carbon capture and utilization systems that listed many technologies was presented.
Brainstorming exercise in MeetingSphere: petroleum refining and chemical industries (40 min) -All participants	The presentations delivered during the two sessions helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and the research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A9.

Table A9 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A9. Brainstorming Session 4 – List of TPI technologies.

Low–thermal budget transformative technologies	Alternative thermal processing
Petroleum refining industry	
• Thermal cracking - Crude distillation/separation • Biodesulfurization - Hydrodesulfurization/hydro-treating (certain fuels) • Advanced synthetic fuel synthesis - Refinery, chemicals • Selective membrane separation - Distillation • Hydrogen fuel cell - Hydrogen generation, electricity • Biomass as feedstock for refinery products	• Progressive distillation - New distillation plants • Electrification - Heating systems, distillation, utilities, process gases, steam generation, and so on • Fuel switching for thermal processing equipment • EM (RF or MW) heating for visbreaking • Dividing wall column distillation • Alternative energy source (electricity) assisted distillation processes • Heat pump assisted distillation

Low–thermal budget transformative technologies	Alternative thermal processing
• Hydrogen-based production of ammonia, methanol, and so on • Advanced catalyst system to replace current generation of catalysts in reforming and other applications • Advanced catalysts for low temperature heavy crude upgrading	• Induction and resistance heated furnaces • Hybrid fuel systems • Solar thermal systems
Chemical industry	

• Auto thermal oxidative dehydrogenation of alkanes to manufacture olefins using short contact time reactor
• Catalysts for oxidative dehydrogenation vanadium based or others
• Oxidative methylation of toluene
• High-temperature Shilov-like catalytic system for methyl chloride
• Ultrasound-RF processing for drying
• Electrolysis and electro-dialysis
• Toluene and methanol feedstock route for styrene monomer
• High-purity ethanol without distillation: carbon nanotube–enabled ethanol dewatering
• Autothermal pyrolysis of lignocellulose wastes to sugars and other biobased products
• Directed EM thermocatalysis for selective conversion of waste plastic to high value intermediates
• Thermocatalytic ethylene production using targeted RF induction heating
	• Fuel switching to lower carbon fuels (e.g., H_2) in traditional processes
	• Hollow fiber column packing
	• MW-enhanced direct cracking of hydrocarbons
	  - Hybrid distillation
	• Solar thermal systems for reactors: heaters
	  - Hybrid heating
	• New drying technologies such as bulk solids cooler, rotary cooler
	• Use of power ultrasound for non-thermal, non-equilibrium separation of ethanol/water solutions
	• Efficient chemicals production via chemical looping
	• EM-enhanced thermocatalytic depolymerization of mixed plastic
	• EM-enhanced HyPOR (Hydrocarbon Pump Oil Recycling) loop for fast fusion cycles

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative TPI technologies for improved efficiency. A dynamic conversation followed in which various crosscutting and sector/system-specific barriers were identified. The importance of identifying and using alternative sources for feedstock such as biomass in producing the hydrocarbon-based end products, developing innovative and transformational technologies for processing materials, reducing carbon emissions, and using carbon capture and utilization systems (CCUSs) are some of the topics addressed during the presentations and feedback from the attendees. Specific areas of R&D include separation processes (e.g., distillation, drying), advanced catalysts for use in various thermal processes used in refineries, chemical processing of materials, use of alternative energy sources including electrification, decarbonization in thermal processes, and recycling of materials. The key takeaways from these discussions, informed by follow-up research done by the workshop team in correspondence with individual participants, are summarized in Sections 5.7 and 5.8.

Waste heat recovery and advanced systems such as heat pumps to recover low- to medium-temperature heat is of high significance because a large amount of heat is discharged but not recovered at less than 550°F. These were discussed in the waste heat management session (session 6).

Brainstorming Session 5: Transformative Supplemental Technologies

The fifth session, held on December 2, 2020, examined crosscutting and sector-specific transformative supplemental technologies (TPI pillar 3) for all manufacturing sectors.

Supplemental technologies enhance the performance of process heating systems with the integration of sensors and smart control systems, predictive modeling, improved material handling, enhanced communications, and so on.

The 3-hour session was attended by more than 90 participants from various research organizations, federal and state agencies, OEMs, and manufacturing companies in the sector. The presentations provided by the workshop team and guest speaker helped orient the participants to the workshop goals and invigorate them for the brainstorming discussions that followed. The agenda for the meeting and an overview of the presentations are provided in Table A10.

Table A10. Brainstorming Session 5 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Part 1: Virtual workshop to collect feedback on transformative supplemental technologies in high-temperature metals and nonmetallic minerals sectors (40 min) -Sachin Nimbalkar (ORNL)	The presentation discussed the opportunity for transformative supplemental technologies (TPI pillar 3) in the high-temperature metals and high-temperature nonmetallic minerals sector. The technologies identified for each industry by the workshop team from literature review were presented, and a few examples were explored in detail for each sector. Implementation of continuous monitoring and real-time quality prediction tools to produce zero-defect slabs in the continuous casting of steel was discussed, along with its potential impact. Similarly, for aluminum, the potential integration of advanced sensing, automated process monitoring, and model-based controls for various applications within the sector were discussed. Implementing industrial IoT, advanced sensors, machine learning–based controls, and other smart manufacturing technologies such as digital twin were also discussed for potential implementation within the nonmetallic minerals (cement and glass) industry. These examples set the stage for participants to contribute their ideas and provide additional insights on technologies for TPI.
Integration of advanced simulation and visualization for manufacturing process optimization (20 min) -Chenn Q. Zhou (Purdue University Northwest)	The presentation explored the value, challenges, and role of using advanced simulation and visualization techniques to optimize thermal processes in the iron and steel sector. Several projects being worked on at the Center for Innovation through Visualization and Simulation at Purdue University Northwest were discussed. The adoption of digital twin to simulate casting operations, application of computational fluid dynamics models to optimize BF performance, and the use of AI tools for smart ladle operation were some of the projects that were explored in detail. Although the presentation drew mainly from projects implemented in the steel sector, most technologies discussed were crosscutting and provided a glimpse of the potential for simulation and visualization techniques for TPI across all sectors.
Part 2: Virtual workshop to collect feedback on transformative supplemental technologies in low/medium and hydrocarbon processing sectors (40 min) -Sachin Nimbalkar (ORNL)	This presentation, like Part 1, explored the opportunity for implementing transformational supplemental technologies in the low- and medium-temperature and hydrocarbon processing sector. Application of advanced spectroscopy-based image processing to reduce food waste was examined in detail, along with the application of advanced sensors, which have crosscutting application in pulp making and the food sector. Specific projects associated with the applications of dynamic control and optimization in the chemical sector (steam methane reformer) and the petroleum refining industry were also discussed.
Brainstorming exercise in MeetingSphere: all industries (60 min) -All participants	The presentations delivered during the first half of the session helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and the research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A11.

Table A11 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A11. Brainstorming Session 5 – List of TPI technologies.

Transformative supplemental technologies	
High-temperature metals industry	Hydrocarbon processing industry
Iron and steel industry - Intelligent control of air-fuel ratio in the coke oven - 3D radar technology that measures and broadcasts the distribution of BF burden in real time - Intelligent control system regulates slag foaming in the EAF - Deep learning that detects stickers and reduces false alarms to prevent breakouts and slowdowns in continuous casting - Predictive models of slab reheating furnace - Digital twin for basic oxygen furnace, BF, and so on - Smart IoT for system optimization with smart sensors - Modular manufacturing: mini and micro mills to produce iron and steel Alumina and aluminum industry - Digital twin for aluminum melting furnaces - Upgrading various types of aluminum scrap using the latest sensor technologies - Smart metal forming with digital process and IoT	Chemical industry - Model-based predictive control for process controls - Database monitoring index method for developing adaptive soft sensors for process control - Advanced process control platform for methane chloride plant - Smart manufacturing platform to join IoT virtualization, operation, sensor data, modeling, and actuation in the real world to achieve productivity and energy efficiency gains Petroleum industry - AI and machine learning technologies for predicting fouling threshold and preventive maintenance tool for controlling heat exchanger fouling - Development of advanced sensors for internal temperature and detection of hot spots on heater components - AI to optimize crude distillation units with uncertain feed composition
High-temperature nonmetals industry	Low- and medium-temperature processing industry
Cement industry - Digital twin for cement kilns - Smart devices and IoT that allow for real-time measurements in the cement making process - AI and predictive models for plant optimization Glass industry - Advanced sensors and control systems that enable continuous monitoring and optimization of heat inputs for fuel savings (glass wool and glass fiber finishing [drying]) - Smart devices and IoT that allow for real-time measurements in the glass making process - AI and predictive models for plant optimization	Food and beverage industry - IoT-based control and regulation of baking and malting temperature with real-time visualization - Wireless sensor network for bakeries for environmental condition monitoring, image capture and processing, and machine speed - IoT image processing with convolutional neural network to identify damaged, unusable raw materials Pulp and paper industry - Computational fluid dynamics and image analysis methods to provide smooth flow velocities during the deinking process - Real-time laser ultrasonic stiffness sensor - New sensors that can directly measure the dissolved lignin content continuously to control the chlorine dioxide stage - Smart drying enabled by multi-source data and machine learning

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative TPI technologies for improved efficiency. Specific projects and applications brought up by participants were discussed. The opportunity for real-time monitoring and smart controls in forging and BFs was identified to be highly impactful, given that these systems are typically operated by archaic “rules of thumb.” Advanced monitoring, fundamental physics-based modeling of the heating zones, and the application of AI for new material development were some of the other areas that were also widely accepted to be critical for TPI. The synergy between electrification of thermal processes and smart manufacturing technologies was explored, and the advantages an electric system brings in terms of faster response times and decentralized operations were noted to be key to implementing some of the more advanced control techniques. The need to justify the value for data analytics through case studies also achieved consensus among participants. The key takeaways from these discussions, informed by follow-up research done by the workshop team in correspondence with individual participants, are summarized in Section 5.9.

Brainstorming Session 6: Waste Heat Management Technologies

The sixth session, held on December 9, 2020, examined technologies for waste heat management for industrial thermal processing sector. The 3-hour session was attended by more than 90 participants from various research organizations, federal and state agencies, OEMs, and manufacturing companies in the sector.

Technologies related to the fourth and final TPI pillar of TPI—Waste Heat Management Technologies—were discussed during the session. The presentations provided by the workshop team and guest speakers helped orient the participants to the workshop goals and invigorate them for the brainstorming discussions that followed. The agenda for the meeting and an overview of the presentations are provided in Table A12.

Table A12. Brainstorming Session 6 – Agenda and presentation summary.

Topics	Presentation summary
Welcome, housekeeping, and orientation (10 min)	
Part 1: Waste heat management technologies: introduction to heat losses and waste heat management (35 min) -Arvind Thekdi (E3M Inc.), Joe Cresco (AMO), Sachin Nimbalkar (ORNL) and Subodh Chaudhari (ORNL)	The presentation provided an overview of the use of heat in process heating applications for US industries and major industrial sectors. The primary source of heat loss or wasted heat discharged from thermal processes in all industries is exhaust gases from fired systems and secondary sources, mainly sources of waste heat in thermal systems. The presentation included characteristics of waste heat (e.g., temperature, presence of contaminants such as particles, corrosive gases, and vapors) discharged from processes used in different industries. The differences between the three areas were discussed, as well as the various options for each of these possible methods of waste heat management. Available options with their pros and cons for waste heat recycling within the heating system itself—as well as heat recovery, which can be used within the plant or can be converted to other form of energy (e.g., electricity, steam, cooling)—were discussed.
Waste heat recovery systems for high-temperature metals manufacturing sector (20 min) -David Schalles (Bloom Engineering)	The presentation from Bloom Engineering, a major supplier of burners and combustion air preheating systems for steel and aluminum industries, discussed currently available recuperators for waste heat recovery and recuperative burners. The speaker described regenerative burners that increase heat recovery efficiency and a system that allows fuel preheating for large furnaces. The presentation included various other heat recovery technology options, equipment, and their effectiveness. This included heat wheels, raining bed type regenerative system, electrical power generation (organic Rankine cycle) systems for secondary heat recovery and the issues that affect the selection and use of these systems—mainly economics and current low prices for natural gas in North America.
High-temperature heat pump: status and technology development activities by national laboratories (35 min) -Kyle Gluesenkamp (ORNL) and Travis Lowder (NREL)	Two presentations related to current developments in high-temperature heat pump (>~175°F) applications were delivered. The first presentation included background of the technology development, its fundamentals, and essential differences between electrically driven and thermally driven systems, as well as limitations imposed by real working fluids and realistic coefficient of performance for various systems. The second presentation included important factors (e.g., electricity price, waste heat temperature and process temperature requirements) and their effects on overall economics controlling heat pump applications for industrial thermal systems.
Part 2: Transformative waste heat management technologies in different industry sectors and RD&D opportunities (30 min) -Arvind Thekdi (E3M Inc.)	This presentation, like Part 1, provided details related to waste heat management opportunities for TPI in all industries. Many different technologies for waste heat management and related TPI for TPI pillar 1 and TPI pillar 2 identified by the workshop team were presented for the industries addressed in this workshop. For each industry, advanced technology application options for heat recycling

Topics	Presentation summary
	and recovery with at least one example were explored in depth. The presentation included example research needs, such as basic research, advanced materials, innovative designs, and manufacturing technologies. Further R&D in many of these areas would have significant impact on waste heat reduction and recovery for all major industries. They may be able to achieve significantly higher (>80%) thermal efficiency for thermal processes used by the industries.
Brainstorming exercise in MeetingSphere: waste heat management industry (40 min) -All participants	The presentations delivered during the waste heat management session helped set the stage for the brainstorming activity. Participants shared their feedback on the technologies identified by the workshop team and provided additional insight on the barriers to adoption, potential impact, and the research requirements. Participants also identified new technologies not captured in the literature review, which were discussed. More details related to the brainstorming exercise are provided in Table A13.

Table A13 provides a list of technologies from the initial literature review that served as a starting point for the brainstorming exercise.

Table A13. Brainstorming Session 6 – List of TPI technologies.

Waste heat management technologies	
High-temperature metals industry	Low- and medium-temperature processing industry
Iron and steel industry -Top gas enrichment via membrane separation and pressure recovery -EAF off-gas heat recovery -Recycling of blast furnace gas with reforming and treatment Use of thermoelectric generation system for radiating heat recovery (EAF, caster, post–hot rolling) -Heat recovery from BF and EAF molten slag -Reheat furnace cooling water heat recovery -Heat recovery from basic oxygen furnaces (steam generation) -Use of non-cooled or air-cooled rolls from thin strip cast reheating furnaces -Hot coke heat recovery (dry quenching) -Secondary heat recovery for reheat and annealing furnaces -Ladle, tundish heating, alternative heating, alternative insulation materials Alumina and aluminum industry -Heat recovery from electrolysis cell (pot): exhaust gas and radiation from the cell walls -Combustion air preheating using furnace flue gases: advanced recuperator/regenerator design -Heat recovery from heated alumina (medium temperature): charge (scrap and other) drying: preheating using heat exhaust gas heat -Heat recovery from (sensible and chemical) anode baking (ring) furnaces -Improved control of molten aluminum bath and combustion system (avoid over-firing) -Anode preheating or “hot” anode transfer -Improved controls to allow heat cascading: use of heat from furnace exhaust other furnaces -Use of ORC and other electricity generation from clean exhaust gases -Use of predictive models and AI for coil annealing furnaces	Food and beverage industry -Heat recovery from low-temperature (<200°F) moisture-laden flue products from ovens/fryers and boilers -Use of multiple-effect evaporators with thermal vapor compression where applicable -Low-temperature heat storage using exhaust gases for water heating -Use of heat pumps for low-temperature heat - Air/water vapor separation from dryer exhaust gas using membrane or desiccant wheel system -Modular air/water heating system integrated with heat recovery to replace steam from centralized boilers -Use of waste heat (e.g., boiler or oven) for absorption cooling -Use of organic waste material (solid or gasified) as boiler fuel Pulp and paper industry -Development of heat recovery or energy conversion systems for low-temperature (<140°F) heat sources, such as exhaust gases with water vapor and other contaminates (e.g., small amounts of fibers or particulates). -Black liquor gasification: bio treatment -A system for dehumidifying medium temperature (≥250°F) air containing fibers or particulates -Development of heat recovery from low-temperature water (~<140°F) for use in a plant - Dual-pressure reheat recovery boiler to increase efficiency - Development of a drying system for solids using waste heat from the exhaust gases -Steam cycle washer for unbleached pulp multiport dryer technology -Use of organic waste material (solid/gasified) as boiler fuel -Absorption heat pump-transformer -High-temperature heat pumps for heat recovery

Waste heat management technologies	
High-temperature nonmetals industry	Hydrocarbon processing industry
Cement industry -Low temperature (<300°F) exhaust gas heat recovery -Heat (thermal radiation – convection) recovery from clinker kiln surface -Use of exhaust gases for fuel (coal and biomass) drying -Electricity generation from (~400°F–600°F) particulate-laden gases using ORC and other systems -Hot gas/air cleaning: filter design and material -CO_2 separation, storage, conversion to CO and H_2 (reforming) concepts and system development Glass industry -Secondary heat recovery from regenerator exhaust gases: recovery of furnace and regenerator wall surface radiation -Hot gas cleaning: filter design and material -Thermal oxidizers design and heat recovery within the plant (fiber glass sector) -Batch drying and preheating sensors and controls -Heat cascading: recovery for glass annealing furnaces -Heat recovery from furnaces fired with oxy-fuel burners -Use of predictive models and AI for melting furnaces	Petroleum refining and chemical Industry -Heat recovery from low-temperature (<200°F) flue products from refinery fuel fired heaters and boilers -Heat exchangers for latent heat recovery from high-moisture-laden gases -Treatment of high-temperature still gases containing corrosive components (e.g., hydrochloric acid) prior to their use -Heat recovery from exothermic processes to produce high-pressure steam or other uses -Development of microchannel heat exchangers for gases with minor presence of solids or other materials -Air-cooled heat exchangers: cooling towers to replace water-cooled units: reduction of water and other utilities -Use of combustion turbine exhaust gas as vitiated preheated air in heaters and boilers -Use of advanced catalyst to reduce process temperature and exhaust gas temperature. -Economically justifiable energy recovery from flared gases Gas separation systems such as membrane for enrichment of process by-products

During the brainstorming discussion, participants were encouraged to share their insight and assess innovative waste heat management technologies that are associated with TPI and improved efficiency. A dynamic conversation followed in which various crosscutting and sector/system-specific areas of heat recovery and associated equipment development were identified. The importance of identifying and using alternative heat recovery systems to improve the overall economics of application of waste heat recovery systems at high temperatures (~>1600°F) and low temperatures (~<150°F for natural gas–fired heating systems) where corrosion is a major concern were discussed. Needs for developing innovative and transformational technologies in the areas listed above are some of the topics addressed during the presentations and feedback from the attendees. Waste heat recovery and development of advanced systems, such as heat pumps to recycle and recover low to medium temperature heat, were of particular interest to the attendees, given that a large amount of heat is discharged but not recovered at less than 550°F. The key takeaways from these discussions informed by follow-up research done by the workshop team in correspondence with individual participants are summarized in Section 5.10.

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