BENEFICIAL ELECTRIFICATION IN INDUSTRY

By Edward Rightor, Andrew Whitlock, and R. Neal Elliott

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Contents

About the Authors

Edward Rightor is the director of ACEEE's Industrial Program. He develops strategic vision for the industrial sector, shapes the research and policy agenda, and convenes stakeholders to advance energy efficiency. Prior to joining ACEEE, Ed held several leadership roles at Dow Chemical during his 31-year career and holds 3 patents. He earned a PhD in chemistry from Michigan State University and a bachelor of science in chemistry from Marietta College.

Andrew Whitlock conducts research and analysis for the Industrial Program, focusing on strategic energy management and decarbonization. Prior to joining ACEEE, he worked as a data analyst with IMG-Crown Energy Services at the U.S. Department of Energy. Andrew holds a bachelor of science in integrated science and technology from James Madison University.

R. Neal Elliott is ACEEE's senior director of research, coordinating ACEEE's overall research efforts. Before joining ACEEE, Elliott was an adjunct associate professor of civil and environmental engineering at Duke University and senior engineering project manager at the North Carolina Alternative Energy Corporation (now Advanced Energy). He is a registered professional engineer in North Carolina and holds six patents. Elliott serves as treasurer of the Southeast Energy Efficiency Alliance and sits on the board of the Industrial Energy Technology Conference. He received bachelor of science and master of science degrees in mechanical engineering from North Carolina State University and a PhD from Duke University.

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Executive Summary

KEY TAKEAWAYS

- Electrification is an important pathway for industrial decarbonization, but it can be beneficial in reducing GHGs only if the electricity comes from low-carbon sources. We need considerable investment in electric infrastructure, energy storage, and interconnections to make electrification a viable beneficial pathway. This transformation will play a key role in enabling industry to achieve net-zero GHG emissions by midcentury.

- The top cross-cutting beneficial electrification opportunities include low- to mid-temperature process heat, machine drives, and intermittent fuel switching (e.g., hybrid boilers). Energy efficiency improvements, including to electric equipment that is already in use (motor drives, compressed air) are another opportunity. Industry-specific electrification opportunities (specialized materials production, heating/drying, surface curing, melting) can also be advanced, providing unique nonenergy and energy benefits.

- Nonenergy benefits (e.g., improved productivity, quality, environmental compliance, capacity, safety, waste reduction, etc.) can often justify equipment replacement. These benefits must be highlighted during demonstrations at increasing scale, particularly when data can be shared.

- RD&D focusing on electrification in industrial clusters is a promising route to encourage engagement, hands-on learning, and risk minimization. This approach can speed development, scaling, and adoption. Stakeholders and policymakers must collaborate to implement an efficient and effective strategy that catalyzes electric technology deployment with a focus on high-priority industries.

- Significant increases in RD&D funding across federal agencies (such as the U.S. Department of Energy's Advanced Manufacturing Office, the national laboratories, and the National Institutes of Science and Technology) and in academia are needed to accelerate innovation. This transformation will take decades but is doable with (1) durable policy support that continuously drives GHG reductions and (2) financial investment that spurs adoption of low-carbon technologies.

The U.S. industrial sector accounts for 23% of the nation's primary energy use (excluding feedstocks) and 22% of greenhouse gas (GHG) emissions.[1] Within industry, manufacturing accounts for 11.4% of the U.S. gross domestic product and the majority of energy use and GHG emissions. Industry faces numerous challenges as it works to transform its energy and GHG footprint, reduce carbon dependence (decarbonize), and grow while meeting new

[1] Numbers for the energy and emissions footprints without feedstock were chosen as they do not include process emissions, and are a better match for discussions on electrification potential impacts in the near to mid-term.

societal needs. Still, the scale, scope, and rate of change needed to achieve net-zero GHG emissions by midcentury are extraordinary.

Several pillars will support this transformation, including energy efficiency; transformative technology; carbon capture, utilization, and storage (CCUS); and fuel switching, which includes increased use of electricity from zero- or low-carbon sources (known as beneficial electrification). Electrification is a promising strategy for many industrial sectors, but its applicability will vary among industries. For example, the fabricated metals and aluminum sectors currently obtain more than 40% of their energy from electricity, whereas for petroleum refining, cement, and chemicals, the proportion of energy from electricity is under 15%. There are opportunities, both cross-cutting (e.g., intermittent fuel switching, heat pumps, waste heat, boilers) and industry specific (e.g., induction heating, UV curing, radiofrequency drying, space cooling, electrowinning), to expand the use of beneficial electric technologies across industrial sectors.

To accelerate electric technology adoption, challenges need to be addressed. These include increasing the proportion of low-carbon electricity used by industry, competitive economics, consistent low-energy supply 24/7, recapitalization, and preparing for new technology (e.g., smart manufacturing, digitization). For electrification, industry will need high levels of power supply that are extremely reliable, constantly available, and low in cost. States targeting 100% renewable power by midcentury have an opportunity to address this opportunity by siting low-carbon power generation, storage, and transmission where it can serve industry. For its part, industry can lower the energy and cost burden for installation of electric technologies by pursuing energy efficiency, including improving the efficiency of current electric equipment such as motor drives and compressed air equipment.

There are several ways to pursue early opportunities for electrification while addressing these challenges, improving technology, and maximizing the nonenergy benefits that are often deciding factors in adoption. Top prospects include pursuing electric technologies in areas where industry is concentrated to get maximum leverage, where low-carbon electricity is available at competitive prices, and where there is local support for adoption. Energy efficiency measures and optimization approaches that improve economics can lower hurdles to electrification such as capital and operating expense burdens.

The nonenergy benefits of electrification have sparked early adoption in multiple application niches, including process heating, motor drive systems, drying, surface curing, and materials cross-linking. These niches create opportunities to build greater recognition of the value of industrial electrification, and this could help accelerate adoption.

Pioneering electrification work is underway in metals, chemicals, and other subsectors. This work could expand electrification in process systems that are at the core of production for these industries. To move beyond pilot scale to commercial scale, durable RD&D support is needed to prove commercial and economic viability at scale. We can accelerate beneficial electrification by increasing the proportion of low-carbon electricity available, achieving more visibility for nonenergy and energy benefits, creating market support for products with lower carbon intensity, and fostering a durable, supportive policy environment.

Introduction

The U.S. industrial sector, which includes manufacturing, accounts for 23% of the nation's primary energy use (excluding feedstocks) and 22% of greenhouse gas (GHG) emissions (EIA 2019a; EPA 2020c). Among the most energy-intensive manufacturing industries are bulk chemicals, petroleum refining, iron and steel, glass, aluminum, metal casting foundries, and cement (EIA 2020a). Considering just the CO_2 portion of GHG emissions, the industrial sector accounts for 28% of the nation's primary energy–related carbon dioxide (CO_2) emissions, excluding feedstocks, totaling 1,064 million metric tons of CO_2 equivalent per year (EIA 2020a, 2017).[1] Given the magnitude of this emissions footprint, it is clear that addressing the challenges of climate change will require the industrial sector to dramatically reduce its GHG emissions while also producing materials that help others reduce their footprints. It is crucial to pursue these parallel goals with care to avoid unintended consequences (e.g., job losses due to offshoring), as manufacturing is an essential contributor to the U.S. economy, accounting for 11.4% of the gross domestic product ($2.33 trillion) in 2018 (NAM 2019). It also employs 12.75 million people (8.5% of the U.S. workforce) and accounts for half of the nation's exports (Amadeo 2020).

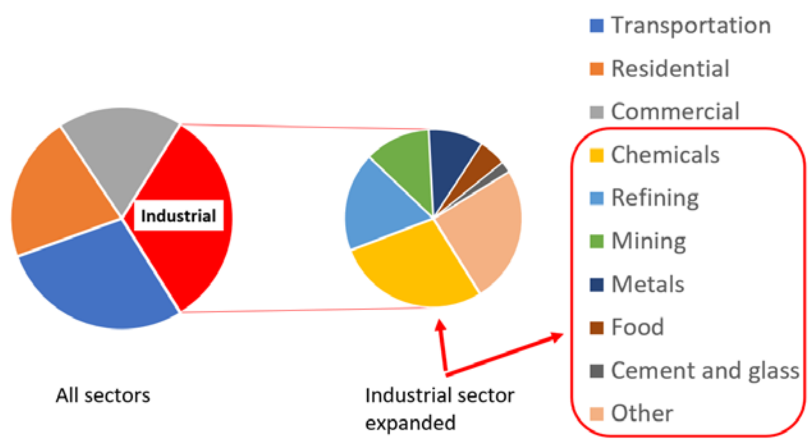

Figure 1. U.S. primary energy use. *Source*: EIA 2019c.

We propose several major approaches to transforming industry's footprint to net-zero GHGs, including energy efficiency; decarbonization of the electric grid; fuel switching; carbon capture, utilization, and storage (CCUS); and the adoption of transformative technologies that are now on the horizon (Williams et al. 2015; Haley et al. 2019). Energy efficiency is a foundational pathway, and pursuing it aggressively could reduce industrial final energy demand by more than 11% by 2050, while also reducing GHG emissions and delivering many nonenergy benefits (Nadel and Ungar 2019; Fleiter et al. 2019). It is essential to pursue energy efficiency in parallel with electrification to preserve critical resources and most effectively use capital while also deploying low-carbon solutions as they become commercial. To add to the impact of energy efficiency, several other emission-reduction pathways must be pursued in parallel due to the magnitude of emissions

[1] Primary energy is energy accounted for before any transformation to other forms. For instance, when natural gas is used to generate electricity, natural gas is the primary energy and electricity is the secondary energy.

reduction goals, diversity of the industrial sector, technology challenges, local variability of generation and energy resources, and other factors.

Beneficial electrification of process equipment within industry is one of the more promising pathways (and is a means of fuel switching). The Regulatory Assistance Project explains that for electrification to be considered "beneficial" in terms of reducing negative environmental impacts (e.g., GHGs), it must not adversely affect grid management or the ability of consumers to save money over the long run (Farnsworth et al. 2018). Also, electrification can itself be a form of energy efficiency when it reduces energy use, emissions, and cost (Molina 2019). Substantial improvements in the efficiency of currently installed electric equipment such as motor drives and compressed air facilities can also help lower energy demand and energy-related CO_2 emissions. Reducing energy demand can decrease the size of capital equipment, which can lower the installation costs of newer electric technologies. It is estimated that energy efficiency management of raw materials, waste streams, and recycling can decrease the cost of decarbonization in heavy industry by around 40% (ETC 2018). The drive to electrify should parallel efforts to grow low-carbon generation capacity so electrification is increasingly beneficial. Also, it is important to advance the electrical interconnections to manufacturing users to aid adoption, increase capacity, and ensure reliability.

In this report, we use several methods to understand the state of electric technology use in industry, where such technologies have established a foothold, and what potential actions could accelerate adoption. We draw on key publications covering electrification of the manufacturing sector, including sources that examine high-level opportunities and challenges. To gauge the current level of electricity use relative to other fuels, we use a number of databases, including the 2014 *Manufacturing Energy Consumption Survey* (MECS), the results of which are reported about every four years by the Energy Information Administration (EIA). We analyze and plot data from multiple MECS tables and from EIA's *Annual Energy Outlook*. We incorporate insights from multiple experts who were interviewed to clarify or augment our findings. We also examine the advance of electric technologies, for example by scouting patents in the heat pump arena using the software PatentInspiration (PatentInspiration 2019).

This report explores prospects for accelerating beneficial electrification across multiple manufacturing industries, processes, technologies, and business needs. It discusses the status of current electric and nonelectric energy use, top cross-cutting applications, barriers to adoption, and ways to catalyze early opportunities. The report closes with recommendations to maximize the potential for electric technologies to deliver deep GHG reductions in industry.

Manufacturing Energy Use

Across the top energy-consuming manufacturing industrial groups (refining, bulk chemicals, cement, iron and steel, food and beverage), electricity accounts for 15% of the energy used for heat and power; the balance comprises a wide assortment of hydrocarbon sources. Understanding the ways in which electricity is currently used in industry, and the ways it *could* be used, is a starting point for exploring opportunities to expand beneficial electrification.

ELECTRICITY

The ratio of nonelectric versus electric energy use varies by industrial sector, as shown in figure 2. Several sectors have comparatively low electricity use including refining, cement, glass, bulk chemicals, and paper manufacturing. The relatively low share of electric use in several industries may suggest opportunities for expanded use of electric technologies, but it also indicates that barriers, such as integrated systems, make replacement more difficult (as explained below).

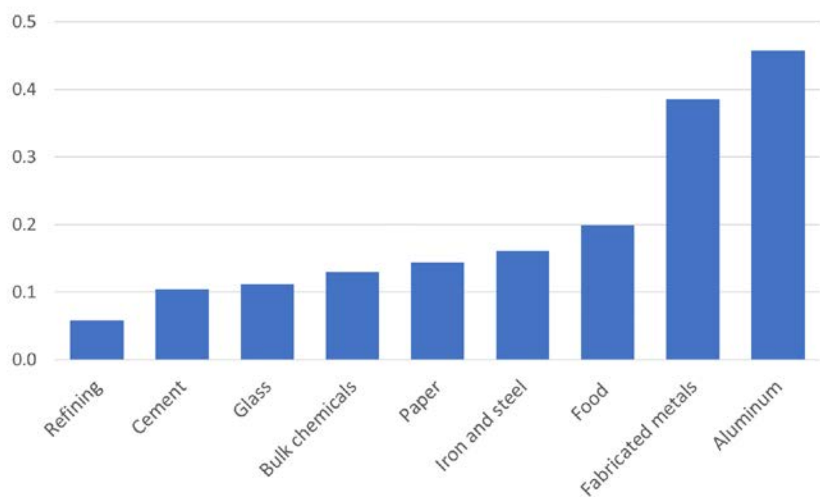

Figure 2. Ratio of electric to nonelectric energy use in selected industries. *Source*: EIA 2017.

In the iron and steel sector, advanced electric technologies developed and commercialized across multiple decades are being widely adopted. For example, the electric arc furnace (EAF) has been increasingly used to process scrap or recycled steel and accounted for 70% of the steel produced in the United States in 2019 (Hites 2020). As EAFs have advanced, however, constraints on the supply of scrap steel have been encountered, slowing further increases in EAF adoption. Several electric-based processes for industries with low electric/nonelectric ratios are in early stages of technology readiness, as will be discussed below.

Several heavy industrial sectors (chemicals and refining in particular) have a high degree of process integration.[2] This makes electrification challenging as replacement of one technology can have downstream impacts (Deason et al. 2018). Process heat generation, for example, can involve the integration of steam generation that are used across a wide array of primary processes (converting raw materials into basic products) and secondary ones (turning the basic products into finished goods).[3] Replacing steam generators with electric technologies in a primary process can lead to process redesign for multiple secondary processes. In another example, if process heat is generated for energy use by combusting

[2] Process integration is an approach to the design of manufacturing systems that emphasizes the efficient use of energy and other inputs and effective management (including reuse) of by-product and waste streams.

[3] Process heat involves the direct use of thermal energy to prepare and treat materials that become manufactured goods.

hydrocarbon coproducts in secondary production, technology replacement could also involve replacement of the secondary energy use.

Despite these challenges, it is worth identifying process needs or operations with unique characteristics that make them more amenable to electrification. This can include operations that are far removed from a central energy source, that require highly reliable onsite peak loads for heat, or that take advantage of cheap "excess" renewable energy generation from variable renewable sources. It can also include operations where modular replacements are possible, allowing isolation or a reduction in pressure on an existing plant. These circumstances provide greater justification for electrification and can lower operational risk. Pursuing these opportunities can also build capabilities and help businesses understand the value of these "new" technologies.

Electric power is used in multiple ways in industry, as shown in figure 3, which also illustrates the proportion of electrical energy used relative to other energy sources.

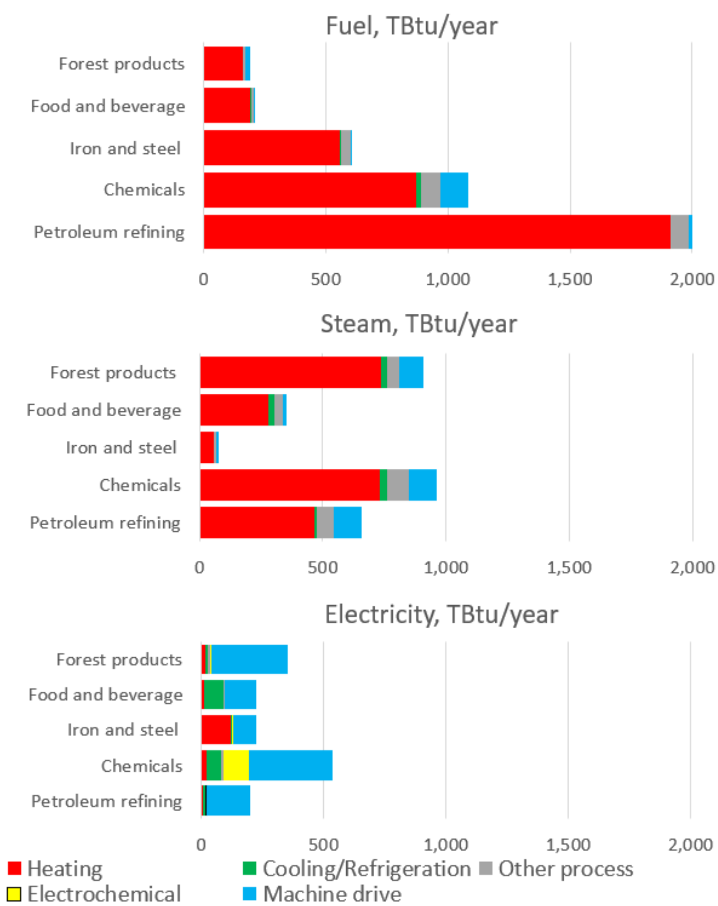

Figure 3. Distribution of electric energy use in select sectors. *Source*: EIA 2017.

In many industries, electricity is used predominantly to drive machines, including motor systems (compressed air, pump, and fan systems) and motor drives (pumps, fans, material handling, and so on.).[4] Electricity also is used in some industries for electrochemical processes that transform metals such as iron, steel, and aluminum. Electricity is also used in large amounts in the production of chemicals (e.g., chlor-alkali) and nonmetallic materials such as sulfur, salt, glass, lime, gypsum, and cement. The food industry also consumes large amounts of electricity, predominantly for process cooling and refrigeration.

NONELECTRIC ENERGY

By examining where electricity is not currently used, we can see where there may be potential for electrotechnologies to replace fossil fuel combustion (see figure 3). Process heating is a major use of nonelectric energy across many industries, as fuels are burned for direct combustion to produce heat or to produce steam that is used in multiple applications. For chemicals and petroleum refining, the use of thermal energy to transform feedstocks to useful products is very high, as evidenced by the high levels of process heat and combined heat and power (CHP).[5] Process heating across industries is a major use of nonelectric energy. Fuels are burned for direct combustion to produce heat, as well as to produce steam that is used across multiple production units and applications. Significant quantities of nonelectric energy are also used for process heating in the iron and steel industries. In addition to the energy-intensive industries such as chemicals and metals, food products, wood products, and paper all use a substantial amount of nonelectric energy. These areas too are prospects for electrification, and studies have borne this out (e.g., EECA 2019).

Opportunities for Electric Technologies

This section describes cross-cutting opportunities as well as sector-specific ones. In both cases we start at a high level before describing more granular opportunities and technologies.

CROSS-CUTTING OPPORTUNITIES

A number of promising strategies exist for increasing electric technology adoption across industrial sectors. One is to lower adoption hurdles via intermittent fuel switching and energy efficiency. Another approach is to replace incumbent fossil-fuel technologies with electric technologies having moderate capabilities while developing greater capabilities for more demanding conditions. A third path is to significantly upgrade our ability to digitize, control, and monitor electric technologies, such as in compressed air systems.

Intermittent Fuel Switching

Intermittent fuel switching is an option for near-term energy supply with lower carbon content. The portion of current industrial energy that could be switched (at least part of the time) to electricity is dependent on fuel prices, location, and the flexibility of installed equipment. In industry, around 6% of nonelectric energy use is readily switchable to electricity based on current hardware flexibility (EIA 2017). That is a modest percentage, but

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[4] Motors are mechanical or electrical devices that drive a machine, drives are electrical devices that harnesses and controls the electrical energy sent to the motor.

[5] CHP, also known as cogeneration, is the concurrent production of electricity and mechanical power.

it represents potential displacement of 34 billion cubic feet of natural gas, enough to supply 340,000 homes for a year (CRMU 2008).

An example of equipment with switchable capacity is hybrid boilers. These dual units (with both gas- and electric-fired boilers) allow operators to switch to electricity when the price of gas is relatively high or when low-priced surplus renewable energy is available. Hybrid natural gas/electric boilers have been used in the Southeast, for instance, to take advantage of off-peak nuclear power (Deason et al. 2018). This ability to switch can improve resiliency, giving companies flexibility when there is a supply outage from one source. For industry, this helps reduce the risk of production shutdowns and elevated emissions that often occur during plant startups. Switching also allows companies to react when prices of electricity and other fuels vary, which is likely to increase as the proportion of variable renewables (solar, wind) and energy storage increases.

Another hybrid approach is to combine electromagnetic energy (microwave or radiofrequency) and convective hot air for accelerating drying processes (DOE 2016b). Selectively targeting moisture with penetrating electromagnetic energy can greatly improve efficiency and product quality, relative to drying with convective air alone.

Maximizing Energy Efficiency

Hurdles to industrial electrification can be lowered, and business opportunities captured, through the concurrent adoption of energy efficiency measures, integrative design, and lean manufacturing approaches that significantly reduce waste. These strategies can reduce energy needs and vastly improve efficiency in energy delivery focusing on end-user needs (Steinberg et al. 2017; Lovins 2011).[6]

For example, as the number of production plants within an integrated chemical or refining facility are reduced or their energy needs are diminished due to optimization the existing steam system can end up with substantial overcapacity. This is in addition to the 18–20% of boiler energy use that is not effectively used due to system maintenance, insulation, leaks, and other issues (Einstein, Worrell, and Khrushch 2001). A whole-system analysis of where electric technologies could better serve current and future needs could expose multiple opportunities for energy and nonenergy savings.

Energy efficiency improvements can help lower the cost of future installations of electric technologies. Efficiency can also decrease by up to 50% the magnitude of future load growth from widespread electrification (Steinberg et al. 2017). Reducing electric load is important as the potential electrical load increase could approach multiple quads (quadrillion Btus) if several industrial sectors were electrified to their full potential (Thirumaran et al. 2019).

Smart data analytics can be used to evaluate whole-system efficiencies in real time. Smart manufacturing (SM) uses information and computer technology to increase flexibility in production while reducing wasted materials and energy. The Smart Manufacturing Institute (CESMII) has developed an SM platform that allows digitization of processes to enable step-

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[6] P. Stephens, Electric Power Research Institute, pers. comm., 2019.

change improvements in manufacturing energy and materials efficiency while ensuring security and retention of intellectual property.[7] Integration of SM methods into electric technologies could deliver additional advantages to early adopters by providing enhanced data flow, analytics, and ability to leverage profiles to additional installations within the company or to supply chain partners.

Nonenergy Benefits

Nonenergy benefits often drive the adoption of electric technologies. So building a case for electric technologies needs to include quantification of both energy savings and nonenergy benefits. For example, when companies install electric induction or microwave heating to dry parts, they find that the drying is more controllable, allows higher throughput, and degrades the material less, thereby reducing waste. Electric boiler manufacturers note that customers have found these units can reduce pollution abatement costs, lower permitting hurdles, have a smaller footprint, and have faster ramp-up times than comparable boilers that combust fuel (coal, oil, gas, etc.).

Facilities seeking to evaluate and justify the purchase of electric technologies to replace incumbent equipment will need to look beyond the engineering analysis and energy use to include the impacts on the overall plant and its operating costs. These impacts can include:

- Operational advantages
- Reduced waste
- Lower GHG emissions
- Environmental compliance
- Improved capacity, yield, productivity, quality, and safety
- Resilience and sustainability, which provide value return, minimize risk, and ensure long-term viability
- Enhanced company reputation and faster response to changing customer preferences due to process improvements such as those above

There are a number of case studies on the co-benefits delivered by electric technologies for drying, membrane filtration, mechanical vapor recompression, and heating across manufacturing, food, chemicals, and other industries (EECA 2019). A study of energy efficiency projects found that the total savings from nonenergy benefits across 77 industrial case studies was greater than the direct energy savings (Finman and Laitner 2001). A look at 52 monetized case studies in the group showed a 4.2-year payback based only on the energy savings; the inclusion of nonenergy savings reduced the payback period to 1.9 years. The magnitude of the nonenergy benefits can be up to 2.5 times that of the energy benefits, depending on the size and context of the investment (IEA 2014).

The sampling of nonenergy benefits in table 1 shows their breadth, value delivery, and crossover that extends well beyond energy and GHG emissions reductions. To highlight these benefits, consider microwaves. In drying applications, these can be turned on or off instantly, eliminating warm-up/cool-down cycles, and microwaves are selectively absorbed by regions of high moisture, thus saving time and energy versus heating blowing air over

[7] Information on CESMII can be found at www.cesmii.org/.

the bulk material. Nonenergy benefits include improved heat distribution (versus thermal heat flux), unlimited rates of heating, and heating times that can be reduced to less than 1% of the time associated with conventional methods (IMS 2019). The uniform energy distribution can minimize fouling from hot spots, and general benefits can include improved yields, fewer operational steps, and better product quality. If the electric technologies are modular, service from other modules can avoid production disruption in the case of an equipment failure.

Table 1. Nonenergy benefits electric technologies in select applications

Process heating [a]	Induction heating [b]	General [c]	Food [d]
Improved process speed Product quality Manufacturer flexibility Cleaner processing Lower emissions Potentially lower capital cost	Better product quality Flexibility Automatic operation Compact installation Better working environment Fast response	Environment Plant productivity Output increase Reduced energy intensity Improved product quality Worker safety Reduced loss-time accidents Increased production speed	Shelf life Increased production Faster processing (drying, sterilization, heating) Faster, more controllable heating Reduction of product cooling time Containment of unpleasant odors Reduced emissions (particles, pollutants) Uniformity of process conditions Product preservation (lower thermal degradation) Reduction of contamination risk (avoided condensation) Increased reaction yields Reduced transportation costs Preserved flavors

[a] Thekdi et al. 2017; Deason et al. 2018. [b] Vairamohan 2014; Deason et al. 2018. [c] Dennis 2016; CEATI 2016. [d] EECA 2019.

A range of benefits also exist for drying with electric technologies, ranging from pre-drying to post-drying. Pre-drying via infrared, ultrasound, or mechanical vapor recompression can be utilized to remove water from materials before organic synthesis. In another example, microwaves and radiofrequency technologies have been used in drying lumber (EECA 2019). Similarly, drying polymers manufactured by aqueous processes with electric technologies is useful to avoid degradation.

Electric boilers offer advantages including higher fuel efficiency, lower upfront cost, and potentially lower capital cost and lower need for environmental permitting (e.g., avoiding emissions permitting). Electrolytic reduction technologies bring induction heating advantages including faster startup and heating; higher production rates; and reduced scaling, energy consumption, and emissions. Advantages of electrolytic separation (for production of chlorine and caustic soda) can include better process control along with lower processing temperatures and less pollution. Distributed electric boilers serving needs around a processing facility also allow more precise control than a centralized system does.[8]

Electric technologies' nonenergy benefits can be very site specific, and identifying all of them requires looking beyond the application of technology to the spillover effects on the overall facility as well as up and down the supply chain. The application of electric technologies may offer important benefits to the facility by eliminating a process line bottleneck or addressing an environmental compliance challenge that goes beyond the process where the technology is applied. A good example is the replacement of steam with electric heating. While in a few cases the cost of purchased electricity may be greater than the cost of the displaced fossil fuel, if the switch allows the retirement of the boiler system, the facility immediately experiences nonenergy cost savings because:

- There is no need to treat boiler water to prevent corrosion.
- The distribution steam system is no longer used, so piping and steam-trap maintenance is no longer needed (if modest amounts of steam are required for a specific process, a smaller unit can supply it).
- Insurance is not required to get a permit to operate the boiler.
- A certified boiler operator is no longer required to maintain insurance coverage.
- Boiler stack monitoring is no longer required to maintain an emissions permit.
- Administrative and recordkeeping associated with the boiler can be discontinued.

The supply and value chains connected to industry are a complex web of suppliers, customers, co-manufacturers, and so on, so it is important to consider electrification impacts and nonenergy benefits beyond industry. Given its position in the middle of many supply chains, industry has an opportunity not only to help customers reduce their carbon intensity (via lower-carbon products) but also to influence suppliers to do the same. Nonenergy and energy-related benefits together can help drive these initiatives among supply chain partners.

For instance, when General Motors (GM) realized that the majority of its extended GHG footprint was in its supply chain, it invited those companies to join GM in reducing their combined GHG footprint, and more than 70% responded. As of 2017, their combined efforts had avoided the emission of 90 million metric tons of GHGs while also saving $23 billion (GM 2017). BHP, a large multinational company involved in ore extraction and mining with value chain partners in steel, is working with its partners on emissions outside of its direct operations (scope 1 emissions) and energy supply (scope 2 emissions) to reduce broader supply chain emissions (scope 3) while seeking to capitalize on longer-term opportunities (BHP 2018).

[8] B. Seitz, pers. comm., May 2020.

Compressed Air

The advanced application of electric technology to compressed air offers a starting point to greatly improve the efficiency of current systems while continuing to identify and pursue opportunities to replace legacy systems with advanced self-monitoring equipment. Although electricity is the primary power source for compressed air, continuous system monitoring and air auditing are helping to evolve air management (Marshall 2018). Improved electronic sensors, easy-to-use data collection and analysis systems, and cloud databases and management systems have led to advancements on the software side, and technology has improved as well, such as in compressor control. To overlook compressed air would be to miss an opportunity, as it is estimated that poorly designed and maintained compressed-air systems in the United States could account for losses of $3.2 billion per year (Humphreys 2009).

Much as steam systems have been ubiquitous in industry for more than a century, compressed air is found in most industrial facilities today and is frequently referred to as the "third utility" (electricity and natural gas being the other two). Throughout a facility, compressed air supports air-driven hand tools, pneumatic motors, clamps, actuators, sprayers, and other machines.

Power and maintenance costs make compressed air systems very expensive (Nadel et al. 2002; DOE 2002). These systems consume a great deal of energy, accounting for about 10% of all industrial electricity and roughly 16% of all motor system energy use in the United States (DOE 2001). Compressed air is also the most expensive utility, averaging three times the cost of electricity because of the inherent inefficiency of air compression. On average, efficiency measures can reduce compressed air system energy usage by 17% with a payback of three years. If all projects implemented in the scope of a U.S. industrial study were pursued, national energy savings would be around 15,700 gigawatt-hours per year, saving $750 million in electric rate charges (DOE 2001).

These cost challenges are compounded by the inefficiencies and losses that are endemic to compressed air systems. Plant-level air systems require constant maintenance to manage leaks, which can exceed 25% of production if not addressed. Many of these are legacy systems that experience the same operational challenges as plant steam systems. They are oversized because they were installed to meet the past plant capacity needs, which in most cases have been dramatically reduced by efficiency and technology changes. Many control systems used to be pneumatic but have been replaced by electronic systems over the past few decades. In addition, in most plants one can find inappropriate applications of compressed air, such as cooling of electric cabinets on the plant floor simply because compressed air is available, with little thought given to the cost. Similarly, system operating pressures may exceed modern requirements (DOE 2002).

Replacing legacy plant air systems and some pneumatic equipment with electric technology can result in significant energy and maintenance cost savings. For the compressed air requirements that remain in particular applications, a small compressor can be installed locally, obviating the need to maintain a plant-level distribution system. Many other applications do not require high pressures and can be served by blowers, which consume less energy and cost less to maintain than a compressed air system (Nadel et al. 2002).

Electric actuators offer fast response, programmability, high positioning accuracy, and much lower energy costs than pneumatic actuators. They can also offer better flexibility, greater precision, and lower maintenance costs compared with pneumatic actuators (Maw 2018). With greater availability, the cost of electric actuators has fallen in recent years. While their initial cost can still be on the order of 10 times the cost of pneumatic cylinders, their greater energy efficiency and reduced maintenance costs mean that operating expenses can be significantly lower. Electric actuators offer positional sensing that enables improved process control and integration with smart manufacturing systems (Kral 2015). Another advantage accrues when a process requires changeovers (e.g., when adapting an assembly line to a different product). Manually resetting pneumatic actuators can be time consuming, resulting in significant lost production, but because electric devices are programmable, the change can be made with little lost time. The greater productivity can make the electric technologies the more cost-effective solution.

Many facilities rely on compressed-air hand tools because of their reliability, low weight, low cost, and safety in potentially explosive environments. However, modern battery-operated hand tools can match the performance of pneumatic tools in many applications. Because the electricity costs for electric tools are lower than for pneumatic tools, it is usually compelling to switch to the electric alternative. The primary benefit of this switch, however, is the ability to reduce or eliminate plant air systems with their maintenance and operating costs (Zolkowski 2019). Also, sometimes periodic review of end-use needs can reveal process requirements that can be met with lower-energy inputs—for instance, gluing metals instead of riveting, or using a heat pump and low-pressure fan to dry instead of high-pressure air.

Process Heat

Process heating offers a significant opportunity for electrification across multiple industries because of the magnitude of energy it consumes and the potential for various electric technologies to increase market penetration, starting with lower-level heat applications. Thermal demand in U.S. manufacturing is currently met almost entirely by fossil fuels, including natural gas (45%), coal (8%), oil (8%), and by-products (process gas, biomass, other waste gases like blast furnace and coke oven gases, fuel oils, and hydrocarbon gas liquids) (EIA 2017).[9] Boilers, furnaces, and related systems combust those fuels to provide 90% of the thermal energy needs of industry. The dominance of fossil fuels in supplying this thermal energy raises questions about the potential for lower-carbon energy sources to supply those needs. In particular, high-carbon-content fuels like coal, oil, and coke could be candidates for replacement with low-carbon energy sources. Electricity accounts for only 1% of the process heat used in pulp and paper, 2% in chemicals, and 1% in the refining industry, so there may be thermal replacement opportunities to pursue especially in the low- to mid-temperature service ranges. It should be noted, too, that there is a large potential to reduce the amount of process heat required and to reduce the temperature at which it is supplied.

[9] In industry, thermal demand refers to the amount of heat resources needed to provide process heat.

In the United States, process heat uses more energy than any other manufacturing system: more than 7 quadrillion British thermal units/ year (or quads), or about 61% of the onsite energy use in the manufacturing sector (DOE 2015b). [10] This accounts for 32% of GHG emissions from the industrial sector and 7% of U.S. GHG emissions across all sectors. As shown in figure 4, process heat is employed in a variety of ways, with fluid heating and distillation, drying, metal refining, and calcining being the top uses.

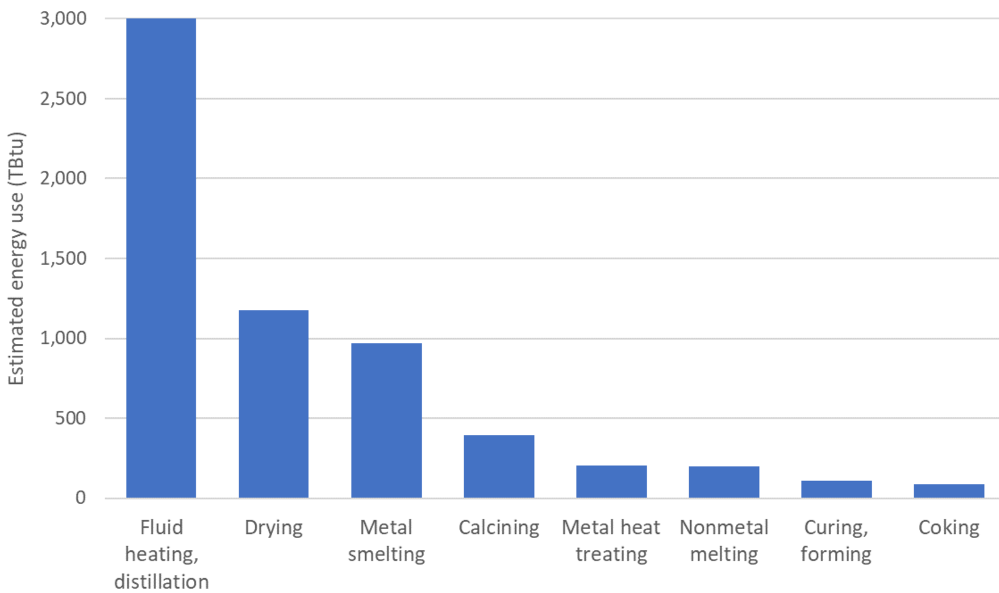

Figure 4. Distribution of process heat across industries. *Source:* DOE 2016b.

There are various temperature ranges to consider for process heat, as shown in figure 5 for the industrial groups that use the highest levels of process heat. About 30% of the process heating demand across these industry groups is in the low-temperature range (<150 °C), which is the best opportunity for electrification with current equipment. For a portion of the low-temperature range, several electric technologies (including heat pumps, microwave, and infrared) can be considered for use in the paper, food and beverage, metals, plastic, textiles, and wood industries (EECA 2019).

[10] A quad is a unit of energy representing 10^{15} Btus (or 1.055 10^{18} exajoules). A tera-Btu (TBtu) is 10^{12} Btus, so there are 1,000 TBtus in a quad.

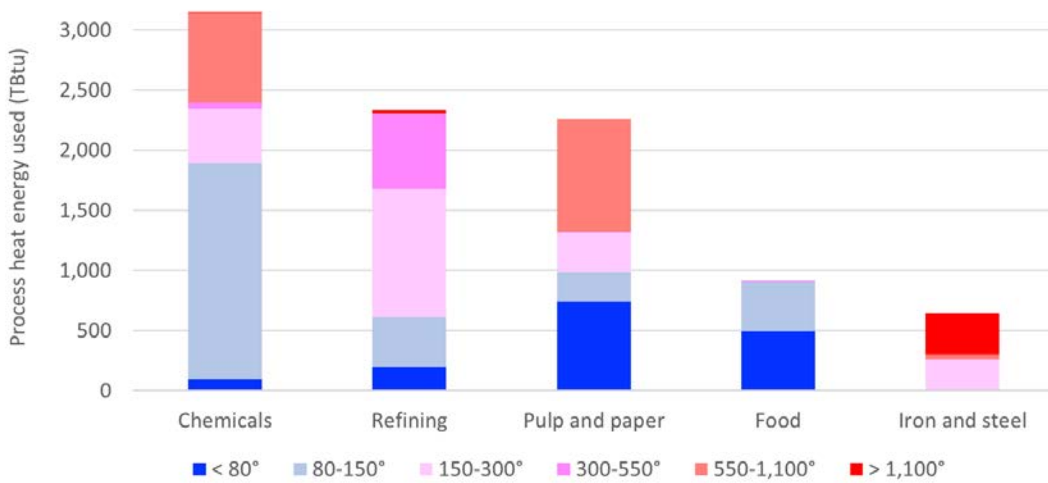

Figure 5. Segmentation of energy use across temperature levels by industry. *Source:* McMillan 2019.

The next-highest group of process-heat-using industry groups are shown in figure 6. It is clear that there is little low-temperature process heat in the cement, lime and gypsum, and glass industry groups, but there is some in aluminum as well as plastics and rubber. As we will discuss below, the processing of plastics and rubber is an area where several electric technologies have demonstrated unique advantages.

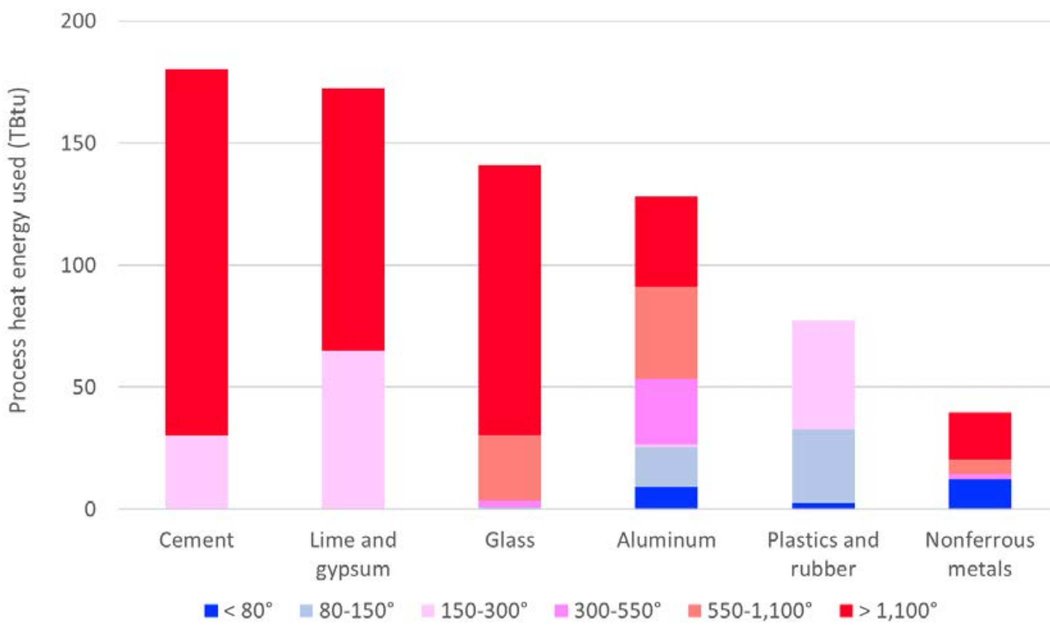

Figure 6. Process heat use in additional industrial segments. *Source*: McMillan 2019.

Steam substitution is a potential prospect for electric technologies in the refining, chemicals, forest products, and other industries, starting with lower-temperature (<100 °C) applications. Steam provides the majority of process heat in pulp and paper, around 45% in the chemicals industry, and 18% in refining. Electrical heating methods such as induction or radiative heating are potentially viable in the lower end of the medium-temperature range of steam applications (Sandalow et al. 2019). The middle portions of the medium heat range are targets for advanced electric technologies like leading-edge heat pumps, induction heating, ultrasound-assisted drying, and microwaves (Euroheat & Power 2006).[11] These technologies could be seen as replacements for steam and in some cases provide localized heat at temperatures needed for the application, which are lower than those currently provided by steam. There are several electric technology options for providing process heat, depending on the temperature range and process parameters, as shown in Appendix A.

Large chemical and refining facilities may have hundreds or thousands of heat sources in an integrated system, complicating the electrification process.[12] Smaller or stand-alone facilities not integrated with steam systems can be less complex and may be a starting point for substitution of steam by electric technologies. As noted above, there may be specific processes at a site that are (or can be) isolated from the main steam heating systems, with potentially significant reductions in distribution loses or improvements in operating efficiency. These situations would be good opportunities for electrification.

The smaller number of large heat sources in a pulp and paper facility could lower the hurdles of fuel substitution. However, a significant portion of this heat is generated from the combustion of wood waste products (e.g., black liquor and wood chips). Considering the low cost of this fuel, hurdles with disposal otherwise (e.g., landfill cost, transport), and the debate on whether replacing biofuels with electric technologies is truly beneficial from a GHG perspective, there will likely be adoption challenges.

By-product hydrocarbons (e.g., still gas) are also used in refining and chemicals, which can complicate the displacement of these sources with electric technologies. Yet, it is worth noting that where waste products are used for heat, the processes may not be highly optimized or efficient, as operators see the process as just getting rid of waste, so electric technologies being considered for such circumstances may have a large potential efficiency advantage if the entire system is considered. One unpublished Australian study compared the operation of boilers in a paper and pulp mill on gas only, and on gas plus wood waste, and found that the reduction in gas use when adding wood waste was only one-fifth of the expected savings. This was attributed to energy losses from the wood feed system.[13]

HEAT PUMPS

The scale of the process heat opportunity has attracted vendors of technologies such as heat pumps. Industrial heat pumps offer potential replacement for a portion of the lower temperature ranges shown in figures 5 and 6. They can supply heat for process heating or preheating, process water heating and cooling, space heating and cooling, steam production, and product drying; they can also capture waste heat for multiple uses (Jakobs,

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[11] J. Jutsen, priv. comm., August 2019.

[12] In an integrated system, hot and cold process streams are sent to heat exchangers where, for example, thermal energy partially conserved by the hot streams helps to preheat the colder streams. These are then returned to the process system, where they require less heat input to reach effective service temperatures.

[13] A. Pears, pers. comm., April 9, 2020.

Cibis, and Laue 2010). Heat pumps have been employed in industry for decades across a wide range of applications to deliver heat as well as cooling (DOE 2003). An example of the latter is continuous cooling of plastics injection molding machines, where cooling water must be delivered at the correct temperature year-round (Kew 1983). At industrial sites where process cooling and process heating are both significant (e.g., breweries, wineries, food processing), dedicated heat recovery chillers can offset significant fossil fuel demands for steam while improving electrical energy efficiency for refrigeration and increasing cost effectiveness.

Industrial heat pumps are often more complex and of higher capacity than their residential counterparts. They also can have more challenging operating requirements, such as longer operating run time, high reliability, low maintenance, and the ability to perform in dirty environments. Whereas standardized products and installations are largely satisfactory for residential use, the unique needs of industry often require adaptations or custom designs, which makes a high level of expertise and support from suppliers crucial. This has been a challenge for the relatively small, emerging group of heat pump providers, and lack of technical support in the field has in the past resulted in several issues, as we discuss below in the Preparing for New Technology section.

Heat pump efficiency is measured by the coefficient of performance (CoP). A CoP of 5 means it provides 5 units of heat (or cooling) for each unit of electricity consumed, so in this case it would consume one-fifth as much electricity as an electric resistance heater. Commercial units can have seasonal CoPs between 9.5 and 11 (Pears 2019). An overarching concern is that when looking at the economics of industrial heat pumps, the overall efficiency of an existing gas system is sometimes not measured but assumed, and assumed too optimistically. This can unfairly undermine the case for modular heat pumps located at the point of use.

In the next level of development, several middle-temperature applications in chemicals, paper, and plastics technologies are in the prototype stage. Heat pumps with advanced capabilities can reach 120 °C, and recent developments point to 150 °C being achievable (Viking Heat Engines 2016). Using large-scale components from the oil and gas sector for applications in energy-intensive industries, a study showed that higher supply temperatures (up to 280 °C) may be technically and economically feasible, with the potential for higher temperatures depending on the availability of suitable heat sources (Zühlsdorf et al. 2019). Additionally, emerging electrochemical heat recovery technologies have the potential to increase the achievable temperature for heat reinjection into processes.

With that higher temperature capability, heat pumps can extend into a wider range of applications—for example, replacing centralized systems that burn natural gas or other hydrocarbon fuels to vaporize and transport water (DOE 2003). In addition to boilers and steam generation, the drying of product and removal of water from solids are of interest, especially as drying in industry accounts for 12–25% of the energy associated with processes (Jakobs 2019). The broad range of potential heat pump applications is shown in table 2.

Table 2. Range of heat pump applications

Process heat–related heat pump applications	Heat pumps
Petrochemicals	Distillation
Chemicals	Concentration of aqueous solutions Waste stream concentration Heat recovery Process water heating Water purification/wastewater treatment Product drying
Wood products	Concentration of black liquor Process water heating Flash steam recovery Product drying
Food and beverage	Concentration of waste liquids Concentration of solutions Heating of process and cleaning water
General	Space heating

Source: DOE 2003

A recent study shed light on the potential of heat pumps to support the transition of the industrial sector to a low-carbon footprint. It found a potential supply opportunity of 68 TWh per year in the chemical, paper, food/tobacco, and wood industries in Europe for heat pumps supplying heat up to 100 °C (Nowak 2017).[14] Adding hot water and space heating yielded an additional annual potential of 74 TWh, and by applying advanced heat pump technology to supply up to 150 °C, another 32 TWh could be added. In total, electric heat pumps could supply some 174 TWh annually to these industries in Europe. This is a significant portion of the total industrial waste heat potential in Europe, which is around 300 TWh per year (Papapetrou et al. 2018). A search of the literature did not reveal a comparable study for the United States.

It should be noted that three-quarters or more of the energy in steam is in the latent heat, the heat associated with phase change. Heat pumps, then, can be used to boil water, and boosting their abilities further can allow them to provide a much bigger share of the process heat for steam production than is provided by just preheating water.[15] It is also possible to boil water at a lower temperature than 100 °C by depressurizing it, making the heat pump more efficient.

Innovation in heat pumps is reflected in the strong rise in the number of patent applications, as shown in figure 9. The highest numbers of applicants are from China, Russia, and

[14] 1 terawatt-hour (TWh) is equivalent to 3.412 x 10^{12} Btus. For perspective, Scotland uses about 25 TWh per year.

[15] A. Pears, pers. comm., April 9, 2020.

Europe. Europe has been at the forefront of electric technology development and application in industry, in parallel with its efforts to substantially reduce GHG emissions.

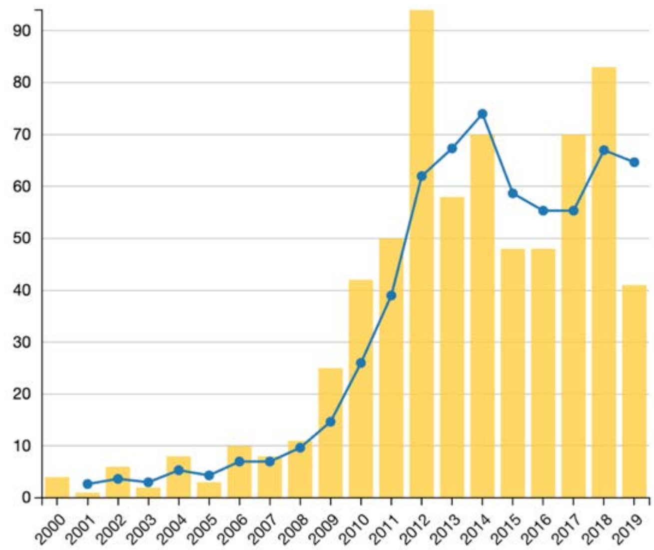

Figure 7. The recent trend in heat pump patents. The bars show the number of patent applications per year, while the line shows the trailing average number of patents. *Source*: ACEEE plot of data from International patent databases accessed with PatentInspiration software.

BOILERS

Electric boilers constitute another major opportunity for electrification and emissions reductions. Some 32% of the combustion energy in industry is associated with boilers (McMillan et al. 2016). Boilers are used extensively to make steam that generates onsite electricity for energy-intensive industries. For example, around 40% of the energy delivered to conventional chemical plants is by steam loops, with the steam coming from a range of boilers or hot gases produced by hydrocarbon combustion (DOE 2015b).

Electric boilers are among the electric technologies showing the highest growth, expanding annually at a rate above 8% (Knoke and Tidball 2011). They are readily integrated with other process equipment as they are controllable/programmable, maintain high efficiency throughout their output range (as opposed to gas boilers, which are less efficient at lower ranges), and do not require air permitting or additional feed-water treatment. These latter two attributes allow companies to save time when implementing the technology.

The cost of electricity relative to natural gas is an important factor. Although the capital cost of electric boilers can be 40% less than that of gas boilers, a study from the National Renewable Energy Laboratory found the hourly fuel cost of an electric boiler can be 2.5 to 3.7 times higher, which can negate some of the capital cost savings (Jadun et al. 2017). The study used gas and electricity prices from 2015, and it is unclear whether demand charges were included in the analysis.

It is also important to note that both relative price and system efficiency need to be considered. If the boiler is not near the application, there will be distribution losses, and if there is poor condensate return as well, efficiency can be low relative to the electric option in the field. Also, as mentioned earlier, intermittent fuel switching can provide energy source flexibility, which can have economic, resilience, and risk benefits. Further, installation of electric technologies can spur inspection and system efficiency gains (e.g., direct electric resistance, immersion, and electric heat tracing), adding to cost justification.

It should also be noted that boiler application, performance, and installation vary considerably, with energy efficiency reflecting fuel type, combustion system limitations, equipment design, and steam system operations requirements (CIBO 2003). This diversity in how the boiler is implemented and optimized to support production of various industrial products suggests elevated design requirements and greater expectations for service and customer support (see Support for New Technology, below).

WASTE HEAT RECOVERY

A portion of the process heat generated by industry (through any means) is not fully recovered, resulting in waste heat. Generating electricity for electric technologies from waste heat provides energy with low additional carbon impact. The lower temperature range of waste heat has a larger work potential than the other temperature regimes due to its vast quantity, creating a significant opportunity for electric technologies (DOE 2016b). Also, heat pumps can upgrade the temperature of waste heat, and not just recover it.

Organic Rankine Cycle (ORC) approaches can be used to generate electricity from waste heat, which in turn can be used to power onsite electric technologies (DOE 2017). If 20% of the 1,800 simple gas turbines in the United States and Europe were retrofit with ORC, an estimated 3 gigawatts of electrical power could be produced (utilizing 90 TBtus of waste heat per year). This would reduce CO_2 emissions by 4.8 million metric tons/year while providing $630 million in economic savings. In addition to ORC, there are other thermodynamic cycles that can be used for waste heat recovery, such as supercritical CO_2, Kalina, and direct electrochemical heat recovery (Jouhara et al. 2018). It is important to note that the theoretical CoP is not as important as the CoP realized in the field as well as overall system efficiency.

The waste heat opportunity also varies across the industrial heat ranges mentioned earlier. A study of industrial waste heat in the European Union showed that one-third of the opportunity was below 200 °C, another 25% in the 200–500 °C range, and the balance above 500 °C (Papapetrou et al. 2018). The total waste heat potential (about 304 TWh/yr) was substantial, at around 16.7% of industrial consumption of process heat and 9.5% of total industrial energy consumption. For the low temperature range, the largest portion of the opportunity is between 100 and 200 °C. This would be a suitable target range for heat pumps. It is likely that this industrial opportunity space is similar in the United States.

For harsh environments (temperatures above 650 °C or containing reactive constituents that complicate heat recovery), the highest potential lies with steel furnaces (46 TWh/year), followed by steel electric arc furnaces (14 TWh/yr), several glass sources, cement, and lime (Vance et al. 2019). The total energy savings potential in these applications is equal to 15% of the heat energy loss in U.S. manufacturing, signaling the need for additional R&D on technologies that would allow recovery of this energy.

Electrolysis to Low-Carbon Energy Carriers

The use of electrolysis to produce low-carbon energy carriers such as hydrogen (H_2), and the use of those chemicals as fuels, reductants, feedstock, and for upgrading petroleum products in refining, represent a low-carbon pathway to net-zero GHG emissions for a number of industrial processes.[16] Electrolysis could play a central role in electrification of multiple processes at the core of several industrial subsectors, so it is important to highlight some cross-cutting and sector-specific aspects of this transformation.

HYDROGEN

Of the hydrogen produced worldwide each year—some 60 million tons valued at $100 billion—some 80% is used in refineries, ammonia production, and metal processing (Brasington 2018). The predominant process for making hydrogen at scale is steam methane reforming (SMR), where methane and water are heated to a high temperature at high pressure in the presence of a catalyst. In addition to hydrogen, this produces CO_2 as a by-product. The heat source can be a variety of hydrocarbons with a high to low carbon content (from coal or coke to natural gas to renewables).

One can think of hydrogen production, then, across a spectrum of carbon intensity (figure 8), from black (SMR using coal or coke) to gray (SMR using natural gas) to blue (SMR using hydrocarbons, but with abatement of CO_2 emissions, for example by carbon capture and storage) to green (electrolysis with low-carbon electricity sources such as renewables or nuclear energy). The current cost for green H_2 is five to seven times that of gray H_2 and three times that of blue H_2, but the cost difference is expected to narrow with increased development and scale (Sandalow et al. 2019). The CO_2 reduction between an electrolytic H_2 via grid-supplied electricity and gray H_2 is around 20–30%. For industry, H_2 via electrolysis using low-carbon sources could drive a much larger drop in CO_2 emissions. This represents a relatively new opportunity to reduce our dependence on carbon-based sources of heat and feedstock.

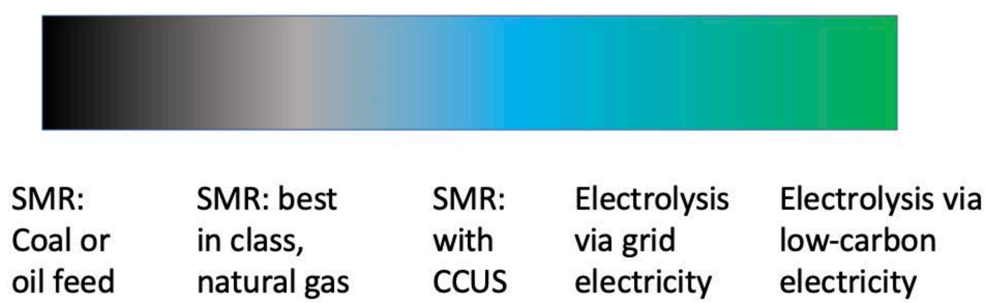

Figure 8. Spectrum of H_2 production carbon intensity. *Source*: ACEEE illustration.

[16] Electrolysis is the use of electricity to effect chemical change in compounds, typically by passing electric current through a liquid or solution with ions.

OTHER LOW-CARBON ENERGY CARRIERS

Electrolysis via electricity from low-carbon sources can provide H_2 for other energy carriers such as methanol, ammonia, and hydrazine and as a result make them lower-carbon products. Methanol is a major chemical with production of 95 billion liters per year globally and is the most-shipped commodity chemical in the world (Hobson and Marquez 2018). Renewable methanol can be produced using the H_2 from renewable electricity or from sustainable biomass. Methanol produced with CO_2 from its production sequestered in Canada at Methanex, when used as automobile fuel, reportedly reduces CO_2 emissions by 30% compared with conventional gasoline.

Ammonia is also among the largest commodity chemicals (due in large part to its use in fertilizers) and accounts for the highest combined level of CO_2 emissions of any chemical produced (ICCA, IEA, and Dechema 2013). The manufacture of hydrogen, a key component of ammonia production, accounts for some 50% of the energy spent and a large part of the GHG emissions in the making of ammonia. Hence, the use of electrolysis from renewables or nuclear is a route of interest for significantly lowering the GHG footprint of ammonia. Yara, one of the major ammonia producers, and Engie are pursuing this opportunity by piloting renewably produced H_2 for ammonia synthesis at Yara's production facilities in Australia. They are also working in Norway with Nel Hydrogen testing new electrolyzer technology (Yara 2019a, 2019b).

INDUSTRY-SPECIFIC OPPORTUNITIES

Several electric technologies have strong growth potential due to industry-specific materials, processes, or nonenergy benefits that deliver product or competitive advantages. Several studies have examined this potential in energy-intensive sectors (Deason et al. 2018). Across those studies, technologies found to have a high potential for adoption include electric boilers, heat pumps, induction melting, and electric arc furnaces. Potential savings by 2030 with these technologies could be as high as 1.27 quads of total primary energy per year (EPRI 2009). Use of electric technologies in industrial applications such as cryogenics, direct arc melting, induction heating, resistance heating and melting, ultraviolet curing (UV), and infrared processing are expected to have very high growth rates (Dennis 2016). An example of the use of UV can be found in polymer processing to induce materials to crosslink at specific surface locations (i.e., enhancing bonds between polymer chains, to improve mechanical stability). The broad portfolio of electric technology options that can be used for various applications is detailed in Appendix A.

Chemicals and Materials

Of the top 11 growth areas for electric technologies in manufacturing, 5 are in materials fabrication (induction heating, UV curing, IR processing, and radiofrequency heating and drying) (Knoke and Tidball 2011). Another area with high expected growth is materials production, which accounts for another three top growth areas (electrolytic reduction, resistance heating, direct arc melting). High growth potential is also seen for electrochemical processes in the primary metals sector. Other promising areas for electric technologies include pulsed power, electroslag processing, acoustics, ultrasound, surface treatments, and curing and drying (Knoke and Tidball 2011).

As shown earlier in figure 5, the chemicals sector uses a substantial quantity of process heat in the low (80–150 °C) and middle (150–300 °C) temperature ranges. This could be an opportunity for electric technologies. Plastics and rubber manufacturing and processing also use significant amounts of process heat in these ranges, as seen in figure 6, and could be another opportunity for expanded application share, growing from the foothold that electric technologies have established already in this application space.

Petroleum Refining

The refining industry is the second-largest energy user in the industrial sector, accounting for about 7% of U.S. energy demand (McMillan et al. 2016). Although each U.S. refinery is unique, one analysis reported that energy efficiency could reduce fuel use in refining by 50% (Morrow et al. 2015). Similar to chemical facilities, refineries can be highly integrated and have high heat loads. They also use a relatively high proportion of heat in the low to moderate ranges (figure 5), suggesting opportunities for electric technologies that can provide heat in those ranges.

For both chemicals and refining, advanced membrane separation technologies hold promise for replacing energy-intensive distillation methods. Here, pressurization handled by electric motors could drive membrane processes such as reverse osmosis, nanofiltration, ultrafiltration, and microfiltration (Van der Bruggen et al. 2003). Membranes are also being utilized in hybrid approaches involving active components, such as in recent work on low-temperature steam reforming of natural gas using a membrane enriched with zeolites (Seeburg et al. 2018).

Iron and Steel

The proportion of U.S. steel made by the basic oxygen furnace (mainly primary steel, made in integrated steel mills) has been on the decline. Meanwhile, the proportion made via the electric arc furnace (typically secondary or recycled steel made in mini-mills) has increased to some 70% (ArcelorMittal 2019b). There may be opportunities for more electrification via additional electric arc furnaces (EAFs), as well as by the introduction of technologies such as electrowinning in basic oxygen furnaces. Electrowinning, which uses electrical energy to reduce iron ore) offers lower capital costs, reduced need to remove the sulfur associated with coal, and lower GHG emissions (Lechtenböhmer et al. 2016). As mentioned earlier, some of the opportunity to transition more production to EAFs could be constrained by availability of scrap steel processing. Electrolytic processes for transforming iron ore into metal and gaseous oxygen (O_2) are in the development stage. These processes would eliminate the need to make coke and the associated emissions of a blast furnace. Electric technologies that reduce the CO_2 emissions of steel and other primary metals are discussed further in the Support RD&D section, below.

The process heat temperature ranges for iron and steel (figure 5) suggest that there may be some opportunity for electric technologies to provide process heat as well in the 150–300 °C range.

Pulp and Paper

As noted above, the pulp and paper industry uses vast quantities of process heat, enough to make it the third-largest industrial energy user (McMillan et al. 2016). About two-thirds of the energy is used to generate steam that is needed for drying and concentrating. This fits with the significant amount of process heat for the <80 °C temperature range (figure 5). There may also be opportunities in the 80–150 °C and 150–300 °C ranges (figure 5).

Steam production is an effective way to utilize the wood waste associated with pulp and paper processes, as is black liquor for chemical use (NETL 2020), because this avoids the need for waste disposal. However, the overall process efficiency needs to be considered as well. The energy content in green wood is only about 10 gigajoules (GJ) per metric ton, compared with air-dried wood at 16 GJ and dry wood at nearly 20 GJ per metric ton (Scion 2008). Considering the large-scale use of wood as a fuel in pulp and paper, there may be opportunities to improve boiler efficiency and boiler capacity by avoiding the energy cost of evaporating the water in the boiler (from wood that is not properly dried). To evaluate whether an electric boiler is an economically viable candidate to replace a current boiler, it is important, then, to consider how the wood waste is being processed/dried and how this impacts whole-system efficiency.

There may be applications for electric technologies starting in smaller facilities, which face challenges in dealing with wood waste and are not as highly integrated. The temperature ranges in the pulp and paper sector are low (compared with those in iron and steel, as well as many of the process heat applications in chemicals and refining), suggesting prospects for electric technologies that provide heat in the low to middle temperature ranges. There are also specific process opportunities for electric technologies such as in paper drying, where for example, infrared dryers, can provide high heat fluxes with absorption of radiation inside the wet web (Stenström 2020).

Food and Beverage

As noted above, the food industry is a large energy user, with process heat usage predominantly in the <80 °C and 80–150 °C temperature ranges (figure 5). This suggests opportunities for electric technologies that can serve those needs today, such as heat pumps, hybrid boilers, induction heating, advanced cooling/refrigeration, and equipment for dewatering, drying, and process heating (EECA 2019). Food preparation and drying providers have readily adopted microwave and infrared for these applications (Knoke and Tidball 2011). In some cases, preservation of moisture in the product is desired as it helps keep the food fresh, but in other cases it is desirable to remove large portions of water to reduce the cost of shipment. In such a case, it is important to remove the water without degrading the product. This is where localized non-thermal or low-thermal electric technologies (such as ultrasound-assisted drying, pulsed electricity field–assisted drying, electromagnetic drying, ohmic heating, or heat pumps) can excel (EECA 2019). The ability to avoid degradation while performing pasteurization/sterilization is also an area where electric technologies (pulsed electric field, ultra-sonification, pulsed light, UV, microwave/radiofrequency) can present advantages.

Some high-temperature applications also exist, such as sugar production, charcoal regeneration (500 °C), and lime kiln firing (316 °C); these are targets for future transformative technologies (Deason et al. 2018). The food sector makes significant use of CHP, signaling high integration. Still, there are likely multiple opportunities for introduction of electric technologies at smaller scale that could pave the way for adoption at larger facilities and at higher scale. The indirect induction heating and cooking of fluids and semisolids is one example of opportunities in this sector; heat recovery chillers are another. In some cases, electric technologies could improve the efficiency of the use of waste biomass (e.g., bagasse, manure) while cutting high-climate-impact methane emissions and waste disposal costs.

A trend to watch in the food sector is the connection of CHP units fueled with renewable energy via microgrids to improve resilience (Dillingham 2019). This could provide an entry point for electric technologies if it prompts redesign of integrated facilities. Indoor agriculture is another trend to watch as it brings production closer to markets, reducing transportation and expanding the range of products made locally. This rapidly growing area could offer an opportunity for electric technologies in handling and moving food products and in onsite preparation.

A key challenge across the food supply chain is reducing food waste. About one-third of all food produced in the United States goes uneaten, most of it ending up in landfills (Vogliano and Brown 2016). In addition to the economic impacts and the squandered opportunity to feed the hungry, food wastage accounts for 3.3. billion metric tons of CO2e emissions/year, one-fourth of the emissions associated with food production. The supply chain accounts for 18% of food-related CO_2 emissions, so it is important to improve the efficiency of the cold chain infrastructure (refrigeration) to minimize food spoilage (Ritchie 2019). Other suggested approaches to minimize waste include the adoption of big data/artificial intelligence and the repurposing and recycling of food waste. All these areas could be potential technical opportunities for electric technologies (Hegnsholt et al. 2018).

Agriculture

The U.S. agriculture sector accounts for 52 million metric tons of CO2e emissions per year from the combustion of fossil fuels (EPA 2016). Agriculture consumes more petroleum products (including distillates) than any other industry in the food system (NCRS 2007). Opportunities in this sector include increased use of electric technologies on the farm, biogas-to-power, and indoor agriculture. Electric membership cooperatives in particular can help farmers increase efficiency, cut costs, and minimize waste (Clark 2018). Co-ops provide power for 56% of the nation's landmass (NRECA 2019). One of the most widespread electrification successes has been replacement of diesel-powered pumping (efficiency 30–40%) with electric motor–driven pumping (efficiency 90%). Besides the efficiency benefits, electric pumps require less maintenance and labor, and variable-frequency drives offer lower costs. The adoption rate of electric pumping is over 70%. Electric water heaters have also achieved high penetration. Electric technologies with good promise for additional penetration include thermal-electric storage systems, radiant heaters, heat pumps, and heat exchangers.

A survey of electric technologies for application in agriculture, and other industries, showed applications in drying, pasteurization, sterilization, cooking and other heating applications (EECA 2019). An example application is space heating of chicken houses. More than 6 billion broiler chickens are produced each year in the United States, and more than 85% of the houses where they are raised are currently heated with fossil fuels (mainly propane, plus 15% natural gas). An estimated 4,755 GWh of electricity would be required to replace these fossil fuels. Electric technologies such as thermal electric storage systems, waste heat recovery, radiant heaters, and heat pumps are candidates.

Meeting Challenges

The acceleration of beneficial electrification faces challenges related to replacing installed capital, economics, and preparation for new technology (including standards, protocols, and capability awareness). These challenges can hamper the adoption and dispersion of new technologies across the various industrial sectors and must be addressed.

ELECTRICITY'S LOW-CARBON FOOTPRINT

For electrification to be beneficial, the electricity provided has to have a smaller carbon footprint than the alternative onsite fuel, which points to changes needed in generation, distribution, and storage. The proportion of renewable power generation varies considerably across the states, as shown in figure 9. Several states in the Northwest and Northeast have relatively high levels of renewable power generation (well above the U.S. average of 17%), typically starting with a foundation of hydroelectric. Four states have set targets for 100% renewable power by 2050 or before, and seven others have set targets for 100% clean power (which includes nuclear) (Fields 2019).

The availability and ramp-up of low-carbon power must be considered when gauging the degree to which beneficial electrification can reduce the industrial carbon footprint. Efforts to shrink this footprint with electrification need to run in parallel with efforts to increase low-carbon generation capacity.

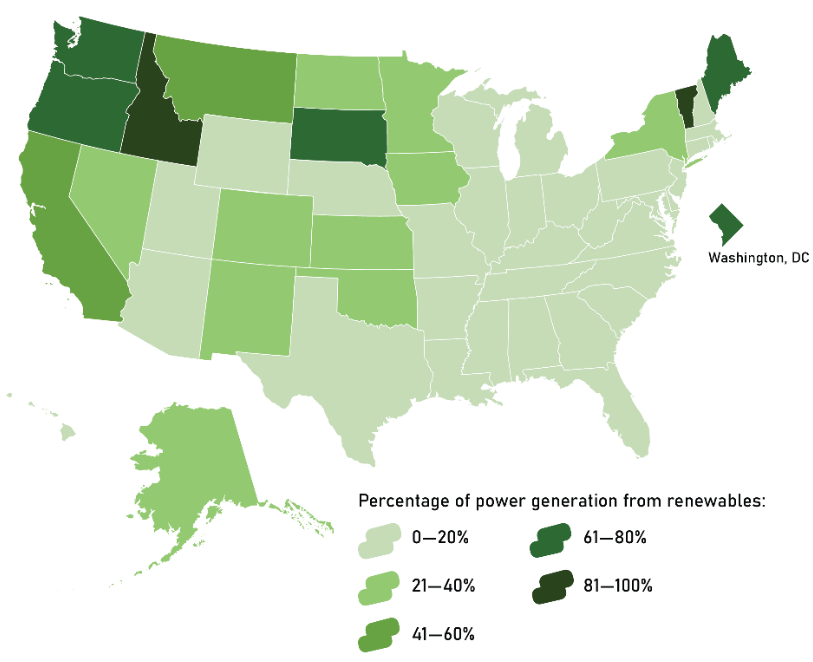

Figure 9. Power generation from renewable energy sources, by state. *Source:* EIA 2020e.

The picture for clean energy (including nuclear) shows greater availability of these resources across states (figure 10).

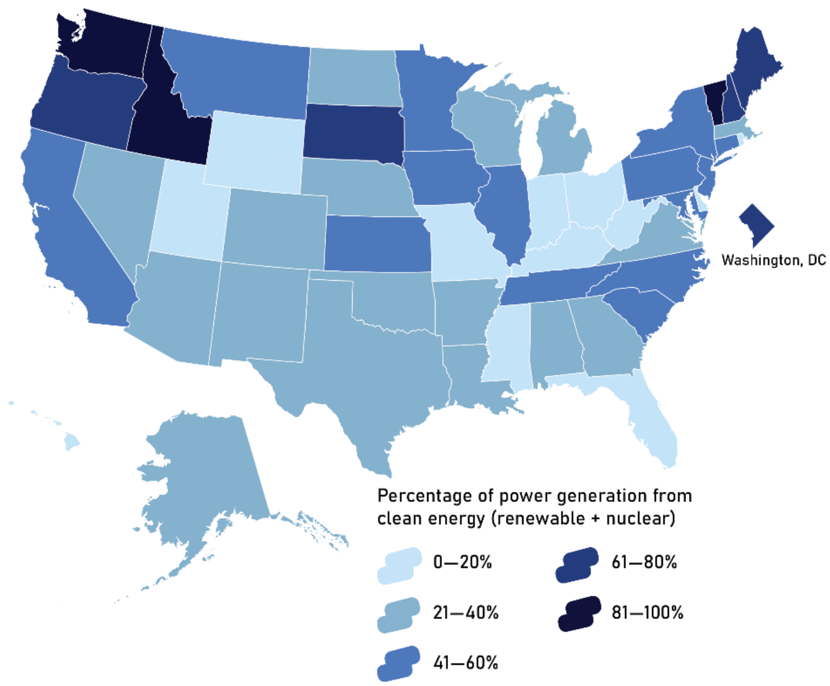

Figure 10. Power generation from clean energy sources, by state. *Source:* EIA 2020e.

Energy-intensive industries tend to locate in areas with inexpensive transportation and fuel and proximity to markets, but these areas do not have high renewable energy capacity today (e.g., compare figures 10 and 15). None of the states along the Gulf Coast, where there is a concentration of chemicals and refining, have more than 20% renewable power generation. California has just over 40% renewable power as well as the third-highest refinery capacity (after Texas and Louisiana). Given its renewable power percentage, it could be a location with moderate potential for beneficial electrification in the refining industry. For electrification to have a significant net GHG reduction, inexpensive low-carbon electricity will need to be distributed to regions with high industrial activity, or low-carbon generation capacity will have to be built in regions where industry is clustered.

ENERGY STORAGE

Industry needs highly reliable power delivery (99.9%+ reliability), and for most applications at scale the delivery needs to be continuous 24/7. Some form of energy storage, then, is key if the energy comes from renewables, as generation is typically variable. There are multiple direct electrical storage options, such as batteries, which have been rapidly developing scale (Bloch et al. 2020). Others are pumped hydro, thermal, flow batteries, and compressed air, including emerging options with direct ties to the grid (Atwell 2018).

An alternative to the direct electrification approach (shrinking carbon footprints via use of renewable energy) is the indirect approach of converting variable energy like wind and solar to the energy carriers noted above (e.g., hydrogen, ammonia, hydrazine, ethanol), storing and transporting those energy carriers, and then using them in industry. This approach would fit well with the experience, value chain, and transportation elements of the chemical and refining industries. It would also avoid some of the expensive changes in existing infrastructure based on fossil fuels and steam, thereby preventing some stranding of assets. Some of these fuels (e.g., hydrogen) could be distributed by pipeline, potentially leveraging the current natural gas pipeline infrastructure. The Fuel Cell and Hydrogen Energy Association (FCHEA) has reported that hydrogen could be blended into natural gas at around 4–5% without major modifications; higher concentrations would likely be constrained by limitations in end-use equipment (FCHEA 2019). The ability of boilers and turbines in particular to run on blends with a higher content of hydrogen is of interest. When these challenges are overcome, the FCHEA *Road Map to a U.S. Hydrogen Economy* estimates that "hydrogen could meet 20 to 25 percent of high-grade, 5 to 10 percent of medium-grade, and up to 5 percent of low-grade heat and power requirements. This could reduce U.S. industrial emissions by 6 percent."

The level of storage needed to supply industry could be immense if electrification took huge steps forward, and conversion to liquid fuels is a good option from an energy density perspective. Considering the concentration of industrial sectors in particular areas (e.g., the Gulf Coast), local needs for electricity and storage could be substantial if electrification rapidly occurred.

Another energy storage possibility is thermal storage. A top option is sensible thermal storage, in which a liquid or solid storage medium (such as water, molten salts, or rocks) is heated or cooled, thereby storing energy (Harvey 2017). Latent heat storage, in which the storage medium changes states (e.g., solid to liquid), is less common; while it can be more expensive, it can offer advantages such as three times higher energy density. Thermochemical storage, in which chemical reactions store the energy, can offer even higher energy density but again can be more expensive.

An additional option is to use this energy to make intermediate products that are suitable for batch production. For example, cement clinker could be produced and stored for grinding when zero-emission electricity is available or cheap.

COST OF ELECTRICITY VERSUS NATURAL GAS

An element of the economic challenge for widespread adoption of electric technologies across industry is the cost of electricity relative to natural gas. In the United States, the average cost ratio ranges from 2 to 14, as shown in Figure 11. States where electricity prices are relatively low and the cost of gas relatively high are shown in dark purple and include Washington, Montana, New York, Pennsylvania, Maryland, and Delaware. Electrification is potentially more financially feasible in these states.

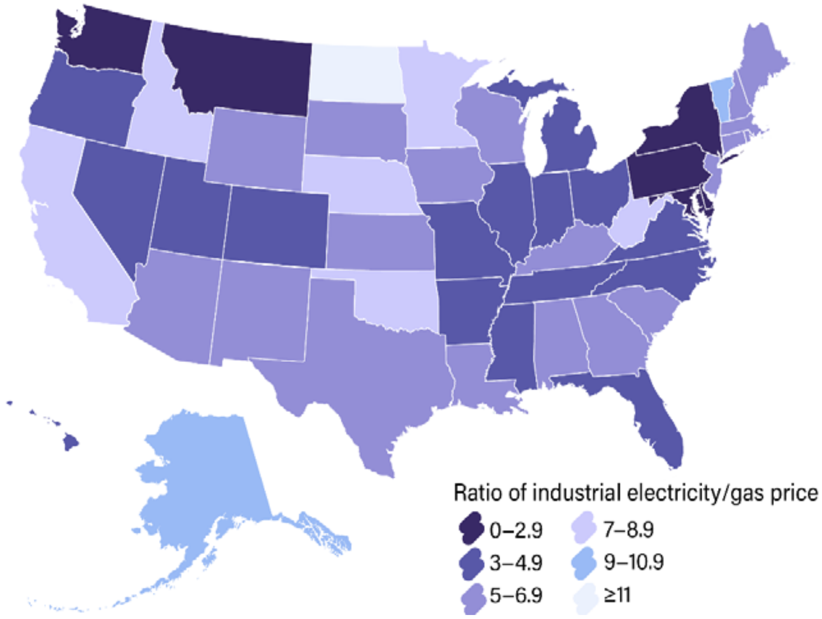

Figure 11. Ratio of industrial electricity to gas price by state. Calculation based on average annual electricity prices and Henry Hub natural gas prices within states. *Sources:* EIA 2020b, 2020e.

It is worth noting that in general the price of delivered electricity has been trending up while the cost of natural gas has been trending down, as shown in figure 12, due to the abundance of shale gas. The severe demand drop for hydrocarbons caused by the COVID-19 pandemic coupled with the oil price war between Russia and Saudi Arabia has sent oil prices well below the economic threshold for shale gas, which puts additional pressure on shale gas producers. It is forecast that following the worst of the crisis, natural gas prices will rise due to decreased production (Rogers and He 2020).

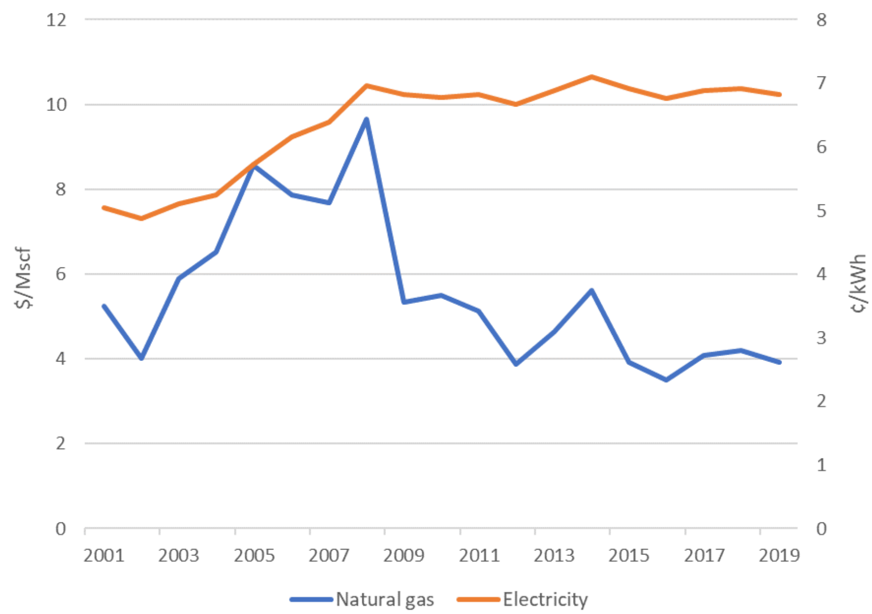

Figure 12. Industrial price trends of natural gas and electricity. *Sources*: EIA 2020b, 2020f.

The benefits of electrification can be more evident when companies' decisions around fuel choice take reliability and flexibility into account. The expansion of natural gas use has resulted in more outages as capacity has been stretched. States with the highest incidence of outages are those with the most extensive infrastructure (Page 2017), including Texas, Louisiana, Wyoming, and Pennsylvania. The ability to use electricity when it is inexpensive, or where peak gas prices create significant costs, can also aid the economic argument.

The presence of a carbon price is another factor that could aid beneficial electrification. In California, for example, the carbon price is beginning to have an impact on natural gas prices in the state (Woo et al. 2017). In Canada the price of natural gas increased by 4 cents per cubic meter after the imposition of a carbon tax, which is slated to increase to 10 cents in 2022 (Direct Energy 2019). There is also a delivery or transportation charge that varies from 0.0036 cents to 0.0084 cents per cubic meter depending on the business classification. Adding these costs to the economics could also aid the case for substitution with an electric technology.

VARIABLE RENEWABLE ENERGY

At times, electricity could be available at substantially lower prices in areas in which there is surplus renewable energy (also called "curtailed" renewable energy). In California, during certain portions of the day when excess renewable energy is available, large users are being *paid* up to $25/MWh to consume power. During the early spring curtailment rates rise; in the spring of 2019 more than 630,000 MWh of wind and solar generation were curtailed in California (Maloney 2019). Where substantial renewables have been deployed, there has been a decrease in power prices (typically $1.3/MWh or less, although California was higher, at $2.2/MWh) (Mills et al. 2019).

Industry could potentially use this energy, particularly for processes that can be run via batch operation, such as the production of chlorine and H_2 via electrolysis. A project in Belgium launched the first commercial H_2 facility powered by surplus renewable energy (Collins 2020). A study of industrial demand response potential in the U.S. Western Interconnection showed that some 24% of the electrical demand was from a wide distribution of industries, and that the percentage of demand response capability ranged from 0.8% to 2.4%, depending on criterion (Starke, Alkadi, and Ma 2013).

Although this would take advantage of inexpensive sources of electricity, asset utilization remains a challenge. This is an issue for wind and solar facilities as it impacts their rates of return when the asset is not utilized full time. It is a significant issue for industry as well, because large, heavily capitalized operations count on high utilization rates to maximize return on capital and operations efficiency. Running intermittently to take advantage of an intermittent renewable source is typically not a good fit at these large manufacturing facilities. However, if the variability could be buffered by utilizing intermittent storage (generation of an intermediate product, for example, or a low-carbon fuel like H_2), or if the source of energy could be readily switched, this could allow industry to take advantage of curtailed energy. The latter case is reminiscent of the hybrid approach for dual-source boilers discussed above.

There are a number of other ways to address the variability of electricity supply so that industry can take advantage of these low-carbon sources via electric technologies. One way is to run at higher rates when electrical energy is lower in cost and large quantities are available. However, while that sounds attractive, there can be limitations in response rate, logistics/supply chain implications for handling the increased product, and market limitations. Industrial processes are often run on the basis of a market demand forecast, and running at higher rates when market demand is not high can result in additional costs for product handling, storage, and transportation. Hybrid solutions at sites where both gas and electricity prices are variable may be a way to provide flexibility while also improving plant reliability.

INSTALLED CAPITAL AND THE RATE OF CHANGE

It only takes a brief visit to a major facility of one of the energy intensive industries to understand the scale of capital equipment investment, decades spent integrating product, heat and energy flows to optimize processes and improve efficiency, and complexity of material and product handling. For example, large chemical or refinery facilities can cover tens of square miles and even simplistic diagrams of their energy or product dependencies can cause most people to ask for something simpler. The level of capital investment, complexity, and risk factors lead to the need for a strong value proposition and persistence to effect change.

Replacing Installed Capital

Industry is ruled by economics, the potential for future value return, and the ability to retain or expand market share to ensure long-term success. Therefore, companies closely scrutinize risk, comparative costs for new technology to replace assets that are already installed (and potentially not yet fully depreciated), and the ability to reliably deliver product that meets customer expectations. The cost of equipment, process complexity, thin margins for large-volume base products, and complicated value chain relationships lead to long equipment lifetimes (30–50 years), making rapid changeover challenging. Emerging competitors can, however, adopt newer technologies and modular options, challenging the status quo and leading a disruptive technology wave that other manufacturers catch up to eventually. Looking to another industrial segment, Tesla is one such firm; because it does not have to manage a large existing manufacturing operation, it can innovate and be agile.

Risk Sensitivity

Investment decisions in industry are strongly influenced by economic parameters including return on investment (ROI), payback period, and discounted cash flow (Elliott 2007). The capital cycle can be a torturous process in large companies that need to balance multiple considerations, such as investment across global regions, businesses growth, technology replacement, environmental and regulatory issues, and safety. Early budget targets are often squeezed and readjusted multiple times during the year in response to market signals. The threshold for capital funding can be higher than 30% ROI, causing projects that have positive economics (such as electrification projects) to have to wait for consideration.

Competition for scarce capital investment funds is fierce; therefore, electrification has to have strong monetary benefits (return on capital, market growth, reduction in future costs such as maintenance) as well as soft benefits (customer support, employee satisfaction, sustainability). Willingness to take technology risks is typically low in such a competitive funding environment, and equipment that has worked well in the past is often the preferred option. This is particularly the case where process integration is high, redundancy is low, and a company’s ability to support new equipment (maintenance, technical) is low.

Low Turnover of High-Capital-Cost Stock

As mentioned, the industrial sector has relatively low stock turnover and high capital costs and operates with relatively low margins. It is also highly competitive and conservative. The result is that industrial capital investment and equipment service life can be many times longer than equipment in residential service (figure 13). In this figure the text on the right shows the number of replacements during a time horizon (e.g., 40 years), the length of bars the average time for replacement of hardware, and colors highlight individual replacements where more than one replacement occurs during this time window. For example, in 40 years electric lighting could have more than 2+ replacements, industrial boilers could have up to one replacement, and core processing facilities (e.g., an ethane cracker in the chemicals industry or oxygen furnace in a steel foundry) might have zero replacements.

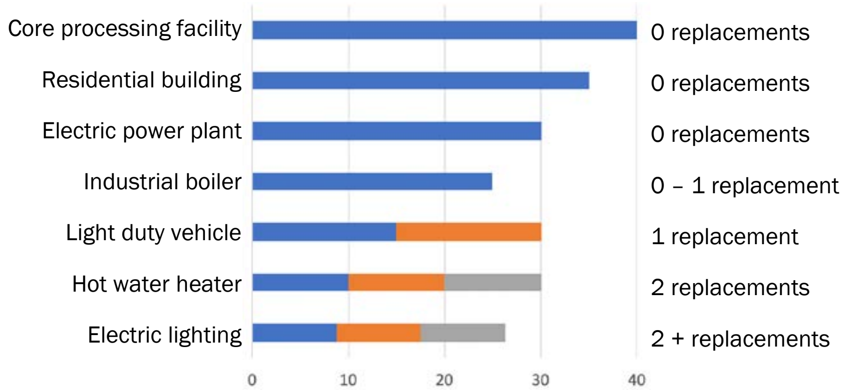

Figure 13. Equipment lifetimes with color bars highlighting replacements so they are more visible.
Source: Williams et al. 2015.

Under normal circumstances it can take decades for technology to transition from demonstration to a high level of adoption (Grubler, Wilson, and Nemet 2016). In larger, more complex industries this takes even longer due to multiple ways that infrastructure is interconnected, large numbers of late adopters, and greater diversity in innovation drivers. The complexity of instituting innovation across multiple systems (versus single technologies) also influences the rate of adoption and the time it takes for innovative technologies to diffuse throughout the sector. Given this capital inertia, it is important that when opportunities arise to replace high-cost, long-lifetime capital equipment, the equipment be replaced with the most effective low-carbon technology.

If the regulatory landscape or societal needs evolve quickly, however, industry may have to leave behind some installed capital (no longer useful to meet customer needs or crippled by step-changes in the regulatory environment), leaving "stranded assets." This represents a risk for corporations, the financial industry, and downstream stakeholders (Material Economics and SEI 2018).

Process Integration

The interrelationship of downstream processes, and their intertwined economics, can also be a challenge for technology replacement. Industry improves the efficiency of energy and heat use via integration across systems. Data handling, workflows, materials and waste handling, and so on need to function reliably, efficiently, and economically across multiple systems. This can make replacement of individual components or systems complicated because changing a component in one system may disrupt other systems that depend on how that component performs. Modifying one component of a system can require changes elsewhere.

Combined heat and power (CHP) is an example of equipment that delivers multiple benefits and hence is highly leveraged and integrated into production facilities. CHP has historically been used in industry to provide reliable heat and power with high efficiency, reliability, and low emissions. CHP units replace separate thermal and power generation facilities with a combined unit, and being onsite, they minimize transmission and distribution losses from grid-purchased power. As shown in figure 14, multiple industries extensively use CHP. Today the 67 GW of installed CHP capacity in U.S. industry supplies 13% of the energy consumed in manufacturing and reduces CO_2 emissions by 200 million metric tons of CO2e per year (DOE 2020b).

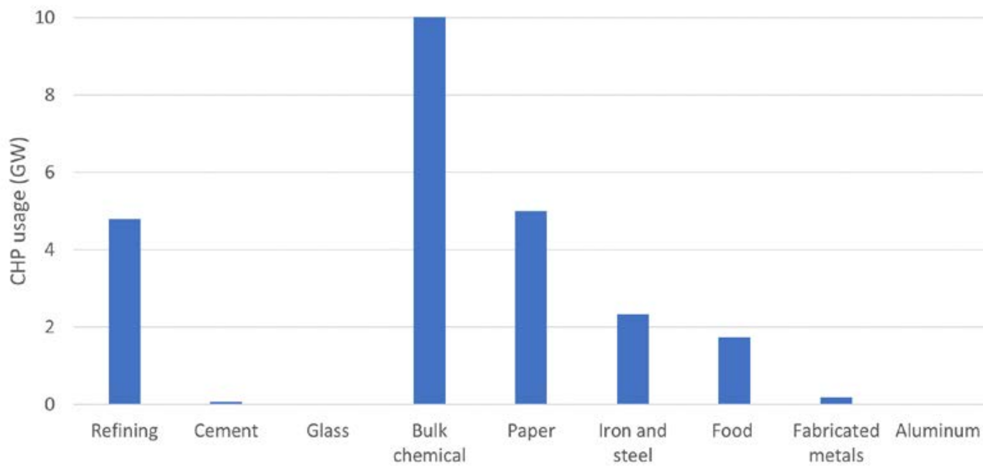

Figure 14. Use of CHP by the industrial sector. *Source:* EIA 2017.

CHP provides both steam and electricity with 25–35% lower primary energy use and thus lower emissions as well (Jadun et al. 2017). Since the heat recycled from CHP is often used in multiple downstream processes, the economics and efficiency of those downstream processes are intertwined with the presence of CHP.

Although the high level of CHP in these industries and the high degree of process integration can potentially make replacement of whole systems with alternative technologies challenging, CHP installations can be integrated with distributed energy resources (wind, solar) and microgrids, helping to balance the variable nature of these resources (ICF International 2019). Markets for hybrid CHP systems are growing. CHP units can also run on renewable fuels, and some 23% of these units do so today. These capabilities add to CHP's versatility. It is also worth noting a trend toward smaller commercial facilities installing CHP to save on energy bills, provide resilience, and improve competitiveness (Hampson and Hedman 2018).

PREPARING FOR NEW TECHNOLOGY

In industry, there are a number of steps to adoption of new technology that make it a more arduous process than in the residential or commercial sectors. For example, in the residential market people can purchase appliances with new technology that are designed for ranges of customer needs, are certified for home application, and have standardized performance measurements (such as ENERGY STAR®). These units are readily installed and plugged in; risks have been minimized through certification, review, testing, and other measures; and service and support are readily available. Conversely, new technology for industry faces a range of application and custom integration needs. There is rarely standardized performance testing or certification, and nationwide service and support from the emerging companies selling such equipment can be questionable. Preparing for new technology will require developing better support and service in the field, understanding new capabilities (like smart manufacturing) to make the technology more effective, building awareness of benefits, and developing standards and protocols that may ease implementation.

Support of New Technology in the Field

Industry needs high reliability, low maintenance, and consistent performance that meets key process indicators. This makes support of new technologies at industrial sites crucial, especially since equipment is often custom designed or tailored to meet specific manufacturing needs. Either the manufacturer or the vendor must be able to provide excellent support in the field, or staff at the industrial site must be trained to have the requisite level of expertise. Receiving high levels of support for customized electric technologies has been an issue in industry. This has led companies to be unwilling to invest in heat pumps until support issues have been addressed, including:

- *Vendor continuity problems.* Past experience with industrial heat pumps have been negative because vendors have discontinued the products or gone out of business, stranding the asset and requiring its removal and replacement with conventional equipment. Evidence that vendors have the capacity and resources to support the product in the long run is needed for expanded industrial adoption of heat pumps.
- *Lack of technical support from vendors.* Electric equipment requires vendor technical support that is not widely available, leading to high costs and the potential disruption of production while waiting for technicians and parts.
- *Thermal integration expertise***.** This is limited and expensive: the analysis of thermal systems to identify opportunities for heat pump applications is specialized and requires specialized engineering skills.

Smart Manufacturing

Smart manufacturing (SM) uses information and computer technology to increase flexibility in manufacturing while reducing wasted materials and energy. The Smart Manufacturing Institute (CESMII) has developed SM profiles that represent an industry-standard way to create sharable, digital templates for any manufacturing asset (sensor, machine, process) (CESMII 2019). The profiles can be scaled and leveraged by other manufacturers who are using similar equipment for similar applications.[17] The profiles allow direct measurement of energy consumption in real time so that it can be more effectively managed, thereby reducing energy use and GHG emissions. Use of these profiles for electric technologies could help speed adoption and quantification of the energy and nonenergy benefits mentioned earlier (see table 1).

Opportunity Awareness, Protocols, and Standards

Even in cases where electrification of industrial processes or systems is a positive move and brings a company energy or nonenergy benefits, those benefits are often not well known

[17] SM profiles provide an industry-standard way to create sharable digital templates for any manufacturing asset, allowing digital data communication and analytics. The standardized profiles allow leveraging of SM capabilities to any company with that type of machine or asset. In effect this crowd-sources expertise in the manufacturing domain, providing access to SM advantages to small and medium-size manufacturers (who often lack the resources to develop these communications and data analytics capabilities on their own).

outside (or sometimes inside) the company. The company may choose to not publish or communicate those benefits and keep them as trade secrets.[18, 19] Competitors can often find creative ways around patent protections, and patent trolls aggressively secure intellectual property, complicating the right to practice.

The lack of published information on economics, engineering, and performance creates challenges for those who seek to justify and encourage the adoption of electric technologies. Acceptance and use of new technologies can spread relatively quickly within companies if the advantages are conspicuous; however, if these advantages are not widely known, companies not on the leading edge take many years to adopt (Rogers 2003). When the time comes to replace equipment, new technologies with little performance data, high perceived risk, and immature supply chains and maintenance infrastructure must compete with incumbents that have decades of data and comprehensive support systems.

For technology to be adopted rapidly, there needs to be a combination of market pull and push. The pull comes from positive economics, recognition of benefits, and willingness to pay for the technology; the push comes in the form of advocacy from vendors and electric utilities and support from policymakers. New technologies need to establish a well-publicized track record to increase companies' confidence in their adoption. Demonstrations are needed for technologies at scale, with case studies, and the information to be available across sectors. Lead users need to be identified, encouraged, and recognized. It is often individuals and small teams that provide leadership in making the case for and implementing new technology. There is emerging recognition that these innovative actions should be recognized, such as with DOE's ITEAM Prize (DOE 2020c). Engineering, economic, and integration information needs to be shared widely.

Centralized clearinghouses are needed for information on the performance of new technologies. This would be precompetitive work so that issues with intellectual property and commercialization are avoided.

Communications and Protocols

For new technology to be readily adopted, a number of technical protocols and standards have to be in place to ensure safe operation of equipment. Organizations that develop code and equipment standards may need to increase capacity to prepare for adoption of electrotechnologies across multiple industries. They will also need to address the disparity in the standards process for electric and combustion-fueled equipment, which makes it difficult to evaluate the relative efficiency and cost effectiveness of electric versus nonelectric technologies (Deason et al. 2018).

It is also important that communications standards be validated between electric technologies and process control systems to avoid interface issues. The challenge of

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[18] P. Stephens, Electric Power Research Institute, pers. comm., 2019.

[19] K. Thirumaran, Oak Ridge National Laboratory, pers. comm., 2019.

troubleshooting an interface issue for new technology creates delays and adds personnel time, which is non-value-added time for industry. If more of the interface and compatibility issues can be addressed up front through common communication protocols, this will lower hurdles for implementation.

As discussed previously, one route to speed up adoption of electric technologies is to increase companies' knowledge of their benefits. Engineering, economic, and interface comparisons are needed from an independent organization for electric technologies in common applications; this would allow a body of information to be assembled to support a company's evaluation process. A number of currently available resources need higher visibility, including DOE's case studies, tip sheets, sourcebooks, and ENERGY STAR guides (DOE 2020a, 2020b).

Maximizing Opportunities

There are several ways to pursue early opportunities for beneficial electrification while addressing the challenges noted above and advancing technology. These include:

- Focusing on top prospects or niche opportunities where multiple benefits or high value can be captured
- Maximizing energy efficiency
- Maximizing nonenergy benefits
- Supporting RD&D
- Optimizing economics
- Strengthening supportive policy

FOCUS ON TOP PROSPECTS

Starting points for beneficial electrification might include identifying geographic opportunity zones where industry is concentrated, where there is a high proportion of current or planned low-carbon electricity, and where support avenues could accelerate adoption.

Concentrations of Industry

Opportunities for electrification for certain industrial applications may be localized in regions of concentrated activity. Figure 15 shows the location of major facilities for petroleum refining as an example of the localization of an industry that uses large amounts of process heat (EPA 2020a). Four states (Texas, Louisiana, California, and Illinois) account for 67% of the emissions in refining in the GHG reporting database (EPA 2020b).

The concentration of chemical production facilities is similar, with three states (Texas, Louisiana, and California) accounting for 60% of the emissions. It is interesting to note that hydrogen production across the chemical sector accounted for 26% of emissions, and ammonia accounted for 19%. Hydrogen production also accounted for the majority of industrial GHG emissions in California. This is a marker for the potential for electrolysis and other low-carbon routes to produce H_2, which is a major input for ammonia production, while also reducing GHG footprint.

For the metals sector, four states account for 70% of GHG emissions (Indiana, Ohio, Michigan, and Pennsylvania), with Indiana alone producing nearly 40% of the total. Pulp and paper production is more spread out, as is food production, but it is likely there are some concentrations in states that could be of interest for leveraging efforts to accelerate beneficial electrification.

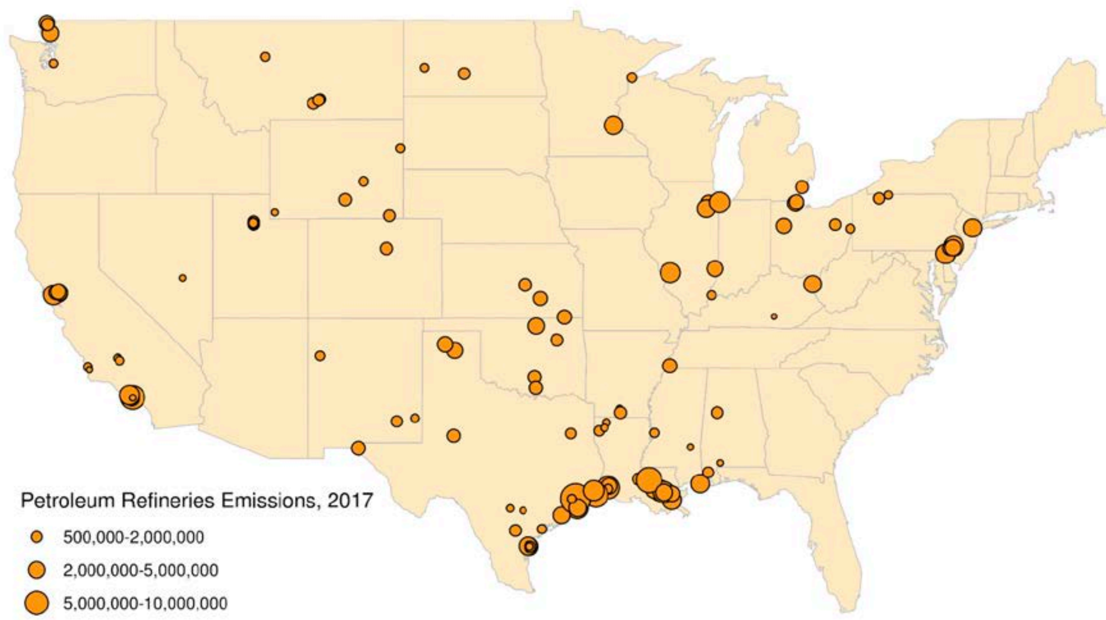

Figure 15. Concentration of petroleum refineries, as measured by CO2e emissions (metric tons/year). *Source:* EPA 2020a.

In the U.S. Northeast, two key electrification opportunities are glassmaking and the production of iron, steel, and other metal products, based on the fuel usage, value, and volume/mass of the products produced (Hopkins et al. 2017). More than half of the glass, iron, and steel value produced in the Northeast is in New York State, and efforts in this state could spur electrification. In California, electrification prospects include key process equipment across multiple industries, and a shift could reduce industrial emissions by 63% (5.7 MMT CO_2 per year) using existing technologies (Stephens and Krishnamoorthy 2019). The economic viability of electric technologies for these applications varies with several factors, including the ratio of local electricity price versus fossil fuel alternatives, capital and maintenance costs, and application efficiency. For example, comparing electric melting technologies versus air–fuel furnaces for glass manufacture, these factors suggest that smaller-capacity electric furnaces (producing less than 75 metric tons of glass per day) are generally viable, furnaces producing from 75 to 150 tons can be viable in some circumstances, and those with production greater than 150 tons per day are unlikely to be viable (Scalet et al. 2013).

One way to lower adoption barriers to electrification in industry is to establish local partnerships where industry is concentrated geographically to pursue demonstration of electric technologies at increasing scale. Partnerships across industry, government agencies, national laboratories, local and state economic development authorities, and other entities could help identify electric technologies that best align with industrial applications. They could also advance the use of these technologies to higher-end applications (e.g., midrange process heat) and provide unbiased data that are accessible by the community of engineers who evaluate and develop justification cases for equipment replacement (e.g., replacing steam service at a facility with an electric heat pump). Additionally, partnerships would allow training for a cohort of engineers at local industrial facilities on implementation of these technologies. They can also provide input on which policies best support this transformation.

Awareness of Low-Carbon Electricity Proportions

For electrification in industry to accelerate *and* be beneficial, the availability of low-carbon electricity at competitive rates must be increased. As the grid moves toward 100% low-carbon electricity, the GHG benefits of electrification will increase, but until then it is important to recognize the proportion of low-carbon energy in the grid to understand the magnitude of electrification benefits in the near future. Regional differences in the proportion of low-carbon electricity, transportation/delivery infrastructure, storage, and so on may influence the ability of industry to realize the full magnitude of GHG reduction benefits immediately.

The low-carbon electricity generation mix varies considerably by state (Popovich 2018). For a hypothetical project implemented in 2017 in Texas, for example, only a 15% share of the electricity would be from low-carbon sources (primarily wind), whereas 45% would be from natural gas, 30% coal, and 9% nuclear. If the project was in California, it would have a better proportion of low-carbon electricity: 20% would be hydroelectric, 16% solar, 6% wind, and 5% geothermal and biomass (for a total of 47%, with the balance mainly natural gas). If the project was in Missouri, the share of electricity from low-carbon sources would be small, since the 2017 source mix was 80% coal, 10% nuclear, 6% natural gas, and around 2% hydroelectric.

The degree to which electricity will be low carbon in the future depends on states' targets and communities' demand for renewable generation and how quickly they move toward those targets. Energy mixes are likely to have greater proportions of renewable energy in the future as multiple states have set goals for utilities to supply 100% renewable energy by 2050; these include California, Hawaii, Maine, Nevada, New Mexico, New York, and Washington, along with the District of Columbia (Quinton 2019). With the exception of California, however, this list of states with aggressive targets for 100% renewable energy largely excludes those with industrial clusters. There is an opportunity for other states with high concentrations of industry to link the benefits of electrification with a target for increased levels of renewable energy generation.

SUPPORT RD&D

Many emerging and frontier electric technologies are in various stages of research, development, and demonstration (RD&D). The Electric Power Research Institute (EPRI) keeps a running assessment of a large number of current and emerging electric technologies that can be used across multiple industries, providing an outlook on application openings and potential impact (Stephens and Krishnamoorthy 2019).

For energy-intensive industries, several research initiatives are underway that could be transformative, potentially expanding electrification in process systems that are at the core of production for these industries. The potential for operating naphtha or gas steam crackers with renewable electricity is also being investigated by a consortium of six chemical companies (Borealis 2019). TNO Voltachem is working with a range of partners to electrify the chemicals industry via three main steps: using electricity to generate or upgrade heat, using renewable hydrogen to shrink the carbon footprint of select chemicals (avoiding the high levels of fossil energy used today to generate hydrogen), and using electricity directly in chemical processes during synthesis. Success in this area could revolutionize energy use and would be a major step for electrification in the hard-to-electrify industries.

Similarly, scientists and engineers at TU Delft are researching where electrochemical production of key chemicals is feasible and economical, starting with methane, methanol, carbon monoxide, and ammonia (TU Delft 2019). A range of research initiatives are targeting dramatic improvements to, or alternatives to, the Haber-Bosch process for ammonia production (mainly used for fertilizers) as it accounts for 1% of global GHG emissions. This research includes electrochemical, atmospheric ammonia synthesis in a ceramic membrane reactor that uses 25% less energy and emits 50% less CO_2 than the conventional process (Boerner 2019). Also, as mentioned earlier, Yara and Engie are collaborating on a project to produce ammonia from H_2 generated by renewable energy (Yara 2019a).

In the aluminum smelting industry, Alcoa and Rio Tinto have launched a joint venture called Elysis that is pioneering a process to make "low-carbon" aluminum. Reductions in CO_2 emissions in this sector are important as on average the aluminum industry generates 12 tons of CO_2 for every ton of aluminum at the smelter (Hotter 2018). This process, which uses proprietary anode and cathode materials, yields a 30-fold increase in anode life, reduces operating costs by 15%, and increases production by 15% (Hotter 2018). It also is projected to eliminate 6.5 million metric tons of CO_2 per year if fully implemented at all existing aluminum smelters in Canada. This is a significant step forward in reducing process-related CO_2 emissions. Apple is facilitating the collaboration and providing technical support. A life-cycle analysis for aluminum production in North America showed that upstream electricity generation accounts for 70% of the electrolysis emissions (the remaining 30% comes from anode manufacture). Aluminum manufacture is a good example of the proportion of renewable energy used as multiple producers have sought out renewable power. In North America, 75% of the power used for aluminum manufacture is from renewables (largely hydropower); adjusting for the difference in power generation efficiencies, renewable energy fills 36% of the energy demand (Aluminum Association 2013).

Advanced processes for other primary metals production with electrification have also evolved from collaborative RD&D. For example, a modular, molten oxide electrolysis process is emerging to directly reduce iron and other metals with emissions of only oxygen (Rauwerdink 2019). The process was developed at the Massachusetts Institute of Technology and received support from DOE. The process requires less energy per ton than the incumbent process, but the level of decarbonization achievable will depend on access to large amounts of low-carbon electricity. Widespread deployment of this technology or similar with low-carbon electricity has the potential to significantly reduce CO_2 emissions as steel is responsible for 7% of global CO_2 emissions. A low-temperature electrolytic process of iron ore in alkaline solution is being developed by ArcelorMittal. Called the SIDERWIN process, it is at the large pilot stage (ArcelorMittal 2019b). The use of electricity for both technologies, if supplied by renewable energy, could significantly shrink the GHG footprint of steel production.

Government should play a greater role in supporting demonstration of electric technologies at commercial scale. DOE runs a number of programs that support electrification (DOE 2016a; Deason et al. 2018). Those programs should be expanded, and partnership with industry and technology developers increased. Demonstrations are needed across various sectors at scale, with case studies. Support should be extended to address questions during technology scale-up in partnership with industry, technology implementers, and venture capital. Industrial networks and centers of excellence for electrification should be established to catalyze technology innovation, adoption, and communication across multiple systems.

OPTIMIZE ECONOMICS

A range of electric rate design options should be pursued to help improve the economics for replacement of incumbent technologies with electric technologies. Utilities have multiple options to enable this effort, including charging less for off-peak electricity and for excess variable renewable energy (time-varying rates) and rewarding newly electrified end uses that have usage flexibility (e.g., demand response) (Deason et al. 2018). In addition, a range of fiscal approaches should be considered to address the cost gaps, including:

- Revolving loan funds
- Loan guarantees and loan-loss reserve funds
- Tax credits
- Grants or in-kind services
- Manufacturer rebates for products
- A risk-sharing program that uses a loan-loss reserve approach

Utilities and regulators should provide incentives for electric technologies when they are cost effective and reduce emissions. Rebates to end-use customers can be helpful but encounter supply constraints; targeting incentives to vendors can be more effective (EPRI 2018). When utilities in California applied incentives targeted to distributors, sales of premium electric motors increased by more than in the four previous years combined (Barbour, Kulakowski, and Harwick 2000).

STRENGTHEN SUPPORTIVE POLICY

Recognizing that equipment turnovers are infrequent, policies should be put in place ensuring that when opportunities arise for equipment replacement, companies have the necessary information and incentives to justify the adoption of electric technologies. Policy approaches could defray some of the extra costs associated with the low capital utilization rates that accompany facilities' use of variable renewable sources of electricity (wind, solar). Policy mechanisms also can mitigate the impact of stranded assets and the risks associated with rapid transitions. Among the multiple approaches is compensation for a portion of the investment stranded (Bos and Gupta 2019).

It is also important that policies recognize the likely disruption and transitional needs of industries that produce and rely on fossil fuels (e.g., petroleum, natural gas, refining, chemicals). Finding ways to minimize worker displacement and stranded assets while maximizing redeployment of the installed capital equipment and skilled labor force to pursue innovative low-carbon opportunities will be vital to retaining GDP and competitiveness during the transition to a low-carbon economy. Policies will need some level of global cooperation to avoid carbon leakage (increased GHG emissions in one country as a result of strict climate and emissions policies in another country) and other unintended emissions impacts or economic consequences.

Recommendations

Beneficial electrification stands out as one of the top low-carbon solutions for industrial decarbonization at the foundation of an energy supply that can serve all industrial sectors. For this pathway to deliver on targeted GHG reductions, it is crucial that the electricity supplied come from sources with an increasing share of low-carbon generation.

Dedicated pursuit of beneficial electrification; increased visibility for nonenergy and energy benefits; market pull for products with lower-carbon intensity; and a durable, supportive policy environment can accelerate the transition to lower-carbon energy use. The following recommendations highlight approaches by which various stakeholders can focus resources, capabilities, and collaborative energies to lower hurdles, advance RD&D, connect infrastructure, and smooth the path for adoption of electric technologies.

INDUSTRY

There are multiple opportunities for industry to facilitate electric technology research, development, demonstration, adoption, and dispersion.

- RD&D and energy management leaders can:
    - Initiate partnerships (with national labs, economic development entities, federal agencies, and others) at industrial clusters to pursue pilots of electric technologies, increase scale, train a network of practitioners, and make comparative, unbiased data available for justification cases
    - Proactively explore the potential of cross-cutting electric technologies (especially to address process heat) from near-term options such as hybrid boilers, heat pumps, and dryers as part of a project portfolio to achieve sustainability goals. Enrich the portfolio by actively scouting emerging and transformative technology to understand where there is a strong fit with process needs. Task improvement engineering organizations with identifying and pursuing opportunities for electrification. Where hurdles are encountered, make them visible to technology partners so they can be addressed.

  - Develop the business case for top candidates, expand economics to include energy and nonenergy benefits, propose projects for capital funding, and pursue research to lower hurdles.
  - Quantify nonenergy benefits and develop case studies to showcase their impact so that those who make financial decisions can support further electrification.
  - Reach out to national labs to partner on discovering technical and applied insights that lower science, engineering, scaling, and implementation barriers.
  - Use data analytics and communications along supply chains to identify "between business" opportunities.
- Implementation leaders can:
  - Actively describe specifications for clean, reliable, low-cost electricity to organizations advancing low-carbon electricity and infrastructure.
  - Include an increasing share of electric technologies in capital equipment portfolios and actively pursue learnings that allow increasing scale.
  - Publish the energy and nonenergy benefits of electric technologies so that others can leverage the learnings for their own equipment justifications.
- Public affairs and sustainability leaders can:
  - Reach across industrial associations to address common challenges and to describe ways to enable the transition to policymakers.
  - Incorporate a drive for beneficial electrification into GHG reduction goals, evaluate the reductions made, and describe the results.
  - Connect corporate efforts to increase the proportion of energy supplied by low-carbon sources with the active use of that energy. For example, strive to use a certain portion of renewable energy from power purchase agreements to power an increasing share of onsite electric technologies, or partner to develop utility-scale renewables to supply electric power near industrial clusters.

UTILITIES

Utilities have a pivotal role to play in beneficial electrification. They must understand industry needs for this transformation, explore routes to meet those needs, enable learning to understand tradeoffs, and lower barriers to implementation.

- Business development and technical leaders can:
  - Ask industrial customers about their needs for decarbonization, challenges, best opportunities, and what it would take for them to trial electric technologies.
  - Encourage trials of the most promising electric technologies, evaluate with industrial partners, and define the path to lower hurdles.

  - Explore how to reduce economic challenges in ways that are good for business, best utilize assets, and improve resilience.
  - Recognize and encourage lead users that have deployed electric technologies
- Strategic planning/infrastructure leaders can:
  - Identify ways to provide industry with increasing levels of low-carbon electricity. Connect industry interest in power purchase agreements for renewable energy with the potential to provide renewable energy locally.
  - Define infrastructure requirements (bus bars, substations, high-voltage lines, storage, and modeling of grid energy flow impacts and costs to serve) to deliver on industrial needs
  - Learn by advancing projects at select industrial clusters, and apply learnings.

GOVERNMENTAL AGENCY RD&D LEADERS

To speed discovery of science and technology fundamentals that accelerate beneficial electrification, governmental research laboratories need to include industrial decarbonization as a top priority and partner with industry and other collaborators. They can:

- Develop research programs for beneficial electrification (e.g., improving convective heat transfer so higher-temperature applications can be accessed, and advancing the efficiency of electrochemical processes), help coordinate RD&D across governmental organizations, and engage industry via partnerships and collaborative research projects.
- Initiate a clearinghouse of knowledge and data for electric technologies to better justify the co-benefits, energy and GHG savings, and routes to lower technical hurdles.
- Support the development of data and protocols that enhance adoption of electric technologies (such as smart manufacturing profiles that allow digital data communication and analytics).

POLICYMAKERS

The pace of adoption of electric technologies will need to dramatically accelerate in order to help attain climate goals. Policymakers can help lower hurdles, catalyze RD&D, spur adoption, and enable capability building and competitiveness by doing the following:

- Create and fund a federal industrial institute that pioneers RD&D, facilitates partnerships, and supports a clearinghouse of knowledge and data on behalf of beneficial electrification and other goals.
- Provide incentives for electrification in discrete and process manufacturing and connections to low-carbon energy so electrification can be beneficial. Especially, incentivize replacement of large capital in process heat (boilers, large service heat pumps) so that when equipment replacement decisions are made, electric technologies compete favorably in justification cases versus incumbent technology

- Support demonstration projects at progressively larger scale, and support research addressing questions that arise during scale-up.
- Support acceleration of permitting and preprocess authorization procedures to enable equipment exchange with electrotechnologies.

FUNDERS

To greatly accelerate adoption of electric technologies, a transformation is needed in the way large capital is funded in industry. Funders can:

- Support the enormous scale of industrial recapitalization via low-carbon technologies with models that encourage partnership and pool resources across government, industry, venture capital, philanthropy, and the investment community. The Sustainable Europe Investment Plan is one such approach that can be leveraged (European Commission 2020).
- Aggregate financial support to spur efforts at clusters of industrial activity to trial promising electrotechnologies and connect with low-carbon energy.
- Offer discounted financing for adoption of electrotechnologies that significantly lessen the GHG footprint of processes.
- Support programs that offer adjustments to depreciation schedules and lower the risk of adopting beneficial electrification technologies.

TRADE AND RETAIL CUSTOMERS

Across the many elements of supply chains that provide raw materials, convert industrial products into consumer goods, and reach end-consumers, there are ways to support and encourage the transition to products with lower carbon intensity, including:

- Driving customer "pull" so energy-intensive businesses see the motivation for low-carbon products.
- Increasing awareness of product carbon intensity.

Conclusions

Cross-cutting and industry-specific applications of beneficial electrification provide opportunities for expanded use of beneficial electric technologies across industrial subsectors. There are multiple applications where electric technologies have already established footholds, their justification often based on nonenergy benefits. Increased awareness of nonenergy benefits could play a key role in accelerating adoption.

Facilitating partnerships where there are high concentrations of industrial companies could also be a way to accelerate RD&D, lower hurdles, minimize risks, and trial technologies and policy approaches. To accelerate electric technology adoption, challenges need to be addressed including increasing the proportion of low-carbon electricity used by industry, competitive economics, consistent electrical supply 24/7, recapitalization, and preparing for new technology. Overcoming these challenges also presents opportunities to improve competitiveness, resilience, and the ability to deliver lower-carbon products—providing ways that businesses can differentiate themselves in the low-carbon future.

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Appendix A. Selection of Electric Technologies

Overall benefits of electric technologies can include lower emissions of CO_2 and other GHGs when the energy comes from low-carbon sources. Challenges include potentially higher energy costs when electricity prices are higher, and susceptibility to peak rates.

Table A1. Benefits and challenges of electric technologies

Technology	Application	Benefits	Challenges	Status
Hybrid boiler	Heating, process heat	Flexibility on energy source, ability to take advantage of price and availability, resilience, minimizing price volatility impact	Somewhat more expensive, support needed for two systems	Commercial
Electric boiler	100–150 °C process heat, food, chemicals, plastics	Low CO_2 when powered by renewable energy, less expensive/ lower capital cost	Low efficiency with thermally produced electricity, higher energy costs on energy basis than natural gas	Commercial
Heat pump, 90–160 °C	Sterilization, melting, reacting, processing	Efficient, convenient, avoid boiler house costs, fast response, safe, durable, low maintenance, cooling and heating options	Requires close proximity to heat source/load for highest efficiency, high electric supply needs, complexity	Experience limited, higher-temperature units emerging
Direct arc melting	Steel and metal transformation of ores	High melt rates and pouring temperatures, excellent control of melt chemistry		
Resistance heating	Primary metals, plastics, chemicals processing	Backup heat for heat pumps below 40 °C		
Electric steam generators	100–150 °C process heat	Convenience, compactness, low capital costs, efficiency, fast response, durability, safety, low downtime, dry steam	Displacement of legacy steam systems, possible need to increase electricity capacity, feed water and steam system O&M still required	Commercial
Heat pumps < 90 °C	Drying/evaporation	Fast response, safety, durability, low maintenance, combined cooling/heating/ dehumidification	Most efficient close to heat source, < 7 °C heat quality varies, higher-capacity units need high power	Commercial
Microwave, radiofrequency	Drying/evaporation, sterilization, melting, reacting, processing	Reduced drying times/ higher throughput, energy efficiency, uniform heating, targeted heating, compactness, increased reaction yields	Materials must be compatible, requires electrical capacity upgrades, payback can be longer	Commercial, TRL 4-8 depending on application

Technology	Application	Benefits	Challenges	Status
Ohmic drying	Drying/evaporation, sterilization, melting, reacting, processing, boost heating (glass), plasma cutting, heat treating	Efficiency, low energy use, emissions-free operation, low cost, small size, controllability	Effectiveness depends on resistance of target material, scarcity, scaling challenges, situation-specific design	Commercial, TRL 8
Infrared drying	Drying/evaporation, melting, reacting, processing, process line heating, mold forming	Reduced operating costs, improved product quality, fast response, durability, low maintenance, safety, low initial cost	High-capacity units may require upgraded electric and network capacity	Commercial
Pulsed electric field	Sterilization, melting, reacting, processing	Faster drying times, ability to be used in combination with osmotic drying, energy savings, increased rate of minerals uptake		Commercial, TRL 8
Ultrasound	Sterilization, enhanced drying	Effective mixing, increased mass transfer, reduced temperature, increased production rate, reduced degradation		Commercial, TRL 7
Pulsed light	Sterilization	Suitability for a range of disinfection applications	Non-penetrating, effects of shadows may limit application	Commercial, TRL 8
Ultraviolet	Sterilization, surface curing	Uniformity for in-package heating	Non-penetrating, effects of shadows may limit application	Commercial, TRL 8
Friction heating	Melting, reacting, processing	High efficiency, fast heating, ability to be used for products with no conductivity	Mechanical with rotating equipment so will have maintenance needs, max 50 °C	Commercial
Induction heating	Melting, reacting, processing, melting of primary metals	Reduced costs, increased throughput, presets that aid quality, safety, fast response	Capital and energy costs, electric capacity, maintenance	Commercial
Indirect electric resistance heating	Melting, reacting, processing	Low energy consumption, efficiency, low space requirements, low cost and maintenance, controllability	Inefficient in large spaces, large-unit power consumption may increase network, installation costs	
Extrusion porosification	Drying/concentration	Enhanced powders mixing		Commercial, TRL 8
Cryogenics	Industrial gas purification	Product quality		
Electroslag, vacuum, plasma	Primary metals			

Technology	Application	Benefits	Challenges	Status
Electric pressurized membranes	Chemicals, refining, food	Potential to lower heat and energy use relative to distillation		

Compiled using information from EECA 201, Deason et al. 2018, and Jadun et al. 2017. TRL: technology readiness level.