Industrial Electrification Technologies Booklet

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INTRODUCTION

Electrification refers to transitioning from fuel-powered systems to electrically-powered alternatives. In an industrial context, this primarily refers to the electrification of process heat, but there are also widespread opportunities to electrify space heating and cooling as well as onsite transportation (e.g., forklifts). Electrification does not refer to one particular technology, but a wide range of technologies that use different methods to transfer electrical energy into a usable form – usually heat.

Organizations pursue electrification for a variety of reasons. In many cases, electrified technologies can improve energy efficiency and enhance productivity. Some electric technologies can be safer and easier to maintain than their fuel-fired alternatives, and some can eliminate downtime and improve product quality. These diverse benefits can add up to significant cost savings for manufacturers. In some cases, electrification can also reduce emissions, though the magnitude (and even the direction) of that impact depends on several factors, including the emissions intensity of the fuel being replaced and the emissions intensity of the electricity used to power the newly electrified alternative.

These benefits are not universally applicable, however. As with any process change, electrification requires an assessment of tradeoffs, and it is not a panacea. Different electric technologies have different advantages and limitations and may only make sense to pursue in certain circumstances, depending on factors as diverse as process temperature needs, production rate, heating medium, and geography. By understanding the advantages, limitations, and common applications of various electric technologies, organizations can make informed decisions about when and where to prioritize electrification. This Booklet is a complementary resource to the Industrial Electrification Assessment Framework.

Purpose of this Booklet

This Booklet is intended to provide an overview of various electric technologies relevant to industrial organizations – primarily process heating, but including heating, ventilation, and cooling (HVAC) and onsite transportation. The Booklet describes different technology types and summarizes their most common applications, benefits, limitations, and potential for integration into existing systems. It is intended to serve as a primer on different technology types to help organizations identify possible electrification opportunities and narrow the scope from the full range of electric alternatives to a select few relevant technologies to be investigated further.

Audience for this Booklet

The primary audience for the Booklet includes engineers, plant managers, and decision-makers in manufacturing facilities who are exploring or implementing electrification technologies. It can also be used by organizational planners looking to understand the feasibility of electrification as an emissions reduction solution for their portfolios, as this document highlights the relative availability and performance of a range of technologies, as well as the process types they are well-suited to.

How to Use this Booklet

This Booklet can be used either in conjunction with the Industrial Electrification Assessment Framework or as a standalone reference.

When used alongside the Industrial Electrification Assessment Framework, it acts as an appendix, providing key details and context for the technologies mentioned in the Framework. The Framework is used to evaluate a specific facility's suitability for electrification, and the Booklet is particularly well-suited to help readers of the Framework understand the technologies referenced in Step 2a of the Framework, "Identifying Strategies for Electrification."

For those using the Booklet independently, it provides an overview of various electric heating technologies and their applications in industrial processes. It can be useful in early-stage brainstorming about electrification strategies, elimination of impractical applications for electrification, or simply as a base level primer to understand the advantages and limitations of various technologies.

ELECTROTECHNOLOGIES FOR PROCESS HEATING APPLICATIONS

Resistance Heating

Resistance heating, also known as resistive heating, uses the electrical resistance of a conductor to produce heat (Figure 1). When an electric current passes through a material, its resistance to the flow of electricity leads to the generation of thermal energy. Resistance heating can take two forms: direct and indirect. In direct resistance heating, the material being processed serves as an electrical resistor, generating heat when an electric current is applied to it. Indirect resistance heating employs electrical modules or heating elements crafted from highly resistive materials to generate heat, which is then conveyed to the material through direct radiation or a combination of radiation and convection.

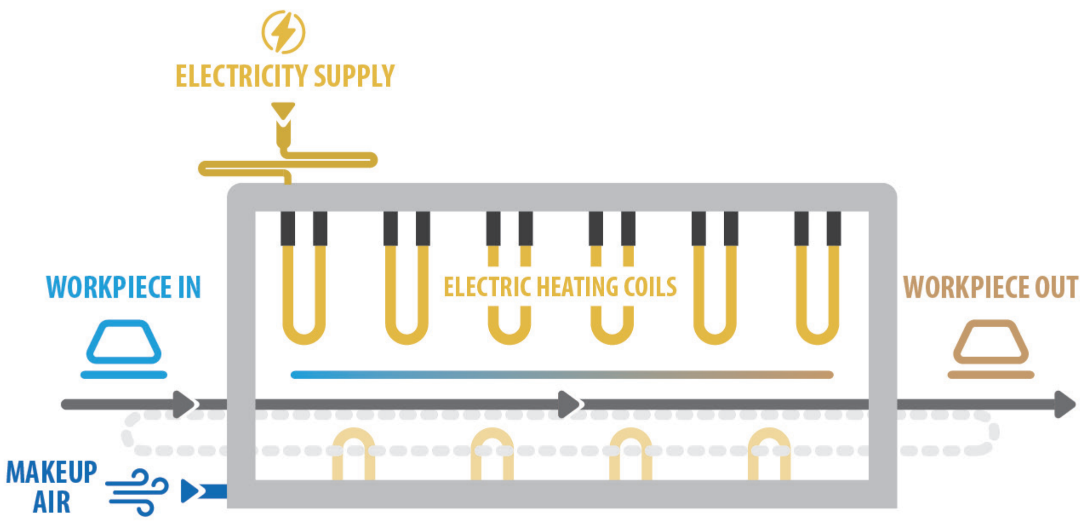


Figure 1. Schematic of a resistance-based heating system.

Table 1. Advantages and Limitations of Resistance Heating

Advantages	Limitations
Broad applicability: The mode of heat transfer is the same as fuel-fired systems and thus can replace most traditional processes without limitations on the shape of the workpiece or its material characteristics.	**Integrity of clamped connections:** Occasionally, with direct resistance heating, adequate electrical connections can be difficult to make to metal parts.
Rapid start-up: Resistance heating has a fast start-up, which can be important for short production runs.	**Electric heating element failure:** Elements may fail in the presence of moisture or through mishandling.
High efficiency: High thermal efficiency (up to 90% has been observed in direct heat treatment of metals)[1].	**Does not scale well:** Resistance heating is not very efficient (compared to some other electric alternatives) for large applications.
Reduced maintenance: Daily cleaning requirements can be substantially minimized, resulting in lower labor costs and reduced downtime.	

[1] Electric Power Research Institute (EPRI), Technical Report – Rapid Metal Heating: Reducing Energy Consumption and Increasing. TR-114864. https://www.epri.com/research/products/tr-114864

Applications of electric resistance heating in industry: Electric resistance heating is well-suited for retrofit applications because the mode of heat transfer uses traditional means (radiation and convection) akin to fuel-fired systems. Thus, electric resistance heating can be a more direct replacement compared to other technologies that utilize different heating mechanisms.

Table 2. Common Applications for Resistance Heating in Process Heating

Industry	Application	Details
Metal fabrication	Metal working	Direct resistance heating is used to produce welds for surface heat treatment.
	Heat treatment in salt bath furnaces	Resistance heating in salt bath furnace heat treatment generates heat directly in the salt by using its resistance to the passage of current. The method must use titanium alloys to avoid sheath breach over excessive durations.
Nonmetallic minerals	Melting of glass	At high temperatures, molten glass becomes a good electrical conductor that can be heated using direct resistance heating.
Pharmaceutical, plastic, chemicals, etc	Electric catalytic oxidizers	Electric catalytic oxidizers use electric heaters instead of gas burners to heat the dirty air to the catalyst's operating temperature.
All industries	Liquid heating	Stainless steel flanged heating elements are immersed in the liquid to be heated. This method is used for lubricant oils, heavy and light oils, waxes, and mildly corrosive liquids.
	Air/gas heating	This method involves heating combustion air and other low-flow gases using duct heaters.
	Jacket heating	In an electrified process, instead of steam coils, electric resistance elements can be used.

SAINT-GOBAIN

In 2023, Saint-Gobain installed an electric furnace to replace natural gas for the drying process in its Fredrikstad, Norway wallboard manufacturing plant.This project is now being replicated in Montreal, Canada, and similar opportunities are being explored across Saint-Gobain facilities in the United States.

Induction Heating

Induction heating is a noncontact heating technology that warms electrically conductive materials using electromagnetic induction (Figure 2). When an alternating electric current flows through a wire, it generates a magnetic field that induces eddy currents (and subsequently, heat) in any conductive material within its effective range.

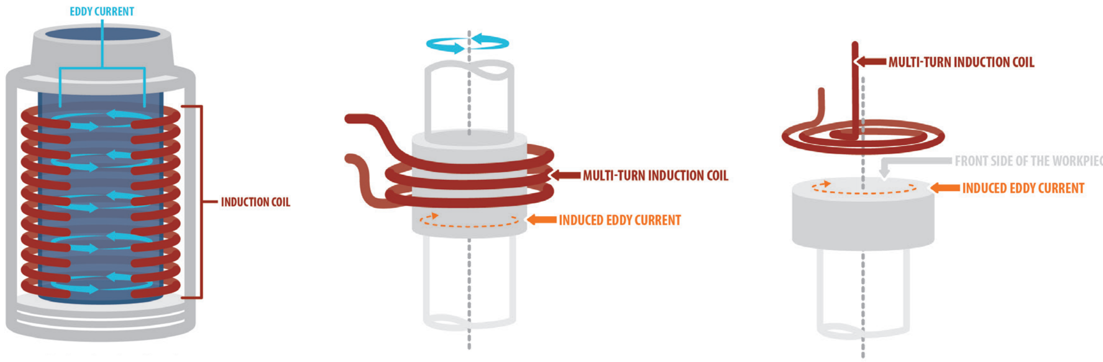


Figure 2. Schematic of an induction-based heating system.

Table 3. Advantages and Limitations of Induction Heating

Advantages	Limitations
Precise heat location: Heat depth can be adjusted to just the surface or the entire cross section. Induction offers improved precision and process control. Only the component is heated and not the furnace walls, leading to efficient operation and faster start-up.	**Material:** It is not possible to heat nonmetals directly with induction. Low-resistivity metals, such as aluminum and copper alloys, are difficult to heat at high system efficiencies.
Higher production rates (up to 10 times faster): The development of heat within the workpiece by induction provides much higher heating rates than the convection and radiation processes that occur in furnaces.	**Workpiece shape:** Complex part geometries are hard to heat and are cost-prohibitive for short production runs on differing parts because each part may require a different coil design.
Reduced scrap: The shorter heating times lead to considerably less scale. Induction heating could result in materials savings of as much as 4%.[2]	**Process:** Induction is done at ambient temperatures and is not suitable for diffusion processes.
Lean manufacturing: Induction is ideal for integration with lean manufacturing techniques, such as single-piece workflow and just-in-time manufacturing.	**Upfront cost:** Equipment cost can be high and typically costs 2.5-3 times as much as gas-fired furnaces of equal capacity.[3]
Compact footprint: Because heat is generated within the workpiece, induction processes typically require no insulated enclosures, yielding a much smaller floor space requirement. Manufacturers can thus make more productive use of their floor space.	**Safety:** Injuries from high-frequency voltages tend to produce severe tissue damage.

[2] American Electric Power - https://www.aepnationalcustomers.com/business/industry-solutions/electrification

[3] Electric Power Research Institute (EPRI), Technical Update - Industrial Process Heating: Current and Emerging Applications of Electrotechnologies. https://www.epri.com/research/products/000000000001020133

Applications of induction heating in industry: Induction heating can be used for directly heating, heat treating, or melting conductive materials (typically metals).

Plastics and other nonconductive materials (e.g., chemicals) often can be heated by first heating a conductive material that transfers heat to the nonconductive material.

Table 4. Common Applications for Induction Heating in Process Heating

Industry	Application	Details
Foundries	Precious metal refineries and recycling units (commonly used) Remelting of alloys/iron for casting (common for alloys)	Most modern foundries use this type of furnace, and many iron foundries are replacing cupola furnaces with induction furnaces to melt-cast iron because the cupola furnaces emit much dust and other pollutants.
Metal fabrication and steel mills	Heat treatment (commercially available)	Induction processes are almost always used for certain types of heating, such as surface and selective heat treating of metal products that can be processed on a continuous basis (such as tubing and gear shafts). Induction heating could result in materials savings of as much as 3-4%.[3] Although annealing, hardening, and other methods can be done with inductive systems, these systems are not widely used.
Food and beverage	Fluid heating (e.g., palm oil)	Induction enables rapid heating and provides ease of maintaining a relatively high temperature, which is difficult to obtain with indirect steam or even thermal fluid heating.
Food and pharmaceutical	Cap sealing	The process consists of a thin layer of aluminum foil placed on the top of a container that has been filled and inspected. The container with the foil is passed under an induction coil, which heats the foil to a sufficient temperature to bond it to the top of the container.
All industries	Product testing/ prototyping and research	Induction heating is commonly used for many smaller nonproduction heating applications.

VOLVO

Volvo Group has implemented induction heating for the treatment of automotive metal components at its Hagerstown, Maryland facility. Induction heat treatment provides faster production rates, better metallurgical results (higher product quality), and reduced overall emissions.

Electric Infrared

Electric infrared (IR) heating works by converting electricity into IR (0.75 to 1,000 μm) radiant heat in a heat lamp (Figure 3). IR radiation can be absorbed and converted into heat energy by most materials rather than being reflected away or transmitted through the object.

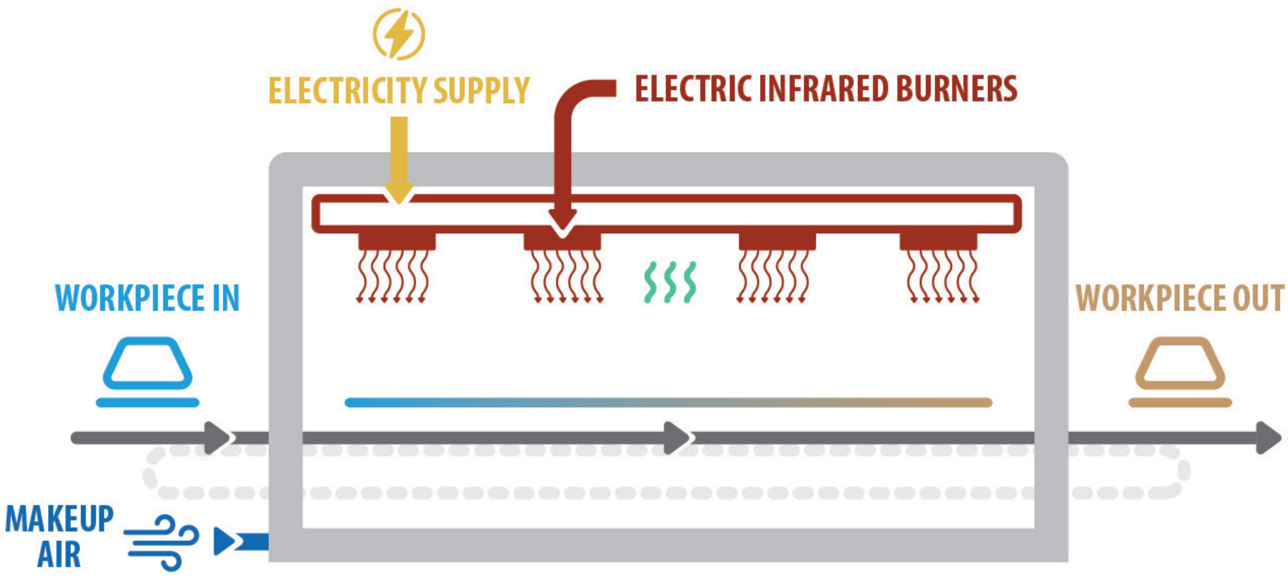


Figure 3. Schematic of an electric IR heating system.

Table 5. Advantages and Limitations of Electric Infrared Heating

Advantages	Limitations
Reduced processing time: Because of the direct transfer of heat by radiation to the product and high power densities, IR systems can heat quickly and efficiently. Processing time can be reduced by as much as 50–85% over convection ovens.[4]	**Geometry:** The shape of the product can affect the array of IR emitters and reflectors to be used. Heating complex-shaped parts uniformly is difficult because heat transfer is line-of-sight and varies with distance and incident angle between the emitter and the part.
Higher-quality products: The surface finish on drying or coating operations is typically better compared with traditional methods.	**Coating barriers:** Some coating might not be ideal for IR. Peak efficiencies are achieved on most products by matching the emission wavelength of the IR heater to the absorption wavelength of the product.
High efficiency: Because IR components heat by radiation, the product, rather than the surrounding air, is heated. Quick start-up and shutdown eliminates costly preheating, which further increases overall efficiency.	**Heating environment:** All IR heaters have high surface temperatures when operating and should, therefore, not be used when the atmosphere contains ignitable dust, gases, or vapors in hazardous concentrations.
Flexibility: Intensity can be easily adjusted for different products.	

[4] Electric Power Research Institute (EPRI), Technical Update - Industrial Process Heating: Current and Emerging Applications of Electrotechnologies. https://www.epri.com/research/products/000000000001020133

Common applications of IR heating: Drying and coating operations that have geometries with an unobstructed view of the product, such as heat coils and sheets, are ideally suited for IR. Because of the difficulties of curing complex parts, hybrid ovens incorporating both IR and convection sections have been developed. For example, in powder coating a complex-shaped part, IR is used to rapidly bring the powder up to the gel point, and the convection oven maintains the temperature and completes the cure of the powder coating.

Table 6. Common Applications for Electric Infrared Heating in Process Heating

Industry	Application	Details
Equipment manufacturing	Paint drying and curing	Air-drying tools can take hours to finalize paint curing tasks. This time is in comparison with IR technology, which, with its powerful heat radiation, can take just minutes to finish the same job.
Plastics and rubber	Curing of extruded plastics, rubbers	Electric IR is particularly suited for treating sheet plastic or extruded rubber before product finishing because it helps achieve the required surface finish.
Pulp and paper	Paper/coating drying	IR is used for drying coated papers. The advantages compared with the multicylinder design are high heat fluxes, absorption of radiation inside the wet web, and profiling possibility.
Metal fabrication	Melting and curing of powder coating	IR booster with an electric resistance oven has shown to increase line speed while reducing equipment footprint. Because of the much smaller oven size and footprint, wall heating losses have been reduced.[5]

QUEENCITYFORGINGCO. People who make the process work | Manufacturing Solutions Forged by Innovation

Queen City Forging Company in Cincinnati, Ohio replaced its gas-fired convection ovens with batch IR furnaces for preheating aluminum billets. The transition reduced preheating times from 1-6 hours to 14-18 minutes. The infrared pretreatment was 75% more energy-efficient than conventional ovens, and the system proved robust under industrial conditions, with a downtime of less than 5% over three years of use in preheating billets.[6]

[5] Industrial Heating Equipment Association (IHEA), Case study: Powder curing with electric infrared, Feb 2014. https:/www.ihea.org/resource/collection/01C9C4DA-9519-4EBE-9F81-0CEC55F05A6D/IR-Shoptalk-0214.pdf

[6] U.S. Department of Energy. Quadrennial Technology Review 2015. Chapter 6: Technology Assessments. https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf

Microwave and Radiofrequency Heating

Microwave (MW) and radio frequency (RF) waves have wavelengths larger than IR (>1 mm). At these frequencies, the electromagnetic fields cause the interaction of polar water molecules and charged ions. The friction resulting from molecule alignment and the migration of charged ions in a rapidly alternating electromagnetic field generates heat within dielectric materials, such as foods, as shown in Figure 4.

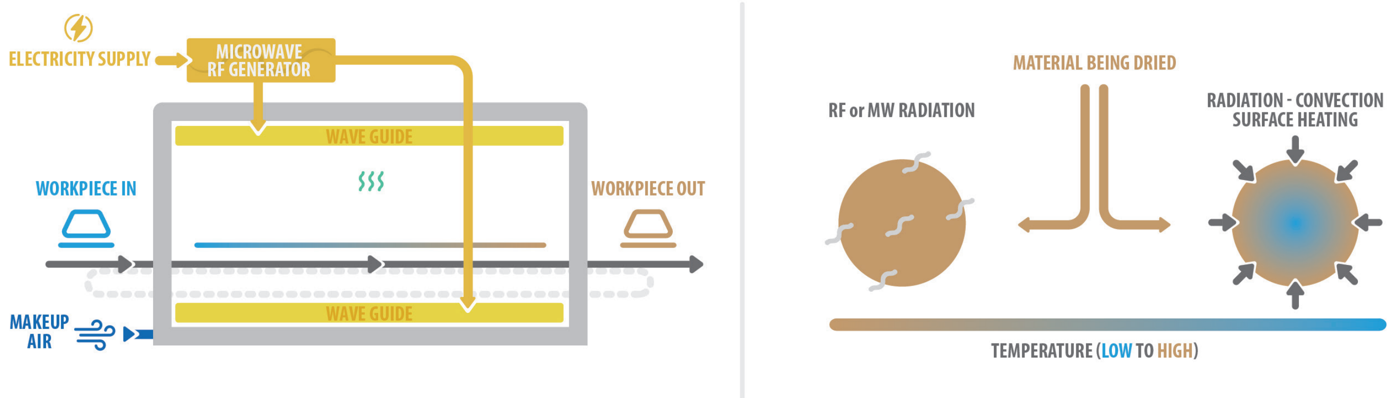


Figure 4. Schematic of an MW heating system and mechanism of heating

Table 7. Advantages and Limitations of Microwave and Radiofrequency Heating

Advantages	Limitations
Volumetric heating: MW and RF systems offer volumetric heating, meaning the material is evenly heated throughout the entire volume rather than heating from the outside and depending on heat transfer by conduction or convection, allowing the method to heat materials that conduct heat poorly.	**Material limitation:** Not all materials are suitable for MW/RF heating, and suitability is determined by the material's characteristic loss factor. MW/RF cannot be used to heat conducting materials.
Selective heating: Because different materials absorb MW/RF energy at different rates, owing to the loss factor, a product with many components can be heated selectively.	**Surface effect:** Rapid heating is not ideal for some materials because they might crack and/or have surface effects.
Product: Efficient MW/RF heating results in increased production rates and improved product quality.	**Safety:** Safety considerations are also important for MW heating, and there is often a concern about the dangers of MW leakage and the need for protection against electromagnetic radiation.

Common applications of microwave/RF heating: Given that microwaves are used to heat water molecules, they are ideally suited for drying applications across sectors. Selective heating uniquely allows the heating of prepackaged medicine or food products to be sterilized without heating the package.

Table 8. Common Applications for Microwave and Radiofrequency Heating in Process Heating

Industry	Application	Details
Food and beverage	Microwave drying and cooking	Microwave heating has a smaller production footprint, higher throughput, and greater yield.
	Sterilization and thawing of packaged food	RF can reduce the thawing time by up to 95%. It can also be performed directly inside packaging.[7]
Chemicals	Preheating resin prior to extrusion	Resin preheating doubles throughput while decreasing production line shutdowns and maintenance, in case studies reported.[8]
	Drying of industrial chemicals	This drying method is applied to activated carbon, filter carbon, foam expanded polystyrene, polyester plate curving, synthetic material, and others.
Nonmetallic	Vulcanization process (processes for hardening rubber)	Microwaves penetrate the material, heating it from the core to the surface immediately, resulting in uniform heating.
Wood products	Wood drying	Microwaves efficiently dry off the wood from inside to surface and prevent wood from cracking and shrinking.

[7] Cresko, Joe, et al. "Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy (Workshop Report).", May 2022. https://doi.org/10.2172/1871912.

[8] Industrial Microwave Systems (IMS): Industrial Microwave Chemical Heating: Case Studies https://industrialmicrowave.com/industrial-microwave-applications/chemical-heating/.

Other Emerging Technologies for Process Heating

In addition to the major electrical heating methods that have been discussed, several other emerging technologies offer innovative approaches for industrial heating and processing, providing unique advantages. This section provides an overview of some of these emerging technologies, highlighting their principles, advantages, limitations, and common applications.

Table 9. Emerging Electrotechnologies for Process Heating Applications

Technology	Principle	Advantages	Limitations	Common Applications
Ultraviolet (UV) Processing	Exposing liquid polymeric substances to UV radiation to transform them into solid coatings	Faster curing, higher product quality	Material compatibility, safety concerns	Coating and finishing, adhesives and sealants, sterilizing medical devices
Electron Beam Processing	Using high-energy electrons to generate heat on the surface of materials	Precision, high energy density, clean process	Equipment cost, material limitations	Welding and joining, deposition and etching in semiconductor manufacturing, pasteurization of fluids (e.g., milk and fruit juices)
Plasma Heating	Ionizing gases to extremely high temperatures to create plasma for heating and melting	High temperatures, efficiency, versatility	Complexity, cost	Metal melting and refining, surface treatment, material synthesis
Laser Heating	Using focused laser beams to deliver high energy density to specific areas of a material	Precision, speed, noncontact process	Cost, material restrictions	Surface hardening, cutting and welding, additive manufacturing (3D printing)
Electrochemical Methods	Chemical reactions driven by electrical energy for processing, such as metal recovery	Efficiency, precision, environmental benefits	Material compatibility, operational complexity	Metal recovery, surface treatment (electroplating, anodizing), battery manufacturing and recycling
Ultrasonics Heating	Using high-frequency sound waves to generate heat within materials through vibration	Noncontact heating, precise control, rapid heating	Material limitations, equipment cost, safety concerns	Cleaning, bonding of plastics, food processing, medical device manufacturing

While the table highlights several emerging electrification technologies, it is important to note that industrial electrification is a much broader field. Industry-specific electrification pathways, such as molten iron electrolysis for steelmaking, have not been included due to their specificity. Additionally, not all electrification strategies follow a direct replacement model. Some pathways fundamentally alter process operations, such as membrane separations replacing thermal separation methods.

Synergistic technologies can further enable the feasibility of implementing electrification strategies. For example, material substitutions like low-bake paints eliminate the need for high curing temperatures, while alternative synthesis pathways operate at lower temperatures, reducing thermal demands. Additionally, technologies such as thermal energy storage (TES) improve the business case for electrification by optimizing heat management and enabling flexible energy use.

TES involves capturing and storing heat for later use, typically using phase change materials or sensible heat storage methods. This allows for shifting the time of use, making it possible to leverage inexpensive electricity to efficiently generate and store heat for later use. This capability is particularly valuable when energy prices fluctuate due to time-of-use (TOU) rates or when trying to avoid demand charges. TES can be especially beneficial in facilities with onsite renewable generation, where electricity production does not always align with production needs. Additionally, it is well-suited for intermittent, high-temperature processes, such as startups and batch operations, where heat can be efficiently generated and stored over time to be deployed rapidly when needed. By enabling the effective use of electricity for heating, TES contributes to energy cost optimization and industrial emissions reduction.

Together, these advancements make it more practical to transition industrial processes into electrified systems.

Heat Pumps for Process Heating

Heat pumps are electrically- or thermally-riven technologies for upgrading low-temperature heat to higher, useful temperatures for industrial applications. Generally, the principle is to transfer heat from a source that contains heat that is:

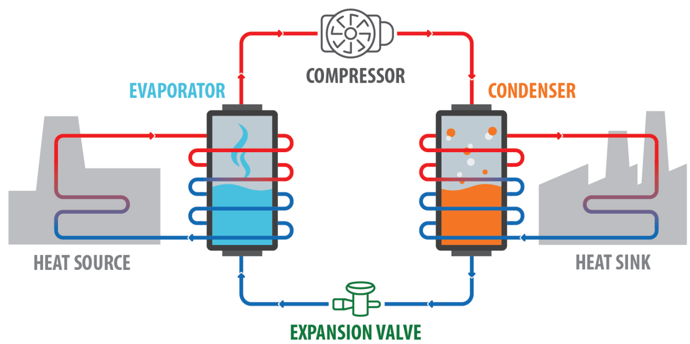
- Too low-quality (i.e., low temperature) to be otherwise recovered for utilization;
- Readily available (e.g., heat contained in ambient air, a water reservoir, or the ground); and/or
- Would otherwise be wasted (e.g., heat contained in a finished product stream).

The heat is then transferred to a process where heating load would typically otherwise be met using a fuel-fired system. In this way, heat pumps serve both as an energy efficiency strategy—by recovering otherwise unused heat—and as an electrification strategy, since electricity is often used as the external energy source to transfer heat. The amount of external energy required depends on the temperature lift, which is the difference between the heat sink and heat source temperatures.

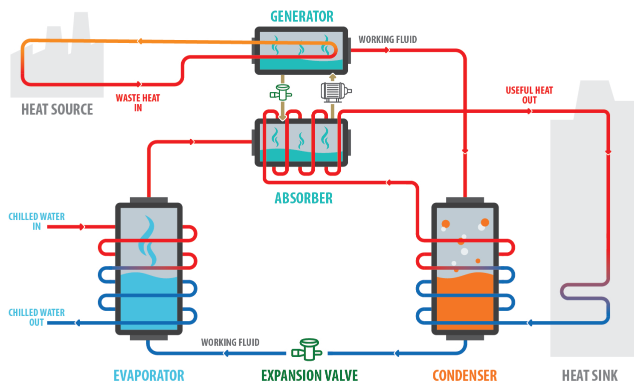
Furthermore, while the most common types of heat pumps—mechanical vapor compression (MVC) and mechanical vapor recompression (MVR) heat pumps—use electricity as their external energy source, some heat pumps, such as absorption and thermocompression heat pumps, rely on thermal energy instead. As a result, these types do not necessarily fall under electrification.

Figure 5 provides a schematic representation of some common heat pump types and Table 10 details, with key distinguishing characteristics, each type of heat pump.

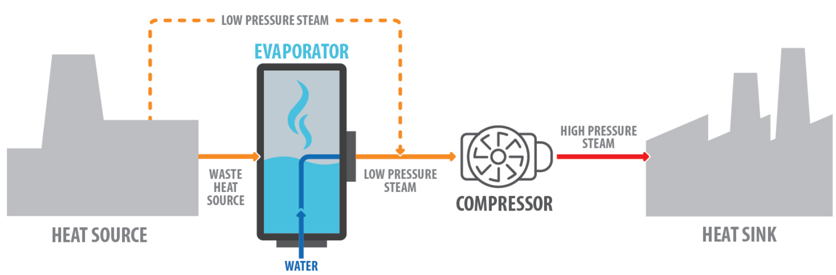
Mechanical Vapor Compression (MVC) Heat Pump



Absorption Heat Pump



Mechanical Vapor Recompression (MVR) Heat Pump



Thermo-compression Heat Pump

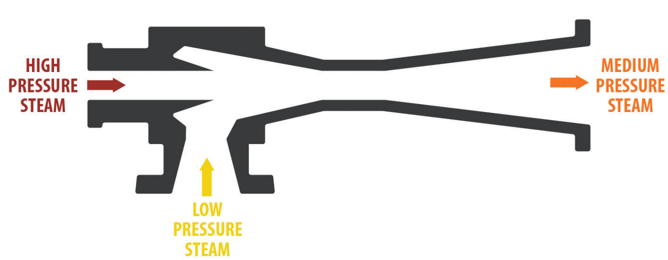


Figure 5. Types of Industrial Heat Pumps.

Table 9. Emerging Electrotechnologies for Process Heating Applications

	Mechanical Vapor Compression	Mechanical Vapor Recompression	Thermocompressor Heat Pumps	Absorption Heat Pumps
Heating Capacity/ Rated Capacity	The systems are typically custom-designed to meet specific industrial requirements and their thermal outputs in the range of several megawatts.			
Operating Temperature	120°F to 320°F	120°F to 450°F	240°F to 450°F	120°F to 390°F
Principle of Operation	Uses mechanical energy to drive a refrigerant cycle	Uses mechanical energy to compress vapor	Uses higher pressure steam (or other gas) to upgrade waste vapor pressure	Uses waste heat and a refrigerant–absorbent mixture
Energy Source	Electricity (compressor)	Electricity (compressor)	Steam or gas, typically utilizing waste heat	Heat (solar, waste heat, natural gas, etc.)
Scalability	Scalable across a wide range of temperature and source mediums	Limited scalability, based on availability of steam or low-pressure vapor	Limited scalability, based on availability of steam or low-pressure vapor	Highly scalable, especially in large systems
Advantages[9]	MVC heat pumps have a good favorable COP for moderate lift temperatures (<790°F)	MVR systems have a favorable good COP for moderate lift temperatures	Thermocompressors are simple devices with low maintenance and capital expenditure (CapEx)	Absorption heat pumps can achieve higher supply temperatures, and their operational expenditure (OpEx) is independent of electricity prices due to the use of waste heat, lower-cost fuel, or steam as a driver
Limitations	Constrained by supply temperature limitations and require a low electric-to-fuel price ratio to be economically viable	Require a low electric-to-fuel price ratio. Their applicability is further limited by the availability of steam or low-pressure vapor	Limited by lower energy efficiency and are only applicable where steam or low-pressure vapor is available	They are limited by high capital costs and require a large footprint

MVC heat pumps are the most common and use a circulating liquid refrigerant as the medium that absorbs and removes heat from the space to be cooled, subsequently rejecting it elsewhere. The principle is employed in heat pumps to absorb heat from a low-temperature energy source and apply external energy to deliver the heat to a higher-temperature load.

Common applications of Heat Pumps in Process Heating: Heat pumps find applications in both HVAC and process heating. Although their use in HVAC is common in the United States, their application in industry is not as widespread. The most common type of heat pump used is the MVC heat pump, particularly in HVAC and some industrial settings. However, industrial applications can

[9] Ed Rightor, et al. "Industrial Heat Pumps: Electrifying Industry's Process Heat Supply." ACEEE, 2021.

also utilize MVR, thermo-compression, or absorption heat pumps, depending on the source of heat available and the specific heat demand of the process. The choice of heat pump technology is often influenced by factors such as temperature requirements, waste heat recovery potential, and overall system efficiency.

Table 11. Common Applications for Heat Pumps in Process Heating

Industry	Application[10]	Details
Several sectors	Hot water, washing/cleaning	Heat pumps find application across all sectors given the need for low to moderate temperature heat for common applications.
Food and beverage	Drying, pasteurization, sterilization, boiling, distillation, blanching, scalding, concentration, tempering, smoking	Heat pumps are highly efficient for applications requiring consistent, controlled heating for a variety of low temperature food processing applications.
Paper	Drying, boiling, bleaching, de-inking	Heat pumps are suitable for low temperature (<450°F) applications and find applications in deinking and bleaching operations, supplementing paper drying.
Metal	Pickling, electroplating, phosphating, chromating	Heat pumps offer an energy-efficient alternative for low temperature heat treatment processes in the metal industry.
Plastic	Injection molding, pellet drying, preheating	In plastic manufacturing, heat pumps find application in injection molding, pellet drying, and preheating.

Electric Steam Boilers

Electric steam boilers are a well-established technology and are commercially available from numerous major vendors. There are two primary types.

Electrode Boilers: These boilers use electrodes to pass current through water, directly generating steam. They are highly responsive and suitable for high-capacity needs. Electrode boilers operate at high voltages (4,160 to 25,000 V), with ratings up to approximately 100 MW and capacities reaching up to 340,000 lb/h.

Resistance Boilers: These boilers use electric resistance heating elements to heat water. They have a simpler design and are used for smaller capacity requirements. Resistance boilers operate at lower voltages (208 to 600 V), with ratings up to about 3 MW and capacities up to 156,000 lb/h.

Despite their long-standing commercial availability, electric steam boilers have not been widely implemented on a large scale because of several factors. Although these systems are highly efficient and offer precise temperature control, their widespread adoption is hindered by the associated high costs and infrastructure requirements.

[10] Cordin Arpagaus, Frédéric Bless, Michael Uhlmann, Jürg Schiffmann, and Stefan S. Bertsch, "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials," Energy 152 (2018).

Table 12. Advantages and Limitations of Electric Steam Boilers

Advantages	Limitations
Rapid response time: Electric boilers can quickly adjust the heating input, leading to faster response times in reaching and maintaining desired temperatures.	**Initial cost:** Electric boilers generally have a higher upfront cost compared with fuel-fired boilers.
Variable output: The electrical input to the boilers can be precisely controlled, allowing for fine adjustments to the steam output and temperature. This ability contrasts with natural gas boilers, in which the combustion process is more difficult to modulate with the same level of precision.	**Operating costs:** The higher rates of electricity compared with natural gas or oil can result in significantly higher operating costs, particularly in regions where electricity prices are high.
Steady heat supply: Electric boilers provide a steady and consistent heat supply without the fluctuations associated with the combustion process in natural gas boilers. This consistency translates to more stable steam production and temperature control.	**Electrical supply:** Many industrial settings may lack the electrical infrastructure to support the high power requirements of electric boilers. Upgrading electrical systems to accommodate these boilers can be costly and time consuming.
	Capacity limitations: In some cases, the local electrical grid may not be able to supply the necessary power without substantial upgrades, which can be a significant barrier.

Applications of Electric Boilers for Process Heating: Electric steam boilers are used across various industries when energy and operational efficiency, as well as precise temperature control, are important. Some individual facilities are also turning toward electric boilers for emissions reduction benefits

Table 13. Common Applications for Electric Steam Boilers in Process Heating

Industry	Application	Details
Chemical processing	Heating reactors, processing equipment	Electric boilers are used for heating reactors and other critical processing equipment, ensuring accurate temperature control necessary for optimal chemical reactions.
Pharmaceutical	Medicine production	In the pharmaceutical sector, electric boilers are relied upon for producing medicines, where cleanliness and precision are essential for ensuring the quality and safety of products.
Laboratories	Small-scale industrial applications	Electric steam generation systems are often used in laboratories and smaller industrial applications where a responsive and on-demand steam supply is necessary.
Food and paper	Dry steam generation	Applications requiring dry steam, such as food processing and paper manufacturing, use electric boilers to generate steam with no suspended water droplets, ensuring efficient heat transfer and maintaining high-quality standards.

Electric Hot Water Generation Systems

Electric hot water boilers and heaters provide a reliable alternative to traditional gas-fired systems for industrial applications. These systems use electric resistance elements to heat water, eliminating combustion-related emissions and improving indoor air quality. While both systems serve the same fundamental purpose of heating water, the distinction is typical based on application and use.

Hot Water Boilers: These heat water and distribute it through a closed-loop system (for space heating or industrial processes). Modern hot water boilers operate below the boiling point (usually around 180-200°F) in contrast to steam boilers that heat water to the boiling point (212°F or higher) to generate steam. So, while a hot water boiler doesn't technically "boil" water, the term has stuck due to historical usage and industry conventions.

Hot Water Heaters: While hot water boilers are usually integrated into closed-loop heating systems, water heaters supply hot water for direct use. These are available in various configurations, including tankless (on-demand) systems and storage-based models. Tankless resistance water heaters do not store any hot water for later use like conventional water heaters but instead heat water instantaneously through resistance heaters in line with the water supply. This lack of needing to heat standby water leads to higher efficiencies in some tankless water heater systems depending on the overall system demand. Limitations on output capacity may be an issue for systems with larger requirements of hot water.

Table 14. Advantages and Limitations of Electric Hot Water Boilers and Heaters

Advantages	Limitations
Efficiency: Electric heating elements have high efficiencies, capturing almost all the generated heat in the fluid.	**Demand increase and unit cost:** Electric heating of water can significantly increase electric demand as a large amount of heat is applied quickly to a fluid. Depending on usage and utility rates, increased demand from distributed heaters can have a significant impact on the overall facility peak electrical demand.
Decreased losses: Tankless and on-demand water heaters provide hot water when needed so storage of hot water in tanks is unnecessary. This eliminates losses in fuel-burning hot water systems from storing hot water for long periods of time in tanks and maintaining the necessary temperatures.	**Distributed integration and increased maintenance:** Tankless and on-demand water heaters are typically installed close to the end use so there is typically an increase in the number of heaters throughout a facility when compared to centralized water heaters. A larger number of components and locations can lead to an increased chance of failure in distributed systems and larger maintenance requirements.

Applications of Electric Hot Water Systems for Process Heating

Although hot water systems are predominantly used in HVAC applications, certain process applications, such as cleaning, washing, pasteurization, sterilization, and chemical processing, also use hot water and are suitable for electrification.

Table 15. Common Applications for Electric Hot Water Systems in Process Heating

Industry	Application	Details
Food and beverage	Cleaning and sanitizing equipment	Electric hot water systems are crucial in the food and beverage industry for cleaning and sanitizing equipment, ensuring hygiene and safety standards are met in food production environments. Jacketed tanks heated by hot water are utilized to melt and store products (e.g., chocolate) that are required to be maintained at optimal temperatures to prevent solidification during processing.
Pharmaceutical	Sterilizing equipment and components	In the pharmaceutical industry, electric hot water systems play an essential role in sterilizing equipment and components, maintaining the cleanliness and precision required in drug production.
Various industries	Downgrading from steam to hot water, hot water heating	Downgrading from steam to hot water systems is common in electrification projects to reduce heat requirements. Electric hot water heaters are often more commonly implemented in industrial facilities than in electric steam systems, offering efficiency and flexibility.

ELECTROTECHNOLOGIES FOR HVAC APPLICATION

Heat Pumps

Heat pumps in HVAC applications function with the same mechanism as heat pumps used for process applications. For HVAC applications, heat pumps typically use air or the ground as the heat source for the vapor compression cycle (denoted as air-source and ground-source heat pumps, respectively). Heat pumps in commercial and residential HVAC applications are becoming increasingly common, especially in mild climates.

Most applications of heat pumps for HVAC in these two sectors can be directly applied to the industrial sector.

Table 16. Advantages and Limitations of Heat Pumps in HVAC Applications

Advantages	Limitations
Flexibility of source: As with all heat pumps, both the temperature of the heat source and the required temperature of the end use can significantly affect the system performance. Since HVAC applications of heat typically require lower temperatures than process applications, various heat sources can be used to provide heat to the HVAC system. These sources can include ambient outside air (air-source), thermal ground heat (ground-source), or waste heat streams from the process	**Low temperature inoperability:** Temperatures below 10°F can cause problems with heat pump functionality. This can require the installation of backup heating systems during extreme temperatures. These systems can include resistance coils and/or natural gas or propane burners. This can lead to a significant increase in capital cost and operational electrical use.
	System overhaul: Existing HVAC systems can require a complete overhaul of heating and cooling systems to be converted to heat pump systems. This is especially true with centralized boiler systems or campus/district steam systems.

Heat pumps can replace or be integrated into existing HVAC systems to improve efficiency and reduce reliance on fuels. Most large HVAC unit manufacturers offer heat pump rooftop units (RTUs) that replace existing gas-fired RTUs. Hybrid systems with gas burners or resistance coils as a backup source of heat at low temperatures are commonly available.

Variable refrigerant flow (VRF) systems are becoming more common in commercial spaces and could have direct application in some industrial applications, but these systems require a much larger amount of capital. VRF systems provide both heating and cooling to various zones or end uses by modulating the amount of refrigerant that is distributed to each zone in a facility. Integrating heat pumps into VRF systems can enhance the efficiency and flexibility of the HVAC system.

Hydronic heat pumps can also be considered to replace centralized hot water heaters. These heat pumps function the same as other heat pumps but heat domestic water in a facility instead of air or refrigerant flow systems. Table 17 outlines common HVAC systems and their suitable heat pump alternatives, along with key details regarding implementation and benefits.

Table 17. Common Applications of Heat Pumps in HVAC Applications

Existing HVAC System	Suitable Heat Pump Configuration	Details
Rooftop unit (RTU)	Heat pump RTU (Water-to-air heat pump)	Heat pump RTUs and water-to-air heat pumps are becoming more common across all applications. These are typically designated by air-source or water-source, referring to the heat source used for the heat pump.
Simultaneous heating and cooling Loads served by VRF	VRF systems integrated with heat pumps	VRF systems are used to move heating and cooling to various parts of a facility using refrigerant as the transporting medium instead of air or water. They typically require a complete redesign and retrofit of the existing system but are very efficient once in place.
Centralized fuel boilers (hot water and steam)	Hydronic heat pumps system (air-to-water heat pump)	Large, centralized systems can be transitioned to individual building systems or employ large, centralized hydronic heat pumps using well fields as the heat source.

Resistance and Electric Infrared

Electric resistance and IR heating function identically to the process heating applications using the electrical resistance of a conductor to produce heat and converting electricity to radiant heat, respectively. In HVAC applications, resistance heating temperatures tend to be lower than the temperature requirements of process heat. Electric IR heating uses radiation to heat objects, not space. In HVAC applications, IR is used in targeted applications to maintain temperatures for certain pieces of equipment or personnel in a certain space.

Table 18. Advantages and Limitations of Resistance and Infrared technologies in HVAC applications

Advantages	Limitations
Efficiency: Electric resistance and IR heating are 100% efficient. These units effectively have no losses and convert all electrical energy to usable heat.	**Demand increase and unit cost:** Both electric resistance and IR heating have an effective coefficient of performance (COP) of 1, meaning that all energy input is output by a ratio of 1:1. Compared with heat pumps with higher COPs, all necessary heat must be input as electricity to the resistance and IR heaters. This can lead to demand peaks during cold periods and significant increases in electricity usage costs if unit costs are high.
Specified applications: Getting electricity to a certain area of a facility is typically easier than piping natural gas into an area. Resistance and IR heating units can be applied to specific pieces of equipment or areas where heating is necessary. This reduces excess heating and can reduce overall energy use.	**Infrastructure upgrade:** Electric resistance and IR heating applications typically require an overhaul and redesign of heating systems, in general. These upgrades usually include electricity infrastructure upgrades to accommodate the increased load.

Applications of Resistance and IR Heating in Industrial HVAC: Resistance and IR heating applications function well as substitutes for miscellaneous heating applications and backup systems, as mentioned previously in the section on HVAC heat pumps. Using these technologies in tandem with heat pump systems can provide benefits for different heating applications. Resistance coils and IR systems are very common in the comfort heating of warehouses, which are typically heated using standalone units. These heaters typically replace gas-fired unit heaters or other gas radiant heaters such as tube heaters or standalone units. In many industrial facilities, gas-fired unit heaters or radiant heaters are used in less-occupied spaces to prevent cold temperatures that could compromise large equipment or electrical systems. Electric radiant heaters or industrial blanket heaters are used in specific applications in which heat is needed in a specific area or for specific equipment.

Table 19. Common Applications of Resistance and Infrared technologies in HVAC Applications

Existing HVAC System	Electric Alternative	Details
Gas-fired unit heaters	Electric radiant heaters	Gas-fired unit heaters are common around production lines and in warehouses for personnel comfort. Electric radiant heaters can be used as a direct replacement in these areas where heat is needed but significant airflow or heating infrastructure is not necessary.
Gas-fired IR heaters	Electric IR heaters	Electric unit heaters can directly replace gas-fired IR heaters in HVAC applications. These are often used in applications in which low temperatures are common and equipment or small areas must remain heated, such as docking bays or pump houses.
Ambient equipment heaters	Electric IR heaters Industrial blanket heaters	In many industrial applications, heaters are used to maintain the functional integrity of equipment and electronics. Localized IR heaters or industrial blanket heaters are viable substitutes that can limit heat to only necessary applications.

The high cost and low coefficient of performance of IR and radiant heaters increase the scrutiny that should be used when deciding to use these technologies. Specific personnel, equipment, and floor space that need to be heated, without a need to heat the air around them, are good candidates for this equipment.

Electric Steam and Hot Water Generation Systems

The types of electric equipment used to generate steam and hot water (boilers and heaters), along with their advantages and limitations, were discussed in the previous section of this Booklet. The steam and hot water produced by these electric systems can also serve the HVAC needs of the facility.

For HVAC applications, steam is generated in a central boiler and used for space heating through steam radiators or steam-based heating coils in air handling units. Although effective, steam systems require meticulous control of pressure, temperature, and regular boiler maintenance. HVAC systems typically do not require steam, and it is also common for facilities to convert the generated steam to hot water using a heat exchanger to meet heating demands. This additional conversion step introduces avoidable thermal losses and inefficiencies, as a portion of the energy used to produce steam is lost during the transition to hot water.

Table 20. Common Applications of Electric Steam and Hot Water Generation in HVAC Applications

Existing HVAC System	Electric Alternative	Details
Centralized fuel-fired boilers with heating coils or radiators	Distributed electrified hot water system	Although steam generation can be directly electrified, a more effective solution would be to transition from steam to hot water by installing hot water boilers to meet the heating load. This would require retrofitting the steam coils at the air handling units.
Centralized fuel-fired hot water	Electric hot water boiler and tankless water heater	Hot water needs that use fuel-powered hot water boilers are increasingly being replaced with highly efficient electric hot water systems. Tankless and on-demand water heaters are often ideal candidates for smaller domestic water use. Distributed on-demand heaters eliminate storage losses and are highly efficient.

Electric Forklifts and Utility Vehicles

Industrial forklifts and other utility vehicles can be electrified in various ways to replace conventional internal combustion engines, which are commonly powered by natural gas or propane. Utility vehicle fleets are typically a promising first electrification opportunity for many organizations because electrification can be pursued in a phased approach with limited interruption to key operations, and with relatively manageable capital costs. The primary electrification options available are listed below and they are compared to one another (and to natural gas/propane forklifts) in Table 21.

Lead Acid Battery Forklifts: Powered by lead acid batteries, these forklifts are economical but have longer recharge times and require regular maintenance, including water top-ups.

Lithium-Ion Battery Forklifts: These forklifts use lithium-ion batteries which provide higher energy density, faster charging, and longer life cycles compared to lead acid batteries.

Hydrogen Fuel Cells Forklifts: These forklifts use hydrogen fuel cells to generate electricity to power the vehicle. Hydrogen fuel cells in forklifts deliver high efficiency and quick refueling advantages, with the benefit of producing zero emissions at the point of use, which improves air quality inside the plant and aligns with operational goals.

Table 21. Options for electrification of forklifts and utility vehicles

	Natural Gas/ Propane	Lead Acid Battery	Lithium-Ion Battery	Hydrogen Fuel Cells
Power and Reliability	Consistent and continuous power profile	Compromised power profile because batteries lose capacity when they are charging/discharging and idling	Maintains a constant voltage throughout the discharge cycle	Comparable with natural gas internal combustion engines
Refueling/ Charging	Refilled quickly and easily at a fueling station	Typically needs ventilated charging space given the production of toxic fumes of lead and sulfuric acid	Needs charging infrastructure, but no need for a dedicated ventilated charging space	Refilled quickly and easily at a fueling station; sourcing hydrogen is usually a barrier
Operation and Maintenance	Requires comparatively less maintenance	Life cycle that averages between 1,000 and 1,500 cycles	Life cycle between 2,000 and 4,000 cycles	Requires comparatively less maintenance
Other Considerations	Lower upfront cost	Emissions reduction; requires watering, equalizing, and battery maintenance in addition to replacement	Emissions reduction, lower cost of ownership, better safety profile	Emissions reduction with good reliability; higher upfront cost

With forklift technology, one of the most important considerations is scheduling of usage and refueling. Typical propane or natural gas forklifts function similarly to conventional combustion engines and require little time for refueling. Hydrogen fuel cell forklifts refuel on similar time scales but often face the hurdle of hydrogen availability and infrastructure. Electrochemical battery forklifts function as the premier electrification solution but often take much longer to charge. This can be ameliorated with strategic charging strategies, however. Depending on facility production schedules, it is often possible to charge electric forklifts during nonproduction hours. Depending on facility personnel and operating procedures and practices, some facilities may choose to plug in forklifts for charging whenever production schedules allow. These practices may cause increases in demand for charges during peak hours or unnecessary wear on forklift batteries because of irregular charging practices. Care should be taken to analyze and optimize the usage and charging schedules for electric forklifts to maximize their lifetime and beneficial output.

CONCLUSION

Electrification is transforming industrial operations by replacing traditional methods with electric solutions. This Booklet covers a range of electric heating technologies, from well-established ones like resistance heating to modern approaches such as microwave heating. Each technology presents unique advantages and limitations, helping users understand the potential for electrification to vastly improve their manufacturing processes. The adoption of these technologies can help manufacturers realize remarkable gains in efficiency and productivity, and meet safety, quality, and environmental goals.

This Booklet provides an overview of the current landscape of industrial electrification technologies. However, technological development is a continuous process. Ongoing research to improve the technologies contained in this Booklet is expected to overcome many of the limitations highlighted here. Staying informed about technological advances is critical, as enhancements in these technologies facilitate their smoother and more cost-effective integration into widespread industrial use.

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