Energy Implications of Electrotechnologies in Industrial Process Heating Systems

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ABSTRACT

Industrial process heating systems consumed 7.2 quads of energy in 2014 in the United States, with more than 90% of the total primary energy coming from fossil fuel-based energy sources.[1] Switching to renewable/clean electricity could allow these systems to reduce their direct fossil fuel use, decreasing their environmental footprints while saving energy. Although electrically heated systems (electrotechnologies) are usually more efficient, provide better process control, and increase product quality, technological gaps and economic factors hinder their widespread adoption. This study explores the potential of current and emerging electrotechnologies to overcome these barriers and pave the path for increased electrification in major industries. Five industries with significant process heating energy consumption were chosen and their heating requirements studied for each manufacturing step. Possible electrotechnology alternatives (both currently available and emerging) were identified for each step, and the barriers associated with large-scale implementation were investigated. Based on this analysis, appropriate routes of electrification were proposed for each industry, and their potential impacts on the U.S national energy consumption were quantified using a standardized methodology. This paper presents the electrification routes that were deemed feasible for each industry along with their quantitative impact on the use of electrical energy at the national level. The technical details of the new systems and processes considered are also presented along with the barriers identified.

Introduction

Process heating (PH) systems such as furnaces, ovens, dryers, heaters, and kilns use thermal energy to transform materials like metal, plastic, and ceramics into a wide variety of industrial and consumer products by melting, drying, heat treating, curing, smelting, and other operations. Many of these systems are mature technologies used ubiquitously throughout the manufacturing sector.

Traditional industrial (thermal) processes predominately use fuel-fired systems. Being combustion based, these systems have intrinsic inefficiencies associated with containing and controlling the heat produced. Most also use fossil fuel and therefore emit carbon. Electricity based PH systems, often called electrotechnologies (ETs), use electric currents or electromagnetic waves to heat materials and are comparatively more controllable, clean, and efficient (DOE 2007). They use direct heating methods to generate heat within the work piece itself, which reduces inefficiencies and provides high controllability of the heat. That means the product temperature can be accurately and consistently controlled within extremely close

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[1] 1 quad = 1,000 trillion Btu

tolerances, resulting in consistently high-quality products (EPRI 2010). From over 500 assessments done by DOE, the typical overall efficiency of fuel-fired systems are from 30% to 60%, ETs have efficiencies in the 60-80% range (ORNL 2010). The unique energy–material interaction seen in emerging ETs using electromagnetic heating could also enable entirely new or enhanced manufacturing processes and products. Use of electricity produced from non-fossil-fuel sources for process heating would allow industries to reduce their fossil fuel use, resulting in energy and carbon productivity advantages.

The paper presents possible pathways to electrification in industrial process heating systems for five industries studied. A methodology to determine the quantitative impact of the large scale implementation of ETs on the use of electrical energy at a national level is proposed and the impact is determined for the industries considered.

Energy Used for Process Heating

Manufacturing facilities in the United States consume almost 20% of the total primary energy used in the country (EIA 2013), and PH applications are the single biggest energy user, accounting for more than 50% (7,200 TBtu) of the total energy used in a facility (EIA 2013). A few industries, such as iron and steel, pulp and paper, glass manufacturing, aluminum manufacturing, and petroleum refining, account for more than 60% of all the energy used for PH in US manufacturing. Figure 1 shows a breakdown by sector and the contribution of electricity to the total energy used in PH applications.

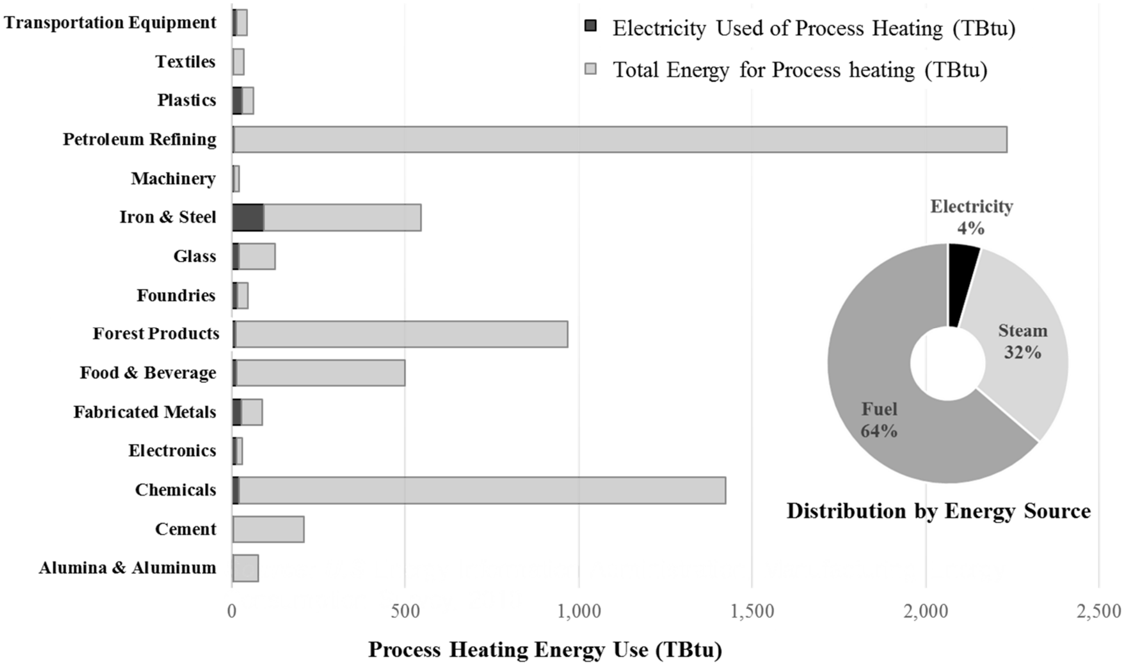

Figure 1. Total energy used for PH in different industries along with the contribution of electricity in these applications. *Source:* MECS 2010.

As shown in Figure 1, only 4% of the total PH energy in manufacturing is currently electricity, with the remaining coming from either direct fuel-fired systems or steam produced primarily by such systems. Electric-heating-based steam production is minimal in the industry at less than 1% of the total steam production (EIA 2013). A few industries do get a higher share of their PH energy from electricity. For instance, extrusion, molding, and other processes in modern plastics manufacturing are primarily heated by electricity, so almost 35% of the total PH energy comes from that source. The iron and steel industries derive around 13% of their total PH energy from electricity, driven primarily by the increased usage of electric arc furnaces (EAFs). The fabricated metals industry does a lot of heat-treating, which is slowly converting to electricity. Together with electricity-based joining and welding processes, they contribute to 21% of the heating energy in the field being electric. These examples indicate how the application of a specific technology could drive electrification in manufacturing.

Analysis of Potential National-Level Impact – Methodology

The methodology followed to determine the quantitative impact of ETs on the use of electrical energy at a national level is laid out in this section. The analysis involves identifying suitable ETs for each traditional industrial process and estimating the incremental energy that would be required with the large scale implementation (impact) of these technologies at a national level. The flowcharts in Figures 2 and 3 show the methodology followed.

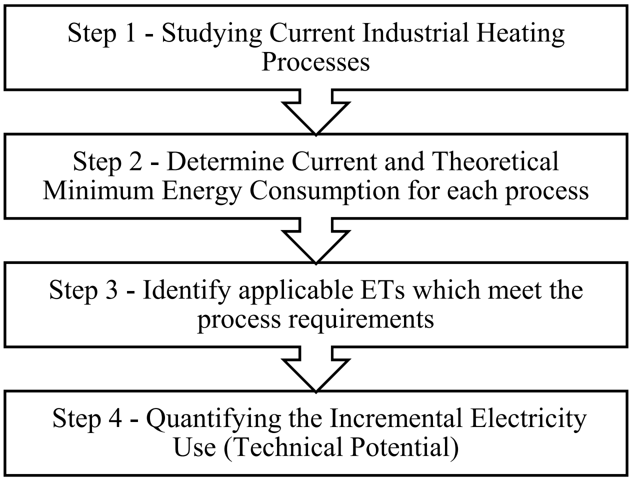

Figure 2. Analysis Methodology. This was followed for each industrial sector considered.

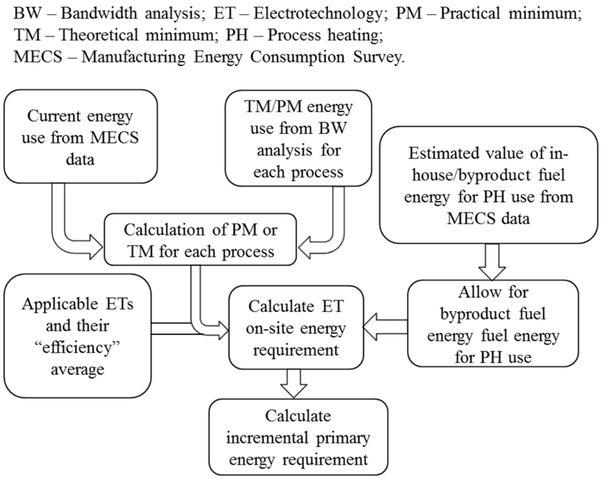

Figure 3. Estimating Incremental Electricity Use – Methodology (Technical Potential).

Step 1 - Studying Industrial Heating Processes: The first step was to study the heating process in detail and determine the heating requirements for each PH step. This included determining the temperature needed for each application, production rate, and product quality requirements. Some other factors considered included the equipment footprint, quality of raw materials, operating environment, and quality requirements.

Step 2 - Determining Current and Theoretical Minimum Energy Consumption: The current energy intensity for each PH step along with its practical and theoretical minimum estimates were determined from the US Department of Energy's (DOE's) bandwidth analysis (DOE 2015a, 2015b, 2015c, 2017a, 2017b). Based on the energy intensity and annual production numbers, the current energy consumption for each PH step in a given industry was determined. These numbers were validated with the Energy Information Administration's Manufacturing Energy Consumption Survey data (EIA 2013), which provides the total energy consumption for each industry. Also, using the practical and theoretical minimum energy intensities provided in the bandwidth analysis, the minimum energy required at each PH step was determined.

Step 3 - Identifying Alternate Electrotechnologies: Once each PH step in an industry was studied and its requirements well understood, appropriate current and emerging alternate ETs were identified. A preliminary matching of traditional thermal process applications with suitable currently available ET, shown in figure 4, is used as a starting point for this evaluation.

No.	Thermal process	RH	IH	EAH	EIP	MWH	RFH	EBP	UVP	PH	LH
1	Fluid heating	▨	▨		▨	▨					
2	Steam generation	▨									
3	Metal heating	▨	▨		▨						
4	Metal melting		▨	▨						▨	
5	Metal heat treating	▨	▨		▨						
6	Smelting, agglomeration etc.	▨									
7	Nonmetal heating, heat treating					▨	▨	▨	▨		
8	Nonmetal melting	▨	▨							▨	
9	Calcining	▨				▨	▨				
10	Drying	▨			▨			▨	▨		▨
11	Curing and thermal forming	▨	▨		▨		▨		▨		
12	Thermal reactors	▨	▨		▨	▨			▨		
13	Other heating	▨	▨		▨	▨	▨	▨	▨		▨

RH: resistance heating; IH: induction heating and melting; EAH: electric arc heating; EIP: electric infrared processing; MWH: microwave heating; RFH: radiofrequency heating; EBP: electron beam processing; UVP: ultraviolet processing; PH: plasma heating; LH: laser heating

Figure 4. Preliminary matching of commonly used fuel-fired PH applications with currently available ETs that might replace or supplement them.ET. Source: (Thekdi 2018)

The chart is compiled based on the historical use of ETs for similar applications in industries. While this information was used as an initial pointer, the analysis involved identifying suitable ETs taking into account several other factors not captured in the figure. Past experiences with the application of ET in the specific process, results from pilot studies on emerging ETs and challenges unique to the industry and application were taken into account to identify suitable potential alternatives. In addition to literature reviews, interviews with various vendors, research personnel, and industry experts were conducted to determine this.

The study focused on whether it is technically feasible to apply a certain ET for a specific application and does not delve into the economic aspects of its implementation. The national-level impact estimated in step 4 is, therefore, based on the technical feasibility of these technologies to replace existing fuel-fired systems. While understanding the economics of implementing an ET is important, it would require a robust life cycle analysis for each ET, which was considered outside this study's scope. While some of the barriers that ETs face are considered, the numerical results represent the potential from a purely technical standpoint.

Step 4 - Quantifying Incremental Electricity Use: Once alternate ET pathways for each industry were determined, incremental electricity use with the switching of fuel-fired systems to ET was estimated. The theoretical minimum energy efficiency from the bandwidth study provided the basis for this estimation. The theoretical minimum numbers represent the minimum thermodynamic energy needed for a specific process without considering any losses associated with the thermal system. Thus, the product of the theoretical minimum energy intensity and the overall efficiency of the ET system gives the energy intensity for the specific process. Whenever theoretical minimum numbers were zero or negative, as in the case of exothermic reactions, practical minimum numbers were used.

Table 1. Electrotechnology Efficiency

Application - ET	System Efficiency
Microwave heating for fluid (Boldor et al. 2008)	80%
Induction heating – metals (Frogner et al. 2011)	60%
Resistance heating (power supply efficiency)	80%
Resistance heating - indirect (Orfeuil 1987)	63%
Electric infrared heating (Orfeuil 1987)	65%
EAF - steel melting (Goodfellow, Ferro, and Galbiati 2005)	60%
Electric steam heating system (Zaidi 2018)	67%

Typical thermal efficiency for the identified ETs (Table 1) was chosen, appropriate process-specific adjustments (discussed separately for each industry) were made, and the electricity consumption was calculated from the theoretical minimum energy numbers. For applications for which more than one ET was deemed feasible and either one could ultimately be used in the industry, an average efficiency of the processes was used for the analysis. It was assumed that the market would implement the multiple technologies in equal fractions because determining the market penetration of each technology was beyond the scope of this work. The amount of byproduct fuel that was produced in the process was estimated and subtracted from the estimated incremental electricity because in most cases it would not be practical to replace this “no cost” fuel source with electricity.

A detailed account of promising ET pathways considered is presented in the following sections for two manufacturing sectors, iron & steel, and pulp & paper. The quantitative results of the analysis for three additional sectors are also presented in the later section. A more detailed report for the five industries will be published separately.

Analysis of Iron and Steel Industry

Process Overview

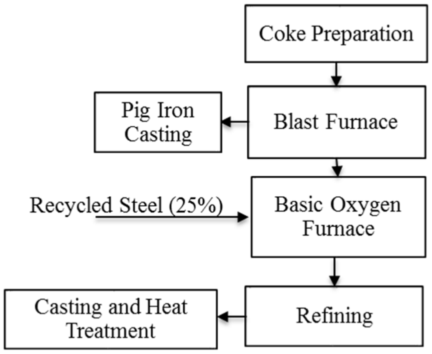

Figure 5a. Integrated Steel Mill. *Source:* DOE 2015a.

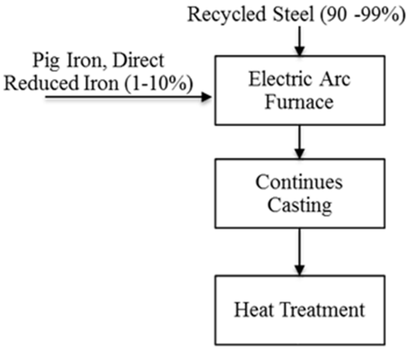

Figure 5b. Mini Steel Mill *Source:* DOE 2015a.

Steel is produced either in an integrated steel mill from iron ore or in mini-mills using recycled steel. Typical process flows for these facilities are shown in Figures 5a and 5b. Integrated steelmaking involves using a blast furnace to chemically reduce and physically convert iron oxides into molten iron, which is converted to steel using a basic oxygen furnace (BOF).

Mini-mills, on the other hand, primarily make use of scrap steel or direct reduced iron (DRI) to produce molten steel in an EAF. From the EAF or BOF, molten steel is semifinished into various solid forms through castings of various shapes and sizes. Rolling and finishing processes are used to produce the finished steel products, followed by appropriate heat-treating processes.

Energy Analysis

An analysis of the iron and steel industry and its PH operations was undertaken based on the methodology described in the previous section. A snapshot of this analysis is shown in Table 2. It should be noted that the energy used for PH included only the energy for heating the materials and not that of the "raw material" used for reactions as in the case of a blast furnace

Table 2. Iron and Steel Industry - Summary of Energy Analysis

Process	Current Energy Intensity (MMBtu/ton)	Current Energy Use (TBtu/year)	Process Requirement	Electrotechnology Options
Pelletizing	0.7	27.8	High-temperature bonding of material at > 2300°F. Energy is supplied by using internal heat content or externally by fuel.	Very high temperature and harsh working environment are not suitable for the use of ET.
Sintering	1.32	7.6	Drying and preheating at up to 1800°F followed by heating up to 2200°F.	While replacement with ET is not directly applicable because the energy source is an integral part of the processed material, sintering and coke making can be skipped using the EAF steelmaking process.
Coke-making	3.83	35.6	Heating of coal under nonoxidizing atmosphere to 1650°F to 2200°F.	
Ironmaking				
Blast furnace	11.72	346.8	Reduction of iron ore into iron using coke and hot air blast.	Alternative 1: Reduction of iron ore by using reducing gases or other materials at 1560°F. Alternative 2: Electrowinning Electrolysis to decompose iron ore to iron
Steelmaking				
Basic oxygen furnace	0.58	19.9	Feed material is molten iron, pig iron, and other material added into the furnace and heated.	Electric heating in EAF to substitute BOF steel production.
Electric arc furnace	1.86	101.2	Use of electricity and fuel. Electricity 1.24 MM Btu/ton, fuel 0.44 MM Btu/ton.	Added electricity use to substitute fuel firing by plasma or other devices. Fuel firing as given in previous column.
Casting	0.08	6.8	Mechanical process with little fuel use.	Very little energy used for PH and hence has not been considered for electrification.

Table 2. Iron and Steel Industry - Summary of Energy Analysis (continued)

Process	Current Energy Intensity (MMBtu/ton)	Current Energy Use (TBtu/year)	Process Requirement	Electrotechnology Options
Rolling (Integrated and Mini Mills)				
Hot	2.58	218.7	Heating of steel shapes to up to 2300°F, mostly by using natural gas fuel.	Induction heating for continuous systems and some batch systems. Use of electrical infrared for batch annealing systems.
Cold	3.48	96.4	Cold rolling energy use includes heat treatment.	
Total		**860.8**		

As shown in table 2, the biggest consumers of energy are the blast furnace operation where iron ore is smelted using a carbon-based reducing agent and hot rolling where steel is reheated. Two alternative pathways were considered to the traditional blast furnace and BOF steelmaking in this study. For both scenarios, a combination of induction and electric infrared (IR) systems were considered for electrifying hot rolling operations.

Alternative 1: Direct Reduced Iron: The direct reduction process involves changing iron ore to reduced iron by a high-temperature mixture of hydrogen and carbon monoxide, which are reducing agents. The iron produced from direct reduction can then be used in an EAF, effectively avoiding the blast furnace and oxygen furnace operations. Direct reduction processes were developed specifically to overcome the difficulties of conventional blast furnaces. A schematic of the electrotechnology pathway is shown in Figure 6. Pelletization of iron is still needed for DRI even though sintering and blast furnaces are avoided.

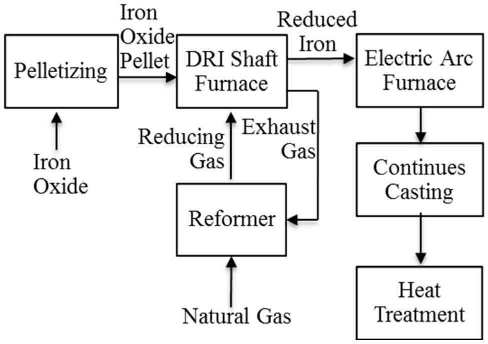

Figure 6. Schematic of DRI-Based Steelmaking

While DRI offers an alternative to the tradition steelmaking process, which is carbon intensive, the process itself is not completely devoid of fuel usage. Further, the electrification of the DRI process also poses its own set of challenges. The reduction process takes place in a shaft furnace where the iron oxide pellets are dropped from the top and made to react with the hot reducing agents rising from below. The reducing agents are derived from natural gas in a reformer. Natural gas reacts with steam in the presence of a catalyst in a high-temperature environment inside the reformer to produce hydrogen and carbon monoxide. While some fuel is used to kickstart this reaction, the process becomes self-sustaining after a point once enough exhaust is recovered from the shaft furnace. With the availability of this by-product energy in the DRI process, electrification becomes impractical, if not impossible, to implement. It is possible that electricity could be used in the DRI process by producing the reducing agents directly, but such systems are in early research phases (Vogl, Ahman, and Nilsson 2018).

Alternative 2: Electrowinning: Electrolysis to decompose iron ore to iron is an attractive alternative to traditional steelmaking. Electrowinning of iron was first demonstrated by Estelle (1918) using a caustic alkaline solution as the electrolyte and iron oxide pretreated with carbonates at 212°F. Various modifications and improvements to the process have since been made. For the purpose of this analysis, the method developed by Yuan and Haarberg (2009) was considered. The method uses concentrated aqueous sodium hydroxide solutions with suspended solid ferric oxide particles as the electrolyte with a rotating disk graphite electrode as the cathode(figure 7). By applying a constant current, the suspended solids are transferred to the cathode and reduced to iron metal. An energy balance for the process was done as in Fischedick et al. 2014, which provided the energy intensity values for the analysis. The electrolysis of iron ore is still in the early research phase with proven results only at laboratory scale. The biggest barriers to electrowinning are related to scaling it for mass production. Market entry is not expected before 2040 (EUROFER 2013).

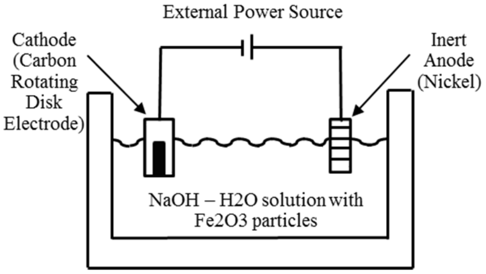

Figure 7. Schematic of Electrolysis

Pelletization and sintering are done in a crude, high-temperature environment, where the presence of carbon soot and other contaminants make it difficult to implement ET; therefore, direct conversion of these processes to ET was not considered.

Results – Summary

The onsite and primary energy consumed in the iron and steel sector currently (baseline) and for the two alternative scenarios discussed are given in table 3. The on-site energy consumption for the baseline is from the bandwidth analysis (a breakdown of which is shown in Table 2). Converting the on-site energy to primary energy took into account thermodynamic efficiency and losses associated with the transmission and generation of energy. A factor of 3 was used for electricity production, while a factor of 1.33 was used for the production of steam (DOE 2012).

Table 3. Iron and Steel Industry - Summary of Results

Description	Total On-site Energy (Site) (TBtu/year)	Total Primary Energy (TBtu/year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy at Generation (TBtu/year)[2]
Baseline – current usage	860	1,174	-	-
Direct-reduced-iron-based steelmaking process	1,028	1,750	277 (~81,180 GWh)	839
Electrowinning-based steelmaking process	945	2,836	847 (~248,231 GWh)	2,567

The energy intensity numbers for the DRI process (alternative 1), which were needed to compute the total energy from the alternative route, assumed that the Midrex DRI process was

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[2] Note: The incremental energy needed at generation was calculated assuming current infrastructure. The average on-site-to-primary-energy conversion for electricity across the United States is 3, which was used for this calculation. Use of alternate methods of electricity production, such as on-site renewables sources, would significantly change these numbers.

implemented. Energy consumption for modern Midrex plants was estimated to be 38.2 MMBtu/t (Kopfle, McClelland, and Metius, 2007). DRI also contains more impurities than scrap steel and consumes more energy in the EAF. These facts were taken into consideration in the analysis by using a factor of 14% for the increase in energy required to melt DRI (Kirschen, Badr, and Herbert 2011). The increase in on-site energy was thus due to the efficiency difference between the processes (blast furnace and DRI). The increase in incremental electricity was from the increased use of EAF and conversion of the rolling processes to ET.

For alternative 2, the incremental electricity in column 4 of Table 3 resulted from the use of electrowinning technology for steelmaking and conversion of traditional fuel-fired rolling processes to induction and resistance-based ET. The numbers for the energy intensity for electrowinning are from the analysis by Yuan and Haarberg (2009). While the primary energy is higher for this alternate scenario for current grid composition, adoption of renewable/ cogeneration systems will significantly bring it down. Further, the technology does not require the use of reducing agents such as coke or reducing gases and several process steps are eliminated.

Scaling-up of the technology to meet demand and high capital cost involved are the biggest barrier to implementation of ETs in the iron and steel industry. While a lot of the technologies under consideration perform well for small-scale applications, systems that can process a million tons of steel a year using ET are presently not economical, compared to traditional systems given the high capital cost. Large-scale testing and process optimization are necessary to improve operational efficiency and bring down cost before such technologies can be adopted. Barriers in the industry have been coming down significantly with the advent of modern methods of steel production, however. For example, induction for hot rolling, which was considered a failed technology when implemented for processing slabs, has successfully been tried for heating thinner direct cast strips, which pose a much smaller technical challenge. It is thus expected that with appropriate research, the iron and steel industry can be electrified.

Analysis of Pulp and Paper Industry

Process Overview

The papermaking process involves processing wood chips and chemically breaking down the lignin, the organic binder in wood, to separate the cellulose fibers using a digester in which temperature and pressure are controlled by use of steam from a boiler (Figure 8). The chemical used in this process, white liquor, is recycled through further processing once it leaves the digester. This involves an extensive recovery process to convert the black liquor (i.e., the post process chemical) from the digester back to white liquor. The cellulose fiber separated in the digester is washed, filtered, and bleached to remove any remaining lignin before being formed, dried, and finished in the paper mills. This method, commonly called the Kraft process, is the most widely used, and almost 85% of the pulping in the United States is done by this process. While this makes papermaking cost effective, it also adds additional PH steps that are energy intensive.

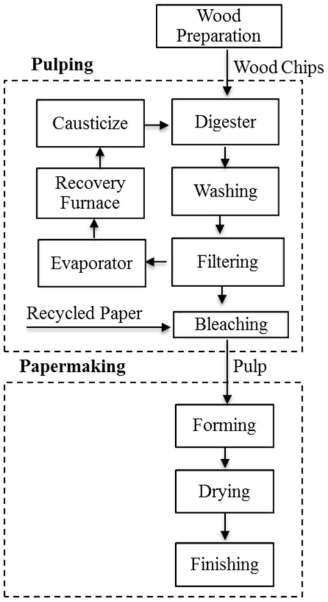

Figure 8. Schematic of Pulp and Paper Processing

Energy Analysis

ETs that could potentially be used in the pulping and papermaking process were studied, and a snapshot of this analysis is provided in Table 4. In addition to the bandwidth analysis, the energy intensity numbers were also taken from the analysis reported in Bajpai 2016.

As shown in the table, the chemical pulping and recovery processes are the most energy intensive. The options for electrification and their barriers in the pulp and paper industry are discussed below.

Using ET for Digestion: Most of the heat used in the pulping process is provided by steam in the pressure range of 300 to 1,000 psig. Conventional industrial boilers that burn natural gas or bark and wood are commonly used to produce the steam, which is strictly used as a carrier of heat in the digester to cook the slurry. Some cooking operations introduce steam directly into the digester, while others use a heat exchanger to heat the liquor separately using steam that is then introduced into the pressure vessel. In either case, steam holds no direct efficiency or process benefits in these operations and is primarily used because it is produced at a minimal cost from burning the by-product fuels. This poses both a barrier and an opportunity for ET to be used in the pulping process. Resistance/induction systems that can heat the slurry directly or indirectly using a susceptor could be built to significantly improve the thermal efficiency of these processes. Currently, electric digesters are used mainly in lab settings to study the pulping process. In addition to scaling, significant improvements to their efficiency and productivity would be necessary for them to be viable in an industrial environment because these electricity-based systems would need to compete with low-cost fuel systems to be economically viable.

While using emerging microwave and/or radiofrequency (RF) methods to separate the cellulose fibers directly from the wood chips could be highly efficient for the pulping process, such systems do not seem to have been developed. However, using microwave heating to pretreat the wood prior to the Kraft process has been shown to increase the yield by almost 40% and to decrease the energy needed at the digesters and the recover kilns (Compere and Parent 2007). Although this hybrid technology was considered a viable route for electrification in the pulping industry, this analysis was based on converting existing fuel-fired systems used for the chemical pulping process to electricity.

Table 4. Pulp and Paper Industry - Summary of Energy Analysis

Process	Current Energy Intensity (MMBtu / ton)	Current Energy Use (TBtu/year)	Process Requirement	ET Options
Pulping				
Thermochemical	0.95	3.76	Softening of wood chips by preheating in steam environment followed by a mechanical pulping process. All the heating is done by steam heat.	Alternative 1: Resistance or induction heating to indirectly heat the digester. Alternative 2: Hybrid technologies with microwave or RF preheating.
Chemical	2.6	137.91	Cooking wood chips and a white chemical liquor in a pressured vessel (digester) at 320 to 340°F by a continuous or batch operation.	
Semichemical	3.86	14.22	Combination of chemical and mechanical pulping with similar PH requirement. All steam heat.	

Table 4. Pulp and Paper Industry - Summary of Energy Analysis (continued)

Process	Current Energy Intensity (MMBtu / ton)	Current Energy Use (TBtu/year)	Process Requirement	ET Options
Chemical recovery	8.04	429.53	Recovering the chemicals used in the digester involves evaporating the black liquor to a solid constancy and burning it to recover the molten salts that are dissolved in process water and recausticized to get white liquor.	Resistance or induction heating to dry black liquor to achieve a higher concentration of smelt.
Bleaching	2.30	148.45	Includes several steps requiring liquid heating to temperature from 75 to 175°F and uses steam as a heat source.	May be able to use microwave heating or resistance heating.
Paper Drying				
Printing paper	5.2	109.43	Mechanical process using electric motors, etc. Use of steam-heated rolls, cylinders at high moisture level, and convection heating at low moisture level. Mostly use of steam, but some supplemental drying using natural gas heat.	Alternative 1: Induction or resistance heating of rolls/cylinders. Alternative 2: Electric Infrared heating Alternative 3: Hybrid technologies with microwave preheating.
Paper and board	4.05	219.71		
Other	4.05	104.42		
Total		**1,244**		

Using ET for Chemical Recovery: The chemical recovery process consists of a concentrator, a recovery boiler, and the causticizing plant. Black liquor concentrators are designed to increase the solids content of black liquor prior to combustion in a recovery boiler, which has long been accomplished using multistage, thermally driven evaporators. While various membrane technologies are in development to make this process nonthermal (Kevlich, Shofner, and Nair 2017), these technologies were not considered because they were outside the scope of this study. The analysis instead calculated the energy impact of induction systems that use the appropriate susceptor for drying the black liquor to achieve a higher concentration (Cloutier, Dontigny, and Beaudoin 2010).

The molten smelt from the recovery furnace is then mixed with water and sent to the causticizing plant, where it is reacted with lime to form white liquor. The causticizing system, in addition to clarifiers and slackers, also uses lime kilns that burns the lime mud and convert it back to lime for reuse in the causticizing process. A large amount of energy is used in lime kilns, the process creates high levels of carbon dioxide emissions. These steps could also make use of induction for heating the liquid/solid mixture.

ETs for Paper Drying: Contact drying with heated cylinders is the predominant method of drying in paper and paperboard machines. The rolls and cylinders are heated using steam, which poses an opportunity for solutions that can directly supply heat. Various ETs are competitive options for electrifying the paper-drying operations, with each one being ideal for specific process conditions.

Induction or resistance heating is used to directly heat the rolls and cylinders, which would make this step a good place for phasing out fuel-fired systems without changing the process. Decentralized (local) steam units that use electricity to produce steam could also be a route for electrification. In recent years, gas IR that uses radiation heating to dry the paper has also seen widespread adoption. The IR drying technology has been widely accepted as an efficient tool for drying, heating, and curing of paper and board products. These fuel-fired equipment could be replaced with electric IR, providing much better control and uniform heating while cutting down on emissions. Microwaves could also play a role in electrifying the paper-drying process. Microwaves have been shown to play a useful function in leveling out the moisture profiles across the wet paper web (Sander, Bold, and Kardum 2003). Also, when the paper is heated using microwaves, high drying rates are realized. By building a hybrid system that uses microwaves, an optimized operation could be achieved.

Pulp and Paper – Results

The onsite and primary energy consumed in the pulp and paper sector currently (baseline) and for the alternative electrification scenario discussed is given in table 5. The baseline energy was calculated from the energy intensity numbers given in Bajpai (2016) then converted to its primary energy using appropriate factors as in the analysis of the iron and steel industry.

Table 5. Pulp and Paper Industry - Summary of Results

Description	Total On-site Energy (Site) (TBtu/year)	Total Primary Energy (TBtu/year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy at Generation (TBtu/year)
Baseline – current usage	1,244	1,693	-	-
Converting to ET	882	1,719	418 (122,503 GWh)	1,254

For the alternate case, the on-site energy was calculated taking into account the conversation of each PH step to the appropriate ET. Hybrid technologies were not considered in the analysis because they would involve using supplemental fuel. For cases in which electrification was possible with the use of more than one technology, a simple average of the systems' efficiency was used in the calculation. A more sophisticated analysis would involve identifying the technology with the most market penetration potential and calculating a weighted average accordingly. This was not done, however, given the scope of the study.

To calculate the incremental energy, the by-product fuel available in the pulp and paper industry was first estimated. The energy available from by-product fuel sources were deemed irreplaceable, with the remaining PH energy expected to be converted to ET. Given the thermal efficiency of the electric systems considered were higher than that of the present steam boiler system, there was a drop in the on-site energy consumption. The primary energy was, however, greater than the base case because electricity production from fuels suffers much greater losses during transmission and generation. A factor of 3 was assumed for this as mentioned in the methodology. Use of alternate methods of electricity production, such as on-site renewable energy production, could significantly change these numbers. For a more holistic electrification of the pulp and paper industry, it would be necessary to consider the use of by-product fuels using other means such as a feedstock or steam-electricity production route.

Key Points from the Analysis of Other Major Industries

Petroleum Refining

Petroleum refining is the largest user of PH energy, and the industry has the highest potential for ET adoption in terms of size. Although about 70% of the PH energy is used for fluid heating and steam generation, very little work has been done toward effectively using ET for heating of process fluids in the industry. This points to a more fundamental barrier in the industry because ET is being used for fluid heating in various other industries. Any adoption is slow due safety concerns, and the availability of in-house by-product fuel, which poses a big barrier for entry for emerging electrotechnologies in this sector. Table 6 summarizes the numbers for the petroleum refining industry considering just the technical potential for ET in the sector.

Table 6. Petroleum Refining - Summary of Results

Description	Total On-site Energy (Site) (TBtu/year)	Total Primary Energy (TBtu/year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy at Generation (TBtu/year)
Baseline	2,249	2,517		
Converting to ET	1,572	3,291	859 (251,748 GWh)	2,578

Aluminum Industry

The aluminum industry is a relativily small consumer of PH energy but has significant potential for electrification, with the largest application being in aluminum melting. While induction and resistance heating have been used for relatively small batch melting, large-scale melting of scrap, specifically materials with organic and inorganic volatiles, needs further development work. For secondary processes like homogenizing and annealing, currently available ETs are considered feasible for large-scale implementation. It is expected that with appropriate research and development, all PH in the aluminum industry can be converted to ET. Table 7 summarizes the numbers for the secondary aluminum industry.

Table 7. Aluminum Industry - Summary of Results

Description	Total On-site Energy (Site) (TBtu/year)	Total Primary Energy (TBtu/year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy at Generation (TBtu/year)
Baseline	81	176		
Converting to Electrotechnology	56	168	11 (3,164 GWh)	32

Glass Industry

Like the aluminum industry, the glass industry is a smaller consumer of PH energy, with a big potential for electric melting. While electric melting is a well-established technology for certain sectors (e.g., fiberglass) of the glass industry, further development work is required to apply ET for large-scale melting processes (e.g., container, flat glass). The downstream processing of glass products is through heat treating (e.g., annealing, tempering), which requires a relatively small percentage of the total energy used in the glass sector. ETs such as resistance heating and, in some cases, electrical IR heating are well established for these processes. Table 8 summarizes the results from the analysis of the glass industry assuming that with further research and development, all the PH in the glass industry can be converted to ET.

Table 8. Glass Industry - Summary of Results

Description	Total On-site Energy (Site) (TBtu/year)	Total Primary Energy (TBtu/year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy at Generation (TBtu/year)
Baseline	161	243		
Converting to ET	116	348	95 (27,796 GWh)	285

Conclusion

A methodology to systematically determine the implications of electrifying industrial process heating applications is laid out and the impact is quantified for five industries in the U.S. The nuances of the industries and the potential barriers associated with each application are taken into account inorder to determine appropriate pathways for electrification. Through this study it is seen that the expanded use of currently available ETs like resistance, induction, and infrared have the biggest potential in most industries considered. The newer generation of ETs such as microwave and RF heating, laser heating, and ultraviolet heating are used mostly for niche markets and are relatively small in capacity, usually in hundreds of kilowatt hours. Large-scale industrial application of the newer generation of ETs will require additional research and technology development. Only a few industries such as iron and steel, glass, and aluminum are currently developing and testing radically different and disruptive technologies that truly make use of the unique characteristics of ETs such as electric arc or plasma melting in the iron and steel industry and direct-contact melting in the glass industry.

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