Electrifying U.S. Industry:

A Technology- and Process-Based Approach to Decarbonization

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Thank You.

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Executive Summary

Thermal energy needs in industry, especially for heat, are a significant challenge for climate change mitigation efforts. Heat represents two thirds of all energy demand in the industrial sector, and one fifth of energy demand across the globe. However, only 10 percent of this demand is met using renewable energy. In the United States, due in large part to the country's relatively inexpensive natural gas, fossil fuel combustion to produce heat and steam used for process heating, process reactions, and process evaporation, concentration, and drying creates about 52 percent of the country's industrial direct greenhouse gas (GHG) emissions.

There is a significant opportunity to decarbonize the industrial sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used.

The report's Technical Assessment provides an analysis of the current state of industrial electrification needs, the technologies available, and the potential for electrification in thirteen industrial subsectors. The subsectors included in this analysis are shown in Table ES1, below, along with the change in total final energy use and CO_2 emissions after electrification of certain processes in those industries. The total technical annual energy savings potential (with 100 percent adoption rate) in the thirteen subsectors studied is over 529 petajoules (PJ) per year in 2019, and 663 PJ per year in 2050. This corresponds to annual CO_2 emissions reduction of over 134 million tonne (Mt) per year in 2050. The report also analyzes a separate scenario for electrification of all conventional boilers in the U.S. industrial sector.

While in almost all cases analyzed the cost per unit of production is higher for the electrified processes compared to the conventional process during the period of study, future prices of electricity, particularly renewable electricity, and natural gas could impact this analysis. The price of renewable electricity may decrease more rapidly and the price of natural gas may increase more substantially than what is assumed in this study up to 2050. It should also be noted that our cost comparison focuses only on energy cost.

Table ES1. Change in total final energy use and CO_2 emissions from electrification estimated in this study

No.	Sectors	Change in total final energy use after electrification (TJ/Year)				Change in sector's net CO_2 emissions after electrification in U.S. (kt CO_2/year)			
		2019	2030	2040	2050	2019	2030	2040	2050
1	Aluminum casting	-2,314	-2,546	-2,800	-3,080	17	-112	-195	-294
2	Paper (from virgin pulp)	-33,995	-32,295	-30,681	-29,147	26,970	9,997	2,075	-5,080
3	Recycled paper	-75,121	-82,634	-90,897	-99,987	4,239	-4,402	-9,827	-16,295
4	Container Glass	-5,745	-6,320	-6,952	-7,647	747	-1,240	-2,498	-3,996
5	Ammonia	-22,695	-24,965	-27,461	-30,207	21,868	-779	-14,516	-30,991
6	Methanol	75,688	86,310	96,933	106,228	11,896	5,046	883	-4,275
7	Recycled plastic	-257,955	-283,751	-312,126	-343,338	-19,743	-16,032	-14,508	-12,519
8	Steel (H_2 DRI EAF)	-123,599	-136,527	-150,024	-154,712	-6,211	-24,022	-35,825	-46,668
9	Beer	-20,591	-22,132	-23,427	-24,660	-92	-669	-1,010	-1,381
10	Beet Sugar	-7,801	-8,385	-8,875	-9,342	662	-441	-1,076	-1,775
11	Milk powder	-3,657	-4,023	-4,425	-4,868	-104	-223	-304	-400
12	Wet corn milling	-20,305	-21,825	-23,102	-24,318	3,717	-1,095	-3,853	-6,892
13	Crude soybean oil	-31,732	-34,107	-36,102	-38,002	-46	-1,865	-2,934	-4,100
Total		-529,824	-573,199	-619,938	-663,079	43,919	-35,837	-83,590	-134,665

Note: Negative values imply reduction in energy use or emissions.

The electrification technologies considered in this analysis may not be the only electrification option for each process and subsector. Other electrified heating technologies might be available and applicable, or may become available in the future. In addition, other processes within the subsectors studied might have electrification potential which is not considered in this study. **In summary, the energy savings and CO_2 reduction potentials shown in this study are only a portion of total savings potentials that can be achieved by full electrification of these industrial subsectors in the U.S.**

The report reviews the major technical, economic, market, institutional, and policy barriers to scaled development and deployment of industrial electrification technologies, as well as proposals that could help to overcome these barriers. Categories of barriers and proposals include technology, knowledge and education, financing, costs, policy, and electric utility connection and reliability.

The report's Action Plan describes actions and policy recommendations that can be taken by industry and others to scale up industrial electrification, given the state of the market and the institutional and policy environment described in the Technical Assessment. Several **key recommendations** are listed below. Detailed recommendations are included in Chapter 8 of the report.

- The industrial sector should initiate partnerships with academia, national labs, think tanks, and other stakeholders to develop or scale electrification technologies.
- Government should provide incentives for electrification technology development and demonstration and use the capacity at the U.S. Department of Energy (DOE) national labs to advance electrification technologies for industry.
- Government and utilities should provide financial incentives in the form of tax credits or grants for pilot projects and demonstration of emerging electrification technologies in industry.
- Techno-economic analysis should be conducted for all electrification technologies applicable to each industrial subsector using capital cost, operation and maintenance cost, and energy cost. This analysis should consider non-energy benefits of electrification technologies as well as possible future costs of carbon.
- Government should create or support an industrial electrification information dissemination platform. This should include development and dissemination of case studies.

- Utilities should evaluate the demand response (DR) potential that increased electrification in the industrial sector can provide to utilities and its financial implications.
- Utilities should provide information about their electric rates, market structures, and grid upgrade implications of industrial electrification.
- Industry should work with different stakeholders to educate policymakers, utilities, and financial institutions about the benefits of electrification and what policy, regulatory, and financial support is required to electrify industrial processes.
- Government should adopt a variety of policies and programs to support industrial electrification.
- Utilities should adopt electricity rate designs that encourage electrification.
- Industry should provide training for employees and contractors about electrified technologies. Government and utilities should support such training programs.

01

Introduction

Industrial thermal energy needs, especially for heat, are a significant challenge for climate change mitigation efforts. Heat represents two-thirds of all energy demand in the industrial sector, and one-fifth of energy demand across the globe (IEA, 2018a). However, only 10 percent of this demand is met using renewable energy (OECD/IEA, 2014). In the United States, due in large part to the country's relatively inexpensive natural gas, fossil fuel combustion to produce heat and steam used for process heating, reactions, evaporation, concentration, and drying creates about 52 percent of the country's industrial direct greenhouse gas (GHG) emissions (JISEA/NREL, 2017).

There is a significant opportunity to decarbonize the industrial sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used. Globally, more than 50 percent of final energy demand is for heating, and about half is for industrial heating (IEA, 2018b). Much of the electrification discussion to date has focused on the transportation and building sectors, with little attention paid to the industrial sector. This report aims to fill some of that void by examining profiles of heat consumption in industrial subsectors and the potential for electrification based on different heat demand profiles and electrification technologies available to meet those heating needs, as well as barriers to industrial electrification and proposals that, if implemented, could help the industrial sector to overcome those barriers.

There is substantial unrealized potential to electrify industrial processes at low and medium temperatures. Some industries have also electrified high temperature processes, the leading example being the steel industry and its use of electric arc furnaces.

This report is comprised of a bottom-up industrial subsector, systems, and technology-level Technical Assessment and an Action Plan. The Technical Assessment provides an analysis of the current state of industrial electrification needs, the technologies available, and the potential for electrification in thirteen industrial subsectors. It also includes a separate scenario for electrification of all conventional boilers in the U.S. industry. The Technical Assessment also reviews the major technical, economic, market, institutional, and policy barriers to scaled development and deployment of industrial electrification technologies, as well as proposals that could help to overcome these barriers. The Action Plan describes actions and policy recommendations that can be taken by industry and others to scale up industrial electrification, given the state of the market and institutional and policy environment described in the Technical Assessment.

02

Profile of energy use and heat consumption in U.S. industry

The U.S. industrial sector accounts for about a quarter of energy use and greenhouse gas (GHG) emissions in the U.S. The majority of the energy used in the U.S. industry is fossil fuels (Figure 1) (US DOE/EIA 2020).

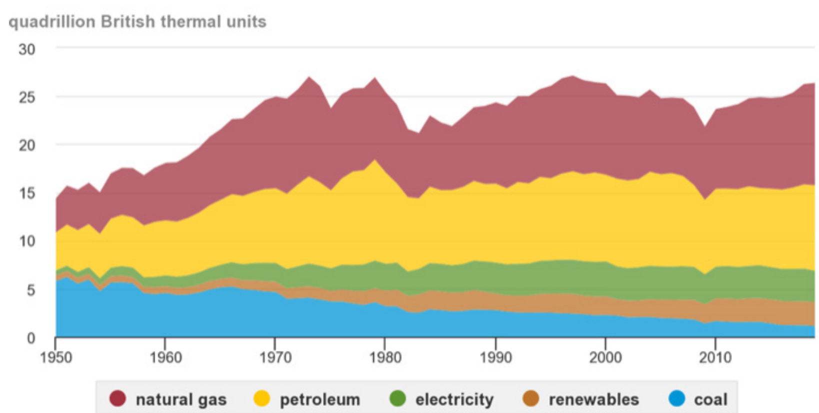

Figure 1. U.S. industrial sector energy use by type, 1950-2019 (US DOE/EIA 2020)

The top five U.S. manufacturing sectors in terms of energy use are bulk chemicals, petroleum refining, pulp and paper, primary metals, and the food and beverage industry (Figure 2- note: construction and mining sectors are not considered manufacturing).

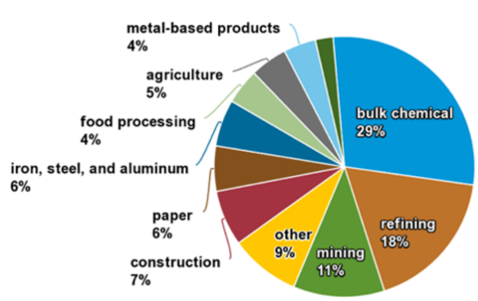

Figure 2. Share of subsectors from total U.S. industrial sector energy use in 2019 (US DOE/EIA 2020)

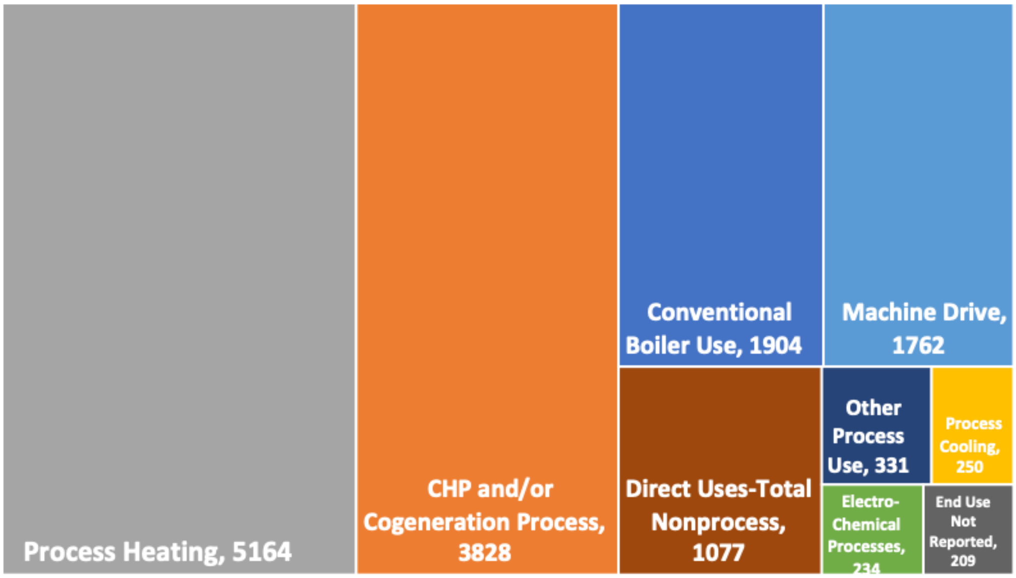

Figure 3. US manufacturing energy use by end uses- values in Trillion Btu (US DOE 2019)
Note: Process heating, process cooling, machine drives, and other processes use steam. We only report the energy use for steam under conventional boiler and CHP to avoid double counting.

In 2014, thermal processes accounted for 74 percent of total manufacturing energy use in the U.S.; process heating accounted for 35 percent combined heat and power/cogeneration for 26 percent conventional boilers for 13 percent (US DOE, 2019) (Figure 3).

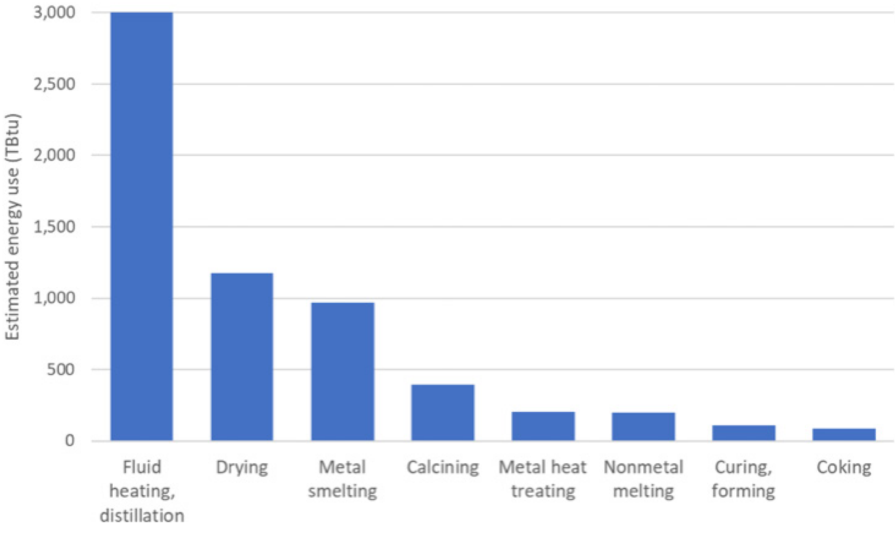

Figure 4. Energy use for process heating in the U.S industry by type of process heat (US DOE 2015a)

Process heating technologies can be grouped into four general categories based on the type of energy consumed: direct fuel-firing, steam-based, electric-based, and hybrid systems (which use a combination of energy types). In process heating, material is heated by heat transfer from a heat source such as a flame, steam, hot gas, or an electrical heating element by conduction, convection, or radiation—or some combination of these. In practice, lower-temperature processes tend to use conduction or convection, whereas high-temperature processes rely primarily on radiative heat transfer. Energy use and heat losses from the system depend on process heating process parameters, system design, operating practices, and other factors (ORNL, 2017).

Around 30 percent of the total U.S. industrial heat demand is required at temperatures below 100˚C. Two-thirds of process heat used in U.S. industry are for applications below 300˚C (572˚F) (Figure 5) (McMillan, 2019). In the food, beverage, and tobacco, transport equipment, machinery, textile, and pulp and paper industries, the share of heat demand at low and medium temperatures is about, or even above, 60 percent of the total heat demand. With a few exceptions, it is generally easier to electrify low-temperature processes than high-temperature processes. Therefore, there is significant potential for electrification of industrial processes for low or medium heating applications. Figure 6 shows the share of industrial head demand by temperature in selected industries.

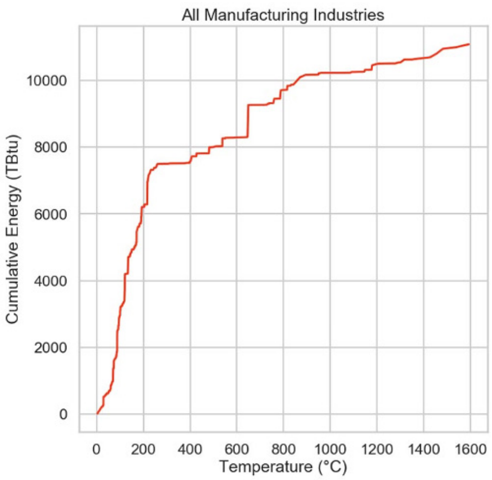

Figure 5. Cumulative process heat demand by temperature in 2014 (McMillan, 2019)

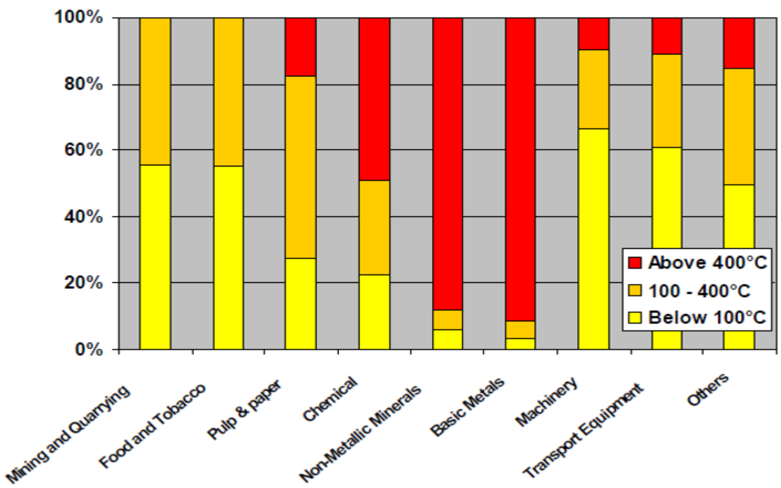

Figure 6. Share of industrial heat demand by temperature in selected industries (Caludia et al., 2008)

Industry uses a wide variety of processes employing different types and designs of heating equipment. Process heating methods used in manufacturing operations largely depend on the industry, and many companies use multiple operations. For example, steelmaking facilities often employ a combination of smelting, metal melting, and heat-treating processes. Chemical manufacturing facilities may use fluid heating to distill a petroleum feedstock and a curing process to create a final polymer product (ORNL 2017). Table 2 shows the industrial process heating temperature profile for various subsectors. As can be seen from this table, a variety of thermal processing is conducted in each industry under different temperature profiles.

Table 2. Industrial process heating temperature profile for various subsectors (DGA 2018)

Industrial Sector	Unit Operations	Temperature Range	
		Celsius	Fahrenheit[62]
Food	Drying	30-90	90-210
	Washing	60-90	150-210
	Pasteurizing	60-80	150-190
	Boiling	95-105	220-140
	Sterilizing	110-120	250-270
	Heat Treatment	40-60	110-150
Beverages	Washing	60-80	150-190
	Sterilizing	60-90	150-210
	Pasteurizing	60-70	150-170
Paper Industry	Cooking and Drying	60-80	150-190
	Boiler Feed Water	60-90	150-210
	Bleaching	130-150	190-330
Metal Surface Treatment	Treatment, Electroplating, etc.	30-80	90-190
Bricks and Blocks	Curing	60-140	150-310
Textile Industry	Bleaching	60-100	150-230
	Dyeing	70-90	170-210
	Drying, De-greasing	100-130	230-290
	Washing	40-80	110-190
	Fixing	160-180	350-390
	Pressing	80-100	190-230
Chemical Industry	Soaps	200-260	430-550
	Synthetic Rubber	150-200	330-430
	Processing Heat	120-180	270-390
	Preheating Water	60-80	150-190
Plastic Industry	Preparation	120-140	270-310
	Distillation	140-150	310-330
	Separation	200-220	430-470
	Extension	140-160	310-350
	Drying	180-200	390-430
	Blending	120-140	270-310
Flour By-Products	Sterilizing	60-90	150-210
All Industrial Sectors	Pre-heating of Boiler Feed Water	60-90	150-210
	Industrial Solar Cooking	55-180	140-390
	Heating of Factory Buildings	30-80	90-190

03

Electrification technologies for industry

This Chapter provides a brief description of some of the main electrification technologies applicable to the industrial sector. A more extensive list of electrification technologies is provided in the Appendix. More detailed information about these electrification technologies can be found in the references cited within the text.

While many of the electric technologies needed for electrification in industry are fully commercialized, some are at the development or pilot stage, especially for high-temperature processes. Further investment in research and development (R&D) is needed, particularly to address some of the high-temperature heating processes used in cement, glass, and some chemical production.

Electric boiler

Electric boilers typically utilize electric powered resistive heating elements that help convert electricity into heat. The flow of electric current and the in-turn heating are controlled by a thermostat. The generated heat can be utilized for purposes such as providing hot water for heating systems or generating steam for industrial processes (Alabama Power, 2020). Larger electric boilers are typically electrode boilers (jet type) that use electricity flowing through streams of water to create steam. A key benefit associated with electric boilers is that they are able to convert electricity into heat with an efficiency of almost 100 percent with minimal radiation losses observed from exposed boiler surfaces (Alabama Power, 2020). On average, the capital cost of an electric boiler is nearly 40 percent less than that of an equivalent natural gas-fired boiler (Jadun et al., 2017).

Heat pump

Heat pumps are devices that extract and transfer heat from one place to another. Common examples of this technology include refrigerators and air conditioners. Inside a heat pump, a refrigerant is cycled across two heat exchanger coils. In the first coil, it undergoes evaporation by gathering heat from its surroundings and in the second coil, the refrigerant is condensed, leading to the release of absorbed heat (NRCan, 2020). The technology offers a high coefficient of performance (COP) and has the potential to save costs through the replacement of gas-fired heating processes (Beyond Zero Emissions, 2018).

Electric arc furnace

Electric arc furnaces melt metals via direct and radiant heating, generated by means of electricity that jumps from the energized to the grounded (neutral) electrode, resulting in high voltage electric arcs (Flournoy, 2018). These furnaces are most commonly utilized for melting steel for recycling, producing almost 30 percent of the world's steel output. They utilize substantially lower energy compared to primary steel production using blast furnace-basic oxygen furnace (Beyond Zero Emissions, 2018).

Induction heating

Induction heating occurs by placing the material that needs to be heated inside an electromagnetic field generated by passing electricity through a conductor or coil. The electromagnetic field helps heat the material by inducing circulating electric currents within the material (GH Induction Atmospheres, 2020). The process is utilized for a wide range of applications including metal hardening, soldering, and annealing. Some of the advantages of this technology are: enhanced process efficiency, uniform and precise heating, and no on-site emissions (GH Electrotermia, 2011; Britannica, 2011).

Radio-frequency heating

Radio-frequency heating is a form of dielectric heating with systems operating in the 10-30 MHz frequency and 10-30 meters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material. Since the entire thickness of the material is heated simultaneously, the process offers uniform heating at low temperatures (Radio Frequency Co, 2020). This technique works well with materials that are poor conductors of heat and electricity due to its greater depth of penetration and is much more efficient than conventional heating processes (Beyond Zero Emissions, 2018).

Electric Infrared heater

Electric infrared heaters operate through the conversion of electricity into radiant heat. The process involves the direct heating of the object instead of heating the air in between, thus ensuring the efficient transfer of heat (Herschel, 2020). These systems can be designed with temperature requirements and the target material's ability to absorb infrared radiation in mind. The technology offers numerous advantages, including high overall efficiency, faster response time than gas convection systems, low cost, and minimal maintenance effort (Beyond Zero Emissions, 2018).

Ultra-violet (UV) heating

UV radiation is primarily utilized for the efficient curing of coatings such as paints, inks and adhesives. The process works by exposing UV formulations (inks, coatings or adhesives containing a small proportion of photo initiators) to UV radiation, resulting in their instant curing. Some advantages of the UV curing process include improved resistance to abrasion, faster production speeds, low energy intensity, and reduction in processing times (Heraeus Group, 2020). The technology is utilized for various applications such as adhesive bonding, general electronics, packaging, semiconductors, and coatings, among others (LightTech, 2020).

Microwave heating

Microwave heating is a form of dielectric heating with systems operating in the 900-3000 MHz frequency and 10-30 centimeters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material (Beyond Zero Emissions, 2018). This process is utilized for a wide variety of industrial applications, including simple heating, drying, and defrosting. It is especially useful for heating products or materials with poor thermal conductivity, large volume and small surface area, and high sensitivity to large surface and bulk temperature differentials (MKS, 2014).

Figure 7 shows some of the characteristics of electromagnetic heating technologies.

Frequency	50 Hz - 500 kHz	10-100 MHz	200-3000 MHz	30-400 THz		1-30 PHz
Wavelength						
	Induction	Radio	Microwave	Infrared	Visible light	Ultra-violet
Max temp °C	3000	2000	2000	2200		N/A
Power density (kW/m^2)	50,000	100	500	300		100
Efficiency	50-90%	80%	80%	60-90%		
Application	Rapid internal heating of metals.	Rapid internal heating of large volumes.	Rapid internal heating of large volumes.	Very rapid heating of surfaces and thin material.		Non-thermal curing of paints and coatings.

Figure 7. Electromagnetic heating technologies (Beyond Zero Emissions, 2018)

Electric induction melting

The working principle behind electric induction furnaces is the induction of a low voltage, high current in a metal (secondary coil) with the help of a primary coil at a high voltage (Atlas Foundry Company, n.d.). The induced current leads to the development of a stirring motion, which maintains the molten metal at a constant temperature, ensuring a homogenous and good quality output. Induction furnaces are categorized into channel induction furnaces and crucible induction furnaces. Channel induction furnaces are utilized for melting non-ferrous metals with lower melting points, operating at an efficiency of around 80 to 90 percent. Crucible induction furnaces are utilized for melting metals with higher melting points (such as steel and cast iron) and they operate at an efficiency of 80 percent (Beyond Zero Emissions, 2018).

Plasma melting

In the process of plasma arc melting, the partly ionized inert gas acting as the plasma arc torch column serves as the source of heat. The metal melting process occurs at a pressure range of around 300 – 1000 mbar (abs.) under inert gas conditions (ALD, 2019). The technique is utilized for a wide range of process heating applications across various industries such as metal, chemical, mineral, and plastic. and has the potential to displace natural gas furnaces (EPRI, 2009). Some of the numerous advantages of the process are reduced impurities, high stability and ease of temperature adjustment, and reduced air pollution (Svirchuk, 2011).

Electrolytic reduction

Electrolytic reduction utilizes the process of electrolysis to extract metals from their compounds. The technique is utilized for the smelting of alumina, where the metal in the ore undergoes chemical reduction, resulting in the production of aluminum (Beyond Zero Emissions, 2018). Another electrolytic technology is electrolysis of iron ore to produce steel (Boston Metal, 2020). The major advantages of this process include reduced impurities and the potential to achieve substantial reduction in CO_2 emissions when low-carbon electricity is used for electrolysis. (Irfan, 2013).

Indirect electrification

Indirect electrification is when renewable electricity is used to produce hydrogen via the electrolysis of water into oxygen and hydrogen, and this hydrogen is then used as a substitute for natural gas in thermal industrial processes (Deason et al., 2018). Hydrogen produced with electrolysis using renewable electricity is known as "green" hydrogen. The cost of production and distribution of hydrogen, especially from renewable energy sources, is high. Figure 8 shows the cost of hydrogen production of selected hydrogen production methods.

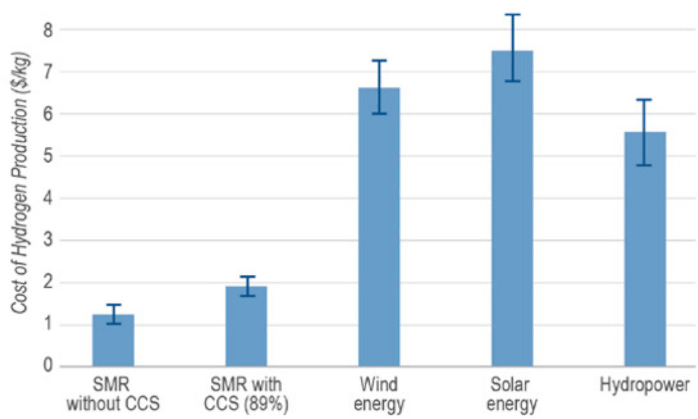

Figure 8. Cost of hydrogen production on ($/kg) of selected hydrogen production methods (unsubsidized) (Friedmann et al., 2019)

04

Sector-specific electrification potential in U.S. industry

4.0 Methodology

This Chapter of the report presents the results of our analysis for electrification potential in thirteen industrial subsectors in the U.S. (Table 3). The sector-specific electrification analysis focuses on electrifying the end-use technologies as opposed to electrifying the steam boilers only. In most industrial processes, steam is used as a heat carrier and steam itself is not needed in the process. Therefore, instead of using steam (whether or not it is generated by fuels or electric boilers), we can consider using end-use electrification technologies (such as the ones described in the previous Chapter) to provide the heat for the process. The electrification of end-use processes has the advantage of increasing efficiency by removing steam distribution losses. Nevertheless, in the next Chapter (Chapter 5), we conducted an analysis for a scenario when all conventional boilers in the U.S. are electrified and quantify the impact.

Table 3. U.S. industrial subsectors that are analyzed in this study

Industry Sector	
1. Aluminum casting	8. Steel
2. Paper (from virgin pulp)	9. Beer
3. Recycled paper	10. Beet Sugar
4. Container Glass	11. Milk powder
5. Ammonia	12. Wet corn milling
6. Methanol	13. Crude soybean oil
7. Recycled plastic	

To conduct this bottom-up, systems-, and technology-level electrification analysis for each industrial subsector, we followed four steps as shown in Figure 9. We analyzed the existing heating systems used in the main processes for each subsector, including the heat demand and temperature profile. Then we identified suitable electrification technologies that can provide the same heat and function for each thermal process. Almost all of the electrification technologies we identified and assigned to processes are commercially available. Having the energy intensity of process heating technologies for conventional and electrified process, we then calculated the energy use, GHG emissions, and energy cost implications of electrification in each industry. We also used projections for the production for each subsector as well as projections in grid emissions factor and unit price of energy in order to project the energy, GHG emissions, and energy cost implications of electrification in each industry. The U.S. electricity grid emissions factor and average unit price of natural gas and coal used in our analysis are shown in Table 4.

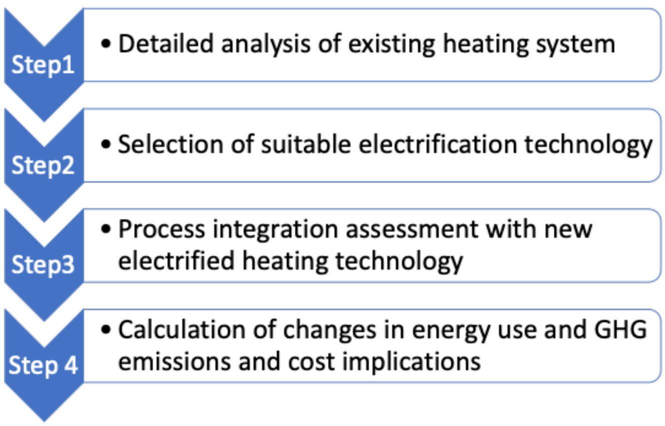

Figure 9. Methodology steps to estimate electrification potential in U.S. industrial subsectors

We also used projections for the production for each subsector as well as projections in grid emissions factor and unit price of energy in order to project the energy use, GHG emissions, and energy cost implications of electrification in each industry. The U.S. electricity grid emissions factor and average unit price of natural gas and coal used in our analysis are shown in Table 4.

It should be noted that the change in energy use and GHG emissions estimated for each subsector in the following Chapters are the total technical potentials assuming a 100 percent adoption rate. The actual adoption of electrification technologies in industry will be gradual and over time. For the energy intensity of processes and technologies used in our analysis, we kept the intensities constant during the study period; 2019-2050. We did not take into account the technology learning curve and gradual improvement in technologies' energy performance (both for conventional and electrified technologies) in our analysis. This was primarily due to a lack of information for projections of energy performance improvement of the range of technologies that we considered in our analysis.

Table 4. U.S. electricity grid emissions factor and average unit price of energy (in final energy) used in our analysis

	2019	2030	2040	2050
Emission factor for grid electricity in US ($kgCO_2$/MWh)	414	207	103	0
Average unit price of electricity for industry in U.S. (2017 US$/kWh)	0.072	0.075	0.074	0.073
Average unit price of natural gas for industry in U.S. (2017 US$/kWh)	0.015	0.017	0.018	0.020
Average unit price of coal for industry in U.S. (2017 US$/kWh)	0.014	0.016	0.016	0.018

Source: Energy price projections are from US DOE/EIA (2018); Grid emissions factor projections is our estimate based on historical trends and future projections (US DOE/EIA 2017b).

The change in energy use results are in final energy terms, which means electricity is not converted to primary energy using average electricity generation efficiency and transmission and distribution losses.

In our energy cost analysis, we assumed natural gas as the primary fuel used in U.S. industries, except for the steel industry where we assumed coal as the main fuel used in primary steelmaking process. Energy prices can vary significantly from state-to-state within the U.S.: The results of our cost per unit of production comparisons are highly sensitive to the unit price of energy (electricity and natural gas).

In addition, renewable electricity prices could decrease more substantially that what we have assumed (based on US DOE/EIA projections) up to 2050, making electrification technologies more competitive. To address this scenario, we included a sensitivity analysis with regard to unit price of electricity in the form of error bars on our price graphs. The error bars show the energy cost per unit of production when the unit price of electricity is reduced by up to 50 percent.

It is also possible that the price of natural gas and other fossil fuels may increase more than what we have projected up to 2050, especially if a carbon tax or carbon price is introduced in the U.S. We have not included such consideration in our natural gas and coal price projections, and we directly used the price projections from US DOE/EIA (2018).

It should also be noted that the electrification technologies we considered in our analysis for each process and subsector may not be the only electrification options. Other electrified heating technologies might be available and applicable to the processes analyzed. In addition, other processes within the subsectors studied might have electrification potential that is not considered in this study. In summary, the energy savings and CO_2 reduction potentials shown in our study are only a portion of total savings potential that can be achieved by full electrification of these industrial subsectors in the U.S.

4.1. Electrification of the aluminum casting industry

4.1.1. Introduction

Aluminum plays an important role in shaping modern industry. Typically, engineering design considerations include size, shape, complexity, wall thicknesses, and required dimensional accuracy. Specific processes of aluminum casting have been developed based on each industry's requirements. In 2019, the total quantity of primary aluminum production in the United States was 1.1 million metric tonnes. Approximately 1.6 tonnes of aluminum are required to produce 1 tonne of finished casting products and the total quantity of aluminum casting products produced in the U.S. was about 690 kton in 2019 (Thomasnet, 2019).

4.1.2. Production process

Casting is defined as a simple and low-cost process that can be utilized for forming aluminum into a wide variety of products. It is the most widely used process for the production of aluminum products. The fundamental principle behind the casting process involves pouring molten aluminum into a mold to obtain the desired pattern. The three most popular techniques are die casting, permanent mold casting, and sand casting (Aluminum Association, 2010).

Conventional process

The main operations in the casting process using a gas furnace involve the following processes (ESC, 2020):

1. Heating of aluminum ingots / scrap to temperatures around the melting point of aluminum (650 ˚C).
2. Transfer of molten aluminum to holding chamber where it is subjected to casting temperatures of around 750 ˚C.
3. Transfer of molten aluminum to a preheated die or mold.

Gas-fired process

The two commonly utilized gas-fired furnaces are reverberatory furnaces and tower furnaces.

Reverberatory: These furnaces melt metals through the use of direct-fired wall-mounted burners. Radiation is the main mechanism through which heating occurs. Gas-fired reverberatory furnaces have efficiencies in the range of 15 to 39 percent. The low cost of operation combined with the ability to process high volumes of metal make these furnaces an appealing option (ESC, 2020).

Tower Furnaces: These furnaces have higher melting efficiencies than reverberatory furnaces as they allow the continuous melting of metals. These furnaces are equipped with burners at the base of the tower and are loaded with aluminum from the top. The primary mechanism through which heating occurs in these furnaces is convection. (ESC, 2020).

Electrified process

Electricity can be used as a heat source for the process of aluminum casting instead of gas-fired furnaces. For several years, electric furnaces have been a primary choice for the low-cost production of high-quality aluminum. In addition to reducing the energy use and the amount of aluminum waste, a reliable power control unit's regulation of the electric furnaces and the temperature controller is highly accurate. The two main electrification technologies are induction coreless furnaces and single-shot induction.

Induction coreless furnace: Induction furnaces are increasingly gaining popularity for use in the casting process. These furnaces melt aluminum with a relatively high degree of efficiency (67.5 percent) as compared to tower furnaces (43 percent) and reverberatory furnaces (37.5 percent). The highest-performing induction furnaces can achieve efficiencies as high as 76 percent. Another merit associated with the use of induction furnaces is that they combine the tasks of melting and holding. This helps eliminate the need for an energy intensive holding stage. Overall, induction furnaces require 37 percent less energy to produce one tonne of aluminum cast component as compared to tower furnaces (Beyond Zero Emissions, 2019).

Single-shot induction: This method involves the utilization of rapid induction to melt limited quantities of metal quickly instead of bulk melting. The process requires 50 percent less energy per tonne of cast component as compared to the most efficient gas-fired alternative. It also leads to a reduction in loss of material through scaling. The process offers a unique prospect for the application of induction melting to the casting process. Since the process is based on well-understood fundamentals, it does not require any technological breakthrough (Beyond Zero Emissions, 2019).

Table 4 illustrates that electrical furnaces have lower material losses as compared to their gas-fired alternatives. In electrical furnaces, the interfacial surface between air (hot gases) and aluminum is reduced; consequently, exhaust gases carry less metal. Table 5 provides a comparison of the energy consumption of conventional and electric processes for the aluminum casting industry.

Table 4. Yield losses in different heating systems (Beyond Zero Emissions, 2019)

Cause of yield loss		Gas-fired		Electrical induction	
		Reverberatory furnace	Tower furnace	Induction coreless furnace	Single-shot induction
Oxidisation	during melting	4%	1.5%	1%	1%
	during holding at furnace	1.5%	1.5%	-	-
	during holding at die-cast	1%	1%	1%	-
Fettling		33%	33%	33%	33%
Failed castings		5%	5%	5%	5%

Table 5. Energy intensities of conventional and electric aluminum casting processes (Beyond Zero Emissions, 2019)

Conventional System Processes		Process Steps	All Electric Processes	
Reverberatory Furnace	Tower Furnace		Induction Coreless Furnace	Single-shot induction
(kWh/tonne)	(kWh/tonne)		(kWh/tonne)	(kWh/tonne)
1332	1066	Melting	700	657
123	123	Holding	-	-
137	137	Transfer and Holding	137	-
1592	**1326**	**Total**	**837**	**657**

4.1.3. Energy, emissions, and cost implications of electrification

Figure 10 shows that electrification will significantly reduce the total final energy use for aluminum casting during the study period, 2019-2050. The switch to the electrified process can help achieve greater than 3,000 TJ of energy savings annually in 2050. Our savings calculation is based on maximum energy savings by replacing reverberatory furnaces with electrified single shut induction furnaces.

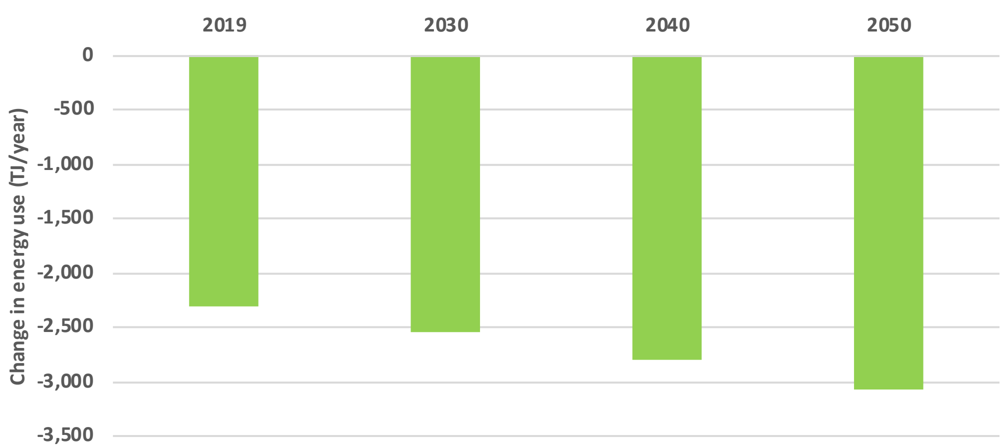

Figure 10. Change in total final energy use of the U.S. aluminum casting industry after electrification (This is the technical potential assuming 100 percent adoption rate)

Electrification of aluminum casting in the U.S. can result in a small increase in CO_2 emissions by 17 kilotonne (kt) CO_2 in 2019 (Figure 11). However, electrification can potentially help realize substantial annual CO_2 emission reductions by 2050 (294 kt/yr). This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

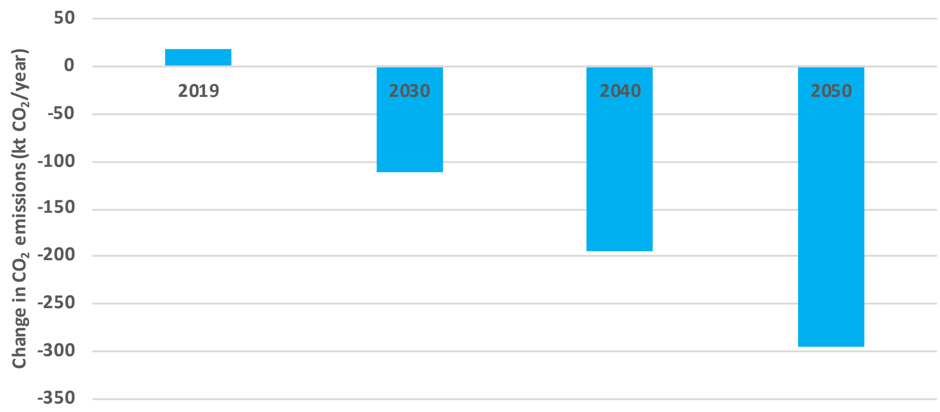

Figure 11. Change in net CO_2 emissions of the U.S. aluminum casting industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 12 shows that the energy cost (in 2017$) per unit of production (tonne of cast aluminum) for the electrified process in the U.S. aluminum casting industry is more than twice that of the conventional process in 2019. Overall, energy cost per unit of production is higher for the electrified process compared to the conventional process during the period of study. However, the electrified process becomes slightly more competitive in terms of energy cost per unit of production by 2050.

The error bars on the graph depict the energy cost per unit of production (2017$/ton product) when the unit price of electricity (2017 $/kWh) is reduced by 50 percent. It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified aluminum casting process, making it even more cost effective than the conventional process in certain scenarios.

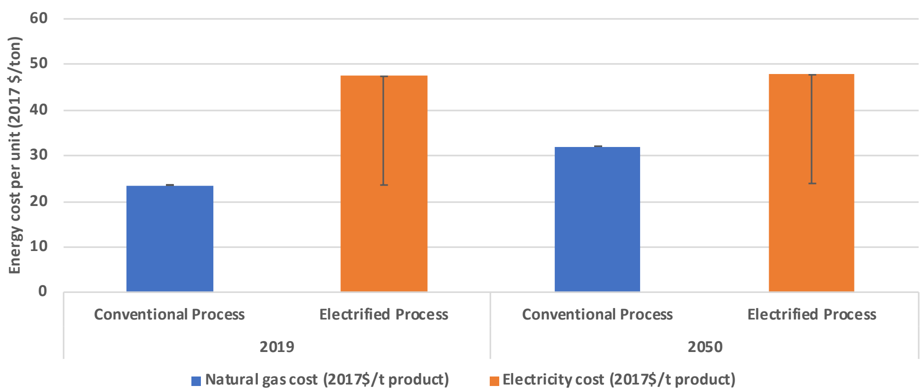

Figure 12. Energy cost per unit of production in the U.S. aluminum casting industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

Also, the price of natural gas can potentially increase more substantially up to 2050 than what we have assumed. It should be noted that our cost comparison focuses only on energy cost. A more comprehensive cost analysis that takes into account the change in capital cost, operation and maintenance cost, and non-energy benefits of electrified technologies (such as improved product quality, reduced waste, increased production rate, and reduced maintenance) can make electrified technologies more financially attractive.

4.2. Electrification of the paper from virgin pulp industry

4.2.1. Introduction

Paper is an important commodity, used for a variety of purposes on a daily basis. In 2017, the total paper and cardboard production across the globe was around 419 million metric tonnes. China, the United States, and Japan are the top paper manufacturing nations in the world (M.Garside, 2020). The pulp and paper manufacturing industry is the third largest energy consumer in U.S. manufacturing. The pulp and paper industry in the U.S. is comprised of pulp mills, mills dedicated to manufacturing paper and paperboard, and integrated mills that process pulp as well as manufacture paper. More than 50 percent of the total U.S. production occurs in the South, while the Northeast, North Central and Western regions represent the remaining production in the United States. In the U.S., there are estimated to be around 386 pulp, paper, and pulp and paper mills distributed across 41 states (Brueske et al., 2015). In 2017, the total pulp, paper, and paperboard production in the U.S. was close to 72 million metric tonnes (FAO, 2017).

4.2.2. Production process

Conventional process

Pulp is obtained from wood by means of chemical or mechanical pulping, or it can be recovered by recycling used paper. The obtained pulp undergoes processing in a paper mill to form a paper web (DEEDS, 2017). The key processes that drive pulp and paper manufacturing are preparation of raw materials, pulping, recovery of chemicals, bleaching, drying of pulp, and producing paper. The pulping and paper drying processes are associated with the highest energy consumption (Worrell et al., 2008). Figure 13 depicts a complete flow diagram representing the pulping and papermaking process. The actual process of manufacturing varies depending on the various raw materials utilized and the final product(s) to be produced. Irrespective of these factors, the elementary principle driving pulping and papermaking does not vary across facilities (Kong et al., 2012).

Electrified process

In the paper and pulp industry, the drying process is the most energy intensive and highest energy consuming process. In our electrification analysis in this report, we will focus only on electrifying the drying process in paper production mills.

In order to electrify the drying process, several suggestions have been made, such as utilizing radio frequency dryers (DOE, 2004), industrial heat pumps (DGA, 2018), and microwave dryers (Kong et al., 2012). In this study, we considered the electrification of the conventional drying process by utilizing a radiofrequency paper dryer, which has an overall heating efficiency of 70 percent and leads to a 10 percent reduction in energy consumption of the drying process (CEATI, n.d.). Table 6 compares the energy intensity of pulp and paper through the conventional and electrified processes.

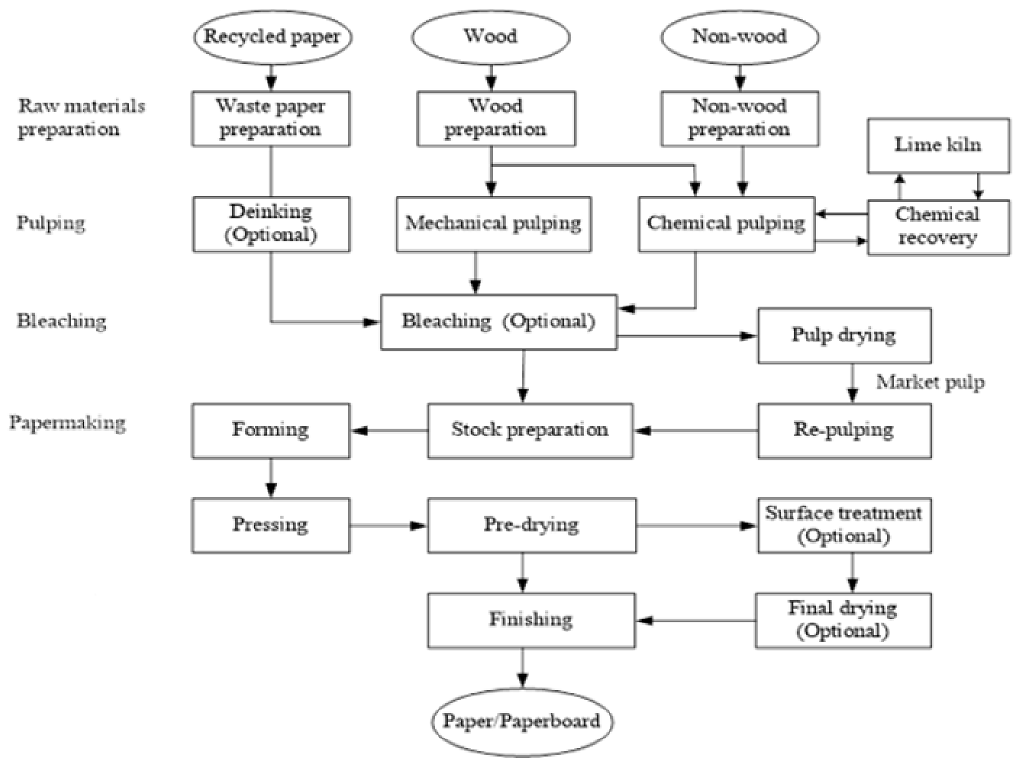

Figure 13. Flow diagram of the pulping and papermaking process (Kong et al., 2012)

Table 6. Energy intensities of conventional and electric pulp and paper production processes (Our analysis based on Brueske et al., 2015)

Conventional System Process			Process steps	Process Using Electric Dryer		
Equipment	**Thermal Demand (kWh/tonne)**	**Electrical Demand (kWh/tonne)**		**Thermal Demand (kWh/tonne)**	**Electrical Demand (kWh/tonne)**	**Equipment**
Liqure Evaporator	996	46	Liqure Evaporation	996	46	Liqure Evaporator
Pulp machine	567	40	Pulping Chemical Preparation	567	40	Pulp machine
Cooking machine	656	95	Wood Cooking	656	95	Cooking machine
Conventional bleaching plant	312	75	Bleaching	312	75	Conventional bleaching plant
Steam/fuel-based dryer	1,245	128	Paper Drying	0.0	1,236	**Infrared dryer**
Paper making machine	310	296	Paper Machine Wet End	310	296	Paper making machine
	4,088	682	Subtotal	2,842	1,791	
4,771			**Total Energy**	**4,633**		

4.2.3. Energy, emissions, and cost implications of electrification

Figure 14 shows that dryer electrification could significantly reduce the total final energy use from paper production during the study period; 2019-2050. Potential energy savings in excess of 29,000 TJ on an annual basis can be realized in 2050. The slight reduction in annual saving potential between 2019-2050 is due to our assumption of a slight reduction in primary paper production during this period.

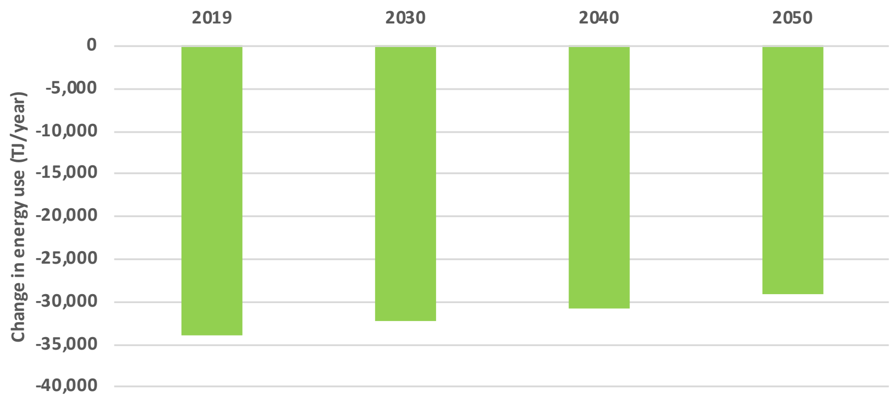

Figure 14. Change in total final energy use of the U.S. pulp and paper industry after electrification (This is the technical potential assuming paper dryer electrification)

Electrification of paper dryers in the U.S. can lead to a rise in CO_2 emissions by 27,000 kt CO_2 in 2019 (see Figure 15). However, during the period of study, a switch to electrification could potentially decrease annual CO_2 emissions by around 5,000 kt CO_2 in 2050. This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO2 emissions factor (grid decarbonization) between 2019 and 2050. It should be noted that around 67 percent of fuel used in paper industry is biomass which is a by-product of the pulping process (US DOE 2019). In our CO_2 emissions analysis we took this into account and assumed biomass as carbon neutral. Note, the carbon accounting for biomass under the GHG protocol is undergoing revision and how biomass is treated could change. If it does, biomass waste material may not be considered carbon neutral automatically as it is now and the estimated carbon and cost benefits could change dramatically.

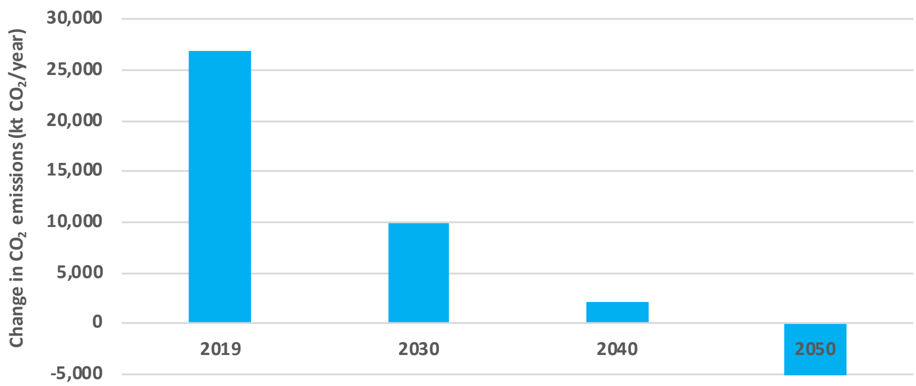

Figure 15. Change in net CO_2 emissions of the U.S. pulp and paper industry after electrification in U.S. (This is the technical potential assuming paper dryer electrification)

Figure 16 shows that energy cost (in 2017$) per unit of production in the U.S. pulp and paper industry for the conventional process is much lower than the electrified process in 2019. It is clear that lower priced electricity could reduce the energy cost of electrified pulp and paper production to levels comparable to the conventional process in 2019 and even lower than the conventional process in 2050.

Around 67 percent of the fuel used in a pulp and paper plant that produced paper from virgin pulp is from biomass and pulping liquor (black liquor) which are by-products of the pulping process and available in the plants (US DOE 2019). These byproducts biomass fuels are available to pulp and paper plants at no cost. Therefore, the cost analysis and comparison done here assumes zero cost for by-product fuels used in conventional process and only includes the cost of natural gas as the remainder of fuel used in an integrated pulp and paper plant.

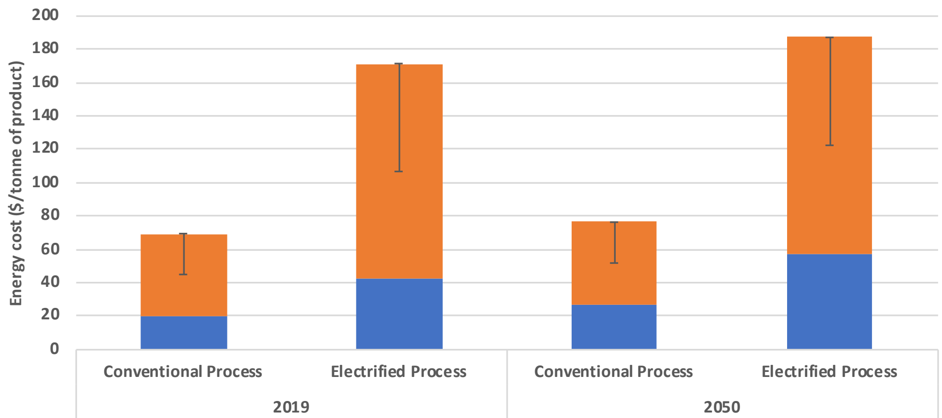

Figure 16. Energy cost per unit of production in the U.S. pulp and paper industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.3. Electrification of the recycled paper industry

4.3.1. Introduction

Over the 2000 - 2018 period, the final energy consumption in the pulp and paper industry grew by 0.3 percent annually, on an average, while the total output from the paper and paperboard industry grew at an annual rate of 1.4 percent. This growth in the pulp and paper industry highlights the need to promote greater recycling, as production through recycling requires significantly less energy as compared to traditional production, in addition to saving trees. The total energy consumed by this industry could be reduced considerably by growing the degree of production from recovered fibers (IEA, 2019).

Recycling is an important aspect of the paper industry since paper can be categorized as a renewable resource. Among various materials, paper exhibits one of the highest recycling rates. In the U.S., the total paper and paperboard recovery was estimated to be around 48 million metric tons. The recovery rate associated with paper and paperboard in the U.S. was around 68 percent in 2018, almost double the recovery rate observed in 1990 (34 percent) (Garside, 2020).

4.3.2. Production process

Conventional process

In the conventional paper recycling process, the recovered paper is collected and sorted before being dispatched to the paper mill. At the paper mill, the paper undergoes the pulping process which involves the chopping of paper into small pieces until a mushy mixture (pulp) is obtained. The pulp is pushed through screens to get rid of contaminants and is cleaned through rotation in large cone-shaped cylinders. In certain cases, the pulp undergoes the deinking process for the removal of printing ink. Once the pulp has been cleaned, it is ready to be converted into paper. The paper making process involves the spraying of the watery pulp mixture onto a wide flat screen, where the water is drained out and the drying process under a heated metal roller occurs. Once the process is complete, the resulting paper is wound into a large roll and removed from the paper machine (Kan, 2013).

The dryer section is tasked with the process of removing water from the paper web through the process of evaporation. Typical techniques employed for drying paper or paperboard are multi-cylinder drying or air drying. The paper drying process is dominated by the multi-cylinder technique which receives the majority of its energy from low-pressure steam (Stenström, 2019).

The major sources of energy consumption for the paper recycling process are pumps, fans, and steam generators.

Electrified process

The infrared heating process uses radiation emitted by electrical resistors, usually made of nickel-chromium or tungsten, heated to relatively high temperatures (CEATI, n.d.). A U.S. study reported that compared to conventional steam drying, the utilization of 100 percent electric infrared process for drying paper could save energy, time, and money. The cylinders would need to be fed with 947 kWh of steam for drying one tonne of paper, which is equivalent to 1263 kWh of natural gas (assuming boiler efficiency of 75 percent). Figure 17 depicts the schematic of a system in which wet paper is passed around metal cylinders while being exposed to infrared radiation every few meters. The infrared radiation wavelength and the distance between the paper and radiation source are optimized to ensure maximum evaporation and help prevent charring. The paper goes through alternate cycles of infrared radiation and cool-down (where fans replace humid air with dry air) (Beyond Zero Emissions, 2018).

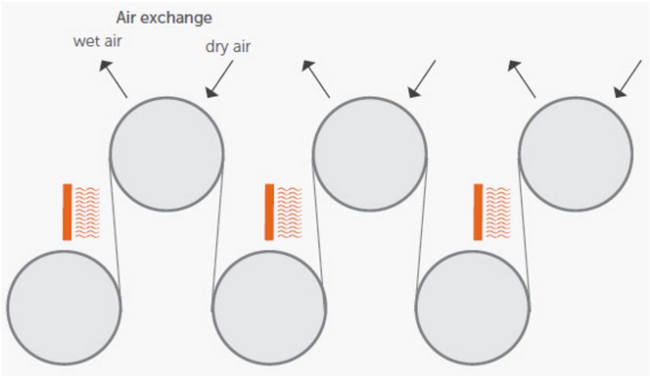

Figure 17. Infrared heating for paper drying (Beyond Zero Emissions, 2018)

Table 7 compares the energy consumption of the conventional and electrified processes for recycling paper.

Table 7. Energy intensities of conventional and electric recycled paper production processes (Brueske, 2015)

Conventional System Process			Process steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Motor and Pump	521	-	Pulping	539	Motor and Pump
Fans	40	-		40	Fans
Steam cylinder dryer	-	1,263	Drying	811	Infrared heating
	561	1,263	Subtotal	1,390	
1,824			**Total Energy**	**1,390**	

4.3.3. Energy, emissions, and cost implications of electrification

Based on current technologies, we assume paper drying consumes equal energy for different types of recycled paper for the scope of this study (Brueske, 2015). Figure 18 shows that dryer electrification will significantly reduce the total final energy use from recycled paper production during the study period, 2019-2050. Despite the projected increase in recycled paper production between 2019 and 2050, the electrification of recycled paper production would help reduce the total energy demand of the process. It could help achieve energy savings close to 100,000 TJ on an annual basis in 2050.

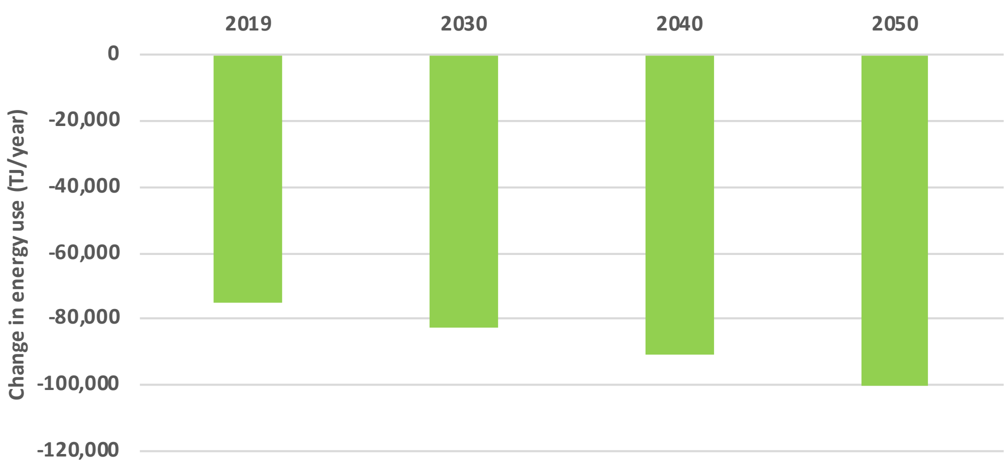

Figure 18. Change in total final energy use of the U.S. paper recycling industry after electrification (This is the technical potential assuming paper dryer electrification)

Electrification of paper dryers in the U.S. can result in an increase in CO_2 emissions by 4,240 kt CO_2 in 2019 (see Figure 19). However, over the period of study, electrifying the recycled paper industry could lead to a reduction in CO_2 emissions by over 16,000 kt CO_2 /year in 2050. This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

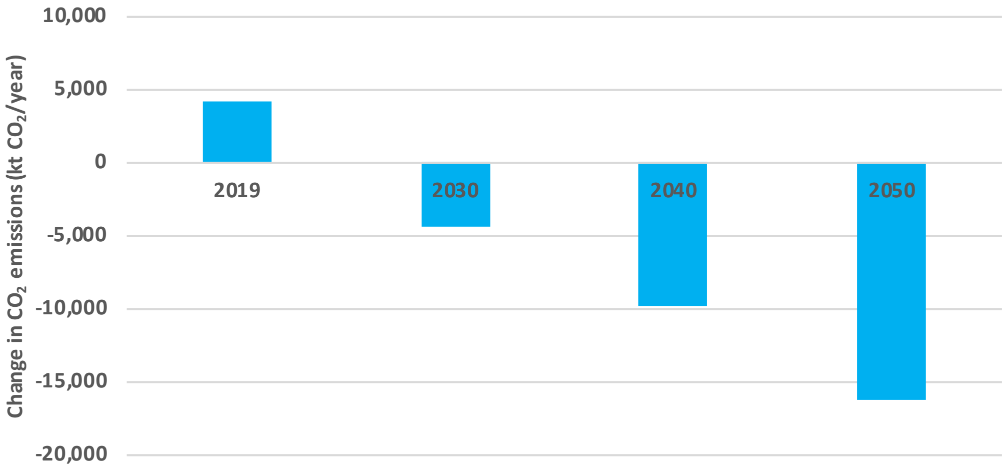

Figure 19. Change in net CO_2 emissions of the U.S. paper recycling industry after electrification in U.S. (This is the technical potential assuming paper dryer electrification)

Figure 20 shows that in the U.S. paper recycling industry, the energy cost (in 2017$) per unit of production for the conventional process is about 60 percent of that of the electrified process in 2019.

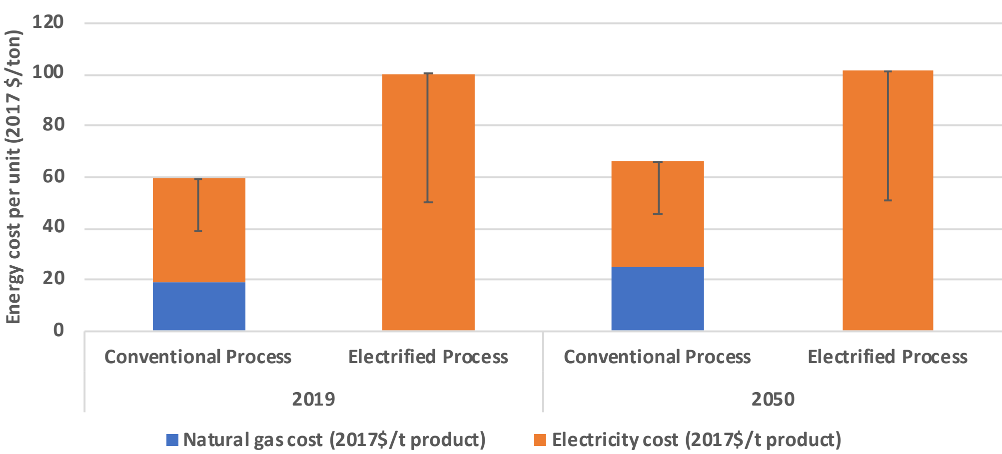

Figure 20. Energy cost per unit of production in the U.S. paper recycling industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.4. Electrification of the container glass industry

4.4.1. Introduction

The glass industry manufactures a wide range of products used across various key sectors of the U.S. economy, including construction, household markets, and automotive. The four major glass products are flat glass, pressed or blown glass, glass containers, and products made from purchased glass (IBISWorld, 2020).

In 2019, the total revenue generated by the U.S. glass manufacturing industry was around $30 billion (Garside, 2020). The total glass production in the U.S. was around 20 million metric tonnes in 2017 (Gaile, 2017). Since container glass products account for around half of U.S. glass production (US DOE, 2017a), the total quantity of container glass production in the U.S. is estimated to be approximately 10 million metric tonnes in 2019.

4.4.2. Production process

Conventional process

Figure 21 illustrates the glass manufacturing process. The production process can be divided into four main process steps (US DOE, 2017a):

1. Batch Preparation and Mixing: During this step, raw materials are subjected to blending, grounding, and mixing prior to entering the melting furnace. These raw materials include silica, limestone, soda ash, borosilicate, additives, recycled glass (cullet), and others.
2. Melting, Refining, and Conditioning: The raw materials prepared and mixed in the previous step are added to glass melting furnaces, which are available in varying sizes and designs. The resulting melted glass obtained from the furnace undergoes refining where it is freed of bubbles, homogenized and heat-conditioned.
3. Forming: This step involves shaping the refined glass into the desired shape. A variety of forming processes such as fiberization, blow forming, and casting can be utilized.
4. Finishing: The formed glass is subjected to finishing processes based on the final characteristic requirements of the product. Some examples of these processes are the drying of glass wool fibers and surface treatments (such as laminating, annealing, and tempering), among others.

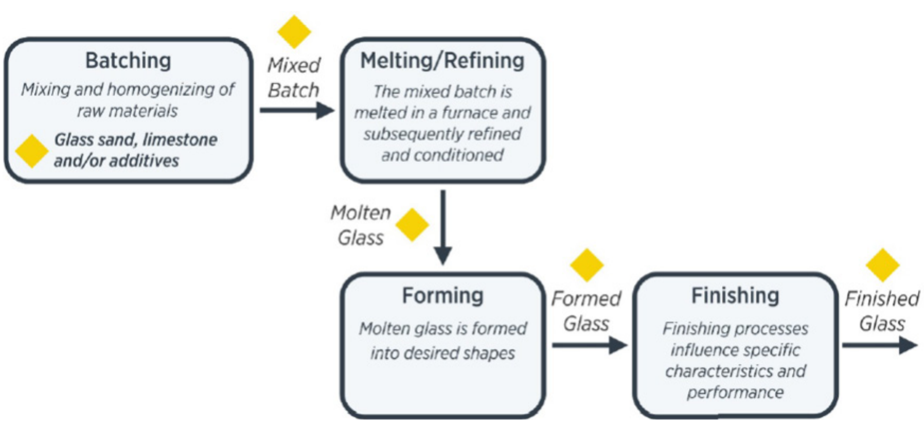

Figure 21. Flow diagram of glass manufacturing (US DOE, 2017a)

Although the batching process remains almost the same across different types of glass products, melting, forming, and finishing processes use different equipment and consequently have different energy intensities. In the container glass manufacturing process, the molten glass is transferred to the forehearth from the furnace where it undergoes uniform heating to the right temperature for forming. The conditioned glass is then directed to a forming machine, where through the help of compressed air or mechanical plungers, it is cut to the desired size and formed into containers. The resulting glass container is placed in an oven (also known as an annealing lehr) where it undergoes cooling in a controlled manner from 600˚C to room temperature (Beyond Zero Emissions, 2019).

Electrified process

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

The transition to an electrified glass container manufacturing process is quite viable due to the commercial availability of electric melting, forming, and finishing equipment for container glass production.

An electric furnace is mainly composed of a refractory lined box supported by a steel frame with electrodes inserted either from the side, from the top or, more typically, from the bottom of the furnace. The melting process is mainly powered by resistive heating as current flows through the molten glass. However, the furnace is dependent on fossil fuel usage for kickstarting the melting process. The furnace operates without interruption and has a typical service lifetime of up to seven years. A layer of batch material is placed on top of the molten glass, which results in its gradual melting from the bottom up. A conveyor system that moves over the entire surface of the furnace is utilized for depositing a fresh layer of batch material on the top surface. Most electric furnaces are equipped with bag filter systems which collect unutilized batch material and feed it back to the melter.

Electric furnaces are typically able to achieve higher melt rates per surface area of the furnace, and the thermal efficiency of these furnaces (on an energy delivered to the furnace basis) is almost twice or three times of that of fossil fuel-fired furnaces (Scalet et al., 2013).

Numerous glass makers have already transitioned to using electric forehearths and annealing lehrs. Major manufacturers of these equipment include Electroglass (for electric forehearths), and CNUD and Pennekamp (for electric annealing lehrs) (Beyond Zero Emissions, 2019).

Table 8 provides a comparison of energy consumption between conventional and electrical processes for the production of container glass.

Table 8. Energy intensities of conventional and electric container glass production processes (Our analysis based on US DOE, 2017a and Beyond Zero Emissions, 2019)

Conventional System Process			Process steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
Electrically-powered mixer/crusher	161.0	0.0	Mixing	161.0	Electrically-powered mixer/crusher
Gas-fired furnace	204.0	1150.0	Melting	860.0	Electrically-powered glass melter
Forehearth and forming equipment	26.0	105.0	Conditioning & Forming	104.0	Electric forehearths
Gas-fired Annealing lehr	25.0	210.0	Post Forming (Annealing)	183.0	Electric Annealing lehr
	416.0	**1465.0**	**Subtotal**	**1308.0**	
	1465.0		**Total Energy**	**1308.0**	

4.4.3. Energy, emissions, and cost implications of electrification

Figure 22 shows that electrification will significantly reduce the total final energy use from container glass production during the 2019-2050 study period. Estimated energy savings of greater than 27,000 TJ can be achieved annually in 2050 by pursuing this electrification pathway.

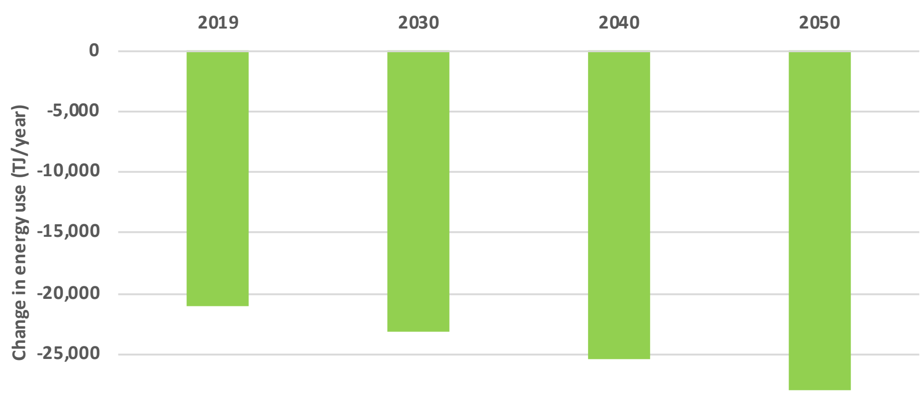

Figure 22. Change in total final energy use of the U.S. container glass industry after electrification (This is the technical potential assuming 100 percent adoption rate.)

Electrification of container glass production in the U.S. can lead to a rise in annual CO_2 emissions by 747 kt CO_2 in 2019 (Figure 23). However, switching to the electrified production process could lead to a decline in annual CO_2 emissions by 4,000 kt CO_2 in 2050. This substantial reduction in CO_2 emissions is the consequence of improvement in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

Figure 24 shows that energy cost (in 2017$) per unit of production for the U.S. glass container industry utilizing the conventional production process is substantially lower than electrified process in 2019. Access to cheaper electricity drastically improves the economics of the electrified process.

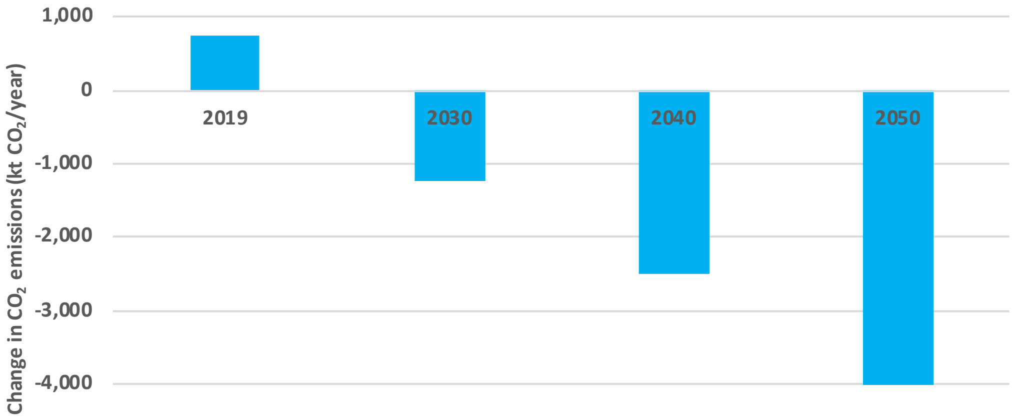

Figure 23. Change in net CO_2 emissions of the U.S. continer glass industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

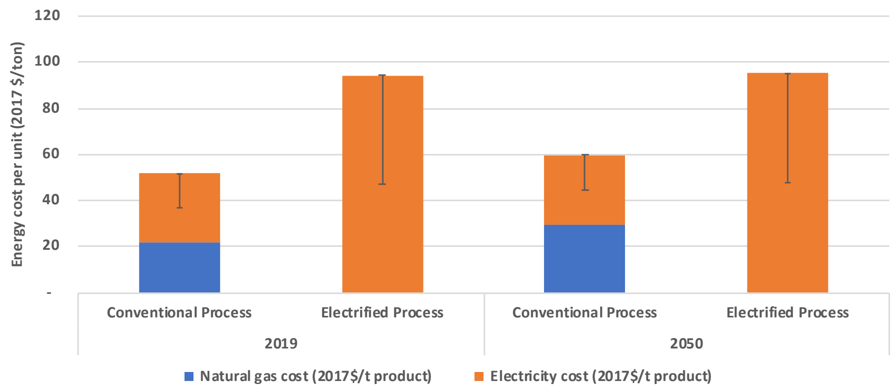

Figure 24. Energy cost per unit of production in the U.S. container glass industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

The quality requirement for most float glass (flat glass is the main type of float glass produced) is significantly higher than for container glass. This makes the electrification of melting for flat glass production more challenging. In fuel-fired container glass furnaces and all-electric container glass furnaces, melting and refining are achieved in one tank. In contrast, in float glass production it is generally considered that melting and a certain degree of refining take place in the main melting chamber, with a secondary refining chamber completing the process, resulting in a comparatively very long residence time. Electric boosting in a fuel-fired float glass furnace can and has been applied, although not nearly as widely as in container glass production. We are not aware of any all-electric furnace being used for float glass production (Stormont, 2020).

4.5. Electrification of the ammonia industry

4.5.1. Introduction

Ammonia production has become one of the most important industries in the world. Ammonia-based fertilizers and chemicals have played a significant role in crop-yield growth. Over the past few decades, engineers have successfully developed processes that have resulted in wider access to ammonia at highly reduced costs. The United States is one of the world's leading producers and consumers of ammonia. In 2019, a total of approximately 14 million metric tons of ammonia was produced in the U.S. by a total of 15 companies across 34 facilities (M.Garside, 2020). Around 88 percent of ammonia manufactured across the globe is utilized for the production of fertilizers, and the remainder is used to support formaldehyde production (AIChE, 2016).

4.5.2. Production process

Conventional process

Anhydrous ammonia is synthesized through the reaction of hydrogen with nitrogen (3:1 molar ratio), which is followed by compression and subsequent cooling of the gas to -33˚C. For this process, nitrogen is obtained from the air, whereas hydrogen is typically obtained through the catalytic steam reforming of natural gas (methane) or naphtha (EPA, 1993). Greater than half of the total industrial production of hydrogen around the world is utilized for manufacturing ammonia (Michael Matzen, 2015). Figure 25 shows a simplified ammonia production diagram (IEA, 2013).

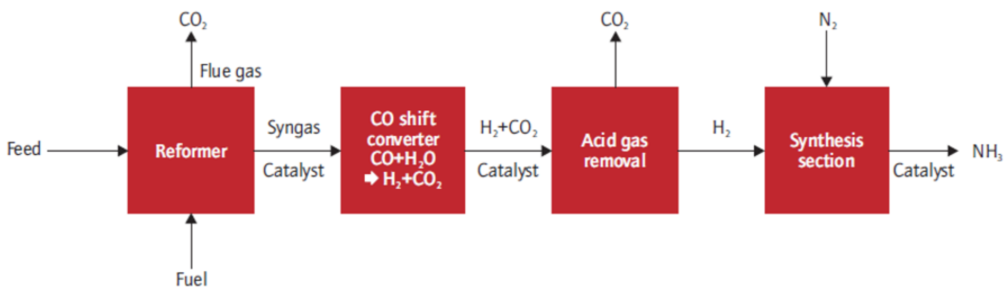

Figure 25. Ammonia synthesis, a simplified schematic

With regards to ammonia plant technologies, the market is currently dominated by three technology licensors: KBR (Kellogg Brown and Root), Haldor Topsøe, and ThyssenKrupp Industrial Solutions (TKIS). Various factors have contributed to the increased proportion of ammonia (from 12 percent to 19 – 21 percent) in the exit stream of synthesis converters. These include improvements in converter design, internal heat exchangers, and synthesis gas treatment. Access to highly efficient turbines and compressors combined with an increased conversion per pass has helped further reduce energy consumption. Other factors, like improved efficiency of CO_2 removal solutions, have helped achieve improved energy efficiency (AIChE, 2016).

Electrified process

The main feedstocks for ammonia production are nitrogen and hydrogen. Nitrogen is generally obtained from an air separating unit (ASU) using electricity to run compressors. Water electrolysis is the main known process for the production of hydrogen from electricity.

Alkaline electrolysis is the most mature technology available at a commercial scale for hydrogen production. The electrolyzer units use process water for electrolysis, and cooling water for cooling. On a higher heating value (HHV) basis, energy efficiency of these electrolyzers used in the production of hydrogen is in the range of 57-75 percent, whereas on a lower heating value (LHV) basis, efficiency is in the 50-60 percent range (Michael Matzen, 2015). Beyond the point of hydrogen production through the alkaline electrolysis process, the manufacturing of ammonia proceeds in a way similar to conventional ammonia plants.

The electrolysis process shifts the hydrogen production from utilizing natural gas and electricity as inputs to utilizing only electricity. The overall energy requirements are broadly similar. While conventional processes utilize around 8.9 MWh of natural gas for fuel and feedstock in addition to 2.1 MWh of electricity, electrolysis utilizes around 9.1 MWh electricity per tonne of ammonia produced, depending on the efficiency of electrolysis.

The technology associated with hydrogen production through electrolysis and nitrogen production through air separation already exists, although there is room for improvement in the electrolysis process efficiency. The key obstacles to transitioning to 'green' ammonia produced using renewable electricity are financial rather than technical. Issues that require consideration include the need to modify existing production units, the availability of low-priced electricity, and proper infrastructure for hydrogen storage and transportation (Material Economics, 2019).

Table 9 compares the energy consumption of conventional and electric processes for ammonia production.

Table 9. Energy intensities of conventional and electric ammonia production processes (Beyond Zero Emissions, 2019)

Conventional System Process			Process steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Primary Reformer Feedstock	-	5,694	Using different process methods	30	Desalination
Primary Reformer Fuel	-	4,083		8,824	Electrolysis
Secondary Reforming	-	-		90	Air separation to acquire nitrogen
CO_2 Removal	-	333		550	Hydrogen and nitrogen reaction in Haber-Bosch process
Methanation	-	83		-	-
Ammonia Synthesis*	-	-555		-	-
Boiler **	-	-1,388		-	-
Turbine, Compressor, Others (Electrical)	1,694	-		-	-
	1,694	**8,249**	**Subtotal**	**9,494**	
9944			**Total Energy**	**9494**	

* hydrogen and nitrogen are reacted at 450 C and 200 bar pressure over a catalyst to form ammonia.
** Primary and secondary reforming and ammonia synthesis all produce waste heat which is reused in the boilers.

4.5.3. Energy, emissions, and cost implications of electrification

Figure 26 shows that electrifying the ammonia industry reduces the total energy demand of the production process, despite the projected growth in ammonia production between 2019 and 2050. Electrification could lead to energy savings in excess of 30,000 TJ annually in 2050.

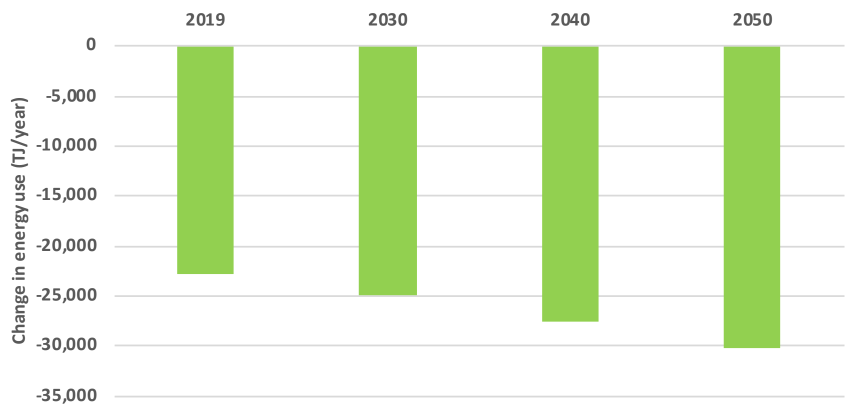

Figure 26. Change in total final energy use of the U.S. ammonia industry after electrification (This is the technical potential assuming 100 percent adoption rate)

Electrification of ammonia industry in the U.S. can result in an increase in CO_2 emissions by about 22,000 kt CO_2 in 2019 (see Figure 27). However, the analysis indicates that electrification could potentially result in 31,000 kt CO_2 /year reduction in the ammonia industry's emissions in 2050. This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

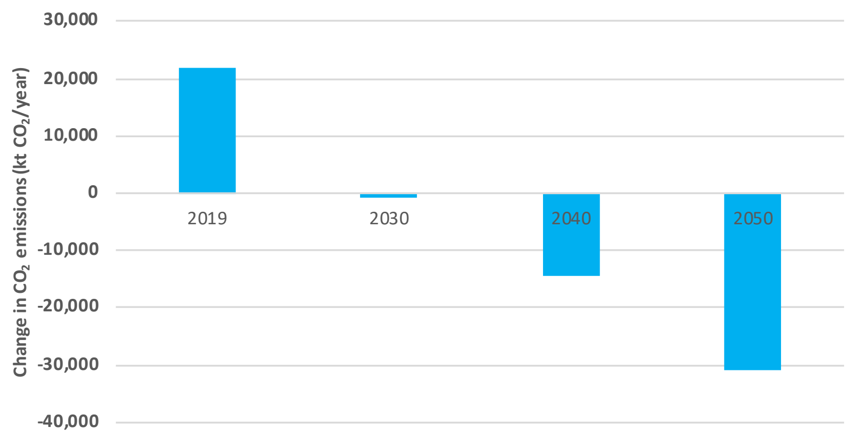

Figure 27. Change in net CO_2 emissions of the U.S. ammonia industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 28 shows that energy cost (in 2017$) per unit of production in the U.S. ammonia industry for the conventional process is about one-third of that of the electrified process in 2019. It is clear that using cheaper electricity can help reduce the energy cost of electrified ammonia production and make it a more competitive process.

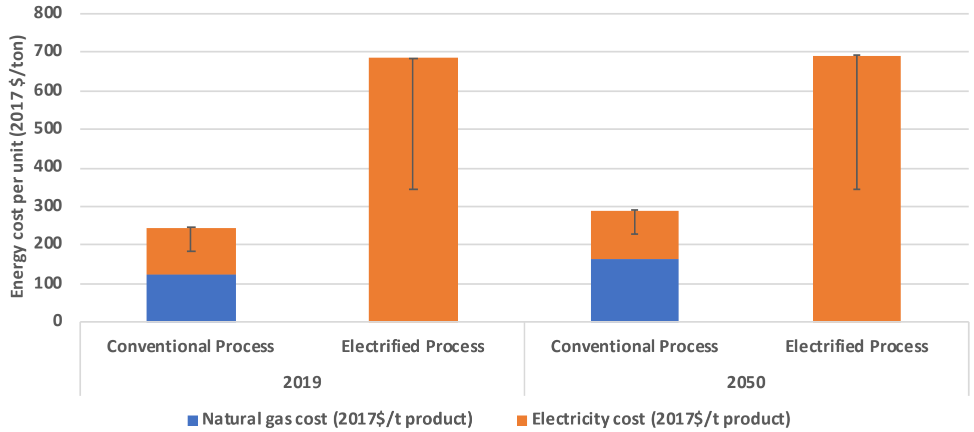

Figure 28. Energy cost per unit of production in the U.S. ammonia industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.6. Electrification of the methanol industry

4.6.1. Introduction

Methanol (CH3OH) is a liquid chemical that serves as a building block for thousands of daily use products, such as plastics, paints, cosmetics, and fuels. It is the world's most commonly shipped chemical commodity (Hobson et al., 2018). Currently, methanol is mostly manufactured for nonfuel usage in the U.S. The substantial demand for methanol in North America is due to the increasing demand for methyl tertiary butyl ether (MTBE), acetic acid, and formaldehyde (Grand View Research, 2019).

In 2019, the total production volume of methanol in the U.S. was estimated to be around 5.7 million metric tonnes. The vast majority of methanol plants are located in the Gulf Coast region and certain new plants are in the final phase of construction (EIA, 2019).

4.6.2. Production process

Liquid methanol is manufactured from synthesis gas, which consists of a mixture of hydrogen, carbon monoxide, and carbon dioxide. These ingredients are fairly easy to obtain as they can be sourced from a wide range of feedstocks by utilizing various technology approaches (Hobson et al., 2018).

Conventional process

The typical process of producing methanol can be carried out in two steps. The first step involves the conversion of the feedstock into a synthesis gas comprising CO, CO_2, H_2O, and H_2. By means of the gasification process, synthesis gas can be generated from any organic matter, such as biomass, solid municipal waste, natural gas, coal, or others. The second step involves the production of methanol from synthesis gas in the presence of a catalyst (Huang, 2015). The different processes utilized for the generation of syngas from natural gas are steam methane reforming, autothermal reforming, and dry methane reforming (Blumberg et al., 2017). Figure 29 depicts the process of methanol production through steam reforming of natural gas.

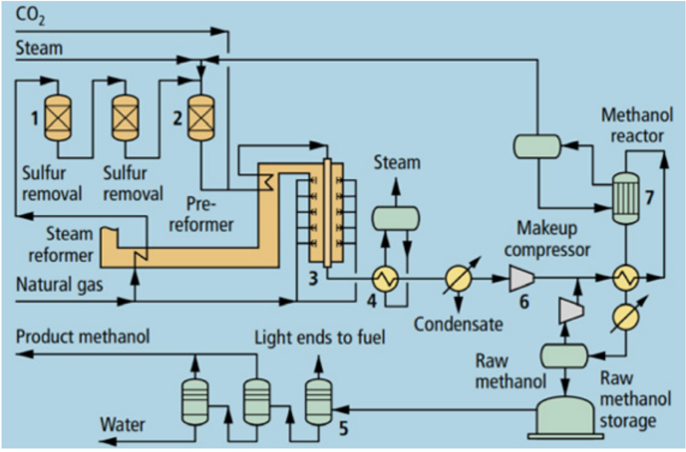

Figure 29. Methanol production based on steam reforming of natural gas (Gulf Publishing Company, 2005)

The average energy intensity of the production of methanol based on current available technologies is around 3,170 kWh/tonne (Brueske et al., 2015).

Electrified process

In the electric pathway, the electrolysis process utilizes renewable electricity for extracting hydrogen from water. The extracted hydrogen undergoes a chemical reaction with carbon dioxide captured from point sources (such as exhaust streams of various industries) or from the atmosphere (Hobson et al., 2018). The three main technologies available for carrying out the electrolysis of water are alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (Bos et al., 2020). A brief overview of these technologies is provided in Table 10 below.

	Alkaline	PEM	Solid Oxide	Unit
Temperature	60-90	50-80	600-1000	°C
Pressure	1.05-30	10-200	1-25	bar
Energy Consumption	4.5-6.6	4.2-6.6	3.7-3.9	$kWh/m^3 H_2$
Max. Capacity	5.3	1.1	n.a	MW
Technology Readiness Level (TRL)	9	5-7	3-5	-

Table 10. Key performance indicators of electrolysis technologies (Our analysis based on Bos et al., 2020)

The data in Table 10 clearly indicate that the alkaline process has the highest technology readiness (TRL = 9): this study focuses on the alkaline process as the hydrogen generation method. The CO_2 feedstock is obtained via carbon capture from flue gas streams. The gas can be obtained from the various waste streams from chemical plants, or it can be captured from the stack of a power plant (Haldor Topsoe, 2019). The CO_2 capturing units are not discussed separately in this study. Figure 30 shows an electrified process for methanol production.

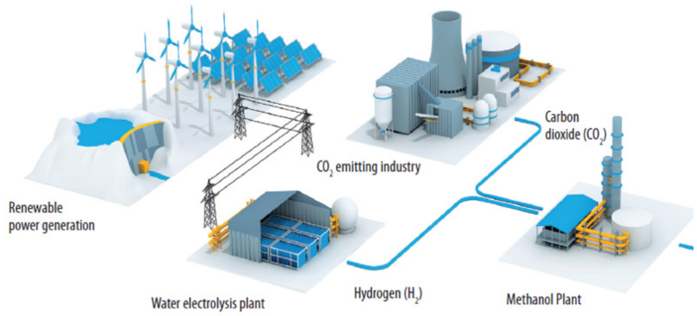

Figure 30. Methanol production based on steam reforming of natural gas (Thyssenkrupp, 2017)

Table 11 compares energy consumption of conventional and electrified processes for the methanol production.

Table 11. Energy intensities of conventional and electric methanol production processes

Conventional System Process			Process steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Steam Reforming	280	1,546	H_2 Production	6,238	Electrolysis system
Conventional Steam Boiler	-	467	MeOH Synthesis	381	Electric steam Boiler
Distillation Unit	-	638	MeOH Distillation	-	-
Motors	240	-	Others	240	Motors
	520	**2,651**	**Subtotal**	**7,055**	
3,171			**Total Energy**	**7,055**	

Electric steam boilers can be used instead of conventional fossil fuel boilers to meet the all-electric process requirement. As the efficiency of electric boilers (99-100 percent) is higher than conventional ones (75-80 percent), the required amount of energy is lower.

4.6.3. Energy, emissions, and cost implications of electrification

Figure 31 shows that electrification will significantly increase the total final energy use from methanol production during the 2019-2050 study period. The substantial amount of energy required by the water electrolysis process for hydrogen production is the main reason for the rise in energy consumption for the electrification process.

Electrification of methanol production in the U.S. can result in an increase in CO_2 emissions by about 12,000 kt CO_2 in 2019 (Figure 32). However, as the electricity grid's renewable percentage increases, the grid's carbon intensity decreases, reducing the carbon footprint of methanol produced via electrification between 2019 and 2050.

Figure 31. Change in total final energy use of the U.S. methanol industry after electrification (This is the technical potential assuming 100 percent adoption rate.)

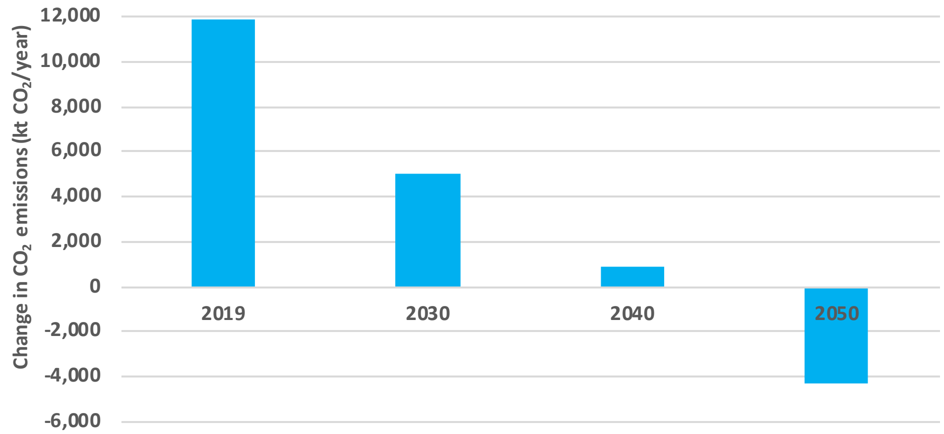

Figure 32. Change in net CO_2 emissions of the U.S. methanol industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate.)

Figure 33 indicates that energy cost (in 2017$) per unit of production in the U.S. methanol industry utilizing the electrified production process is over five times higher than that of the conventional process in 2019.

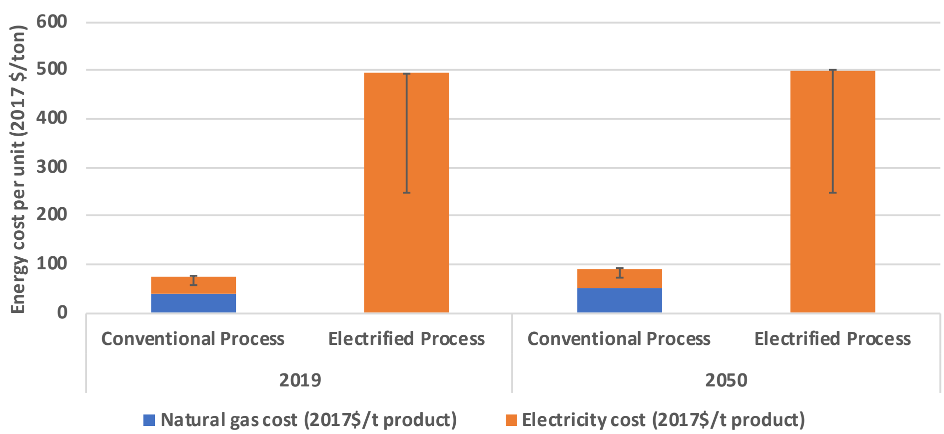

Figure 33. Energy cost per unit of production in the U.S. methanol industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

Other researchers have also estimated the production cost for methanol production based on fossil fuel and electrolysis-based processes. It is clear that methanol manufactured by utilizing the electrified process is not cost-competitive with methanol generated from the conventional process. Despite the reduction in costs of renewable technologies as discussed above, competing with fossil fuel-based production processes is extremely difficult in this case (Bos et al., 2020).

4.7. Electrification of the plastic recycling industry

4.7.1. Introduction

Plastics are a rapidly rising proportion of municipal solid waste (MSW). In the U.S., while different types of plastics cover the entire range of MSW categories, the containers and packaging category accounted for the highest plastic tonnage (around 14 million tons) in 2017. Major commodities included under this category are bags, packaging materials, polyethylene terephthalate (PET) bottles and jars, high-density polyethylene (HDPE) bottles, and other containers (EPA, 2017).

The main goals of recycling plastics are to reduce plastic pollution while lessening the burden on virgin materials for manufacturing of new plastic products. This is a sustainable approach that leads to resource conservation and reduces the amount of plastics dumped in landfills and oceans. In 2015, the U.S. recycled around 3.14 million tons of plastics, which indicates that close to 9 percent of total plastic production in the U.S. was recycled during that year (Leblanc, 2019).

Due to the continued growth in plastic production and recycling, for the purposes of this study, we assume that 3.5 million tons of plastic were recycled in the base year 2019.

4.7.2. Production process

The two highest-volume recycling techniques for plastics are mechanical reclaiming and waste-to-energy (chemical reclaiming). In the mechanical reclaiming process, waste plastics are recycled into new secondary raw materials without changing the base structure of the material, while in the chemical reclaiming process, plastics are converted to their original molecular forms so that they can be processed into entirely new products. A new emerging method of chemical recycling involves use of solvents and other processes to depolymerize the polymers so they can be repolymerized.

In this study, we compare the energy intensity of the mechanical electrified plastic recycling process with the traditional method of producing virgin resins in petrochemical plants. The goal is to demonstrate the energy- and emissions-saving potential of the electrified plastic recycling process in the U.S. which is in addition to all other environmental benefits that plastic recycling delivers. It should be noted that virgin resins produced in petrochemical plants can be used in a wide range of low-to-high value applications while mechanically recycled plastics typically have found application in the low value range.

Conventional process

Virgin plastics – including polyethylene, polypropylene, polyvinyl chloride, and polyethylene terephthalate – are made in petrochemical plants during the polymerization process. The polymerization process helps transform a substance having low molecular weight into one with a higher molecular weight while maintaining the substance's composition and the atomic arrangement of the base molecules (Speight, 2020).

Polymers can be generated by a wide range of processing methods, such as bulk, solution, suspension, emulsion, and precipitation techniques. The general framework followed by the polymerization process is largely comparable to the autoxidation process as it involves radical formation and chain initiation, propagation of the reaction chain, and finally chain termination (Coletti & Hewitt, 2014). The energy intensity associated with the production of three important polymers (used as plastic main materials) is shown in Table 12.

Table 12. Energy intensity of original polymer production (Gervet, 2007)

	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Total (kWh/tonne)
Polyethylene (PE)	15,274	4,166	19,439
Polypropylene (PP)	16,107	4,166	20,272
polyethylene terephthalate (PET)	8,609	14,718	23,327
Average	13,329	7,683	21,012

Electrified process

Typically, mechanical plastic recycling processes involve the collection of plastics followed by their sorting, shredding, washing, and melting. The melted plastic is transformed into pellets. The recycling process varies for different varieties of plastic resins or types of plastic products. However, most plastic recycling facilities adhere to the following two-step approach (Leblanc, 2019):

1. Automatic or manual sorting of plastics to ensure the removal of any contaminants from the plastic waste stream.
2. The direct melting of plastics to obtain a new shape or shredding plastics into flakes prior to the melting process. The melted plastic is finally processed into granulates or pellets.

As the melting temperature of most plastics is lower than 300 ˚C (Polymer Handbook, 2005), complete electrification of the mechanical plastic recycling process is possible.

Newtecpoly, an Australian manufacturing and plastics recycling organization, utilizes the PolyWaste technology for recycling plastic waste into new products. The technique is energy efficient and helps drastically reduce the energy intensity of the plastic recycling process. As shown in Table 13, Newtecpoly only needs around 540 kWh per tonne of product (based on the availability of a high proportion of polyethylene in the feed) (Beyond Zero Emissions, 2018).

The feed can include high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), nylons, polyesters, and polyethylene terephthalate (PET).

Table 13. Energy intensity of all electrical plastic recycling process (Beyond Zero Emissions, 2018)

Process	Temperature (°C)	Electrical Demand (kWh/tonne)
Shredding	-	0
Water cooling	10	70
Air compression	-	20
Melting	190	270
Extrusion/Molding	-	120
Lighting	-	60
Total energy	540	

4.7.3. Energy, emissions, and cost implications of electrification

Figure 34 shows that using the mechanical electrified plastic recycling process will significantly reduce the total final energy use compared to virgin resin production during the study period; 2019-2050. Since electrified recycling decreases the total energy demand of the process, over 250 TJ of energy can be saved on an annual basis. Additionally, annual energy savings of greater than 340,000 TJ per year can be achieved in 2050.

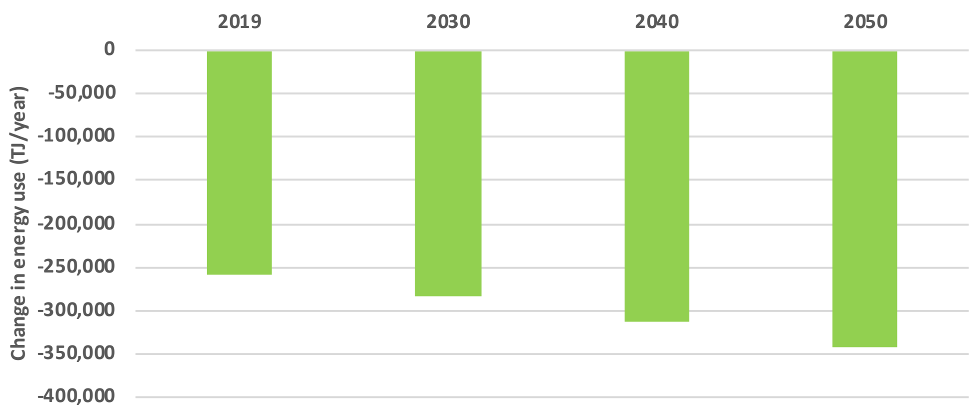

Figure 34. Change in energy use of the U.S. plastics industry using electric recycling process

The electrified plastics recycling process in the U.S. can result in a substantial reduction in annual CO_2 emissions by 20 Mt CO_2 in 2019 (Figure 35). The annual CO_2 emissions reduction decline by 63 percent over the period of study and could lead to a 12.5 Mt CO_2 /year reduction in 2050. This decline in CO_2 emissions reduction is the consequence of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

Figure 36 shows that energy cost (in 2017$) per unit of production in the U.S. plastics production industry using the conventional process is about 19 times higher than the electrified plastic recycling process in 2019 and about 21 times higher in 2050. This means that the energy cost of the electrified plastic recycling process is about 5 percent of the cost of conventional plastic manufacturing process.

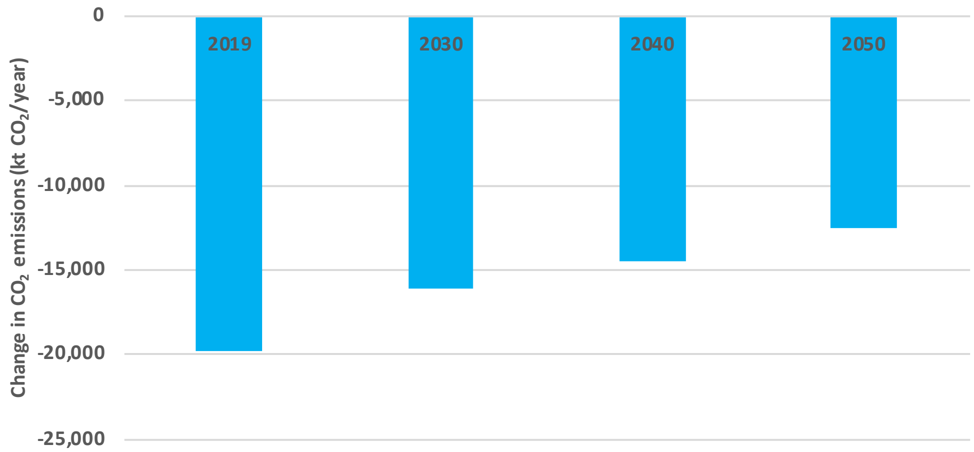

Figure 35. Change in net CO_2 emissions of the U.S. plastics industry using electrified recycling plastic process

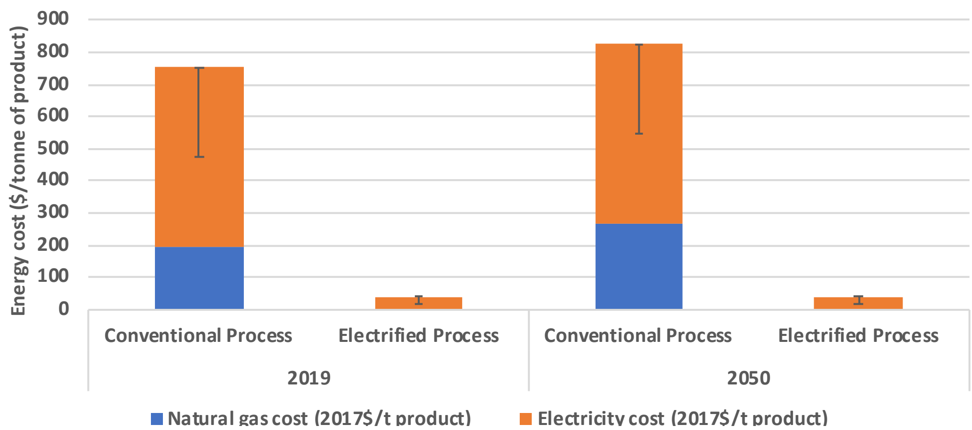

Figure 36. Energy cost per unit of production in the U.S. conventional plastics industry vs. electrified plastics recycling process

4.8. Electrification of the steel industry

4.8.1. Introduction

The U.S. steel industry produced 87 million tonne (Mt) of crude steel in 2019: 30 percent was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF), and 70 percent was produced by the electric arc furnace (EAF) production route which mainly uses steel scrap. The U.S. also imported 27 Mt and exported 6.7 Mt of steel mill products in 2020. The value of raw steel produced by the U.S. iron and steel industry in 2019 was about $92 billion. The BF-BOF plants in the U.S. that produce pig iron and crude steel are operated by three companies that have integrated steel mills in nine locations. The EAF steel plants are owned by fifty companies producing crude steel at 98 mini-mills. Indiana accounted for an estimated 26 percent of total raw steel production, followed by Ohio with 12 percent; Michigan, 5 percent; and Pennsylvania, 5 percent, with no other state having more than 5 percent of total domestic raw steel production. Construction accounted for an estimated 44 percent of total steel use in the U.S., followed by transportation (predominantly automotive), 28 percent; machinery and equipment, 9 percent; energy, 6 percent; appliances, 5 percent; and other applications, 8 percent (USGS, 2020).

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. The use of coal as the primary fuel and feedstock for the chemical reduction of iron oxide, coupled with the sheer volume produced, means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. The iron and steel industry accounts for around a fifth of industrial energy use and about a quarter of direct industrial CO_2 emissions in the world. Globally, iron and steel production accounts for over 7 percent of global GHG emissions.

4.8.2. Production process

Figure 37 is a simplified flow diagram of steel production using BF-BOF, EAF, and direct reduction. The following subsections describe the main production steps.

Conventional BF-BOF steel production process

As shown in Figure 37, crude steel production process from iron ore using the BF-BOF production route consists of iron ore pelletization or sintering, coke making, blast furnace, and oxygen furnace. The produced crude steel then goes through casting, rolling, and finishing processes to produce finished steel products.

Sintering: In sintering, iron ore fines, other iron-bearing wastes, and coke dust are blended and combusted; the heat induces incipient fusion to convert the fines into coarse lumps (sinter) that can be used as raw material (charge) in a BF.

Pelletizing: In pelletizing, iron ore is crushed and ground to remove impurities. The resulting beneficiated (iron-rich) ore is mixed with a binding agent and then heated to create durable, marble-sized pellets. These pellets can be used in both BF and direct reduction steel manufacturing.

Coke Making: Coke is a carbon product formed by thermal distillation of metallurgical coal at high temperatures in the absence of air. Coke is produced in batteries of coke ovens. Coke is used to provide a reducing atmosphere in a BF and is also a source of fuel.

Blast Furnace (BF): A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal (also called pig iron).

Basic Oxygen Furnace (BOF): The BOF converts liquid hot metal from the BF into steel. The main operation is the addition of oxygen to remove carbon from the hot metal. In recent years, extensive ladle metallurgy processes have been developed to improve steel quality. Few energy data are available for these operations (Hasanbeigi et al. 2013).

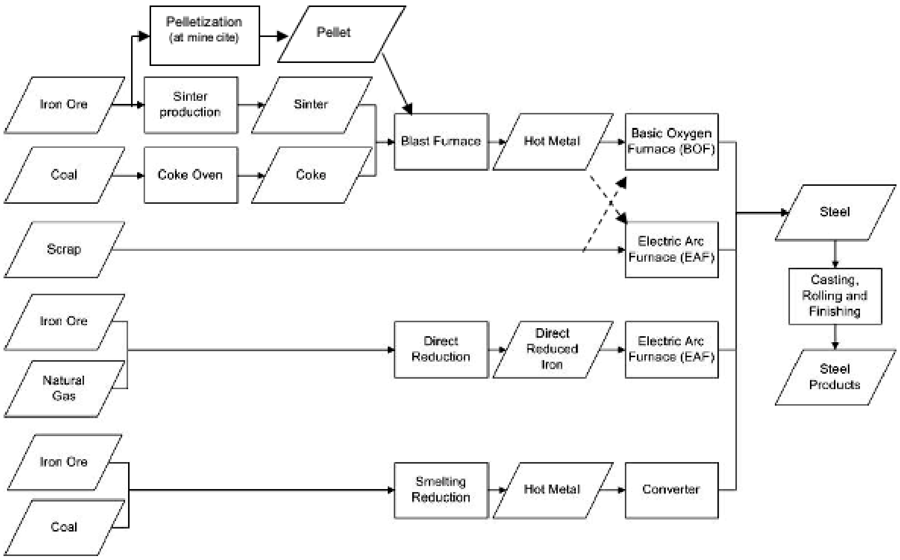

Figure 37. Flow diagram of steel production (Hasanbeigi et al., 2013)

Electrified steel production processes

Scrap-based EAF steelmaking

EAFs are mainly used to produce steel by recycling steel scrap. But direct reduced iron (DRI) (see below for explanation) and hot metal/pig iron can be fed to the EAF as a scrap substitute. EAFs are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in scrap-base EAF-steelmaking is much lower than in the BF-BOF route. The liquid steel from an EAF is generally sent to a Ladle Metallurgy Station (LMS) to improve the steel quality. Recycling of scrap into steel saves virgin raw materials (i.e., iron ore) as well as the energy required for converting them (Hasanbeigi et al., 2013).

Hydrogen DRI-based EAF steelmaking

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, and reducing agents. The majority of DRI production worldwide is based on natural gas and takes place in shaft furnaces, retorts, and fluidized bed reactors. The iron ore is reduced in a solid state in the DRI furnace, before being melted in the EAF. Carbon monoxide is the main reduction agent in the BF-BOF route, while hydrogen and carbon monoxide play more balanced roles in the DRI-EAF route. DRI-EAF facilities mainly use natural gas to generate the reducing syngas (carbon monoxide, carbon dioxide and hydrogen), but can also use gasified coal (used mainly in China and India where coal is abundant and natural gas availability is limited), while BF-BOF producers mainly use coke and coal, with natural gas injection being less common. Instead of using natural gas to produce hydrogen, it can be produced by electrolysis using (renewable) electricity (IEA 2020). Using electrolytic hydrogen as primary reducing agent in DRI production when electricity is generated from low or zero carbon sources can substantially reduce the GHG emissions of steel production. The hydrogen-based DRI is currently being piloted under the project name 'HYBRIT' in Sweden (HYBRIT, 2020).

Steelmaking by electrolysis of iron ore

Electrolysis of iron ore in steelmaking is an emerging technology. Electrolysis of iron ore allows the transformation of iron ore into metal and gaseous oxygen (O2) using only electrical energy. Adoption of electrolysis technology would eliminate coke making and blast furnace and emissions associated with them (Hasanbeigi et al., 2013). There are two main types of electrolysis processes that are being developed for steelmaking:

- The low-temperature electrolysis of iron ore in alkaline solution at 110 ˚C, so-called electrowinning. This is currently being developed by ArcelorMittal in the SIDERWIN project. The SIDERWIN project is working towards developing a pilot-scale plant in the next few years (IEA, 2020).
- The high-temperature reduction of iron ore in molten oxide environment at 1,600 ˚C, pioneered at MIT and currently being developed by the start-up Boston Metal. It is being further developed to a pilot scale plant (Boston Metal, 2020).

Table 14 provides a comparison of the energy consumption of conventional and (mostly) electric steelmaking process routes. The energy intensities are derived based on analysis from several sources including Hasanbeigi et al. (2019), IEA (2020), and US DOE (2015).

Table 14. Energy intensities of conventional and (mostly) electric steelmaking process routes

BF-BOF Steel Production			Scrap-EAF Steel Production			H2 DRI-EAF Steel Production			Steel Production by Electrolysis		
Main production processes	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)	Main production processes	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)	Main production processes	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)	Main production processes	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)
Sintering/pelletization Coke making Blast Furnace Basic Oxygen Furnace Casting, Rolling and finishing	621	4,861	EAF Casting, Rolling and finishing	710	667	H2 production DRI production EAF Casting, Rolling and finishing	3,500	667	Electrolysis of Iron Ore Casting, Rolling and finishing	3,300	556
Total Energy (kWh/t)		5,482			1,377			4,167			3,856

4.8.3. Energy, emissions, and cost implications of electrification

As mentioned earlier, the U.S. steel industry produced 87 million tonne (Mt) of crude steel in 2019, of which 30 percent was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF) and 70 percent was produced by the electric arc furnace (EAF) production route which mainly uses steel scrap (USGS, 2020).

We conducted an analysis to quantify energy, GHG emissions, and cost implications of converting all BF-BOF steelmaking in the U.S. to electrified steelmaking using one of the three electrified steelmaking processes. Figure 38 shows that electrification of steelmaking will significantly reduce the total final energy use for steel during the 2019-2050 study period. As expected, the scrap-EAF route results in the largest energy use reduction; 386,000 TJ and 482,000 TJ in 2019 and 2050, respectively.

Replacing BF-BOF steelmaking with electrified steelmaking in the U.S. can also result in a substantial decrease in annual CO_2 emissions from the steel industry of around 37 Mt CO_2 in 2019 and 47 Mt CO_2 in 2050 (Figure 39).

Although H_2 DRI-EAF and electrolysis process routes result in a relatively smaller total energy savings, since the majority of energy used in H_2 DRI-EAF and electrolysis is electricity, we can see that their CO_2 emissions reduction is comparable with scrap-based EAF in 2050 as the electricity grid is decarbonized.

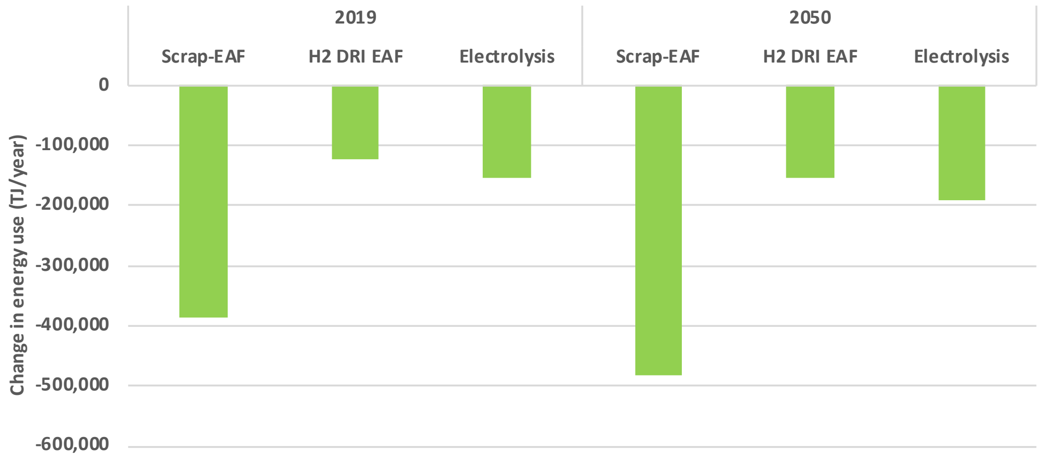

Figure 38. Change in total final energy use of the U.S. steel industry after electrification (This is the technical potential assuming 100 percent adoption rate)

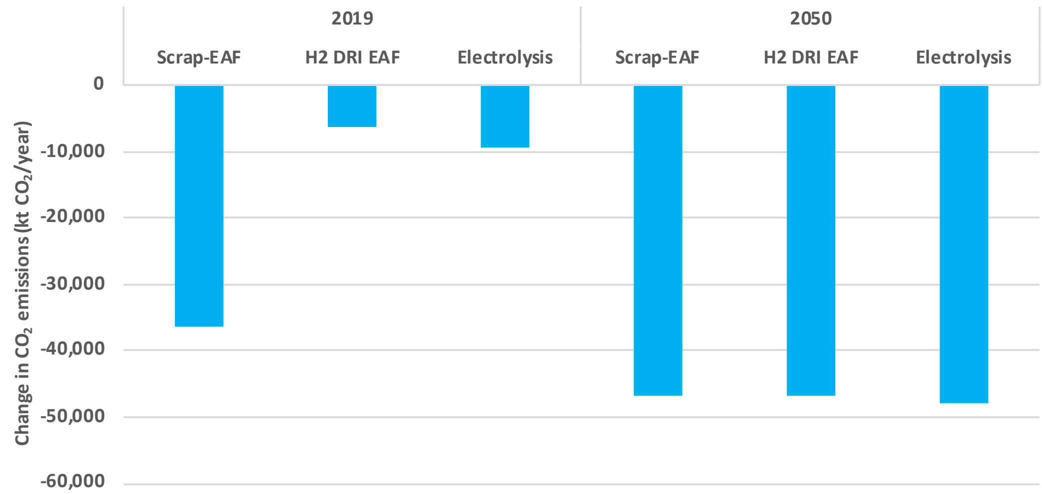

Figure 39. Change in net CO_2 emissions of the U.S. steel industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 40 shows the energy cost (in 2017$) per unit of crude steel production for all four steelmaking production routes studied in the U.S. The scrap-based EAF has lower energy cost than BF-BOF steelmaking and other two electrified processes. This is mainly because of substantially lower energy demand (Table 14) by scrap-EAF compared to other process routes.

We can also see that the energy price per unit of production for H_2 DRI-EAF and electrolysis process routes is substantially higher than of BF-BOF steelmaking. This is primarily because of low-priced f fossil fuels (coal and natural gas) compared to electricity. Access to low-cost electricity can reduce the energy cost of electrified steel processes substantially, making them even more cost-competitive relative to the conventional BF-BOF steelmaking process.

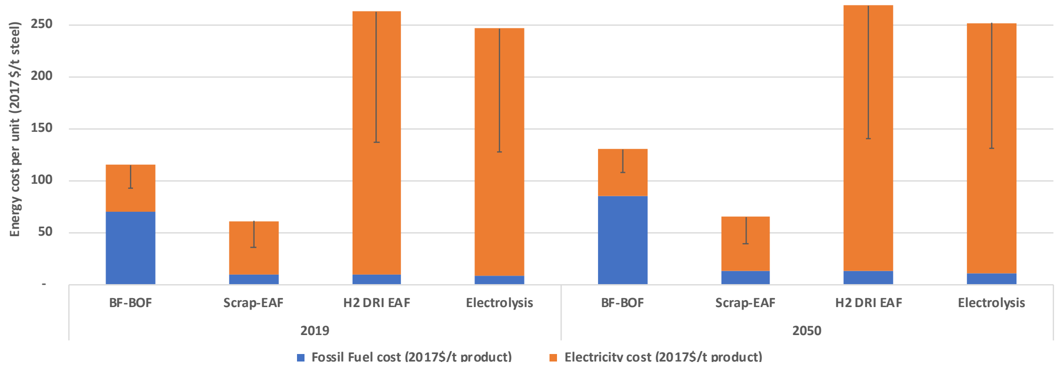

Figure 40. Energy cost per unit of production in the U.S. steel industry

Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.9. Electrification of the beer industry

4.9.1. Introduction

There has been a steady growth in U.S. brewing over the past decade. In 2019, there were reported to be over 8,000 U.S. breweries (Conway, 2020) with total annual beer production of around 211 million barrels. In 2050, production is expected to rise to 252 million barrels (US DOE, 2017b). Brewing is one of the highest energy-consuming subsectors of the food and beverage industry (US DOE/EIA, 2017).

4.9.2. Production process

The brewing process is a large-scale and highly complex procedure that transforms yeast, water, grains, hops into beer. Variations of ingredients and production conditions (hops varietals and temperature, for example) yield a wide range of beer types and styles (Sánchez, 2017).

Conventional process

The brewing process utilizes a number of ingredients such as malted barley or cereals, unmalted grains or sugar or corn syrup, hops, water, and yeast for the production of beer. Malted barley is the most popular raw material choice among U.S. brewers. The brewery location and its incoming water quality affect whether water undergoes pre-treatment via a reverse osmosis carbon filtration process or some other filtering procedure. (LBNL, 2003). Figure 41 depicts an overview of the major beer production stages. The key processes are discussed below (Aroh, 2018).

Malting and Milling: This process involves the modification of barley to malt by the maltster and its subsequent milling immediately prior to use.

Mashing and Lautering: During the process of mashing, the tank containing the water and malt mixture is constantly agitated. Hot water is added to the malt to aid the conversion of starch into sugar by enzymes. The mash is heated in stages with the help of steam jackets available on the outside of the tanks. The process of lautering refers to the separation of the sweet liquid produced (wort) from the residual grain.

Boiling and Whirlpool: The wort undergoes boiling in the kettle for a duration of 60-90 minutes for purpose of sterilization. On the completion of the boiling process, the wort is cooled down to around 20 degrees C by means of a heat exchanger.

Fermentation and Maturation: In the fermentation tank, yeast is added to the wort. The yeast helps ferment the wort and transforms it into beer. At the end of the fermentation process, the resulting beer is chilled to 10□ C and then further to 4 degrees C and stored in a tank for maturation, usually for a period of three weeks.

Filtering into a bright beer tank: This process involves the filtering of beer to remove yeast, resulting in crystal clear beer stored in a bright beer tank.

Packaging: The final step of the brewing process involves packaging the beer into either kegs, cans, or bottles.

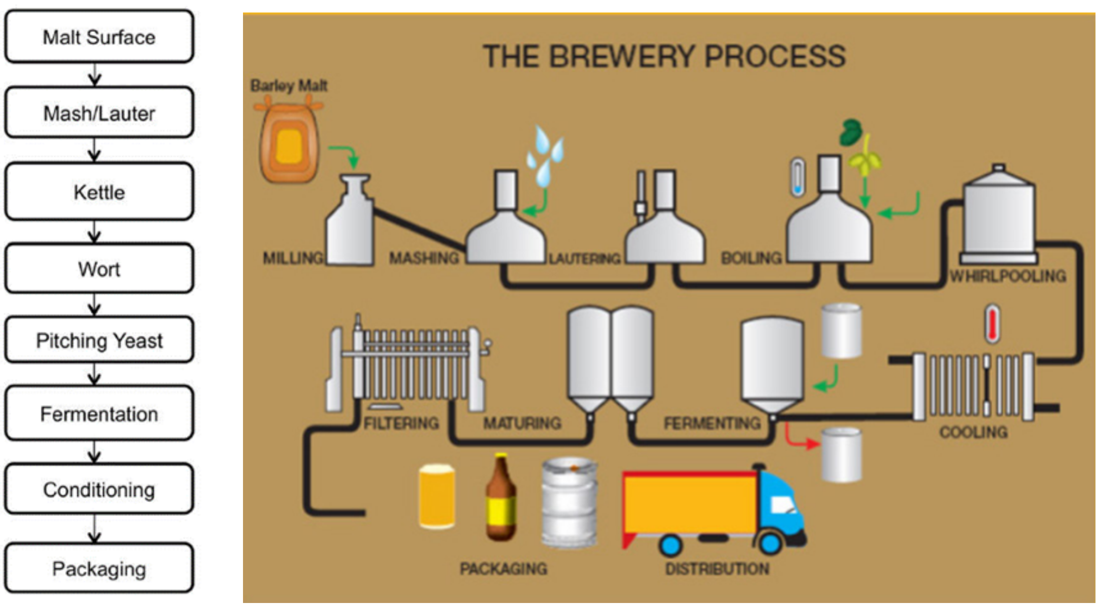

Figure 41. Microbiota of malting and brewing (Bokulich, Bamforth and Mills, 2012)

Electrified process

The processes of mashing, boiling, pasteurization, cleaning, and production support have heat requirements during beer production. The boiling process requires heating to 100 OC while other processes require heating below that temperature. Therefore, heat pumps are a good solution for the electrification of the beer industry.

Industrial heat pumps are active heat recovery systems that can capture energy savings in applications where conventional passive heat recovery is not ideal (DOE, 2003). For electrifying the beer production process, heat pumps could be utilized in four process stages. The coefficient of performance (COP) of these heat pumps is included in Table 15.

Table 15. Heat pump specifications (Beyond Zero Emissions, 2019)

	Process Stage	Output Temperature (^{o}C)	Coefficient of Performance
Heat Pump 1	Boiling	110	1.8
Heat Pump 2	Boiling	110	1.8
Heat Pump 3	Pasteurization	60	5
Heat Pump 4	Mashing & Cleaning	80	4

Heat pumps in process stages three and four shown in Table 15 will operate with very high effective efficiencies of 400 to 500 percent (COP of 4-5), due to the relatively low temperature required for mashing, pasteurization, and cleaning. The two heat pumps for boiling, heat pumps in process stages one and two, will operate at a lower COP of 1.8 due to the higher temperature uplift required. See Table 16 for a comparison of the energy intensity of the conventional and electrical processes.

Table 16. Energy intensities of conventional and electric beer production processes (Beyond Zero Emissions, 2019)

Conventional System Process		Process steps	All Electric Process	
Heating Equipment	Thermal Demand (kWh/Hectoliter)		Electrical Demand (kWh/Hectoliter)	Heating Equipment
Centralize Gas Boiler System	2.9	Mashing	0.6	Heat Pump 4
Centralize Gas Boiler System	12.9	Boiling	6.1	Heat Pump 1&2
Centralize Gas Boiler System	5.2	Pasteurization	0.9	Heat Pump 3
Centralize Gas Boiler System	12.0	Cleaning & Production Support	2.6	Heat Pump 4
	33.0	**Subtotal**	**10.2**	
33.0		**Total Energy**	**10.2**	

4.9.3. Energy, emissions, and cost implications of electrification

Figure 42 shows that electrification will significantly reduce the total final energy use from beer production during the study period; 2019-2050. Electrification of the industry would reduce the total energy demand of the beer production process, in spite of the projected increase in production between 2019 and 2050. Energy savings greater than 24,500 TJ/year can be achieved in 2050.

Electrification of beer production in the U.S. can result in a reduction in CO_2 emissions by 92 kt CO_2 in 2019 (Figure 43). Over the study period, electrification could potentially reduce annual CO_2 emissions by 15 times, resulting in a 1,380 kt CO2 annual reduction in 2050. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

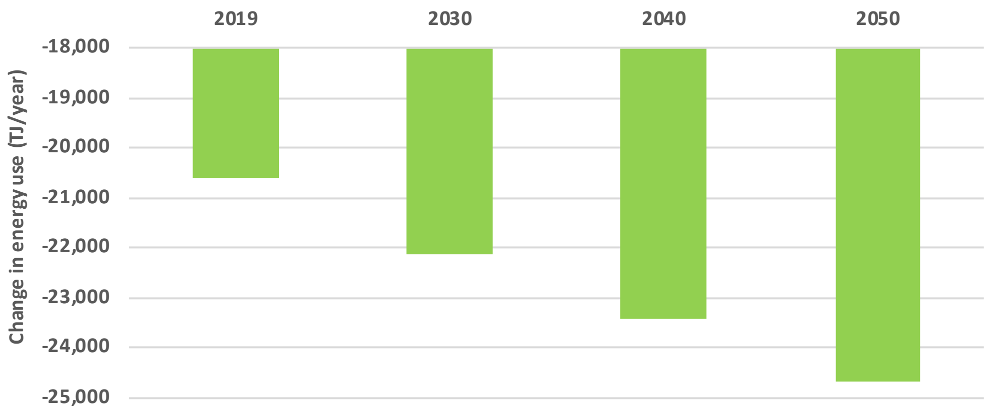

Figure 42. Change in total final energy use of the U.S. beer industry after electrification (This is the technical potential assuming 100 percent adoption rate)

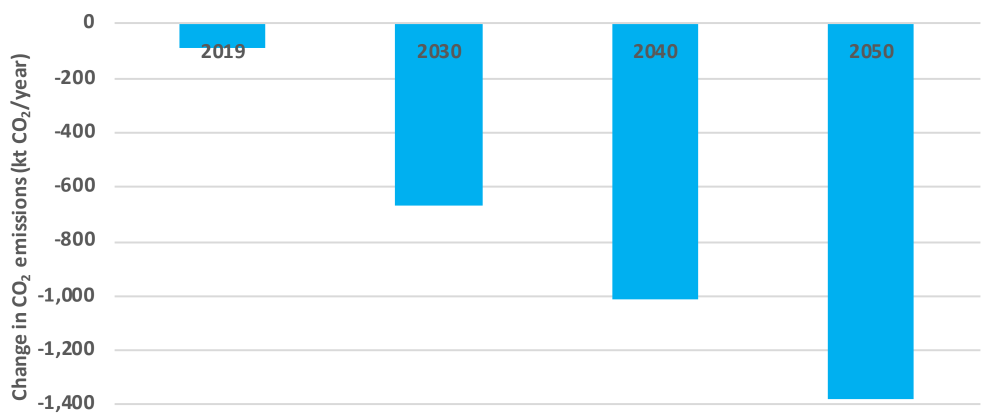

Figure 43. Change in net CO_2 emissions of the U.S. beer industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate.)

Figure 44 depicts that energy cost (in 2017$) per unit of production in the U.S. beer industry for the conventional process is about 66 percent of that of the electrified process in 2019. However, the energy cost per unit of production for the electrified process becomes much more competitive in 2050.

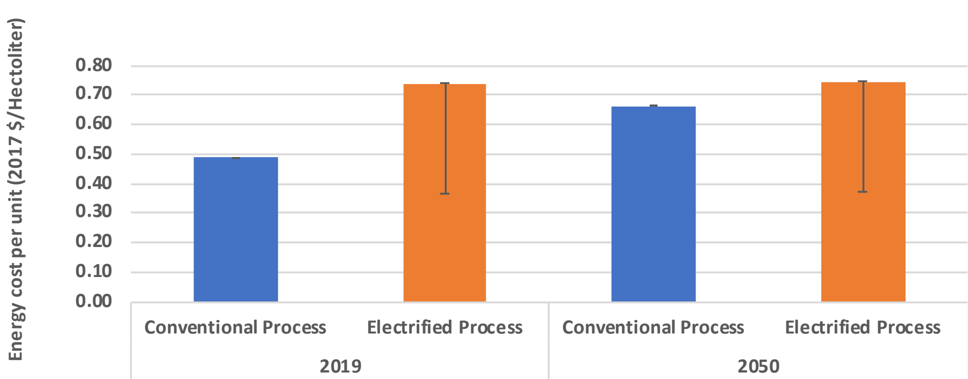

Figure 44. Energy cost per unit of production in the U.S. beer industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.10. Electrification of the beet sugar industry

4.10.1. Introduction

One of the most popular and widely available sweeteners, granulated white sugar, is extracted from sugar cane and sugar beet plants. It is colloquially referred to as "sugar" or table sugar and is considered among the purest (about 99.95 percent) food products. The sugar content of beet and cane juices is quite similar; but they differ in terms of amounts of impurities present; impurities present in beet and cane juice are around 2.5 percent and 5 percent respectively. Because of this, as well as the materials' compositional differences, the processes and the chemicals utilized for refining cane and beet sugars vary (Campos, 2020).

Bagasse, a dry pulpy residue obtained as a by-product of the sugar manufacturing process from sugar cane, is utilized as a fuel in cogeneration systems that provide heat and electricity for the sugar production process. Over the last few years, numerous sugar cane factories have produced excess electricity that can be sold to the grid, providing an additional revenue stream (Ensinas, 2006). Therefore, electrification of the sugar cane production process was deemed less likely and the study focused on electrification of beet sugar production. Total annual U.S. beet sugar production is estimated to be around 4.6 million metric tonnes (Bandwidth Food, 2017). It is also one of the highest energy-consuming subsectors of the food and beverage industry.

4.10.2. Production process

Conventional process

Figure 45 depicts the conventional beet sugar process. Production begins with the washing and slicing of beets into thin slices called cossettes. Cossettes are exposed to hot water for the extraction of sucrose from them, in the form of the resulting diffusion juice. This process takes place in the diffuser: Its electrical drives are among the main electricity consumption sources of the process. The residual pulp, or sugar-deprived cossettes, are compressed, dried, and processed as animal feed.

In the purification section, the impurities in the juice are filtered out and the resulting clear or purified juice is directed to the evaporation section. The main steam requirements for the diffuser and purification sections are for the heat exchangers that heat the juice.

The evaporation section reduces the level of water in the juice, increasing the sugar content of the juice and producing syrup. This process is carried out in a multiple effect evaporator, where the boiling of the juice occurs in a sequence of vessels. This section is responsible for the greatest amount of steam consumption in the entire production process.

Finally, the syrup feeds the sugar-end, where sucrose is crystallized to obtain granulated refined sugar and molasses (by-product). This crystallization process also consumes a significant energy (Pablos, 2017).

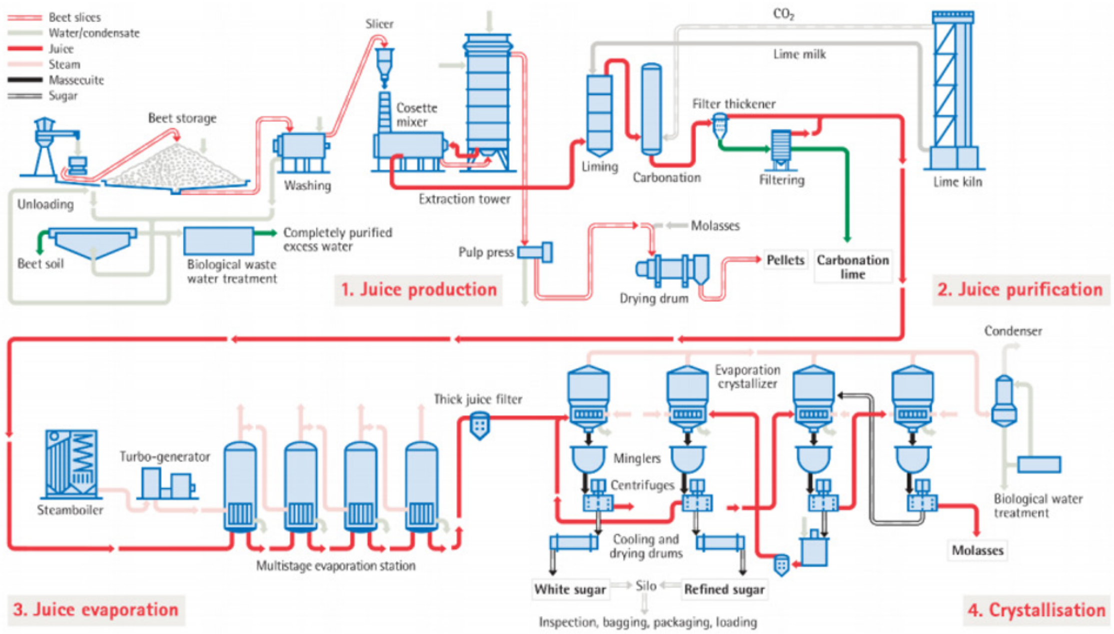

Figure 45. Simplified schematic of a typical sugar factory (Südzucker, 2018)

Electrified process

It is possible to achieve electrification of a significant proportion of the overall beet sugar production process. This can be better understood by considering the operational temperature for each process indicated in Table 17. The operational temperatures for each process are in a range that can mostly be provided efficiently by conventional heat pumps (primarily temperatures under 160 ˚C).

The final step of beet sugar production, the complex crystallization process, requires steam for heating and formation of crystals. This process step is carried out in batches for the production of crystalline white sugar. The thick juice is boiled in three steps with temperatures in the range of 70 ˚C, 75 ˚C, and 80 ˚C, respectively (Smejkal, Bagherzadeh, 2008). The steam can be generated by an electric steam boiler. Here we assume the same energy conversion factor (COP: 2.5) from fuel-based to electrified equipment for all production, purification, evaporation, and crystallization. It is worth pointing out that the majority of heating required by this production process is for juice evaporation.

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Table 17. Operational temperature of beet sugar processes

Process	Level	Operational Temperature (ºC)	Reference
Juice Production	Cossettes cleaning	60	SKIL, 2018
	Sugar extraction from cossettes	69-75	Merino Gómez, 2001.
Juice Purification	Lime addition in the first carbonization step	83	Smejkal, Bagherzadeh, 2008
	Lime addition in the second carbonization step	93	Smejkal, Bagherzadeh, 2008
Juice Evaporation	First Step of evaporation	135	Smejkal, Bagherzadeh, 2008
	Second Step of evaporation	115	Smejkal, Bagherzadeh, 2008

Sugar beet pulp, the residue left after the sugar is extracted from the beets, is mainly utilized as feed for animals such as cattle. The pulp is dried in rotary drums by passing the pulp through the flue gases from a directly fired furnace. Tang et al. proposed another pulp dryer that uses steam or hot air as a heating source (Tang et al., 2000). Figure 46 shows the simplified diagram of the drying chamber. Hot air can be provided by an electric resistive element using a fan.

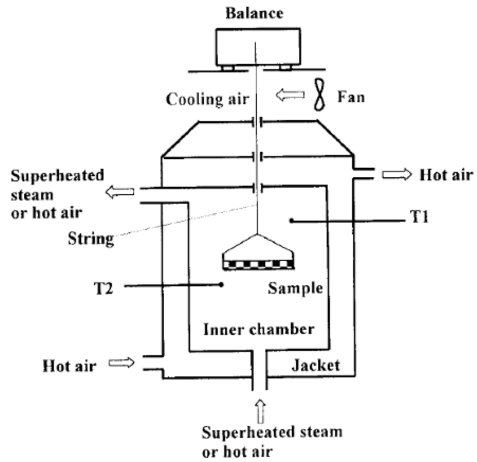


Figure 46. Simplified diagram of the drying chamber (Tang et al., 2000)

Table 18 provides an energy consumption comparison between the conventional and electric processes for beet sugar production.

Table 18. Energy intensities of conventional and electric beet sugar production processes

Conventional System Process			Process steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
Conventional Steam Generator	153	778	Juice Diffusion	464	Heat Pump
Conventional Steam Generator			Juice Purification		Heat Pump
Conventional Steam Generator			Evaporation		Heat Pump
Conventual Steam Generator			Crystallization		Electric Steam Boiler
Direct Fuel Base Dryer		806	Pulp Drying	806	Electric Air Dryer
	153	**1,584**	**Subtotal**	**1,270**	
	1,737		**Total Energy**	**1,270**	

4.10.3. Energy, emissions, and cost implications of electrification

Figure 47 shows that electrification will significantly reduce the total final energy use from beet sugar production during the study period; 2019-2050. Switching to an electrified production process could lead to energy savings of greater than 9,300 TJ annually in 2050.

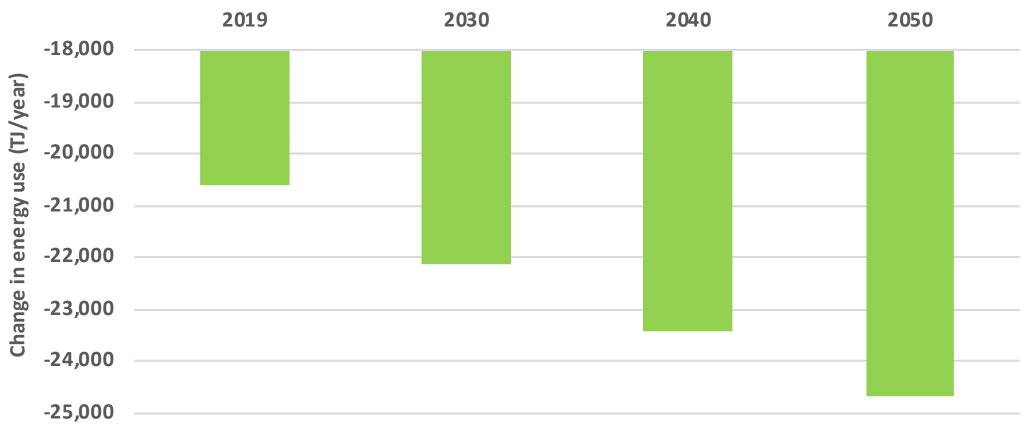


Figure 47. Change in total final energy use of the U.S. beet sugar industry after electrification (This is the technical potential assuming 100 percent adoption rate)

The total CO_2 emissions associated with the beet sugar industry in the U.S. could increase by 662 kt CO_2 in 2019 upon electrifying the production process (Figure 48). However, over the study period, electrification could potentially reduce annual CO_2 emissions by 1,775 kt CO_2 per year in 2050.

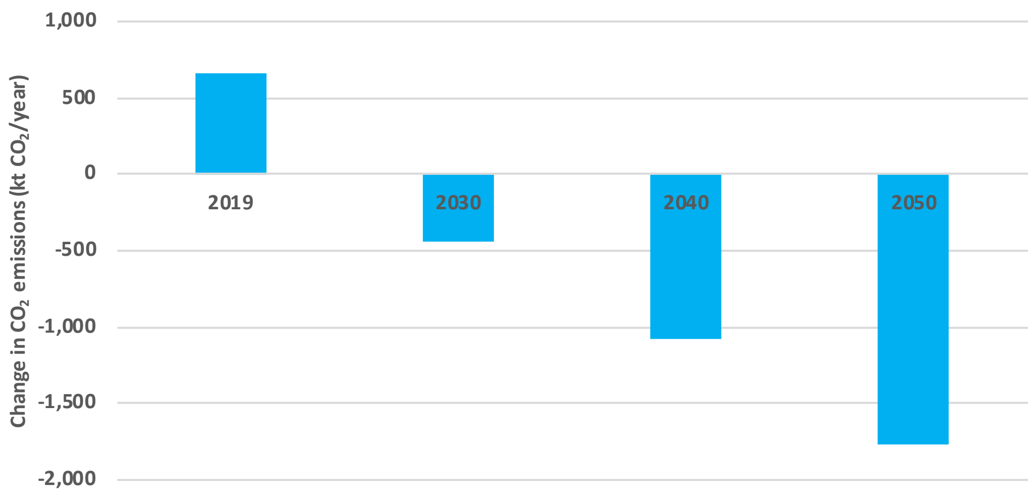


Figure 48. Change in net CO_2 emissions of the U.S. beet sugar industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 49 indicates that the energy cost (in 2017$) per unit of production in the U.S. beet sugar industry using the conventional process is about 37 percent of that of the electrified process in 2019.

The error bars on Figure 49 show that access to low-cost electricity could drastically change the competitiveness of the electrified production process in terms of financial viability.

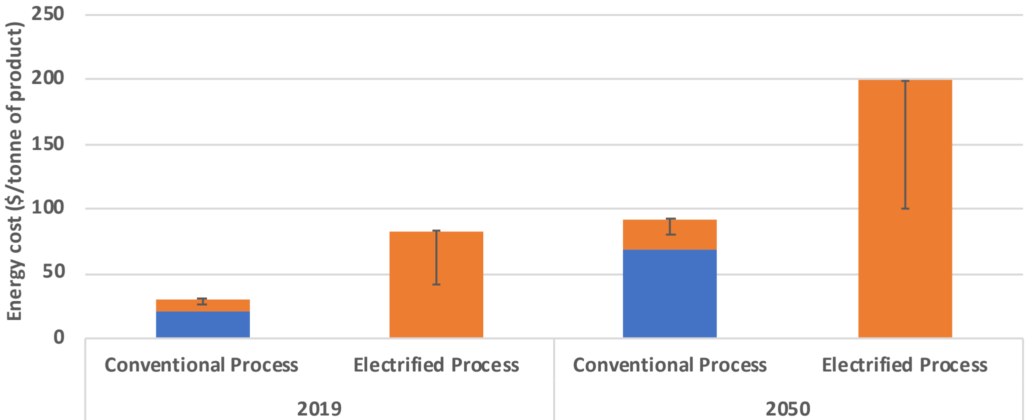


Figure 49. Energy cost per unit of production in the U.S. beet sugar industry

Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.11. Electrification of the milk powder industry

4.11.1. Introduction

Powdered milk or dried milk is obtained through the dehydration of liquid milk with the help of several drying processes until it is transformed into powder form. Preservation of milk is one of the main reasons for drying it since milk powder exhibits a much longer shelf life as compared to liquid milk and has no refrigeration requirements (Rotronic, 2015). The United States is the world's single largest manufacturer of skim milk powder (SMP) or nonfat dry milk, with close to 1.1 million tonne produced in 2019. The volume of SMP production in the U.S. has continued to rise over the years and the country currently comprises almost a quarter of the total SMP global production. SMP exports by the U.S. have been on the rise, with over 50 percent of production destined for overseas markets (U.S. Dairy Export Council, 2015). The dairy industry is also one of the largest energy consuming subsectors of the food and beverage industry.

4.11.2. Production process

Conventional process

Figure 50 shows the milk powder production process schematically. The manufacturing process can be divided into four main process steps (Pearce, 2017):

1. Separation / Standardization: The traditional way of producing milk powder begins with pasteurizing and separating the raw milk obtained from the dairy factory into skim milk and cream, with the help of a centrifugal cream separator.
2. Preheating: Standardized milk is heated to temperatures in the range of 75 to 120˚C for a specified time interval varying from a few seconds up to several minutes. Preheating can occur indirectly (through heat exchangers), directly (through steam injection or infusion into the product), or as a combination of the two.
3. Evaporation: Preheated milk is concentrated in multiple stages or "effects" from approximately 9 percent total solids content for skim milk and 13 percent for whole milk, up to 45-52 percent content of total solids. During this process, milk is boiled at temperatures below 72˚C under vacuum conditions, and water is removed in

the form of vapor.

4. Spray Drying: The milk concentrate is atomized into fine droplets. Prior to atomization, the concentrate might be heated to help reduce its viscosity and enhance the total energy available for drying. The process is carried out inside a large drying chamber, with hot air (with temperatures above 200 ˚C) flowing through it, utilizing either a series of high-pressure nozzles or a spinning disk atomizer.

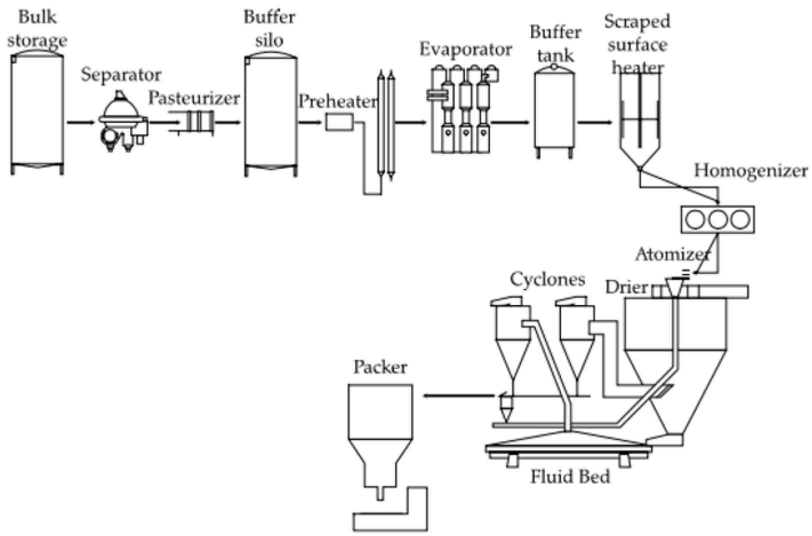


Figure 50. Flow diagram of the milk powder process (Pearce, 2017)

Electrified process

The equipment that could be utilized for electrifying the milk powder production process is described below (Beyond Zero Emissions, 2018):

1. Reverse osmosis technology utilizes membranes to partially remove water from milk. It helps reduce the energy demand on both the pre-heater and the evaporator by increasing the total solids content from 10 to 30 percent.
2. A heat pump, indicated as Heat Pump 1 in Table 19, provides heating and cooling simultaneously. The cooling output is utilized for refrigerating the milk, and provides waste heat at 35-40˚C. This waste heat is reused by the heat pump to produce hot water at 85˚C for heating the milk, as well as hot water at 55˚C for the washing process. The heat pump achieves a combined COP for heating and cooling of 4.6.
3. A two-stage, low-energy mechanical vapor recompression system, that is responsible for dehydrating the milk to obtain concentrated milk with solid content exceeding 53 percent.
4. A second heat pump, indicated as Heat Pump 2 in Table 19, with a COP of 2.5, would help recover the waste heat from the dryer exhaust at 75˚C and produce hot air at 140˚C.
5. High-temperature electric air heater receives air at 140˚C from Heat Pump 2, and raises its temperature to 210˚C by means of hot elements.Table 19 provides a comparison of energy consumption between conventional and electrified processes for the production of milk powder.

Table 19. Energy intensities of conventional and electric milk powder production processes (Beyond Zero Emissions, 2018)

Conventional System Process			Process Steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Centrifuge	13	3	Separation	13	Centrifuge
-	-	-	Reverse Osmosis	35	Reverse Osmosis Pump
Steam Boiler	-	388	Pre-Heating	47	Heat Pump 1
Mechanical and Thermal vapor recompression	90	133	Evaporation	27	Mechanical and vapor recompression
Steam Boiler	50	1,139	Drying	492	Heat Pump 2, Electric air heater
Fluidized Bed	45	111	Cooling	148	Fluidized Bed
	198	**1,774**	**Subtotal**	**762**	
1,972			**Total Energy**	**762**	

4.11.3. Energy, emissions, and cost implications of electrification

Figure 51 shows that electrification will significantly reduce the total final energy use from milk powder production during the study period of 2019-2050. The electrification of milk powder production would reduce the total energy demand of the process, in spite of the projected increase in production between 2019 and 2050, and could lead to energy savings in excess of 4,800 TJ annually in 2050.

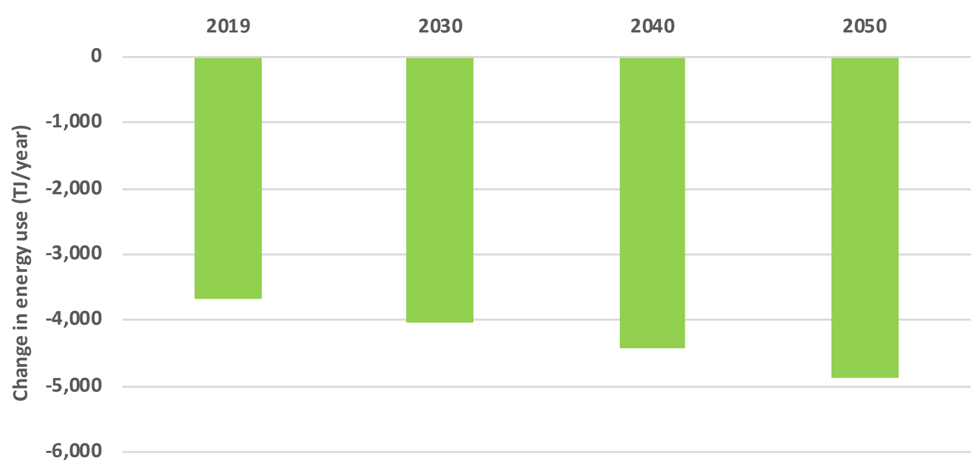


Figure 51. Change in total final energy use of the U.S. milk powder industry after electrification (This is the technical potential assuming 100 percent adoption rate)

Potential CO_2 emissions reduction of 104 kt CO_2/year could be realized in 2019 through the electrification of the milk powder industry in the U.S. (see Figure 52). Over the period of study, electrifying the milk powder production process could quadruple annual CO_2 emissions, potentially realizing an annual reduction of 400 kt CO_2 in 2050. This large decline in CO_2 emissions is the consequence of improvement in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

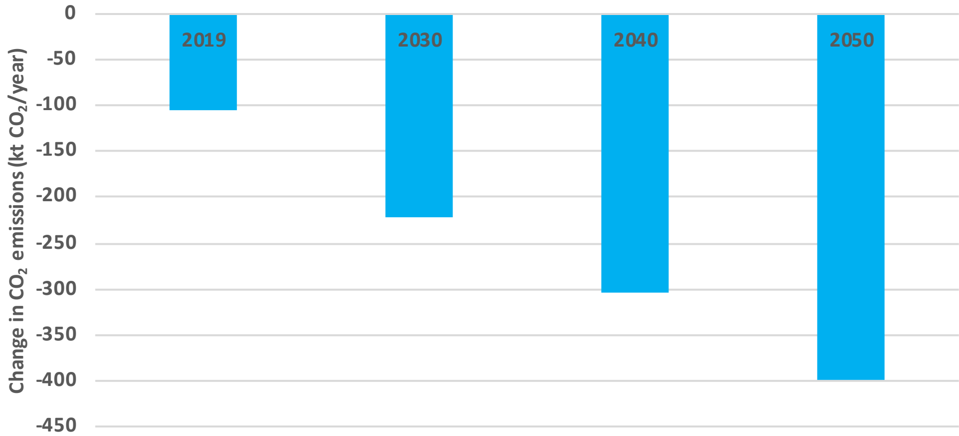


Figure 52: Change in net CO_2 emissions of the U.S. milk powder industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 53 shows that energy cost (in 2017$) per unit of production in the U.S. milk powder industry for the conventional process is equivalent to 73 percent of that of the electrified process in 2019. However, the energy cost per unit of production becomes more competitive for the electrified process over time.

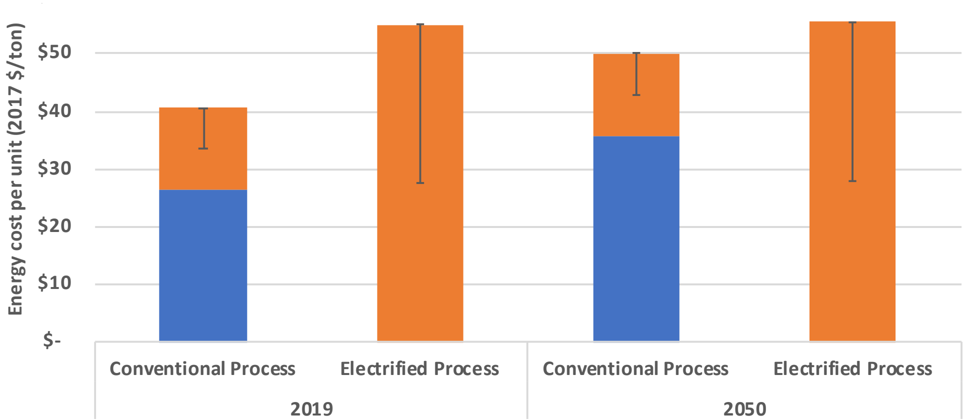


Figure 53. Energy cost per unit of production in the U.S. milk powder industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.12. Electrification of the wet corn milling industry

4.12.1. Introduction

The wet-milling and dry-milling processes are the two common techniques utilized for processing corn in the U.S. Ethanol is the primary product of the dry milling process, and is also a byproduct of the wet milling process. The efficient separation of various products and shelled corn parts for a variety of food and industrial purposes can be achieved through the wet corn milling process. Corn starch and edible corn oil are the primary products of the wet milling process (O'Brien & Woolverton, 2009). In this study, we focus on the wet corn milling process. In the U.S., the corn refining industry comprises 25 corn refining plants and four additional processing plants. In 2018, the manufacturing value added by the industry was estimated to be around $12 billion (CRA, 2019). The total production by the U.S. wet corn milling industry in 2019 was around 30 million tonnes (US DOE, 2017b). It is also one of the largest energy consuming subsectors of the food and beverage industry (US DOE/EIA, 2017).

4.12.2. Production process

The wet corn milling process splits corn into its four basic elements: starch, germ, fiber, and gluten (CRA, 2020).

Conventional process

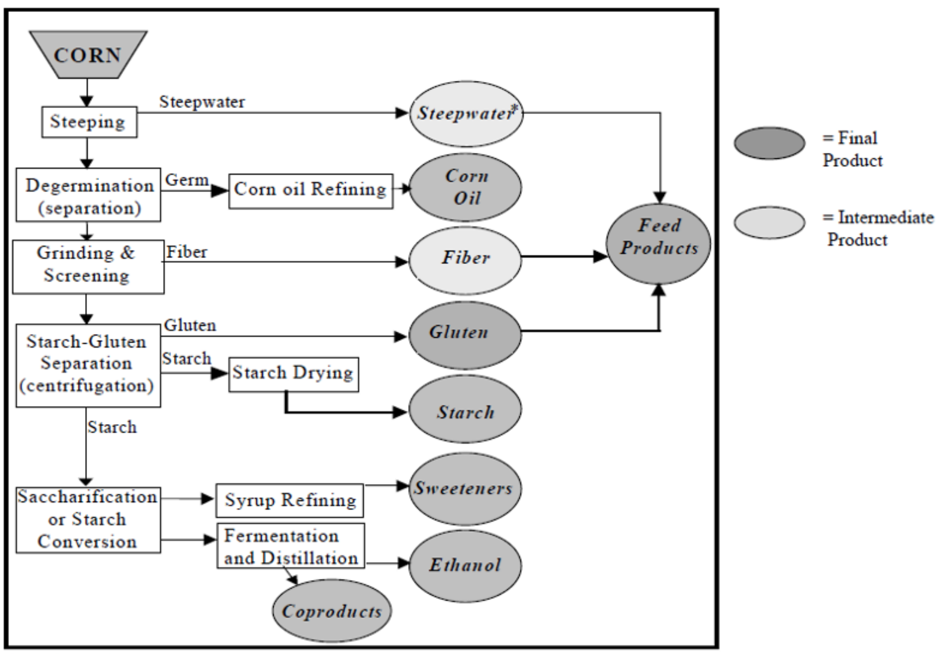
In the wet corn milling process, highly purified products are obtained through the extraction of components of corn kernels. A large proportion of the products obtained via this process are valuable and are demanded by the food industry. The process helps produce quality ingredients from various parts of corn. It relies on the principle of physical separation of components on the basis of their weight and size. Water is utilized as a separation/carrying agent during the washing steps. Aqueous sulfur dioxide (SO2) solution is the only chemical utilized for wet corn milling. The corn is steeped in the SO2 solution to soften the kernel and ensure easy separation, and to prevent the oil in the germ from contaminating other products, (Galitsky et al., 2003). Figure 54 provides a schematic diagram of the wet corn milling process. Table 20 highlights the energy intensity of each process step.

Electrified process

The conventional heating equipment that can be replaced by the electrical devices in the wet corn milling industry are described below:

- With operational temperatures of around 51˚C (Ramirez et al., 2008) for the steeping process, a heat pump can supply the required thermal energy.

Figure 54. Overview of the processes and products of wet corn milling (Galitsky et al., 2003)



*Certain grades of steepwater may also be a final product

- Mechanical vapor recompression (MVR) is an open heat pump system. The process of compression results in a rise in both pressure and temperature, along with an increase in the corresponding saturation temperature. The required energy for compression is very small compared to the amount of latent heat available in recycled steam (Klop, 2015). MVR can be utilized for the steep water evaporation process (Ramirez et al., 2008). Typically, its economical and energy-efficient usage results in a minimum COP of 3.5 (Marsidi, 2018).
- Conventional fluidized bed dryer is the main apparatus required for the process of germ dewatering and drying process (Ramirez et al., 2008). Some companies like Metso have developed electric fluidized bed dryers that can be used to replace conventional ones (Metso, 2014).
- The conventional rotary dryer is deemed essential for processes such as gluten thickening and drying as well as starch dewatering and drying (Ramirez et al., 2008). However, technology manufacturers can supply electric rotary dryers that could serve as a replacement.
- A conventional ring dryer is used for the gluten feed drying process (Ramirez et al., 2008). It could be replaced with an indirect resistive heater for air heating.

Table 20 provides an energy consumption comparison between conventional and electrified processes for wet corn milling.

Table 20. Energy intensities of conventional and electric wet corn milling production processes (data from various sources stated above)

Conventional System Process			Process Steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
	4.9	-	Corn Receiving	5	
Central Steam Systems	2.5	36	Steeping	11	Heat Pump @ 51 °C
Central Steam Systems	6.1	225	Steep water evaporation	70	Mechanical Vapor Recompression
	7.9	-	Germ recovery (1st grind)	8	
	4	-	Germ recovery (2nd grind)	4	
	0.3	-	Germ recovery (germ washing)	0	
Conventional Fluidized Bed Dryer	5.1	78	Germ dewatering and drying	5	Electrical Fluidized Bed Dryer
	24.9	-	Fiber recovery	25	
	4.4	-	Fiber dewatering	82	
	11.5	-	Protein (gluten) recovery	12	
Conventional Rotary Dryer	5.9	41	Gluten thickening and drying	47	Electrical Rotary Dryer
	5.5	-	Starch washing	6	
Conventional Rotary Dryer	30.8	312	Starch dewatering and drying	343	Electrical Rotary Dryer
Conventional Ring Dryer	11.2	259	Gluten feed dryer	270	Electrical Ring Dryer
	125	**951**	**Subtotal**	**888**	
1,076			**Total Energy**	**888**	

4.12.3. Energy, emissions, and cost implications of electrification

Figure 55 shows that electrification could significantly reduce the total final energy use from wet corn milling process during the study period of 2019-2050. Potential energy savings of over 24,000 TJ /year can be achieved in 2050 as electrification reduces the total energy demand of the wet milling process despite the projected rise in production between 2019 and 2050.

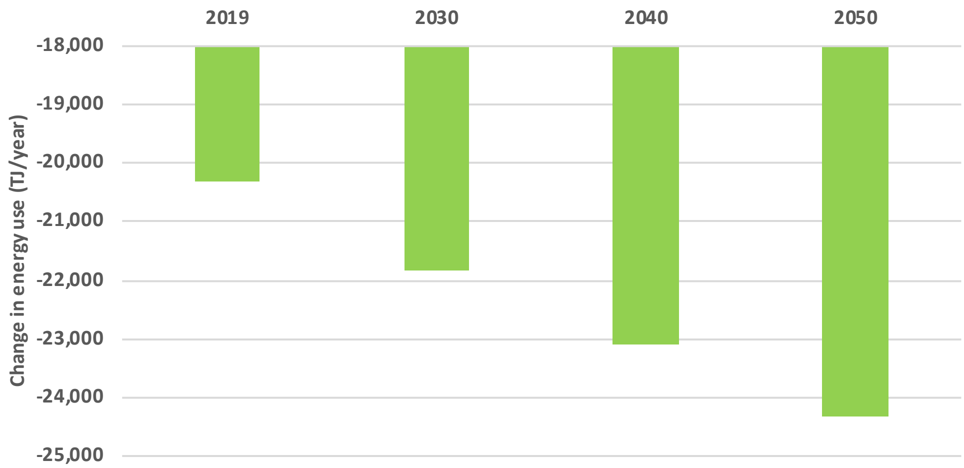


Figure 55.Change in total final energy use of the U.S. wet corn milling industry after electrification (This is the technical potential assuming 100 percent adoption rate)

In the U.S., electrification of the wet corn milling process can result in an increase in CO_2 emissions by 3,717 kt CO_2 in 2019 (Figure 56). However, electrification has the potential to reduce CO_2 emissions by 6,900 kt CO_2 /year in 2050.

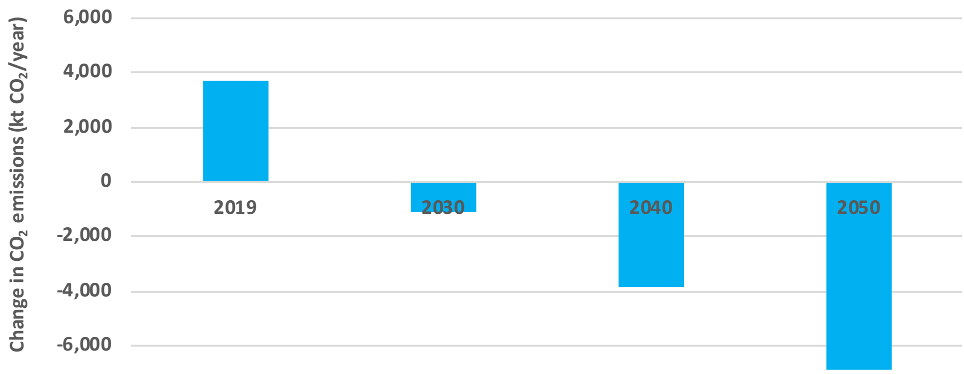


Figure 56. Change in net CO_2 emissions of the U.S. wet corn milling industry after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 57 shows that in the U.S. wet corn milling process, the energy cost (in 2017$) per unit of production for the conventional process is about 64 percent lower than for the electrified process in 2019. Over the period of study, energy cost per unit of production is higher for the electrified process compared to the conventional process.

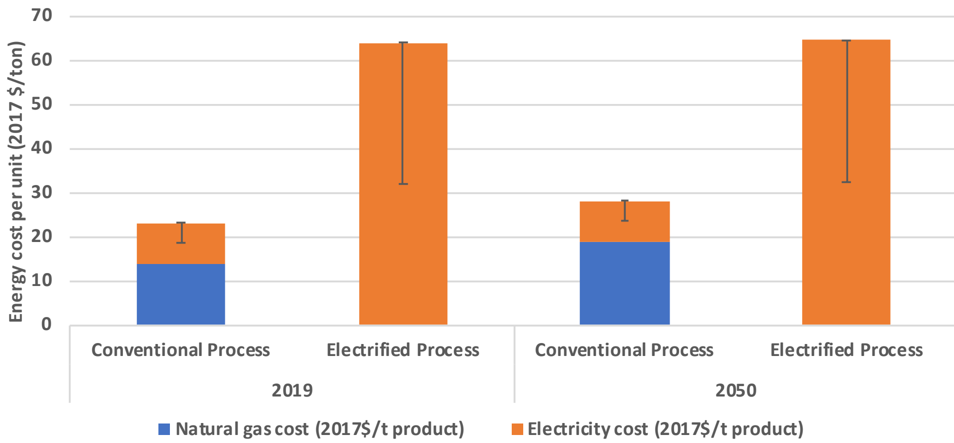


Figure 57. Energy cost per unit of production in the U.S. wet corn milling process
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

4.13. Electrification of the crude soybean oil industry

4.13.1. Introduction

Soybean oil, extracted from soybean seeds, is among the world's most broadly used natural oils. It is used for a vast range of applications such as nutritional supplements, cosmetics, food, and agriculture. The industry is being driven by the rising demand for soybean meal for livestock. This has resulted in a considerable increase in the production of soybean oil as well (EMR, 2020). In 2019, the total production volume of soybean oil in the U.S. is estimated to be around 9.5 million tonnes (US DOE, 2017b). It is also one of the largest energy consuming subsectors of the food and beverage industry (US DOE/EIA, 2017).

4.13.2. Production process

There are two main techniques for the production of vegetable oils: Pressing or extrusion for small to moderate capacities, and solvent extraction of the pretreated oil seeds in case of larger capacity requirements (Kong et al., 2019).

Conventional process

The solvent commonly utilized for the extraction process is hexane, and the initial stages of the process can utilize a mixture of hexane and oil, called miscella. Figure 58 illustrates the conventional method of soybean oil (SBO) production. The oil production process comprises the following steps:

1. First, the delivered oilseeds are pretreated; drying, dehulling, flaking.
2. The actual leaching process occurs where crude SBO undergoes solvent extraction (by means of hexane) on a belt conveyor.
3. Hexane is separated out from both the miscella and from the cake. The miscella undergoes a two-stage evaporation process and direct steam stripping, while the soybean meal receives heat treatment in a multiple hearth desolventizer/ toaster/ cooler.

4. The vapors of the solvent as well as water are then condensed in a multi-stage cooling process.
5. The residual water vapors are finally stripped off of hexane through absorption in paraffin and the recovered hexane is ready for reutilization in the leaching process (Martinho et al., 2008).

The entire soybean oil production process is highly energy-intensive and requires large amounts of steam and cooling water, mainly for the solvent removal and recovery sections of the process. The energy consumed by the conventional SBO production process is provided in Table 21 (Kong, 2019). In the crude soybean oil extraction process, the electricity consumption is around 125 kW/ton of crude soybean oil (Kong et al., 2018).

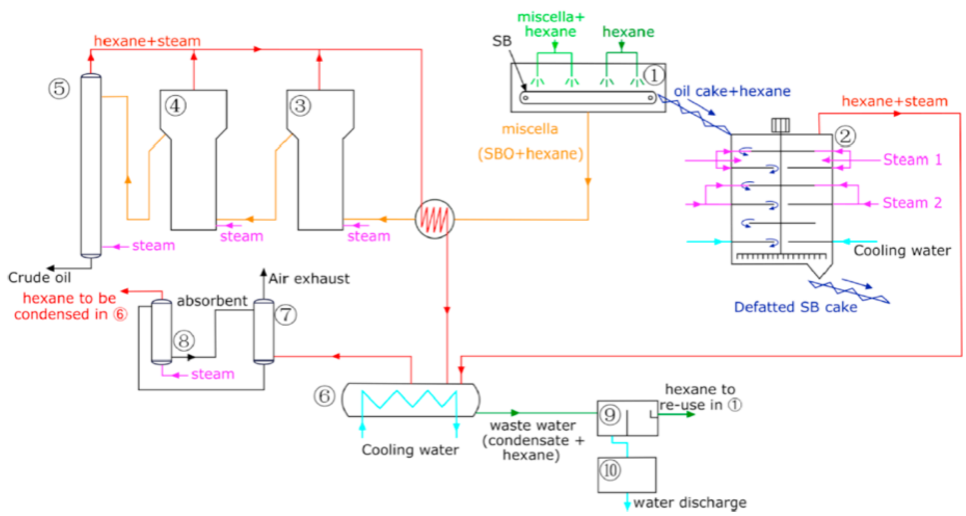


Figure 58. Traditional SBO solvent-extraction: 1. Leaching, 2. Desolventizer/toaster/cooler, 3. 1st evaporator, 4. 2nd evaporator, 5. Stripping tower, 6. Cooler, 7. Absorption, 8. Desorption, 9. Water/hexane separator, 10. Waste water treatment plant. Steam 1 is indirect or direct steam for hexane volatilization, Steam 2 is indirect steam for toasting (Kong, 2019)

Electrified process

Based on the operational temperatures and technologies utilized by the soybean oil production industry, complete electrification of the production process is achievable. The leaching process has an operating temperature of around 47-53 ˚C (Kong et al., 2019) and a typical heat pump could fulfill the heating requirements of this process. Steam requirements for the evaporation section range between 1,430 kWh/tonne and 5,010 kWh/tonne for direct and indirect supply of steam respectively (Kong et al., 2019). An electric steam boiler can be utilized for fulfilling the direct steam generation requirement while resistive electrical elements can provide the required indirect heating.

Kong et al. also proposed a new energy-saving electric technology for the desolventizer that utilizes hot air / nitrogen instead of direct steam (Kong et al., 2019). Here we consider this innovative fluidized bed desolventizer/toaster/cooler that can utilize electrical resistive elements for preheating air /nitrogen. The energy saving potential of this switch is demonstrated in Table 21. Figure 59 shows the schematic of a fluidized bed desolventizer.

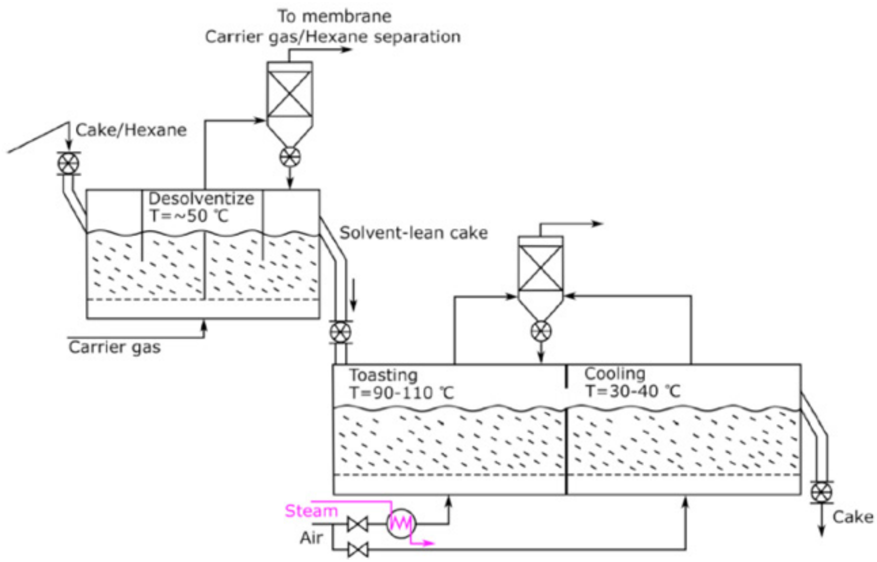


Figure 59. Design of fluidized bed desolventizer/toaster/cooler (Kong, 2019)

Table 21 provides a comparison of the energy consumed by the conventional and electrified soybean oil production processes.

Table 21. Energy consumption of conventional and all electric crude soybean oil production process

Conventional System Process			Process steps	All Electric Process	
Heating Equipment	**Electrical Demand (kWh/tonne)**	**Thermal Demand (kWh/tonne)**		**Electrical Demand (kWh/tonne)**	**Heating Equipment**
Conventional Steam Generator	-	17	Leaching	7	Heat Pump
Conventional Steam Generator	-	143	Evaporators	124	Electric Steam Boiler
Conventional Steam Generator	-	501		501	Indirect Resistive Heating
Conventional Steam Generator	-	18	Stripping	16	Electric Steam Boiler
Conventional Steam Generator	-	815	Desolventizer	212	Fluidized Bed Using Air/Nitrogen
Conventional Steam Generator	-	293	Tail gas stripper	-	
	125	-	Electrical devices	125	
	125	**1,787**	**Subtotal**	**984**	
	1,912		**Total**	**984**	

4.13.3. Energy, emissions, and cost implications of electrification

Figure 60 shows that electrification will significantly reduce the total final energy use from soybean oil production during the study period, 2019-2050. It has the potential of achieving energy savings greater than 38,000 TJ on an annual basis in 2050.

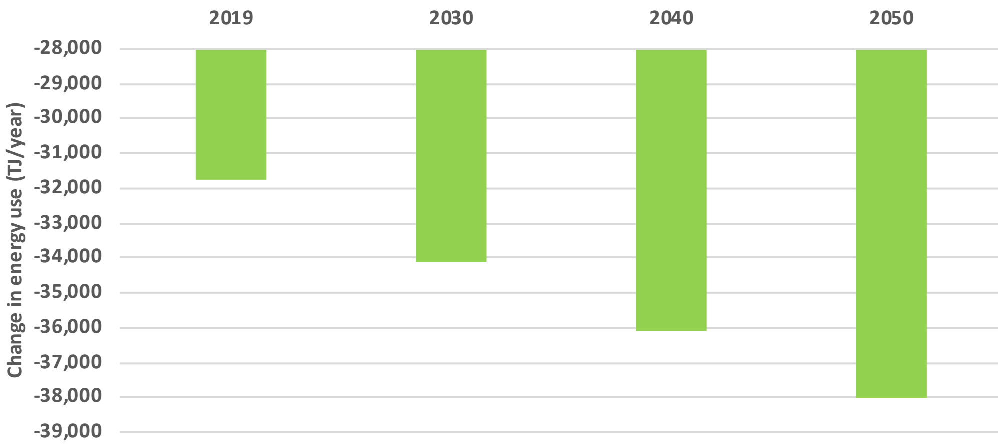


Figure 60. Change in total final energy use of the U.S. soybean oil industry after electrification (This is the technical potential assuming 100 percent adoption rate)

Electrification of soybean oil production in the U.S. reduce CO_2 emissions by 46 kt CO_2s in 2019 (Figure 61). Over the period of study, electrification could result in a decline in annual CO_2 emissions by 88 times and help realize an emission reduction of over 4,000 kt CO_2 /year in 2050. Such a considerable reduction in CO_2 emissions is the effect of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050.

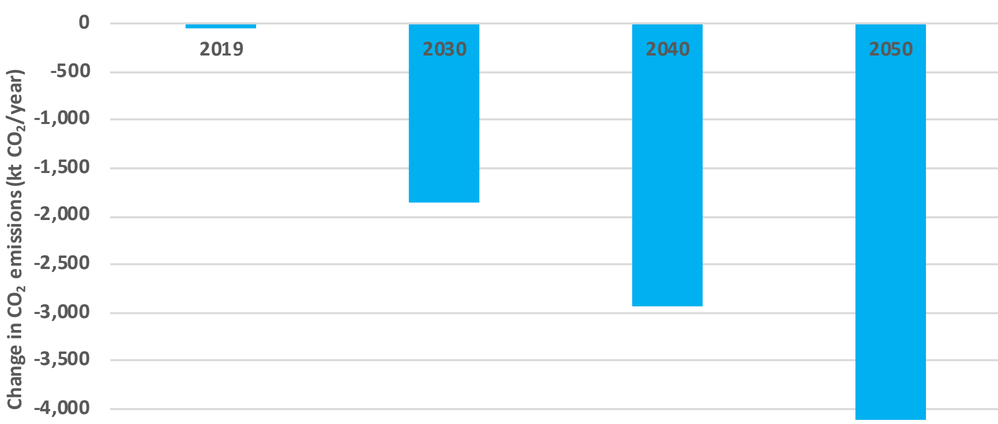


Figure 61. Change in net CO_2 emissions of the U.S. soybean oil after electrification in U.S. (This is the technical potential assuming 100 percent adoption rate)

Figure 62 shows that in the U.S. soybean oil industry, the energy cost (in 2017$) per unit of production for the conventional process is about 50 percent lower than that of the electrified process in 2019. However, the energy cost per unit of production becomes more competitive for the electrified process in 2050.

We can clearly see that access to low-cost electricity can help bridge the economic gap between the electrified and the conventional processes. In certain scenarios, the cost of the electrified process could even end up being lower than its conventional alternative.

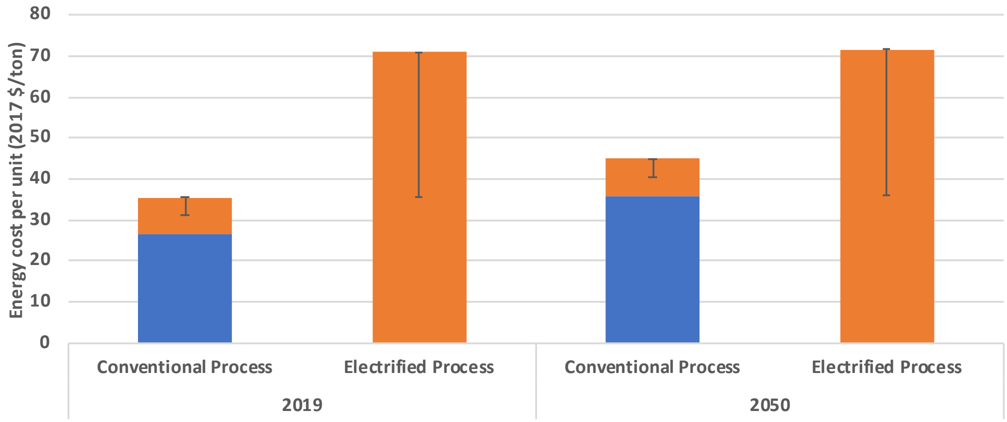


Figure 62. Energy cost per unit of production in the U.S. soybean oil industry
Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

05

Electrification of industrial steam boilers in the U.S.

5.1. Introduction

Steam is used extensively as a means of delivering energy to industrial processes. It holds a significant amount of energy on a unit mass basis that can be extracted as mechanical work through a turbine or as heat for process use. Steam can be used to control temperatures and pressures during chemical processes, strip contaminants from process fluids, dry paper products, and in other miscellaneous applications. Equipment that uses steam varies substantially among industries and is generally process- and site-specific (Energetics, 2012). Table 22 provides examples of steam end-uses, equipment, and processes in energy-intensive industrial subsectors.

Table 22. Steam end-use equipment in energy-intensive industries (US DOE, 2012)

Equipment	Process Application	Industry Sub-sector
Distillation tower	Distillation, fractionation	Chemicals, petroleum refining
Dryer	Drying	Forest products
Evaporator	Evaporation/concentration	Chemicals, forest products, petroleum refining
Process heat exchanger	Alkylation, process air heating, process water heating, gas recovery/light ends distillation, isomerization, storage tank heating, visbreaking/coking	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Reboiler	Fractionation	Petroleum refining
Reformer	Hydrogen generation	Chemicals, petroleum refining
Separator	Component separation	Chemicals, forest products, petroleum refining
Steam ejector	Condenser operation, vacuum distillation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Steam injector	Agitation/blending, heating	Chemicals, forest products, petroleum refining
Steam turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive, feed pump mechanical drive	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Stripper	Distillation (crude and vacuum units), catalytic cracking, asphalt processing, catalytic reforming, component removal, component separation, fractionation, hydrogen treatment lube oil processing	Chemicals, petroleum refining
Thermo-compressor	Drying, steam pressure amplification	Forest products

Steam systems are made up of a range of components. Figure 63 provides a schematic of a typical steam system. The use of steam in different industry sub-sectors varies widely.

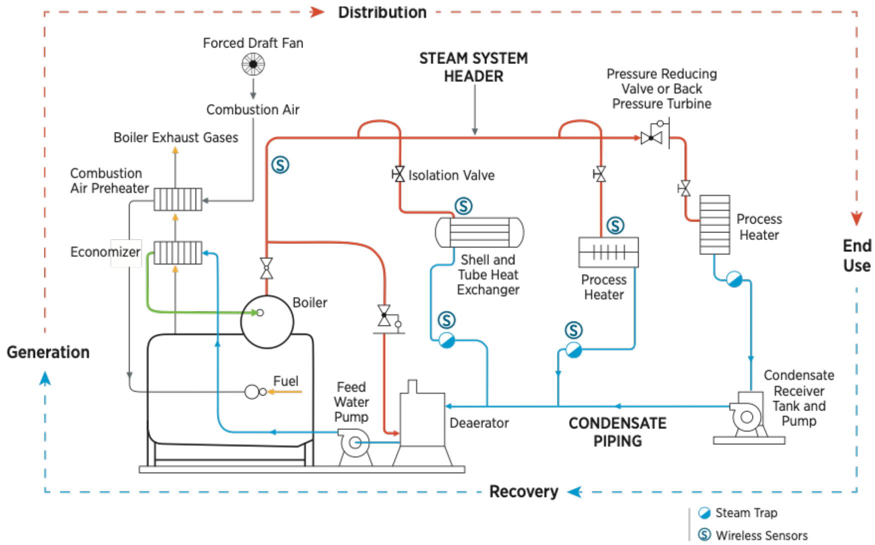


Figure 63. Steam system schematic (US DOE, 2012)

In developed countries, more than 50 percent of the industrial boilers use natural gas as the primary fuel and about 76 percent of the total boiler population is more than 30 years old. New boilers running on coal, oil, natural gas, and biomass can reach efficiencies of 85 percent, 80 percent, 75 percent, and 70 percent, respectively. Boiler efficiency can be improved by preventing or recovering heat loss (IEA, 2010). However, it should be noted that the boiler is only one part of an industrial steam supply system; distribution losses throughout the system can be quite important. While there are no detailed statistics regarding global system efficiencies, a study conducted by Energetics in 2012 estimated that the overall industrial steam system efficiency in the United States is around 60 percent (Energetics, 2012).

In the United States, the top five steam-consuming industrial sub-sectors are chemicals, petroleum refining, forest products, food and beverage, and iron and steel (Energetics, 2012). Figure 64 shows the estimated share of energy use by boilers as a proportion of total fuel consumption in thirteen U.S. industrial sectors (US DOE/EIA, 2017).

In the previous Chapter of this report, we discussed electrification of end-use processes. This type of electrification will require end-use processes and technologies to be replaced by electrification technologies. This will allow greater flexibility in the use of various electrification technologies that best suit the process. However, electrification of the end-use process will require changes to existing production processes and technologies.

Electrification of boilers will require changes only in the boiler room to replace the existing boilers with electrified boilers. It will not require any changes to end-use processes and technologies. While there are benefits associated with the electrification of boilers as it does not require changes in the production process, the downsides are energy losses during steam distribution and use and the missed opportunities to take advantage of efficiency gains that some end-use electrified technologies (e.g., heat pumps) provide.

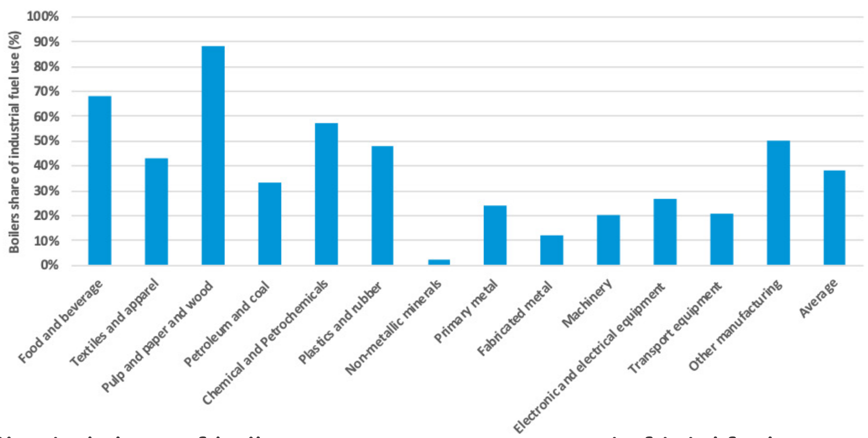


Figure 64. Estimated share of boilers energy use as a percent of total fuel consumption in U.S. industry (US DOE/EIA, 2017)

In the subsection below, we briefly describe conventional and electrified boilers and present the results of our analysis for the scenario in which we electrified all conventional industrial boilers (not CHP systems) in the U.S. manufacturing sector. In this analysis, we included only fossil fuel-fired steam boilers and analyzed their replacement with electrified boilers. We did not include boilers that use biomass or waste heat for steam generation in this analysis.

5.2. Steam production process

Conventional boilers

Steam boilers are basically similar to shell-and-tube heat exchangers, which convert water to steam. The combustion of fossil fuels generates heat and the resulting hot combustion gas can be utilized for heating tubes containing the water (water tube boiler), or the hot gas can be passed through tubes while being surrounded by water present in the shell (fire tube boiler) (Hall, 2012).

Water Tube Boiler: In principle, a water tube boiler is basically the opposite of a fire tube boiler. In this setup, the water flows through and is heated inside the tubes (Babu et al., 2016). These boilers have the ability to utilize a diverse set of fuels and equipment for the generation of steam at different pressures and temperatures.

Fire Tube Boiler: As suggested by its name, the fire tube boiler comprises a large number of tubes which facilitate the flow of hot combustion gases. In these boilers, the tubes carrying the hot gases are ducted around a closed vessel or shell that contains water. These hot gases flowing through these tubes help heat up the water and convert it into steam, which stays in the same vessel. Due to the presence of both water and steam in the same vessel, a fire tube boiler is unable to generate high pressure steam

Electrified boilers

Electric steam boilers are available on a commercial basis and are mainly classified into two categories: electric resistance and electrode boilers.

Electric resistance boilers comprise an electric powered resistive element which transfers heat to the water, raising its temperature to the desired level. The flow of electric current and the in-turn heating is controlled by means of a thermostat.

Electrode boilers are utilized for certain specialized applications and represent a different class of boilers. Typically, industrial applications requiring quick recovery and high thermal outputs utilize these boilers. In an electrode boiler, heat is directly generated by the flow of alternating current across three or more electrodes. The generated heat can be utilized for purposes such as providing hot water for heating systems or generating steam for industrial processes (Alabama Power, 2020).

Electric boilers are able to convert electricity into heat with an efficiency of almost 100 percent, with minimal radiation losses observed from exposed boiler surfaces (Alabama Power, 2020). On average, the capital cost of an electric boiler is nearly 40 percent less than that of an equivalent natural gas-fired boiler (Jadun et al., 2017).

Low natural gas prices are the current fundamental challenge to the economics of electric boilers, although this may change as gas prices increase and renewable electricity prices continue to decrease. We have seen examples of hybrid natural gas/electric boilers being used in the past in the Southeast when inexpensive off-peak nuclear power is available (e.g., at Duke Energy in South Carolina).

Using the typical efficiency of conventional and electric industrial steam boilers, we estimated the energy use in conventional and electric steam boilers in the U.S. industrial subsectors. This analysis used the 2014 EIA manufacturing energy survey data (US DOE/EIA 2017).

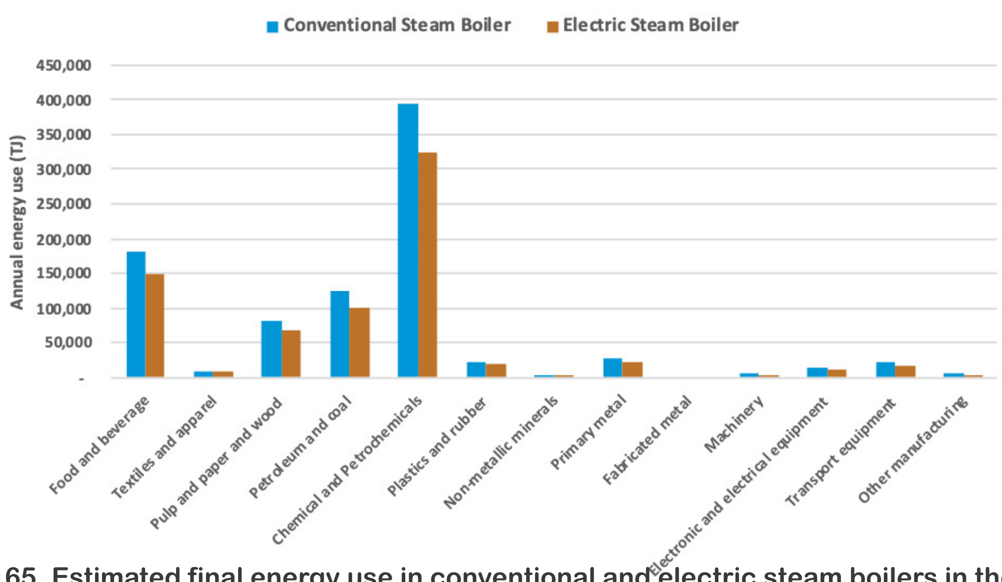


Figure 65. Estimated final energy use in conventional and electric steam boilers in the U.S. industrial sectors (EIA 2014 manufacturing energy survey data was used for this analysis)

5.3. Energy, emissions, and cost implications of electrification

Figure 66 shows that electrification could significantly reduce the total final energy use in industrial steam boilers during the study period; 2019-2050. Around 150,000 TJ of energy could be saved annually in 2019. This is equal to approximately 17 percent of total energy use in fossil fuel-fired conventional boilers in U.S. industry.

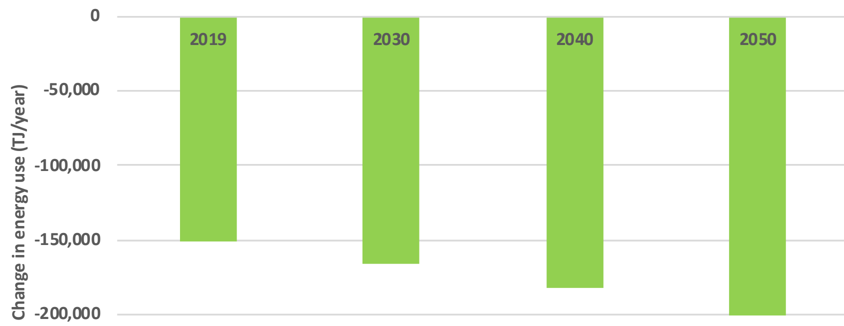


Figure 66. Change in total final energy use of U.S. steam boilers after electrification (This is the technical potential assuming all electrification)

The electrification of steam boilers in the U.S. can initially lead to a rise in CO_2 emissions by around 31,000 kt CO_2 in 2019 (Figure 67). However, electrification is projected to decrease CO_2 emissions by over 100,000 kt CO_2 /year in 2050. This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2019 and 2050 because of higher share of renewable energy in the power generation up to 2050.

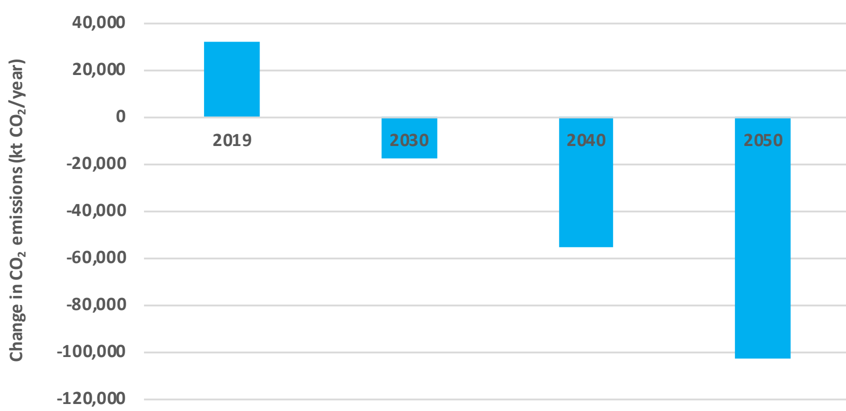


Figure 67. Change in net CO_2 emissions of U.S. industrial steam boilers after electrification (This is the technical potential assuming all electrification)

Figure 68 shows that in the U.S. steam boiler industry, the energy cost (in 2017$) per tonne of steam production for the electrified process is more than three times of that of the conventional process in 2019. Overall, energy cost per tonne of steam production is higher for the electrified process compared to the conventional process during 2019-2050. Using lower-cost electricity can reduce the energy cost of the electrified industrial steam boilers as shown on the graph with error bars. Also, it should be noted that we did not consider capital or operation and maintenance cost of boilers. In general, electric boilers are cheaper than conventional fuel-fired boilers.

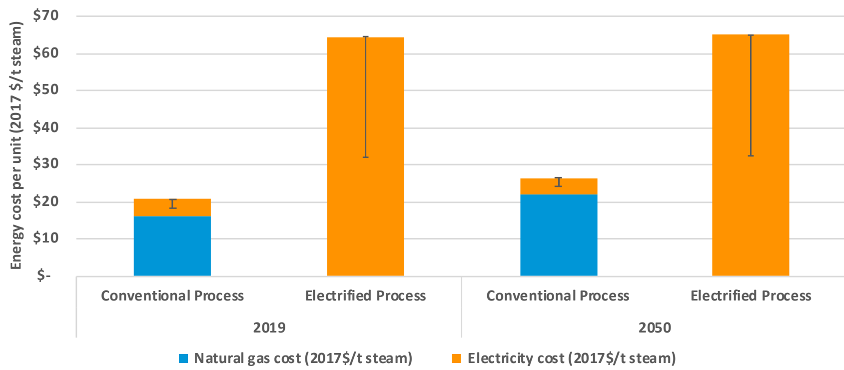


Figure 68. Energy cost per tonne of steam in the U.S. industrial steam boilers

Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50 percent.

06

Barriers to electrification in industry

The wide range of specific temperatures and applications required for various industrial processes is one of the challenges of meeting the heating needs of the industrial sector with electrified technologies. Different technology types are capable of delivering different temperature heat for different applications. Certain technologies may be well suited for particular applications and not for others. This creates complexity for industrial energy users.

The lack of reliable information on and familiarity with thermal electrification technologies poses a barrier to increased deployment. Potential users of these technologies may not be aware of the benefits that could be realized, and financing institutions unfamiliar with these technologies may deny needed capital or increase the cost of lended capital to mitigate their own risk (IEA, 2014). Policymakers may also be unaware of electrification technologies or the technologies' ability to reduce emissions, resulting in a lack of policies and incentives to encourage further development and deployment.

This Chapter will review the major technical, economic, market, institutional, and policy barriers impeding the scaled development and deployment of industrial electrification. It will include input from industrial energy experts and practitioners collected through an online survey. Chapter 7 will address proposals that can help to overcome each of the barriers.

6.1. Technology

As seen in Chapter 3, there are a number of existing electrification technologies that are commercially available and ready to be deployed. Chapter 4 demonstrates how many of these technologies can be applied in existing industrial processes. Further research and analysis can deepen our understanding of the best applications of these technologies in additional industrial sectors and processes, and explore new technologies not discussed in this report as well as their potential applications. Not all industrial heating processes currently have an electrified solution available, but more research and analysis dedicated to electrification technologies can help to fill these gaps.

At present, most industrial processes are not designed to use electrified heat and electrified alternatives are not currently available for many applications (Deason et al., 2018). The industrial sector has a diverse set of subsectors and final products that use a variety of process heating applications: this will require uniquely tailored process design and development (Deason et al., 2018). In some industrial subsectors, commercial readiness of different electrification technologies will vary depending on the sector: electric arc furnaces for steel can already be deployed, electric furnaces for other products such as cement and chemicals are still under development (Energy Transitions Commission, 2018). Cement kiln electrification may not be commercially ready until 2040, while electrochemical iron ore reduction is unlikely to be market-ready before the late 2050s (Energy Transitions Commission, 2018).

Survey respondents indicated that lack of commercial availability of needed technologies was a significant concern: more than 60 percent indicated it was a barrier that was important to their decision making, with more than 47 percent saying that it was very important or the most important factor.

Companies that do install new technologies will require support to successfully utilize and maintain new systems. Survey respondents are also worried about having sufficient support for technology in the field, with more than 91 percent indicating that this is a barrier, and 65 percent indicating it is a barrier that is at some level important in their decision making.

Respondents were less concerned that new technologies would not be compliant with future standards: Just under 70 percent indicated it is a barrier, but only about 43 percent said it was important in their decision making.

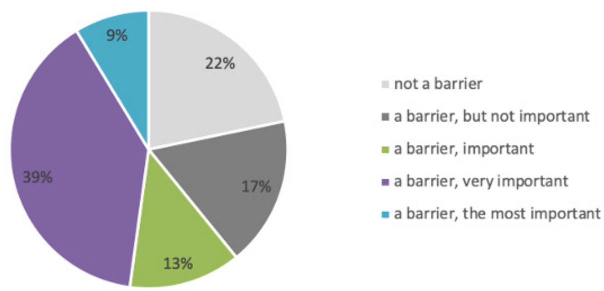


Figure 69. Needed technology not commercially available

6.2. Knowledge and education

Company knowledge

Various knowledge barriers impact increased adoption of electrification technologies. Lack of information about what electrification technologies are available in the marketplace and what technologies are feasible for individual processes impacts increased deployment.

There is insufficient data about manufacturing and manufactured products, including information on fuel use, energy consumption, and energy management that could be used to identify trends and show how new technologies would impact the sector (Whitlock et al., 2020).

Industrial consumers may be particularly risk-averse and avoid new, unfamiliar technologies (Deason et al., 2018). Technologies that use electricity must compete with familiar processes that have been used for decades and are already well understood by manufacturers and their supply chains (Beyond Zero Emissions, 2018). When replacing outdated equipment, there is a strong tendency to use the same fuel, and lack of familiarity with electrified technologies can also have an impact (Deason et al., 2018). Electric alternatives are not as well understood and there is less collective experience in their use (Beyond Zero Emissions, 2018). Manufacturers may also be unsure of how new technologies will perform both operationally and financially, adding to the perceived risk of switching to electrification from current processes (Beyond Zero Emissions, 2018). This perceived risk may be even more pronounced in low-margin, commodity-type industries including glass, cement, and food processing.

Survey respondents strongly indicated that insufficient knowledge of available electrification technologies (83 percent) and what technologies are feasible for their processes (72 percent) are barriers. Nearly 74 percent of respondents said that both of these factors are not only a barrier, but are to some degree important in their decision making. Survey respondents thought that lack of examples of electrified processes was less important, with 30 percent saying that it was not a barrier at all, and less than 48 percent indicating that this was both a barrier and important in their decision making.

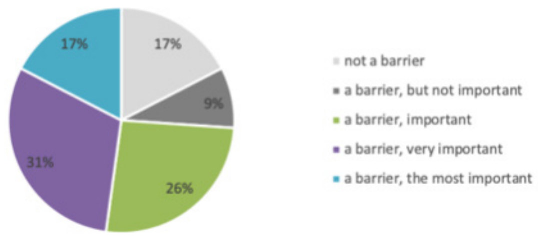


Figure 70. Insufficient knowledge of available electrification technologies

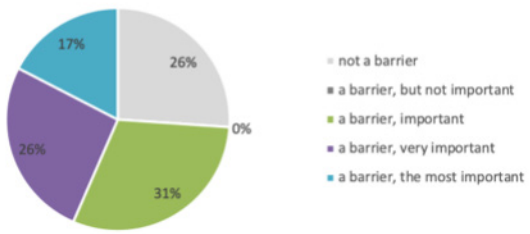


Figure 71. Insufficient knowledge of technologies feasible for processes

Worker knowledge and education

Knowledge and education of employees and contractors can also be a barrier to increased electrification. As new technologies and processes are introduced, workers in many areas will need to be retrained: engineers and technicians will need to learn how to operate new technologies and implement best practices to ensure that facilities and equipment operate efficiently (Whitlock et al., 2020). Companies may hire employees to run their thermal energy systems, or may rely on third-party contractors to provide these services. In either case, companies must ensure that workers know how to install, use, maintain, and repair new, electrified thermal systems.

Nearly 87 percent of survey respondents indicated that worker knowledge is a barrier, with 56 percent saying that it is a barrier and important to their decision making to some degree.

6.3. Cost

Upfront costs

The costs associated with adopting electrification technologies are a significant barrier to increased deployment. High upfront costs to replace existing direct fuel equipment with electric power alternatives can discourage investment in new technologies. The relative upfront costs of direct fuel and electric equipment may vary, and converting existing direct fuel equipment to electric may require additional changes – and expenditures – related to integrated industrial processes and electric service feed or other electrical system upgrades (Deason et al., 2018).

Carbon-reducing alternatives to electrification, such as utilizing lower-carbon fuels in existing or retrofitted systems, may have lower costs: Capital costs for process changes to electrification are generally higher than those for switching to alternative fuels (Sandalow et al., 2019). Companies may be able to leverage existing combustion-based industrial process designs and require only retrofits of existing processes in order to successfully use hydrogen and biofuels, such as biogas and renewable natural gas (RNG) or biomethane (Sandalow et al., 2019).

Financing may help address high upfront equipment or systems costs, but this strategy poses its own challenges; described further below.

It is clear that industrial energy experts think upfront costs are a significant barrier to increased industrial electrification: all respondents said that high upfront costs are a barrier, while 96 percent said that this barrier is important, and 44 percent said it is the most important factor in their decision making.

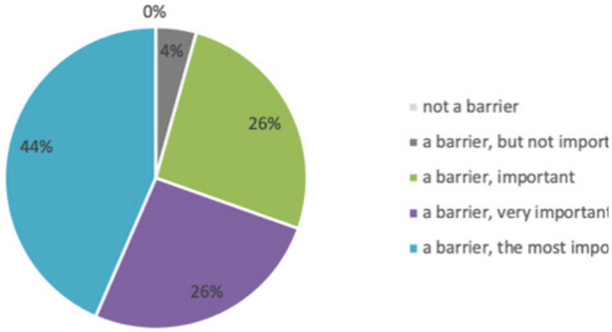


Figure 72. High upfront costs

Process modification costs

In addition to costs of new equipment and upgrades, electrifying one industrial thermal process may require additional modifications to other processes. Industrial processes are frequently highly-optimized, integrating various processes to take maximum advantage of energy used.

Industrial processe that are optimized for combustion-based processes take advantage of waste heat for combined heat and power (CHP) or recuperating it through heat exchangers or heat pumps: replacing combustion heat with electric heat in these cases may require substantial plant redesign (Sandalow et al., 2019). Heat-integration systems that can no longer use waste heat may require a series of process changes throughout a facility (Sandalow et al., 2019).

Process redesigns may also be required since electric heat is generally not delivered from point sources or burners, which can significantly change the distribution of temperatures within a furnace and the heating rates of the work material (Sandalow et al., 2019). Electrifying processes may also create the need to manage high-voltage electric power distribution through active cooling or electrical isolation (Sandalow et al., 2019). Architecture and design assumptions of electric process heat are different from combustion-based process heat, leading to the need for process redesigns (Sandalow et al., 2019).

Survey respondents also think process modification costs are a significant barrier to increased electrification: all respondents said that high process modification costs are a barrier, while 91 percent said that this barrier is important, and 43 percent said it is the most important factor in their decision making.

Return on investment

Electrification of thermal processes and associated upgrades face internal competition for capital. Companies need to balance numerous considerations, including investment across locations, business growth, technology replacement, environmental regulations, and safety (Rightor et al., 2020). The threshold for capital funding can be high, resulting in projects, including those with positive economics, forced to wait for consideration and implementation (Rightor et al., 2020).

In addition, many industrial products are globally traded commodities whose prices are set by international trade (Sandalow et al., 2019). Even small increases in production costs could lead to a drastic loss of market share and loss of competitiveness, resulting in a reluctance to increase costs (Sandalow et al., 2019).

Survey respondents unanimously thought that low return on investment for electrification was a barrier and important to some degree, with 43 percent indicating that this barrier is most important in their decision making.

Existing technology

Existing manufacturing processes are deeply entrenched, and existing process systems represent sunk costs: if existing systems have not exceeded their operating life, there are financial disincentives to making new capital investments (Beyond Zero Emissions, 2018). Industrial equipment has a long life span, with many components having a decades-long useful life (Whitlock et al., 2020). While some components may be replaced more frequently, it may take 30-60 years to replace core components of a large industrial facility (Sandalow et al., 2019). Stranded assets created when equipment is replaced before full depreciation could impact a company's bottom line (Whitlock et al., 2020).

Equipment with long life spans can be a barrier to increased industrial electrification (Mai et al., 2018). Ninety-six percent of survey respondents identified equipment not being at the end of its useful life as a barrier, and 74 percent said it was important to some extent.

Relative fuel costs

The relative cost of fuels for industrial heating processes can also make electrification unattractive. In instances where there are commercially available electric and non-electric options for a particular end use, relative fuel prices often explain adoption decisions (Deason et al., 2018). In those markets where natural gas is inexpensive and electricity is expensive, electric heating systems will be at a disadvantage (Sandalow et al., 2019). These operating economics of electrified and direct combustion systems impact the adoption of electric technologies (Deason et al., 2018).

Eighty-seven percent of survey respondents think that relative fuel costs is a barrier, with 35 percent saying that it was the most important factor in their decision making. Only 13 percent of survey respondents did not think relative fuel costs is a barrier.

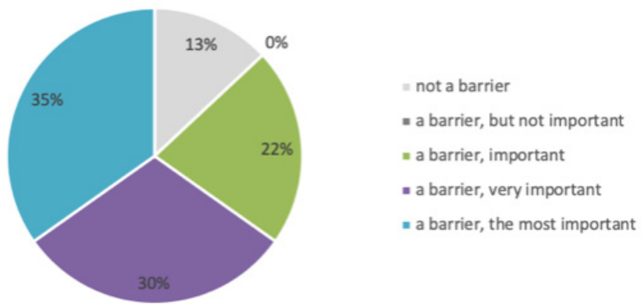


Figure 73. Relative fuel costs do not favor electrification

6.4. Financing

Electrification of processes and associated upgrades can face the same challenges of competition for financial resources and requirements for high returns on investment when seeking third party financing as when seeking internal capital expenditures (Mai et al., 2018). Investors' unfamiliarity with electrification can impact access to capital. Uncertainty about how electrification technologies will perform financially adds to the perceived risk of switching to electrified processes from current processes (Beyond Zero Emissions, 2018).

Survey respondents were most concerned about the high cost of capital: 83 percent identified high cost of capital as a barrier, with 61 percent indicating that it was important in their decision making to some degree.

Other aspects of financing were not as concerning to survey respondents. Many did not see external financing being unavailable or not compelling for electrification deployment as a significant barrier to increased industrial electrification: 44 percent said that this is not a barrier at all, while an additional 13 percent said that while it is a barrier, it is not important in their decision making. In addition, 8 percent of respondents said that non-energy benefits being given more importance in their firms' financial decisions, impacting investment in electrification of processes, was not a barrier, and 39 percent identified it as a barrier, but not important in their decision making.

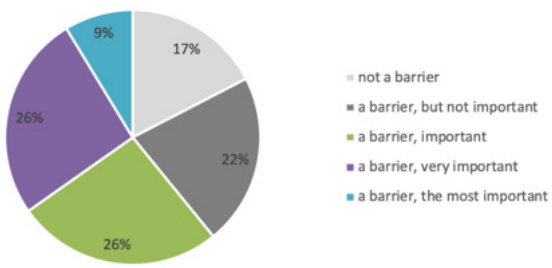


Figure 74. High cost of capital

6.5. Policy

Policies have the potential to encourage increased industrial electrification, policies may also prevent or impede widespread adoption. Even where government policies may favor electrification, heavy industries such as steel, cement, and chemicals may be considered core national assets that affect national security and the balance of trade, and therefore may be exempt or receive waivers from carbon pricing and environmental regulations (Sandalow et al., 2019).

Other policies may hinder electrification or impact a company's fuel choice such as building energy codes, appliance and equipment standards, and policies not directly related to energy such as health and safety protocols (Deason et al., 2018).

Policies that take electrification unattractive were of importance to survey respondents: 82 percent said that such policies are a barrier, with 50 percent indicating that this barrier was important to their decision making to some degree. In contrast, survey respondents did not see policies that prohibit electrification as an important barrier to industrial electrification: 45 percent said this is not a barrier, while an additional 41 percent said it is a barrier, but is not important in their decision making.

6.6. Electric utility connection and reliability

Costs and upgrades

Switching from a direct combustion process to an electrified process results in companies relying more heavily on electricity, and may also result in companies relying more heavily on their electric utilities and electricity suppliers to supply, transport, and deliver that additional electricity. Higher levels of electrification at industrial facilities will change customers' demand and load profiles, requiring them to work with suppliers to ensure grid reliability (Whitlock et al., 2020).

Additional infrastructure or upgrades may be required at various points in the electric system. Companies that electrify their thermal processes in an effort to reduce their greenhouse gas emissions will likely seek to purchase renewable electricity to meet their increased electricity demand. While some industrial facilities may be able to locate renewable generation on-site or nearby, many are located far from large-scale renewable resources, requiring additional infrastructure and transmission capacity to connect renewable resources to the electric grid and to electricity customers (Sandalow et al., 2019). Extensive changes in large industrial facilities could require transmission system upgrades in the long-run (Deason et al., 2018).

Regardless of the source of the additional electric generation capacity, utilities will need to provide large amounts of power to electrified industrial facilities. Electrification increases the load on electricity delivery infrastructure (Deason et al., 2018). This increased load may require additional infrastructure such as distribution grid build-out and transformer installation (Sandalow et al., 2019).

Managing this new load can be challenging for the electric utility: utilities will have to navigate the impact on local grid operation and consider demand requirements and quick ramp ups from industrial facilities that operate in batch mode or otherwise require rapid increases or decreases in overall power demand (Sandalow et al., 2019).

Finally, at an individual industrial facility, converting existing direct fuel equipment to electric may require an upgrade to the building's electricity service feed: this one-time change can be sufficiently costly to deter otherwise cost-effective electrification (Deason et al., 2018).

Each of these upgrades or new infrastructure outlays will come at a cost. Though utility costs may be able to be recovered from all of a utility's customers (Deason et al., 2018), industrial facilities may have to bear some costs directly.

In addition to the cost of upgrades, utilities may be unable to complete needed upgrades due to lack of space or other constraints. Survey respondents did not find this to be as much of a barrier: 30 percent of respondents said that this was not a barrier while 48 percent indicated it was a barrier and important in their decision making to some degree. No respondent said that it was the most important factor in their decision making.

Vulnerabilities

Additional reliance on the electric utility makes in industrial facility more vulnerable to impacts to the electric grid. Vulnerabilities to power outages may discourage electrification (Deason et al., 2018). Using more grid electricity also puts facilities at risk of losing power due to cyber-attacks on utilities and power infrastructure (Deason et al., 2018).

Survey respondents saw the possibility of power outages as an important barrier: 87 percent indicated that this is a barrier to industrial electrification, with 70 percent saying that this barrier is important in their decision making to some degree. Survey respondents did not see the risk of cyber-attacks as a significant barrier to electrification: 44 percent said that it was not a barrier, while 43 percent identified it as a barrier, but said it is not important to their decision making, and none of the respondents thought it is a very important or most important barrier.

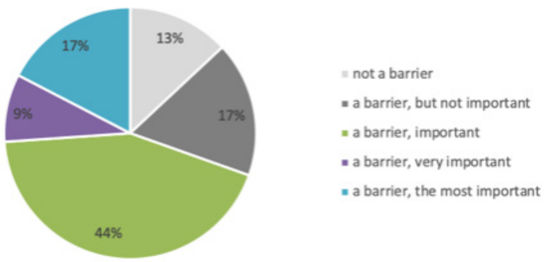


Figure 75. Processes cannot withstand power outages

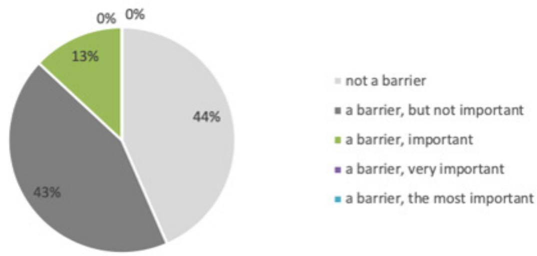


Figure 76. Risk of cyber attacks on utility infrastructure too high

6.7. Additional barriers

Survey respondents were given the opportunity to list additional barriers to industrial electrification that they see. One trend that was noticeable in the responses was a concern about sustainability and the environment. Respondents indicated that impacts on sustainability goals and the availability and cost-effectiveness of sustainable electricity or renewable alternatives were important barriers. A lack of understanding about the climate impact of different fuels and energy efficiency benefits was also identified as important barriers.

07

Proposals to overcome barriers

While the barriers to increased industrial electrification described above are significant, there are numerous ways in which they could be overcome. This Chapter describes proposals to overcome barriers to industrial electrification. The following Chapter of this report, the Technology Action Plan, describes how some of these proposals can be implemented to increase industrial electrification.

7.1. Technology

The wide range of specific temperatures and applications required for various industrial processes poses a challenge to increased electrification, but additional information about technology capabilities can help companies determine which technologies may be well suited for their needed applications. Technology research, development, and demonstration (RD&D) of process development and redesign in a wide variety of applications, including both direct and indirect electrification, can help to determine the best electrification options for various applications (Deason et al., 2018).

Further RD&D programs at government agencies, universities, nonprofit organizations, utilities, and regional groups can generate data and analysis of specific technologies and applications to inform industrial companies about what options may best fit their needs (Deason et al., 2018). Collaboration with international RD&D programs can expand the knowledge base and benefit multinational and domestic firms alike (Deason et al., 2018).

While early stage research and development is critical, so too is continued support for demonstration projects for technologies that are moving towards market readiness. A gap in support often appears when a project nears commercialization, but still requires technology validation and demonstration (Whitlock et al., 2020). Supporting demonstration projects at progressively larger scales can also inform large industrial facilities' decisions about electrification. Addressing questions that arise during scale-up can help technologies further along the development process continue to make progress towards

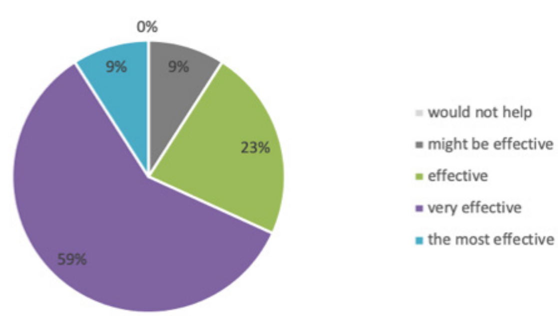


Figure 77. Technology RD&D

commercialization. Finally, industry may be able to work with public institutions to form public-private partnerships that are focused on developing electrification technologies for industrial applications.

All survey respondents thought that technology RD&D might be effective in overcoming barriers to increased industrial electrification to some degree, with 59 percent saying that it would be very effective. More than 78 percent of respondents thought that government, utilities, and vendors should all conduct the RD&D.

Survey respondents also thought that continued support for technology beyond initial research and development could be effective. All thought that supporting demonstration projects at progressively larger scales and supporting research that addresses questions that arise during scale-up might be effective to some degree. For 30 percent of respondents, supporting demonstration projects at progressively larger scales was rated as the most effective strategy for overcoming barriers to industrial electrification.

With regard to public-private partnerships (P3s), all survey respondents thought engaging in P3s might be effective in overcoming barriers to industrial electrification to some degree.

7.2. Knowledge and education

Increasing awareness about the availability and capabilities of electrification technologies can help to overcome barriers, as can building on existing knowledge with additional research and analysis and information sharing. In the industrial sector, joint research and knowledge-sharing about electrification strategies may be particularly important to minimize process redesign costs (Deason et al., 2018). In addition to technical information, industrial facilities may also benefit from information about how electrification can be economically viable where it is implemented together with demand response, time-varying rates, electric vehicle and rooftop solar integration, and industrial process improvements (Deason et al., 2018).

Electric utilities can also support increased comprehension of their rates and connection capacity, allowing industrial facilities to better understand the ramifications of electrification on their business and facilities.

Governments can create or expand technical assistance programs, while academic institutions can provide support with research and analysis, and engineering groups or associations can share first-hand experiences with electrification adoption. Examples of this type of knowledge transfer and dissemination can be found in the U.S. and abroad; international organizations may also have a role to play in marshalling and sharing information (Beyond Zero Emissions, 2018; Sandalow et al., 2019).

All survey respondents thought that general awareness, education, and outreach might be effective in overcoming barriers, while 59 percent thought that it would be very effective or the most effective. Of those that thought awareness, education, and outreach might be effective to some degree, nearly 80 percent thought that government, utilities, and vendors should provide the education and outreach.

Survey respondents also thought that specific knowledge creation and information dissemination programs would be effective in overcoming barriers. When asked about setting up an information dissemination platform and campaign to develop and disseminate informative materials related to electrification of processes in various industries, 83 percent said that this would be effective, very effective, or the most effective. A large proportion of respondents (78 percent) thought the same about creating and funding a federal industrial institute that includes beneficial electrification that pioneers RD&D, facilitates partnerships, and supports a clearinghouse of knowledge and data.

7.3. Research needs

In addition to general research and platforms to disseminate information and provide education, there are specific research needs that, if addressed, could allow for a more comprehensive understanding of industrial electrification. Earlier sections of this report fill some existing gaps by examining available and new electrification technologies, their application in specific sectors and processes, and their ability to reduce emissions. Given the wide range of potential industries and processes that could benefit from industrial electrification, there is still much to be learned about technologies and applications, and much to be analyzed as technologies are implemented.

Table 23: Research needs (Deason et al., 2018)

Quantification of benefits of electrification	Modeling and case studies	Design and demonstration	Utility-related	Economic
air quality	process-level analysis and modeling	development of direct electrification process designs, equipment costs, demonstrations	electricity rate structures	impact on electricity prices
health benefits	disaggregated modeling of electrification potential	demonstrations of hydrogen electrolytic production and integration as a feedstock replacement	market rate design	comparisons of costs and benefits of direct vs. indirect electrification
economic development	case studies on specific electrification efforts	applicability and expansion of induction heating	load growth	
grid management			flexible load benefits of existing electrified equipment	
quality of industrial products			value of additional electrification on electric system, including improvements in capacity factors, load shifting, and flexibility	

A variety of specific research needs have been outlined in the literature (Deason et al., 2018), and can be categorized as shown in Table 23. Survey respondents were asked about a number of these specific research needs, as discussed on page 85.

While increased industrial electrification can produce various benefits, they may seem intangible. Quantification of air quality, health outcomes, economic development, grid management, and the quality of industrial products when using electrified industrial processes can help industrial facilities, policymakers, and public better understand how electrification fits into decarbonization plans while still supporting the economy and maintaining product quality.

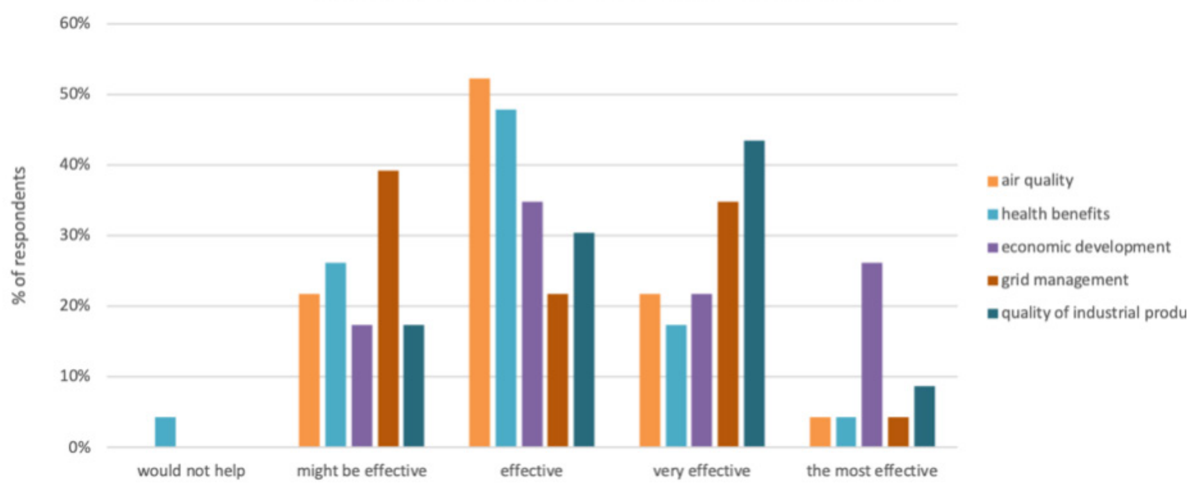


Figure 78. Quantification of the benefits of electrification

Nearly all survey respondents thought that quantification of each of the five benefits described might be effective in overcoming barriers to some degree. Though there are variations among the responses, some trends do emerge.

Since this survey targeted responses from industrial energy experts, rather than utilities or public health officials, it is perhaps unsurprising that more than half of respondents said that quantification of the quality of industrial products would be very effective or the most effective in overcoming barriers to industrial electrification, while just under 50 percent said that quantification of economic development benefits would be very effective or the most effective. Since electrified processes can have some key differences from direct fire processes, industrial users will need to know what impact, if any these differences will have on their products. Industrial products may have to meet quality standards or requirements, and industrial facilities will want to ensure that their products are of the same quality as they were before process electrification.

In addition to quantification of benefits, the survey asked respondents to provide their thoughts about how effective case studies on specific electrification efforts; applicability and expansion of induction heating; process-level analysis and modeling; and development of direct electrification process designs, equipment costs, demonstrations would be in overcoming barriers to industrial electrification. Again, nearly all respondents thought that each of these areas might be effective in overcoming barriers to some degree.

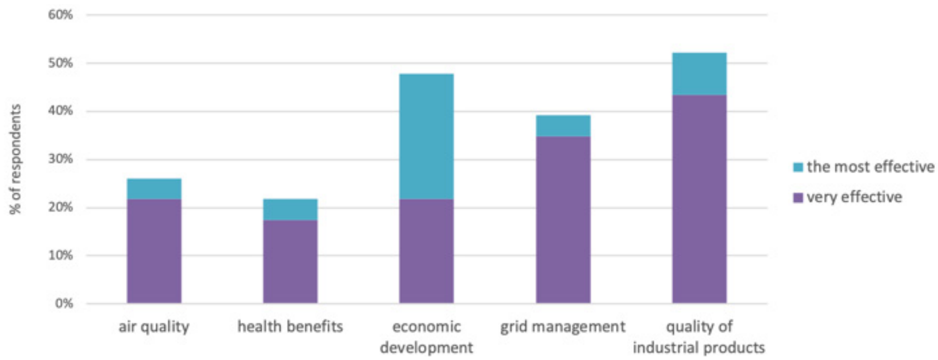


Figure 79. Quantification of benefits of electrifcation: very and most effective

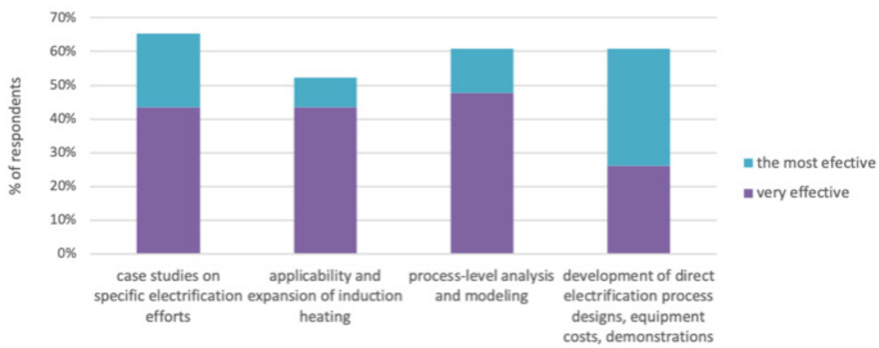


Figure 80. Research needs: very and most effective

For each research area, more than half of respondents thought that it would be very effective or the most effective in overcoming barriers to electrification.

7.4. Cost

The numerous costs involved in transitioning an industrial facility to electrified processes pose barriers to electrification. However, there are a variety of proposals that could help to overcome these cost barriers. All survey respondents thought that providing incentives for technology deployment would be effective to some degree, and, as discussed below, there were some noticeable trends among respondents regarding various incentive options.

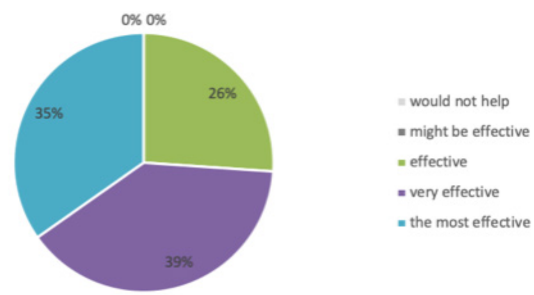


Figure 81. Incentives for technology deployment

Incentives for technology deployment can take different forms and be offered by different entities. Utilities may offer incentives to industrial customers for using or installing energy efficient equipment and processes, and electric utilities in particular may see benefits for themselves in promoting electrification of industrial processes (Deason et al., 2018).

Governments may also provide incentives through tax and other fiscal policies. A variety of policies have already been utilized to promote the development of renewable electricity generation, and similar policies may help with the decarbonization of industrial heat, such as tax incentives including investment or production tax credits or the waiver of sales, value added, or import taxes; grants; loan guarantees; feed-in-tariffs; and contracts for differences (Sandalow et al., 2019). Several of these, including tax incentives, grants, and waivers, could be particularl useful incentives for industrial facilities looking to electrify their processes, as described in Table 24.

Table 24. Financial incentives for industrial electrification (Sandalow et al., 2019)

Policy	Impact on Industrial Electrification
Investment tax credit	Tax credit for a percentage of the capital costs incurred in transitioning to electrified industrial heat
Production tax credit	Tax credit for products manufactured using electrified industrial heat
Waiver of sales, value added tax (VAT), or import taxes	Waiver of taxes that would otherwise be imposed on products manufactured using electrified industrial heat
Grant	Monetary assistance to defray capital costs associated with transition to electrified industrial heat
Loan guarantee	Government-backed loan for capital expenditures made to transition to electrified industrial heat

Survey respondents were asked to evaluate three types of financial incentives and how effective they would be at overcoming barriers to industrial electrification: tax incentives, grants, and loan guarantees.

In general, respondents tended to think that these types of incentives at least have the possibility of being effective, but there were differences in which mechanisms respondents thought would be most effective: 74 percent thought that tax incentives would either be very effective or the most effective at overcoming barriers to industrial electrification, while 43 percent said this about grants, and only 13 percent said this about loan guarantees.

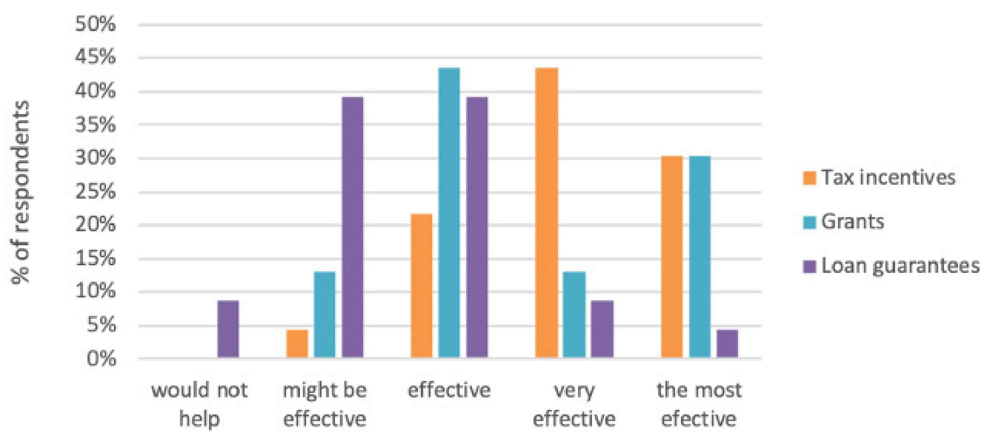


Figure 82. Types of incentives for electrification in discrete and process manufacturing

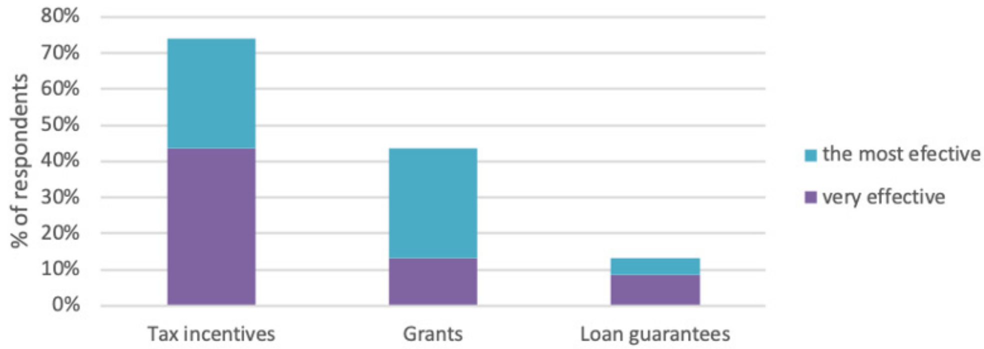


Figure 83. Types of incentives: very and most effective

7.5. Financing

In addition to proposals that can reduce costs, policies that support financing of industrial electrification projects can help to overcome barriers. Industrial facilities that are interested in electrifying their processes may seek financing to overcome initial cost barriers or to expand their access to capital, and will need to obtain it at rates and through structures that they find acceptable. As discussed above, government loan guarantees for capital expenditures could reduce risk to lenders, cut the cost of debt, and help to make a project financially viable (Sandalow et al., 2019).

Survey respondents were asked about the availability of third-party financing, and its effectiveness in overcoming barriers to industrial electrification. Of the respondents, 87 percent said that availability of third-party financing at least had the possibility of being effective at overcoming barriers, while 30 percent indicated that it would be very effective or the most effective.

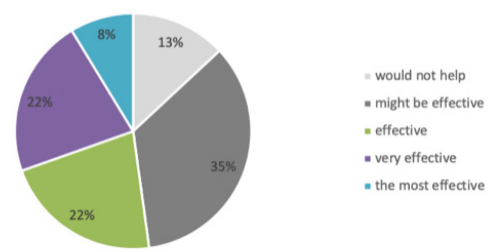


Figure 84. Availability of third party financing

7.6. Policy

A wide range of policies can impact adoption of electrification technologies for industry: including those pertaining to thermal energy use, electricity markets, emissions, standards for products and equipment, and permitting and procurement. This section will consider policy options within each of these five broader categories, and look across categories at what might be more effective in overcoming the barriers to industrial electrification.

Thermal energy use

Policies aimed at impacting how facilities use thermal energy can encourage and even require electrification. Setting targets can encourage electrification, which can be set by government entities or within an individual company (Deason et al., 2018). Targets may be set to reduce emissions overall or from specific sources, or to increase use of electrification. Many companies have set goals or made voluntary commitments to decarbonize their electricity use, and a growing number are focusing on their thermal energy use as well. Electrification is likely to be an important strategy in decarbonizing thermal energy use.

While targets can be an important tool to promote electrification, it should be noted that they may also create impediments to electrification, depending their structure (Deason et al., 2018). For example, if emissions targets only cover electricity generation and exclude other fuels, increases in power sector emissions due to electrification would make it more difficult to achieve targets, even if total emissions decrease due to reductions in direct fuel usage (Deason et al., 2018). However, as noted in Chapter 4, it is anticipated that increased penetration of renewable resources will result in a decline in the electric grid's CO_2 emissions factor between 2019 and 2050.

Government policies can also require use of renewable thermal technologies, including electrification, by enacting renewable portfolio standards (RPS) for thermal energy. At the state level in the U.S., RPS requirements were important for the early growth of wind and solar power (Sandalow et al., 2019). Requiring industrial actors to meet standards or prohibiting them from using fossil fuels could make electrification of industrial thermal energy use more attractive, and spur further deployment (Sandalow et al., 2019).

In general, most survey respondents thought that these types of policies could be effective in overcoming barriers to industrial electrification. More than 40 percent thought that target or goal setting would be very effective or the most effective, while more than 60 percent thought that enacting renewable portfolio requirements for thermal energy would be very effective or the most effective in overcoming barriers.

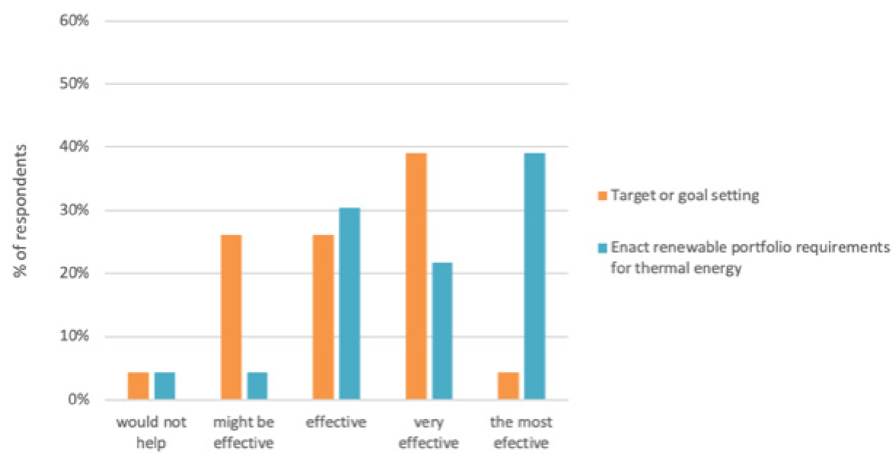


Figure 85. Policy: using thermal energy

Electricity markets

The electrification of industrial thermal energy use will also be impacted by electricity markets: facilities that choose to electrify will increase their electric use, which may require the facilities to rely more on their electric utility's services, including transmission, distribution, and generation. This increased demand for renewable electricity resources will in turn impact electricity markets. Efficient, well-functioning wholesale power markets can help to mitigate potential concerns that may arise as a result of increased electricity demand, including congestion and additional use of transmission and distribution systems. Electric market structures and rate designs can make electrification more or less attractive to a facility considering electrification.

Electricity rate designs and market structures have the opportunity to encourage electrification, depending on how they are designed. Electric utilities employ a variety of rate structure options, and industrial facilities can work with their electric utility to better understand their options and what will work for them based on their load requirements.

Demand charges could create a disincentive for electrification, as newly electrified processes could establish a new, higher peak hourly demand for a facility (Deason et al., 2018). However, if facilities can be flexible about their electricity use and can manage it to avoid creating large peaks, they may be able to lower electric bills (Deason et al., 2018). Industrial facilities may also be able to take advantage of time of use rates by shifting the run times of their processes to take advantage of lower electricity prices (Deason et al., 2018). Accelerating the adoption of electricity storage systems can also help industrial facilities to manage electric demand peaks and accommodate additional renewable electricity generation.

Demand response programs also offer a potential revenue stream to electrified end uses, if electrified loads can be shifted away from system peaks (Deason et al., 2018). Designing markets that can accommodate variable electricity generation resources with flexible demand will be important to the operability and efficiency of the electric grid, especially as more intermittent resources such as wind and solar are added to the generation resource mix (Deason et al., 2018). Deploying electricity storage resources can allow for further utilization of intermittent renewable resources while supporting demand and electric grid management: when renewable electricity supply exceeds demand, storing this excess electricity and deploying it at a later time allows additional renewable resources to power the electric grid and can help to manage increased demand requirements.

Survey respondents generally thought that electric rate and market policies had the potential to be effective in overcoming barriers to industrial electrification. More than 90 percent of respondents thought that electricity rate design would be effective to some degree, while 70 percent thought the same of demand response programs and electricity market design.

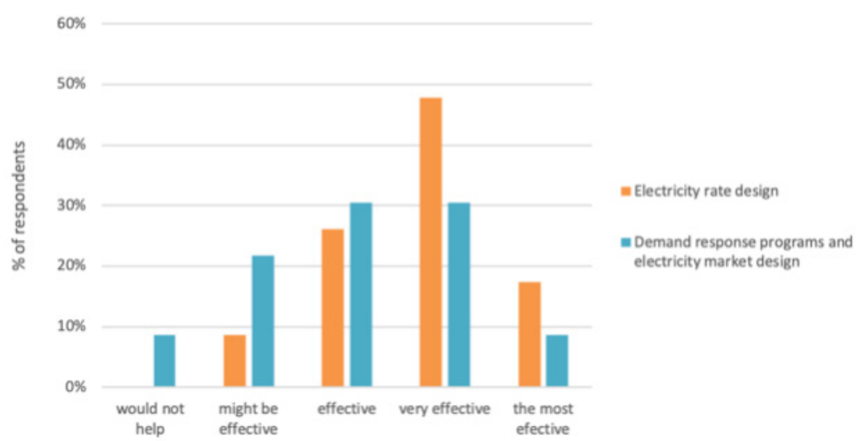


Figure 86. Policy: electricity rates and markets

Emissions

Regulating greenhouse gas and other emissions resulting from industrial and other processes can take various forms, including air quality regulation, carbon pricing, and carbon tariffs.

Attaining existing air quality standards could encourage use of electrified equipment, especially if industrial facilities are located in areas that currently have poor air quality, and incentives for improving air quality and public health in these communities could also promote electrification (Deason et al., 2018). As noted above, emissions regulations that cover only electricity generation but not direct fuel use could discourage electrification, but where all fuels are subject to regulations and as the emissions intensity of electricity generation declines, emissions regulations could drive electrification (Deason et al., 2018).

Carbon pricing provides an incentive to reduce emissions, and can be implemented through emissions trading programs or tax mechanisms, and provides an incentive to reduce emissions (Sandalow et al., 2019). However, very few carbon pricing programs have resulted in prices sufficient to significantly reduce emissions, and strong opposition from businesses and individuals most exposed to energy price increases has resulted in governments unwilling to impose prices that would be sufficient to reduce emissions further (Sandalow et al., 2019).

The federal government could put a price on carbon that includes domestic and imported goods, and support international action to reduce the embedded carbon in manufactured goods (Beyond Zero Emissions, 2018).

Carbon tariffs are another option that could have an international impact on emissions. Steel, chemicals, and other products that require heat in their manufacturing processes are traded internationally in high volumes: governments may be reluctant to impose decarbonizing costs on these products out of concern that they will be disadvantaged in international trade (Sandalow et al., 2019). Carbon tariffs could address this concern by eliminating the disadvantage domestic manufacturers may face from higher costs, but practical concerns, including World Trade Organization rules, design and administrative questions, and the impact to domestic manufacturers selling their goods abroad, have thus far prevented adoption (Sandalow et al., 2019).

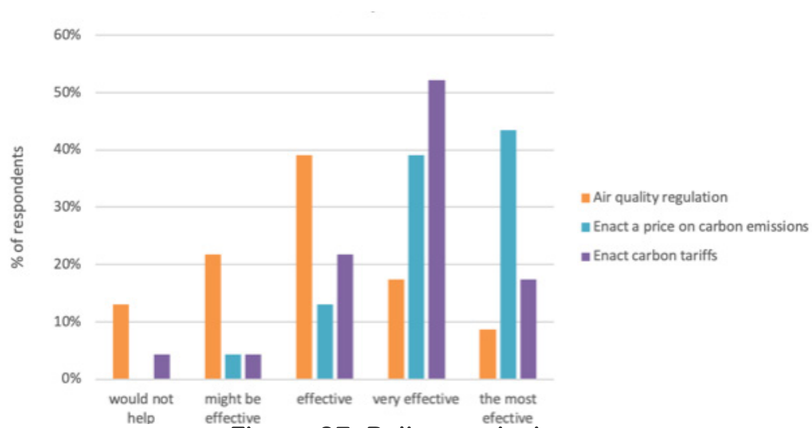


Figure 87. Policy: emissions

When considering emissions policies, 83 percent of survey respondents thought that enacting a price on carbon emissions would be very effective or the most effective in overcoming barriers to industrial electrification, while 75 percent thought the same about carbon tariffs. Only 26 percent of survey respondents thought that air quality regulation would be very effective or the most effective.

Standards for products and equipment

Low-carbon product standards set limits on a product's life cycle emissions, and have been adopted in some states in the U.S. (Sandalow et al., 2019). Standards could be applied to a range of products that are currently manufactured using fossil fuel generated heat, providing an incentive for manufacturers to find alternative sources for their industrial heat needs (Sandalow et al., 2019). However, many industrial products that require large amounts of heat to produce are inputs into other products or finished goods, adding significant complexity (Sandalow et al., 2019).

Setting standards for the appliances and equipment that industrial facilities use can ensure that efficient technologies enter the market and induce market transformation (Whitlock et al., 2020). Equipment efficiency standards are set separately for electric and combustion-fueled devices, so any such policy would need to account for this separation in standards (Deason et al., 2018).

With regard to codes and standards for products and equipment, 45 percent of survey respondents thought that enacting low-carbon product standards would be very effective or the most effective in reducing barriers to industrial electrification, while 30 percent said that codes and standards for equipment would be very effective, but none said it would be the most effective.

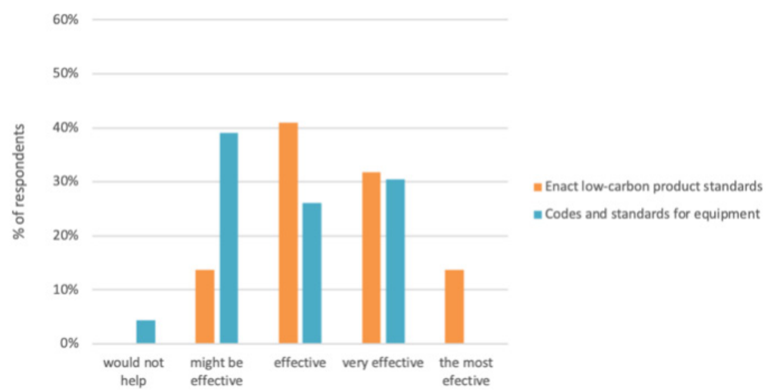


Figure 88. Policy: products and equipement

Permitting and procurement

Government policies can also encourage electrification by lowering permitting barriers and using government buying power to increase demand. Industrial facilities may require a variety of permits for environmental impacts (Rightor et al., 2020). Accelerating the timeline for permitting and preprocess authorization procedures can allow for a more rapid switch to electrified technologies.

Governments also have significant buying power and are major purchasers of steel, cement, chemicals, and other products that require heat in manufacturing processes (Sandalow et al., 2019). Governments can send a market signal by purchasing low-carbon goods for their own operations (Whitlock et al., 2020). Government purchasing can play an important role in starting and building new product markets, and government purchase requirements can help establish standard technical specifications for new products and catalyze supply chains (Sandalow et al., 2019). Large corporations can also support low-carbon good through their own procurement standards (Beyond

Zero Emissions, 2018). Procurement standards can give preference to products with the lowest embedded carbon content or products manufactured without the use of fossil fuels to generate heat, or authorize purchasing official to base decisions on lifecycle emissions of products (Sandalow et al., 2019).

Of the survey respondents, 74 percent thought that supporting the acceleration of permitting and preprocess authorization procedures would be effective to some degree in overcoming barriers to industrial electrification, while about 70 percent thought the same for enacting procurement standards that require lower-carbon products.

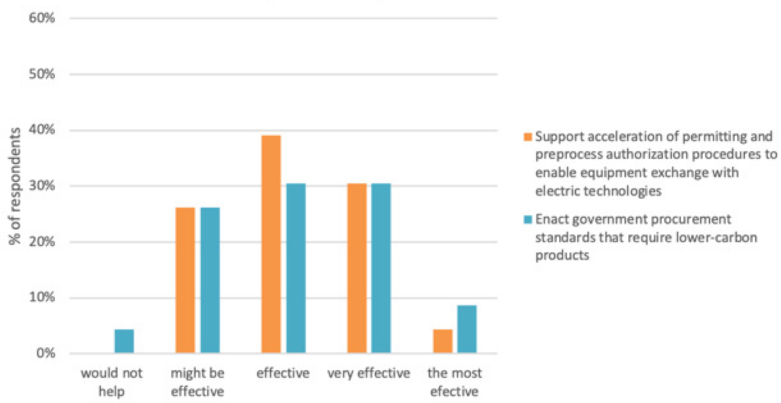


Figure 89. Policy: permitting and procurement

Looking across policy proposals

Survey respondents identified three policy areas that they think would be highly effective in overcoming barriers to industrial electrification: carbon pricing or tariffs, electricity rate design, and renewable portfolio requirements for thermal energy.

More than 80 percent of survey respondents said that enacting a price on carbon emissions would be very effective or the most effective policy in overcoming barriers to industrial electrification, while about 70 percent of respondents said the same for enacting carbon tariffs. About 65 percent of respondents said that electricity rate design would be very effective or the most effective, while 61 percent said the same for enacting renewable portfolio requirements for thermal energy.

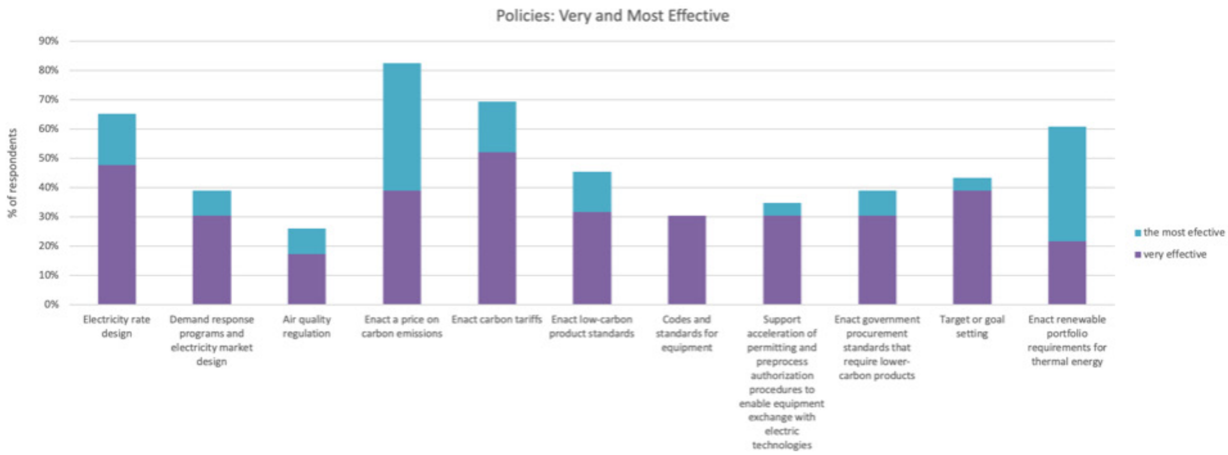


Figure 90. Policies: very and most effective

7.7. Electric utility connection and reliability

As previously discussed, increased industrial electrification will likely require industrial facilities to rely more on their electric utilities and electricity providers to provide electric transmission, distribution, and generation services. This increased demand may require electric utilities to review their resource and infrastructure plans, and consider how to bring renewable electricity resources to demand centers.

Increased electrification may require additional generation, transmission, and distribution infrastructure, as well consideration of how programs and incentives for demand-side management are designed (Deason et al., 2018). Making the most of demand management programs can help industrial facilities to manage their electricity costs and help electric utilities to manage the electric grid (Energy Transitions Commission, 2018). Alignment of incentives, rate and market designs, and infrastructure planning can help to smooth the transition to electrification (Deason et al., 2018).

When asked about energy planning, that is the alignment and integration of incentives, rate and market designs, and infrastructure planning, only 4 percent of survey respondents said that this would not help in overcoming barriers to industrial electrification, while about 43 percent of respondents said that this proposal would be very effective or the most effective in overcoming barriers.

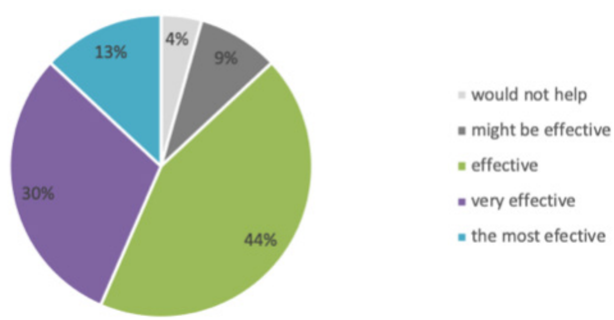


Figure 91. Energy planning

Industrial facilities and utilities alike will need to anticipate the distribution effects of increased electrification (Energy Transitions Commission, 2018). Transmission and distribution planning processes are important venues to explore and resolve electrification issues (Deason et al., 2018). The transition to electrification may require new infrastructure, and governments can facilitate the development of infrastructure through permitting, financing, or other measures (Sandalow et al., 2019). Dedicated storage can help alleviate how much industry has to rely on the grid.

Facilities that do electrify their processes will likely want to ensure that their additional electricity demand is being met with renewable electricity generation resources. Utilities will need to ensure that renewable resources can connect to the electric grid and that these resources can be delivered to load centers. When asked about providing connections to low-carbon energy so electrification can be beneficial, all survey respondents thought that this might or would be effective to some degree in overcoming barriers to industrial electrification, while about 57 percent said it would be very effective or the most effective proposal.

08

Action plan to accelerate the electrification of industry

While there are numerous benefits to electrifying industrial processes, including reduced energy demand and emissions, barriers still inhibit development and deployment of electrified technologies. As discussed above, various policies and actions can aid in reducing these barriers and increasing deployment. The following subsections, broken into different policy areas, review key insights from the prior sections of the report and their implications for policy development, and identify key actions that should be taken to accelerate electrification of thermal energy in industry.

8.1. Technology research, development, demonstration, and deployment

Key insights

- While many of the electric technologies needed for electrification in industry are fully commercialized, some are at the development or pilot stage, especially for high temperature processes. Further investment in research, development, demonstration, and deployment (RDD&D) is needed for development and commercialization of electrification technologies for industry.
- The electrification of some of the high temperature heating processes such as cement, glass, and some chemical production is especially challenging and requires further RDD&D.
- Optimal electrification strategies are influenced by many variables (including sector, location, and processes).
- Technology development must be accompanied by RDD&D on scale-up and integration of technologies into industrial processes. Some of the RDD&D activities are listed below.

Key actions

- Industrial companies can:
  1. Initiate partnerships with academia, national labs, think tanks and other stakeholders to develop and/or scale electrification technologies.
  2. Explore the potential of cross-cutting electric technologies from near-term options such as hybrid boilers, heat pumps, and dryers as part of a project portfolio to achieve sustainability goals (Rightor et

al., 2020).

iii. Develop the business cases for electrification technologies by including both energy and non-energy benefits.

iv. Work to reduce costs of distributed manufacturing of molecular hydrogen. Industry can work with academia to conduct RDD&D to support small scale reformer and electrolyzer development with aim to increase efficiency and reduce capital including increased safety and reduced capital intensity of local hydrogen storage and delivery systems.

v. Work to reduce the energy intensity and cost of hydrogen liquefaction – 40 percent of energy content of the weight shipped is consumed by liquefaction.

- Governments can:
  i. Provide incentives for electrification technologies' development and demonstration.
  ii. Use the excellent capacity at the US DOE national labs to advance electrification technologies for industry
  iii. Provide financial incentives in the form of tax credit or grants for pilot and demonstration of emerging electrification technologies in industry.
  iv. Support research on future green hydrogen storage needs and type of storage to satisfy U.S. demand.
  v. Support research on safety and regulation needed to enable blending green hydrogen into existing natural gas networks.
- Utilities can:
  i. Provide incentive for electrification technologies development and demonstration.
  ii. Partner with industry and government to support RD&D activities for industrial electrification.
  iii. Collaborate with industry and research institutes to evaluate the grid implications of industrial electrification in their area of service and nationally.
- Suppliers of electrification technologies or equipment can:
  i. Work with industry, academia, national labs, think tanks and other stakeholders to develop and/or scale electrification technologies.
  ii. Enhance the business cases for electrification technologies by including both energy and non-energy benefits.
  iii. Work with industry to pilot and demonstrate new electrification technologies and disseminate the results.
  iv. Conduct R&D on the safe storage and transmission of green hydrogen to industrial users, including the dual use of natural gas pipelines.

8.2. Economics of electrification

Key insights

- Overall, energy cost per unit of production in almost all cases analyzed is currently higher for the electrified process compared to the conventional process during the period of study.
- Energy cost is only a small portion of total manufacturing cost for most industrial subsectors, except for several industries such as the cement and steel industries where energy accounts for 30 percent-40 percent of total manufacturing cost. In sectors where energy cost is only a small portion of production cost, a small or even moderate increase in energy cost per unit of product resulting from electrification will have

a minimal impact on the price of final product. Therefore, it will have minimal impact in the price that final consumers will pay for the product or the products that are made from those materials.

- Energy prices can vary significantly from state to state or even from county to county within the U.S. The results of cost per unit of production comparisons are highly sensitive to unit price of energy.
- Renewable electricity prices are anticipated to continue to decline, and may decline faster than predicted, making electrification technologies more competitive with conventional fossil-fuel based technologies.
- Prices of natural gas and other fossil fuels may increase more than we have projected, especially if some type of carbon pricing policy is introduced in the U.S. We have not included such considerations in our natural gas and coal price projections and we directly used the projections from US DOE/EIA (2018).

Key actions

- Industrial companies can work with academia to:
    i. Conduct techno-economic analyses for all electrification technologies applicable to each industrial subsector integrating sector-specific costs of capital, operation and maintenance, and energy.
    ii. Conduct life cycle costing to assess the economic viability of electrification technologies relative to fossil fuel-based technologies.
    iii. Include non-energy benefits of electrification technologies (including product quality improvement, reduced process time, better control, lower emissions, lower maintenance cost, etc.) into techno-economic analysis.
    iv. Develop economic analysis scenarios that integrate possible future costs of carbon for fossil fuels.

8.3. Industry education

Key insights

Industrial consumers may be particularly risk-averse and avoid new technologies due to a lack of familiarity, and technologies that use electricity must compete with familiar processes that have been used for decades and are already well understood. Companies and industrial facility operators need more information about thermal electrification technology availability, applicability, and integration into existing systems. Employees and contractors may require training on new technologies and their installation, operation, and maintenance.

Key Actions

- Industrial companies can:
    i. Seek information about available electrification technologies.
    ii. Participate in technical assistance programs that are offered.
    iii. Engage with an industrial facility's electric utility to learn about electric rates and if additional infrastructure for connection is required.
    iv. Where electrification of processes has occurred, disseminate information or case studies about challenges and successes.
- Governments can:
    i. Conduct or support research and development of electrification technologies that are not market-ready.

ii. Support demonstration and deployment of electrification technologies that are already developed.
iii. Offer or support technical assistance programs for industrial electrification.
iv. Create or support an industrial electrification information dissemination platform. This will include development and dissemination of case studies.
v. Conduct or support research and analysis on the quality of industrial products made using electrified thermal processes.
vi. Conduct or support research and analysis on the economic development potential of industrial electrification.
vii. Conduct or support process-level analysis and modeling.
viii. Conduct or support development of direct electrification process designs, equipment costs, and demonstration.
ix. Support grants that create fellowships to provide dedicated staffing support to industries to help pilot electrification efforts.

- Utilities can:
  i. Evaluate the substantial demand response (DR) potential (including financial impacts) that increased industrial electrification can provide to utilities.
  ii. Provide information to industrial customers about the utility side implications of electrification and potential economic gains from demand response if applicable to each industrial plant.
  iii. Provide information about their electric rates and market structures.
  iv. Provide information about required connection upgrades.
- Suppliers of electrification technologies or equipment can:
  i. Engage with industrial companies to learn about their electrification needs.
  ii. Provide information about available technologies and those under development to industrial companies, governments, and utilities.
  iii. Where electrification of processes has occurred, disseminate information or case studies about challenges and successes.

8.4. Other stakeholders' education

Key insights

Utilities, policymakers, and the financial community may not be aware of the benefits of industrial electrification, or of companies' or facilities' interest in pursuing it as a way to reduce their energy use and emissions. Those outside the industrial sector also require additional information about electrification technologies and the benefits they can deliver. Better understanding of industrial electrification technologies' capabilities and the need for additional investment and support can improve policy and investment decisions.

In addition to understanding industrial electrification technologies, more education will be needed about the implications of increased electrification for electricity demand and the electric grid. Presently, there is interest in electrifying vehicles, buildings, and industrial facilities, using renewable electricity to reduce the emissions from these applications. This increased demand across sectors will require additional supply of renewable electricity, as well as an electric transmission and distribution system that can adequately manage the increased volume of electric energy.

Key actions

- Industrial companies can:
  i. Educate their peers about benefits of electrification.
  ii. Educate policymakers about their interest in industrial electrification and the benefits that could be realized by adopting electrified thermal processes, including industrial decarbonization.
  iii. Educate utilities, policymakers, and the public about the increased demand for renewable electricity as a result of increased electrification.
  iv. Educate financial institutions and potential investors about the benefits of electrification.
- Governments can:
  i. Educate the public about the benefits that could be realized by adopting electrified thermal processes, including decarbonization, air quality and health, and economic development opportunities.
- Utilities can:
  i. Educate policymakers and the public about the increased demand for renewable electricity, energy storage and demand response, transmission system expansion needs, distribution system hardening, and grid modernization as a result of increased electrification.

- Suppliers of electrification technologies or equipment can:
  i. Educate policymakers and the public about their technologies or equipment and the benefits that could be realized by adopting electrified thermal processes, including industrial decarbonization.
  ii. Education financial institutions and potential investors about their products and the benefits of electrification.

8.5. Policy development

Key insights

A wide range of policy options could be pursued to increase the deployment of electrified thermal technologies in the industrial sector. While more options are described above in the proposals to overcome barriers Chapter, those listed here can be viewed as first steps. As new technologies are developed and more research is conducted, additional or different policies may become more important to meet the challenges of industrial electrification deployment.

Key actions

- Industrial companies can:
  i. Engage with policymakers to discuss their interest in electrification of thermal processes and the benefits that could be realized.
  ii. Engage with utilities about electrification needs and viable solutions.
- Governments can:
  i. Adopt policies to support additional research and development of electrification technologies.

ii. Adopt policies to support demonstration and deployment of electrification technologies that are market-ready.
iii. Adopt procurement policies that consider the emissions or carbon profile when making purchasing decision.
iv. Adopt tax policies that encourage investment in electrified thermal technologies.
v. Adopt policies that price carbon emissions at a level that supports electrified technologies.
vi. Adopt electricity rate designs that encourage electrification.
vii. Adopt renewable portfolio requirements for thermal energy.

- Utilities can:
  i. Adopt electricity rate designs that encourage electrification.
  ii. Support policies that allow for more on-site generation, storage and microgrid deployment to help address reliability concerns and mitigate costs to all ratepayers of increased industrial load.

8.6. Workforce development

Key insights

In addition to company knowledge, employees and contractors at industrial facilities may require training on new technologies and their installation, operation, and maintenance. The industrial sectors, governments, and utilities can work together with trade groups and educational institutions to ensure that current and future workers are prepared to meet the new demands of an increasingly electrified industrial sector.

Key actions

- Industrial companies can:
  i. Provide training for employees and contractors about electrified technologies.
  ii. Engage with trade groups, educational institutions, and utilities to discuss education and training needs and develop appropriate programs.
- Governments can:
  i. Offer or support education and training programs for those that will install, operate, and maintain electrified thermal systems.
- Utilities can:
  i. Engage with the industrial sector, trade groups, and education institutions to discuss education and training needs and develop appropriate programs.
- Suppliers of electrification technologies or equipment can:
  i. Provide training about their technologies or equipment.
  ii. Engage with trade groups, educational institutions, and utilities to discuss education and training needs and develop appropriate programs.

8.7. Public-private partnerships

Key insights

Public-private partnerships (P3s) provide an opportunity for private industry to work together with government bodies to develop electrification technologies for industrial applications. Both the industrial sector and public institutions can take actions to advance P3s.

Key actions

- Industrial companies can:
    i. Engage with public institutions to develop and invest in public-private partnerships.
- Governments can:
    i. Adopt policies that allow public-private partnerships investment.
    ii. Engage with the industrial sector to develop and invest in public-private partnerships.

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Appendix

Appendix 1. Electrification technologies for industry and their benefits and challenges

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

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

Source: Rightor et al. (2020)

Appendix 2. About the survey and additional results

This report and the Technology Action Plan were informed in part by an online survey of industrial energy experts on the electrification of industrial thermal energy use. The survey was designed to gather information about the potential for industrial electrification, barriers to increased industrial electrification, and proposals that can help to overcome these barriers.

I

ndustries represented by survey respondents included:

- Aerospace
- Agriculture
- Automotive
- Chemicals
- Computers and electronics
- Construction
- Consumer household goods
- Food and beverage
- Furniture
- Machinery
- Metals
- Mining (except oil and gas)
- Oil and gas extraction
- Plastics and rubber
- Steel
- Textiles and apparel
- Wood products
- "Other," including healthcare, medical device, pharmaceutical, equipment manufacturing, electricity generation, energy storage, and consultant

Survey respondents were asked to evaluate barriers to industrial electrification on a scale of "not a barrier" to "a barrier, the most important factor in my decision making." Barriers were broken into six major categories: technology, knowledge and education, financing, costs, policy, and add electric utility connection and reliability.

Survey respondents were also asked to evaluate proposals to overcome these barriers on a scale of "would not help overcome barriers" to "the most effective proposal to overcome barriers." Proposals were also broken into seven major categories: technology, knowledge and education, research needs, financing, costs, policy, electric utility connection and reliability.

Some survey responses are described in Chapters 6 and 7 of the report and additional response summaries can be found in this Appendix.

Barriers to electrification

Knowledge and education barrier

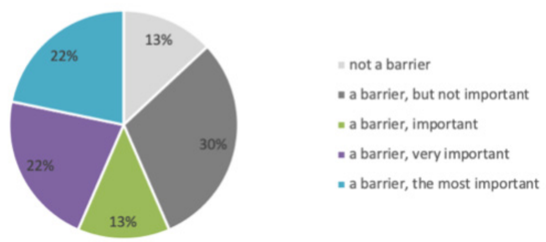

Figure A. Employees or contractors unfamiliar with electrification technologies

Costs barriers

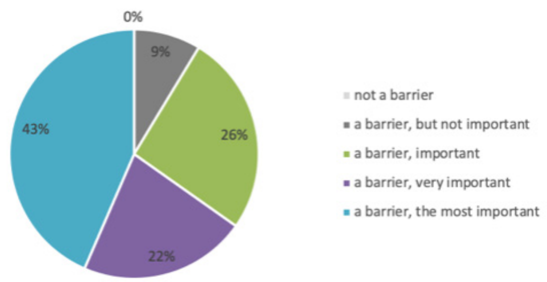

Figure B. High process modification costs

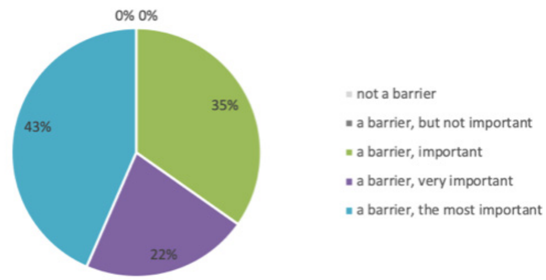

Figure C. Return on investment too low

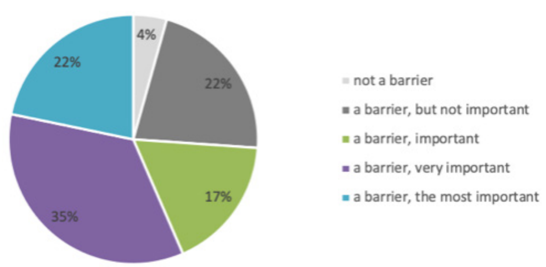

Figure D. Existing technology not at end of useful life

Financing barriers

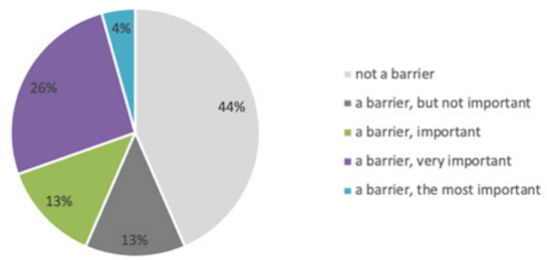

Figure E. External financing unavailble or not compelling

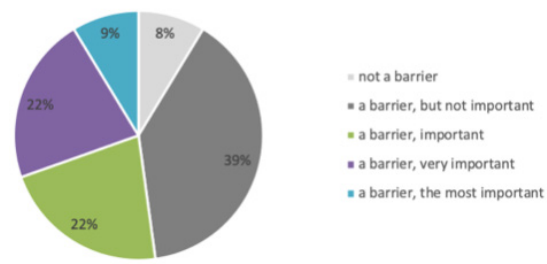

Figure F. Non-energy benefits given more importance

Policy barriers

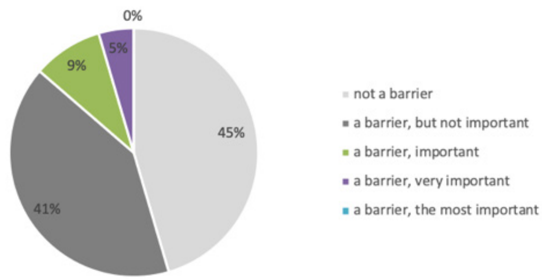

Figure G. Policies prohibit electrification

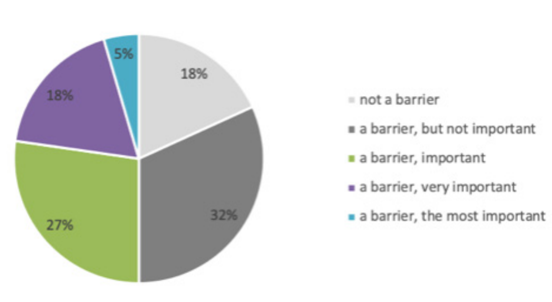

Figure H. Policies make electrification unattractive

Electric utility connection and reliability barriers

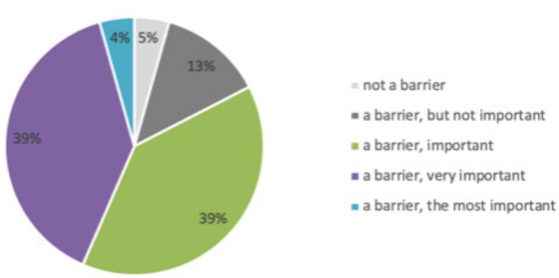

Figure I. Utility upgrade costs too high

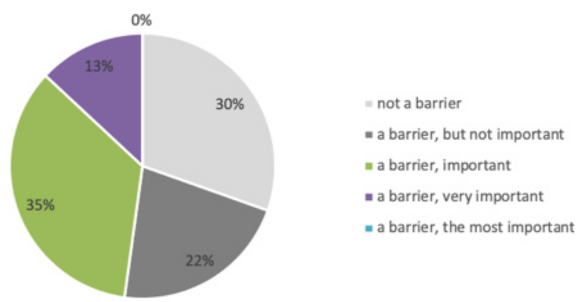

Figure J. Utility unable to complete necessary upgrades

Proposals to overcome barriers

Technology

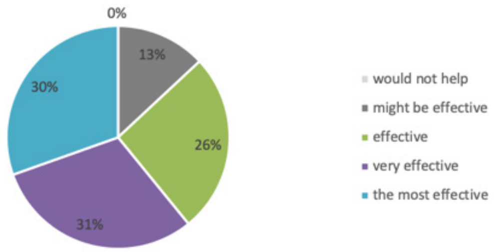

Figure K. Support demonstration projects at progressively larger scale

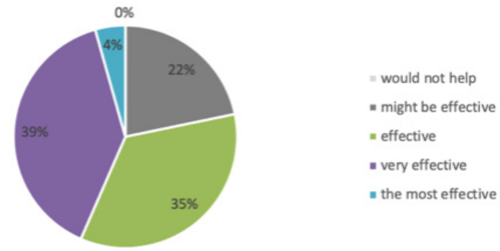

Figure L. Support research that addresses questions that arise during scale up

Knowledge and education

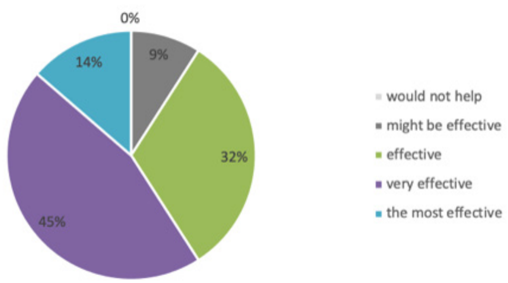

Figure M. Awareness, education, and outreach

Research needs

Electric utility connection and reliability

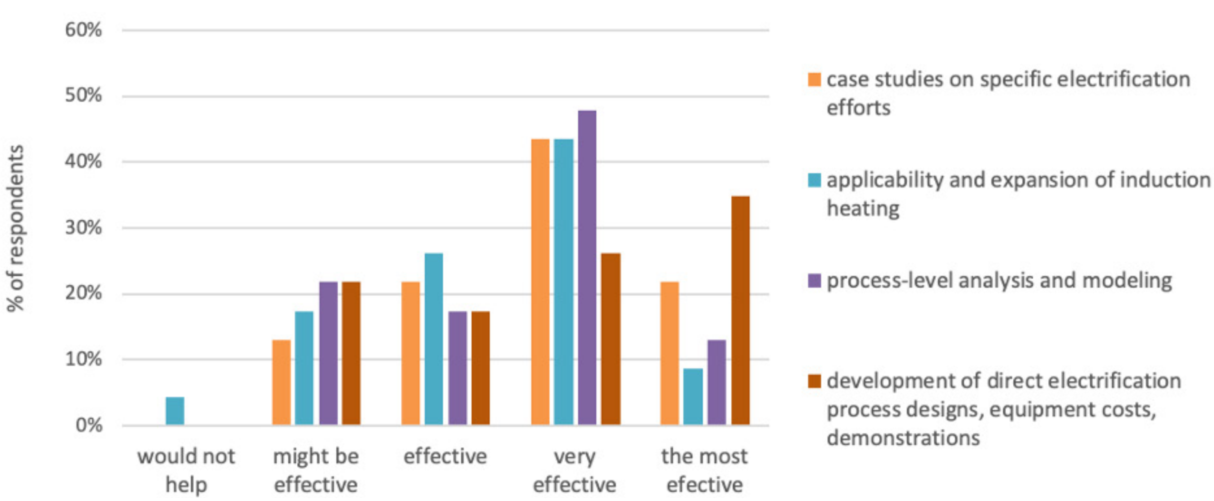

Figure N. Research needs

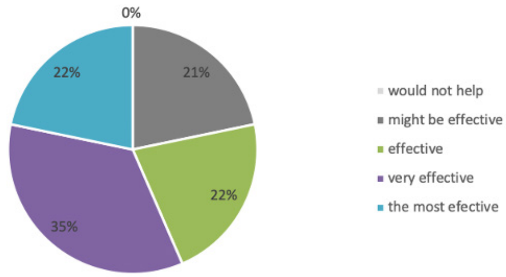

Figure O. Providing connections to low-carbon energy

The Renewable Thermal Collaborative (RTC) serves as the leading coalition for organizations that are committed to scaling up renewable heating and cooling at their facilities and dramatically cutting carbon emissions. RTC members recognize the growing demand and necessity for renewable heating and cooling and the urgent need to meet this demand in a manner that delivers sustainable, cost-competitive options at scale.

The Renewable Thermal Collaborative was founded in 2017 and is facilitated by the Center for Climate and Energy Solutions, David Gardiner and Associates, and World Wildlife Fund.

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