Systems- and technology-level analysis of electrification potential in U.S. manufacturing

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Abstract

Heat represents two thirds of all energy demand in the industrial sector, and one fifth of energy demand across the globe. We conducted a study to analyze the current state of industrial electrification needs, the technologies available, and the potential for electrification in thirteen industrial subsectors. The total technical annual energy saving potential in thirteen industrial subsectors studied is over 815 Petajoules (PJ) and 1,000 PJ per year in 2019 and 2050, respectively. This corresponds to annual CO_2 emissions reduction of over 181 million tonne (Mt) per year in 2050. Because of space constraint, we only presented detailed results for three subsectors in this paper. In addition, we conducted a cost analysis for energy cost per unit or production for conventional Vs electrified processes. We also present several key actions and policy recommendations to scale up industrial electrification in the U.S.

1. 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% 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% of the country's industrial direct greenhouse gas (GHG) emissions (JISEA/NREL, 2017).

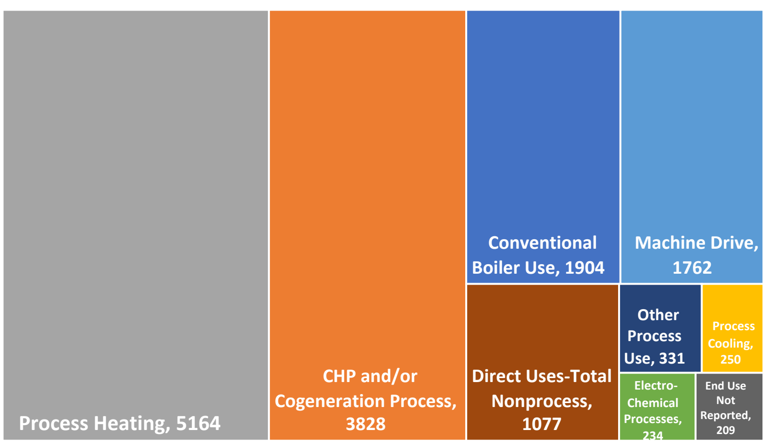
There is a significant opportunity to decarbonize the industrial sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used. Globally, more than 50% of final energy demand is for heating, and about half of that 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 paper 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.

This paper is comprised of a bottom-up industrial subsector, systems, and technology-level technical assessment for electrification of industry in the U.S. The technical assessment provides an analysis of the current state of industrial electrification needs, the technologies available, and the potential for electrification in three industrial subsectors. We conclude the paper by providing several key recommendations to stakeholders in the U.S.

2. 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 U.S. industry is fossil fuels. In 2014, thermal processes accounted for 74% of total manufacturing energy use in the U.S.; process heating accounted for 35%; combined heat and power/cogeneration for 26%; conventional boilers for 13% (US DOE, 2019) (Figure 1). Industrial process heating operations include drying, heat treating, curing and forming, calcining, smelting, and other operations. Five industries account for more than 80% of all U.S. manufacturing thermal process energy consumption: petroleum refining, chemicals, pulp and paper, iron and steel, and food and beverage (US DOE/EIA, 2017).

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, and operating practices (ORNL, 2017).



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.

Figure 1. U.S. manufacturing energy use by end uses- values in Trillion Btu (US DOE, 2019)

Around 30% 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) (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% 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 2 shows the share of industrial head demand by temperature in selected industries.

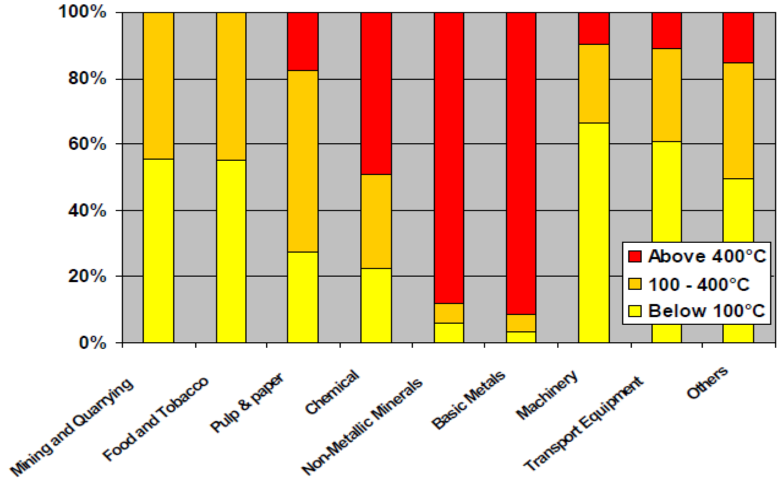


Figure 2. Share of industrial head demand by temperature in selected industries (Caludia et al., 2008)

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).

3. Methodology

We conducted the analysis for electrification potential in thirteen industrial subsectors in the U.S. (Table 1). These subsectors were selected to represent a broad set of industrial sectors. Also, these are the subsectors for which we could obtain sufficient data to do the analysis explained here at this stage. 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 to provide the heat for the process. The electrification of end-use processes has the advantage of increasing efficiency by removing steam distribution losses.

Because of the space constraint, we only present the results of electrification of three industrial sectors in this paper. To see the results of electrification analyses for other ten industrial sectors as well as analysis for electrification of industrial boilers in the U.S., please read our full report (Hasanbeigi et al. 2021).

Table 1. U.S. industrial subsectors analyzed in our study

No.	Industry subsector	No.	Industry subsector
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 3. 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.

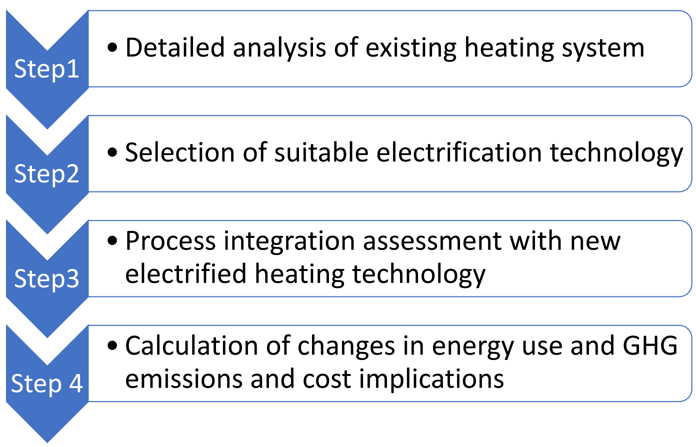


Figure 3. Methodology steps to estimate electrification potential in U.S. industrial subsectors

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 2.

It should be noted that the change in energy use and GHG emissions estimated for each subsector in the following sections are the total technical potentials assuming a 100% 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.

Table 2. 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).

4. Results and discussions

4.1. Electrification of the recycled paper industry

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% in 2018, almost double the recovery rate observed in 1990 (34%) (Garside, 2020).

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 reports that compared to conventional steam drying, the utilization of 100% 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%). 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).
Table 3 compares the energy consumption of the conventional and electrified processes for recycling paper.

Table 3. 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 Final Energy**	**1,390**	

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 4 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.

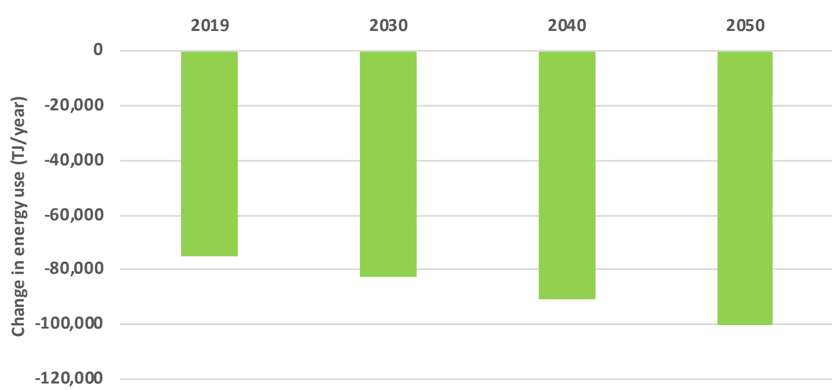


Figure 4. Change in total final energy use of the U.S. paper recycling industry after electrification (This is the technical potential assuming paper dryer electrification)

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 5). 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.

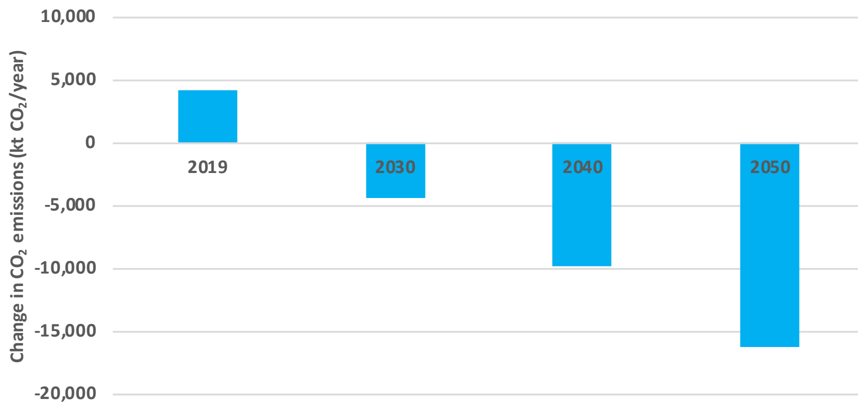


Figure 5. Change in net CO_2 emissions of the U.S. paper recycling industry after electrification in U.S. (This is the technical potential assuming paper dryer electrification)

Figure 6 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% of that of the electrified process in 2019.

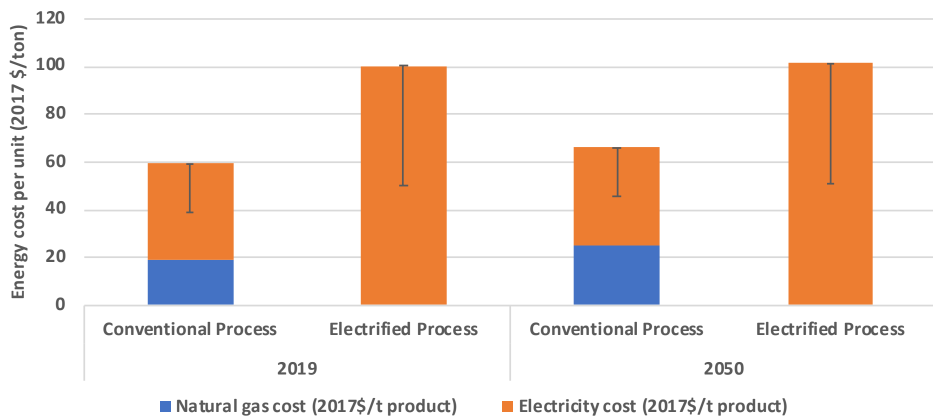


Figure 6. Energy cost per unit of production in the U.S. paper recycling industry (Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50%)

4.2. Electrification of the container glass industry

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, 2020b). 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 (U.S. DOE, 2017a), the total quantity of container glass production in the U.S. is estimated to be approximately 10 million metric tonnes in 2019.

Production process

Conventional process:
Figure 7 illustrates the glass manufacturing process. The production process can be divided into four main process steps (U.S. 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).

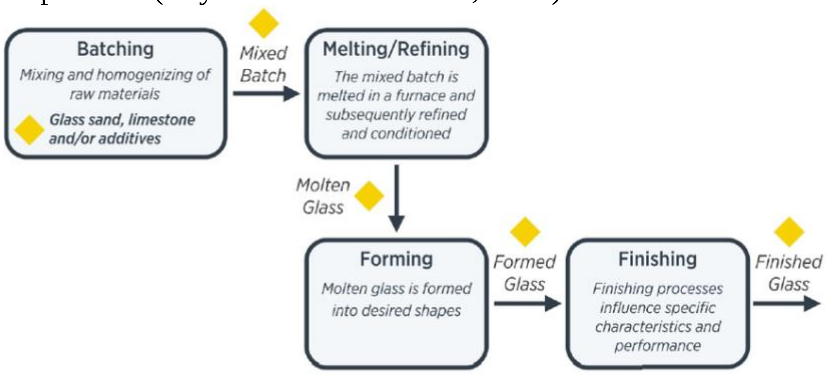


Figure 7. Flow diagram of glass manufacturing (U.S. DOE, 2017a)

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

Table 4. 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**	

Energy, emissions, and cost implications of electrification

Figure 8 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.

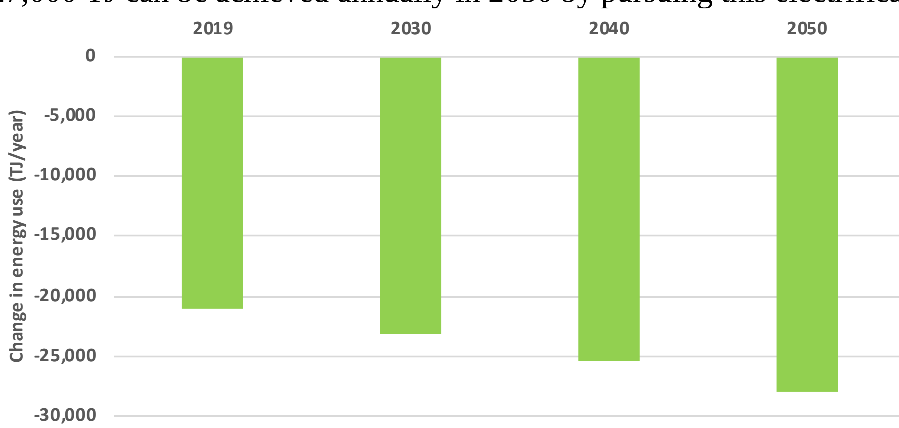


Figure 8. Change in total final energy use of the U.S. container glass industry after electrification (This is the technical potential assuming 100% adoption rate.)

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 9). 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.

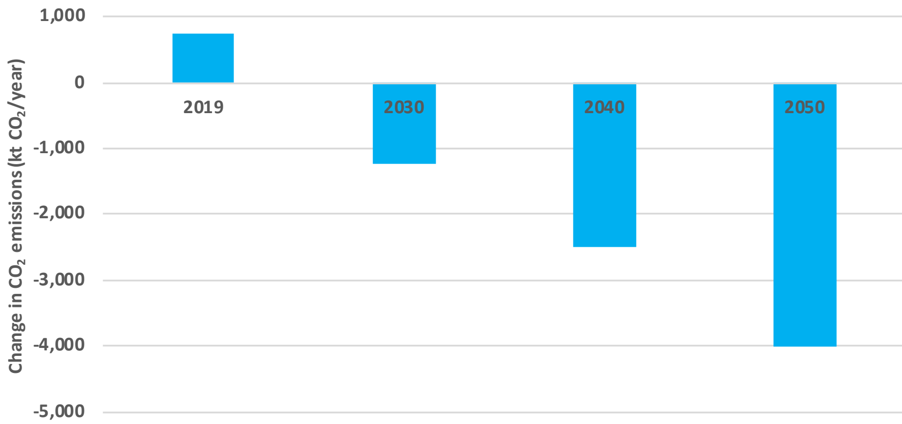


Figure 9. Change in net CO_2 emissions of the U.S. container glass industry after electrification in U.S. (This is the technical potential assuming 100% adoption rate.)

Figure 10 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. It should be noted that despite higher energy cost, glass producers are still transitional to electrified processes, presumably because of other benefits such as the increase in throughput.

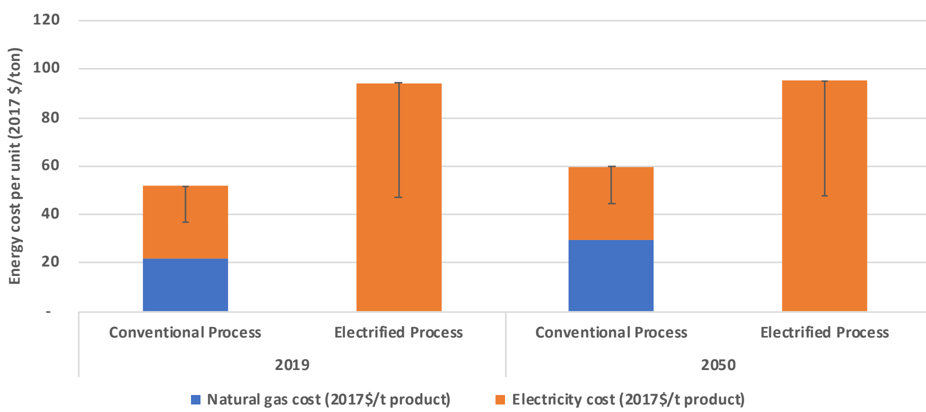


Figure 10. Energy cost per unit of production in the U.S. container glass industry (Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50%)

4.3. Electrification of the ammonia industry

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 (Garside, 2020c). Around 88% of ammonia manufactured across the globe is utilized for the production of fertilizers, and the remainder is used to support formaldehyde production (Venkat, 2016).

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 (US EPA, 1993). Greater than half of the total industrial production of hydrogen around the world is utilized for manufacturing ammonia (Matzen, 2015). Figure 11 shows a simplified ammonia production diagram (IEA, 2013).

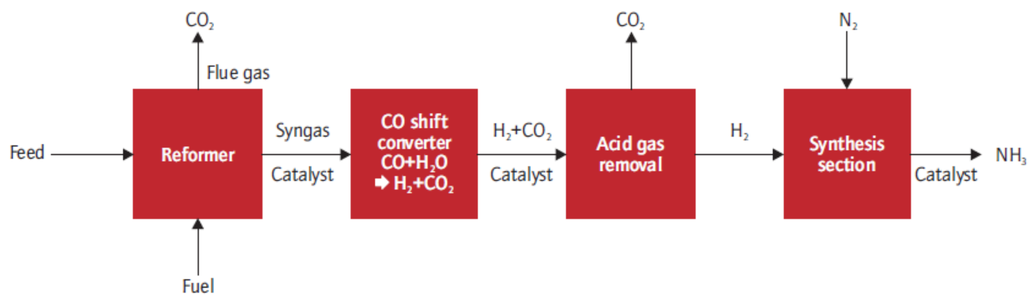


Figure 11. Ammonia synthesis, A simplified schematic

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%, whereas on a lower heating value (LHV) basis, efficiency is in the 50-60% range (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 5 compares the energy consumption of conventional and electric processes for ammonia production.

Table 5. 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.

Energy, emissions, and cost implications of electrification

Figure 12 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.

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 13). 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.

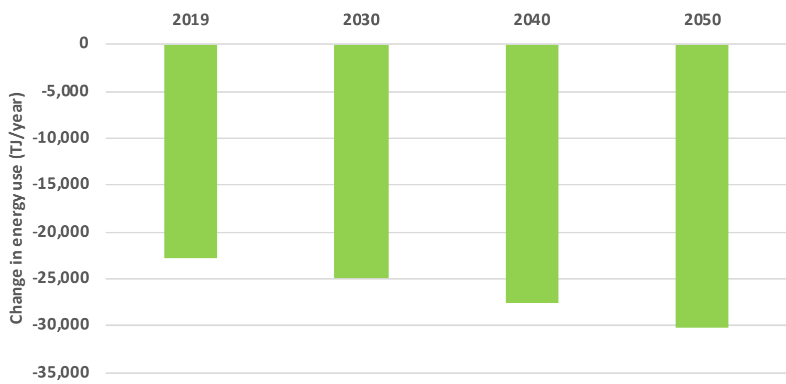


Figure 12. Change in total final energy use of the U.S. ammonia industry after electrification (This is the technical potential assuming 100% adoption rate)

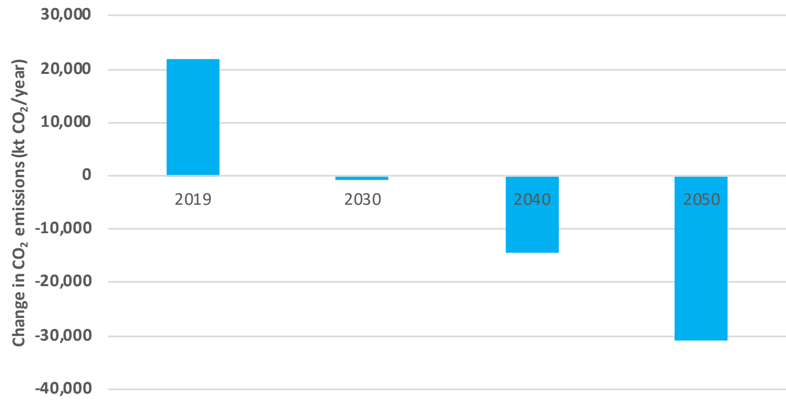


Figure 13. Change in net CO_2 emissions of the U.S. ammonia industry after electrification in U.S. (This is the technical potential assuming 100% adoption rate)

Figure 14 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.

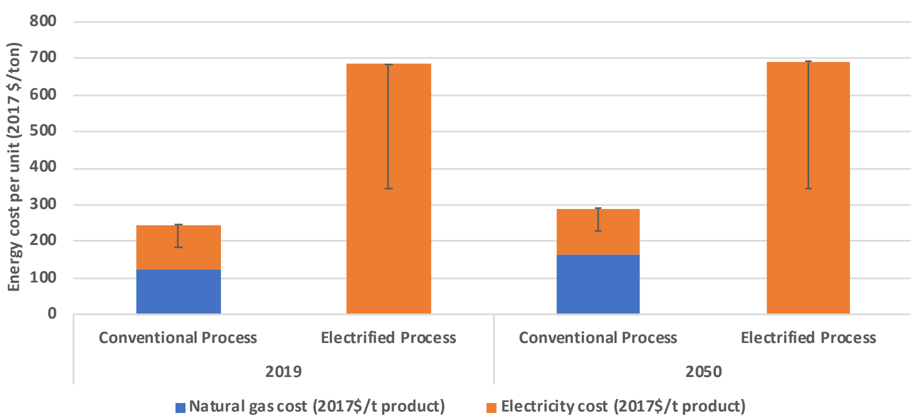


Figure 14. Energy cost per unit of production in the U.S. ammonia industry (Note: The error bars show the energy cost per unit of production when unit price of electricity is reduced by 50%)

4. Conclusions and recommendations

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. Our study analyzed the current state of industrial electrification needs, the technologies available, and the potential for electrification in thirteen industrial subsectors. The subsectors included in our original analysis are shown in Table 6, below, along with the change in total final energy use and CO2 emissions after electrification of certain processes in those industries. The total technical annual energy savings potential (with 100% 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 CO2 emissions reduction of over 134 million tonne (Mt) per year in 2050. *In this paper, because of space constraint, we presented only the detailed analysis for three industry subsectors.*

Table 6. Change in total final energy use and CO2 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.

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.

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 CO2 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.

We also investigated 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 in our study. Categories of barriers and proposals include technology, knowledge and education, financing, costs, policy, and electric utility connection and reliability.

Our study'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 our full report (Hasanbeigi et al. 2021).

- The industrial sector should initiate partnerships with academia, national labs, think thanks 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.

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