ENERGY INNOVATION POLICY & TECHNOLOGY LLC®

Decarbonizing Low-Temperature Industrial Heat in the U.S.

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JEFFREY RISSMAN

ENERGY INNOVATION POLICY AND TECHNOLOGY LLC®

98 BATTERY ST. SUITE 202, SAN FRANCISCO, CA 94111

EXECUTIVE SUMMARY[i,ii]

U.S. industrial facilities use low-temperature heat (up to 165 degrees Celsius) in numerous manufacturing processes, accounting for approximately 35 percent of industrial process heat demand. Low-temperature industrial heating produced 171 million metric tons of carbon dioxide (CO_2) in 2021 (3.5 percent of total U.S. energy-related CO_2 emissions), equivalent to the annual emissions from 37 million gasoline-powered cars, 22 million homes, or 430 natural gas-fired power plants.

There exist a range of technology options to reduce these emissions. Energy efficiency, material efficiency, and circular economy measures can reduce the demand for low-temperature industrial heat and are important complements to zero-carbon heat generation. Direct electrification using heat pumps is the most efficient and cost-effective method of supplying low-temperature heat for industrial processes. Heat pumps can be several times more efficient than combustion technologies because they move heat like a refrigerator or air conditioner, rather than creating heat from their input energy, and they do not lose heat in combustion exhaust gases. Other zero-carbon solutions, such as burning electrolytic hydrogen, burning sustainably grown bioenergy, or carbon capture and sequestration, cannot economically compete with heat pumps at supplying heat in the low-temperature range.

Shifting from fossil fuel combustion to industrial heat pumps for low-temperature industrial process heat was modeled using the Energy Policy Simulator, a free and open-source computer model. Industry sector greenhouse gas (GHG) emissions decrease by 77 MMT (5 percent) in 2030 and by 284 MMT (16 percent) in 2050 relative to a business-as-usual (BAU) case.[iii] Associated reductions in non-GHG pollutants prevent more than 1,000 premature deaths in 2030 and more than 3,000 deaths in 2050 (Figure ES1).

[iii] The BAU case does not include the effects of the 2022 Inflation Reduction Act. The Act's effects have not yet been incorporated into U.S. Energy Information Administration and other government datasets used to form the BAU case in the Energy Policy Simulator.

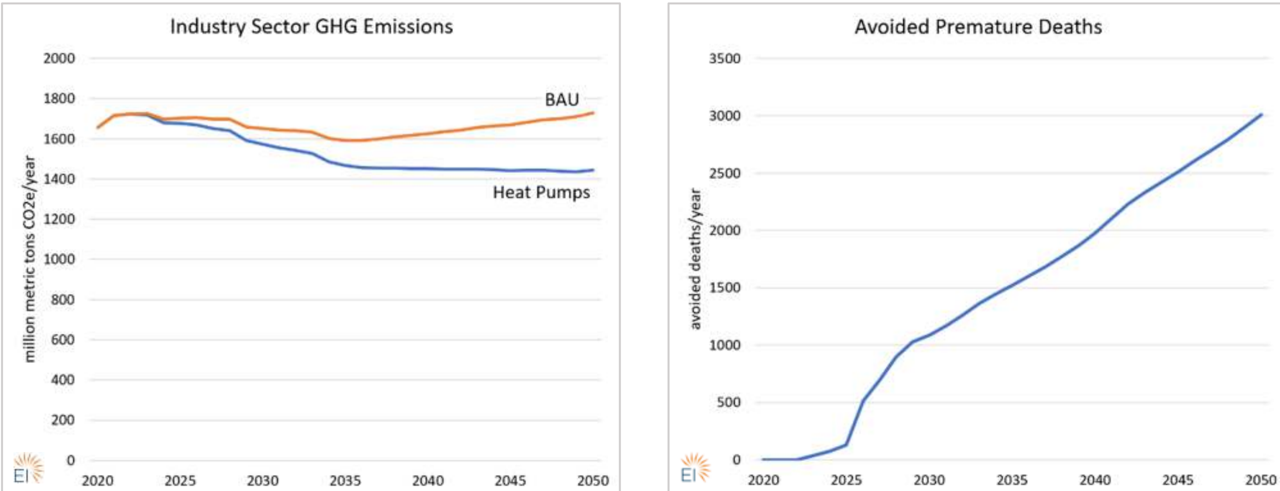

Figure ES1. Industry sector GHG emissions and avoided premature deaths from industrial heat pump scenario vs. BAU

The transition to heat pumps for the industrial sector would benefit the U.S. economy and workers. Gross domestic product increases by more than $42 billion in 2030 and $8 billion in 2050, while there are over 275,000 more U.S. jobs in 2030 and around 75,000 more jobs in 2050 relative to the BAU case in those years. Job gains are concentrated in electricity supply, construction, finance, business services, wholesale and retail trade, and manufacturing of electrical equipment and machinery.

Industrial electricity demand in 2030 increases from 946 terawatt-hours (TWh) to 1,059 TWh (12 percent), and in 2050 from 1,016 TWh to 1,428 TWh (41 percent) (Figure ES2). Most new capacity to meet this demand is wind and solar photovoltaics (PV) because these are the most cost-effective resources. New renewables reduce the marginal price of electricity, making it harder for other plants to compete economically. As a result, some coal, natural gas non-peaker, and nuclear plants retire. New renewables are built to replace fossil and nuclear capacity retirements, in addition to meeting demand from new heat pumps. Thus, industrial heat pumps serve as a catalyst and have a larger effect on transforming the power sector than is suggested by narrowly looking at heat pumps' own electricity demand.

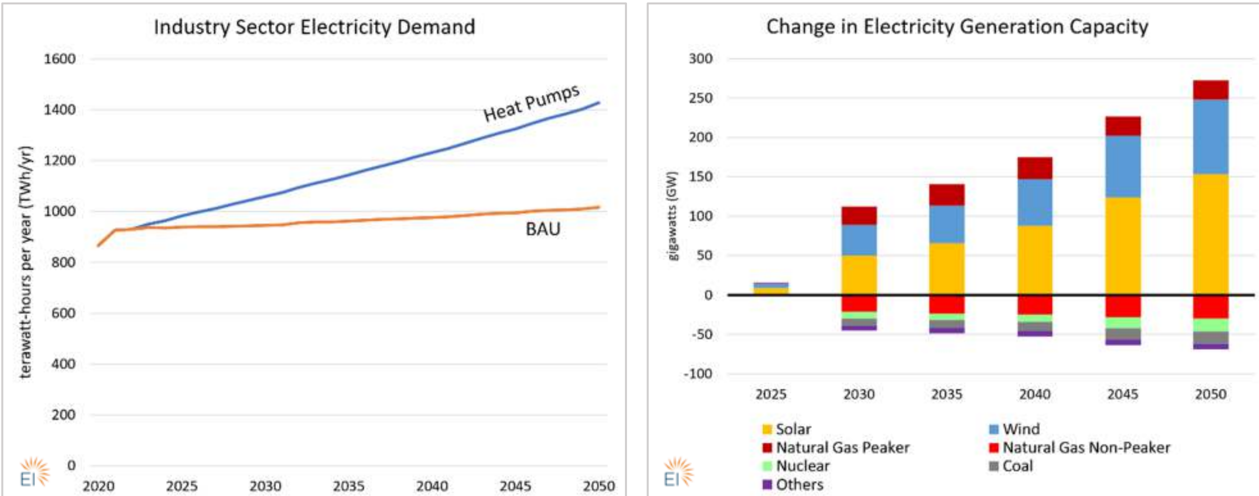

Figure ES2. Change in industrial electricity demand and electricity generation capacity from industrial heat pump scenario vs. BAU. The second panel shows the difference in capacity that exists in each listed year relative to BAU, so each stacked bar effectively cumulates changes up through that year.

Heat pumps are cost effective for industrial firms (Table ES1). In 2021, there was no significant difference in energy costs per unit heat output between natural gas technologies ($18-35 per megawatt-hour of thermal output (MWhth)) and heat pump technologies ($20-34/MWhth). Heat pumps have higher capital costs, so their total cost per unit heat output was slightly higher ($41-60/MWhth for heat pumps, versus $36-50/MWhth for natural gas technologies). This price gap is small and likely has already vanished because natural gas prices have increased since 2021.

The Henry Hub natural gas spot price in August 2022 was $30/MWh ($8.81/MMBtu), almost double the value used in Table ES1. Natural gas prices are likely to remain volatile and exhibit no long-term upward or downward trend in the decades ahead, but electricity generation costs are on a long-term downward trend driven by deployment of low-cost wind and solar generation, and heat pump technology will continue to improve, so the cost comparison will consistently favor heat pumps in the longer term.

In 2021, the global market for heat pumps was around $53-68 billion, but the vast majority of these pumps were for building HVAC systems or water heating. Industrial heat pumps accounted for $0.6-1 billion, representing under 2 percent of the heat pump market. This report reviews 49 specific heat pump manufacturers, many of whom may help to meet increased demand for industrial heat pumps.

Table ES1. Cost and performance characteristics for industrial heat pumps and three alternate technologies in 2021

	Natural Gas Steam Boiler	Natural Gas CHP	Electric Boiler	Heat Pump (80-100°C)	Heat Pump (100-180°C)
Efficiency/COP	0.95	0.85	0.99	3.7	2.2
Full load hours (hours/year)	2000	6000	2000	6000	6000
Capex ($/kW)	234	900	175	700	870
Capex ($/MWhth)	12	12	14	19	23
Non-energy opex ($/MWhth)	6	3	3	2	3
Fuel/electricity cost ($/MWhth)	18	35	75	20	34
Total cost ($/MWhth)	36	50	92	41	60

Capex = capital expenditures (excluding installation/integration costs). Non-energy opex = annual operational expenditures other than energy, such as staffing and maintenance. CHP = combined heat and power. COP = coefficient of performance, a measure of efficiency where 1.0 is complete conversion of input energy to usable heat. MWh = megawatt hours of fuel or electricity input. MWhth = megawatt hours of thermal (heat) output.

Financial support is the most important near-term federal option for increasing U.S. industrial heat pump penetration. Key policy tools include research, development, and demonstration (RD&D) support, grants and tax incentives, lending mechanisms, and facilitating access to low-cost financing. Two provisions of the 2022 Inflation Reduction Act (IRA) authorize funding that could be used for these purposes. The U.S. Department of Energy (DOE) is well suited to take the lead on administering these programs, particularly the Advanced Manufacturing Office or its successor offices, the Advanced Materials and Manufacturing Technology Office and the Industrial Efficiency and Decarbonization Office, collaborating with the DOE Loan Programs Office where relevant.

Technology-neutral energy-efficiency standards administered by DOE and emission standards administered by the U.S. Environmental Protection Agency (EPA) are in theory other powerful tools for accelerating industrial heat pump deployment. These federal agencies would have to work through rulemaking processes, including opportunities for industry and public comment. Due to regulatory delays and the risks of judicial appeals, financial support might be a more rapid near-term mechanism for accelerating industrial heat pump adoption. Relevant considerations are discussed in detail in this report.

Industrial heat pumps are the most promising mechanism for supplying zero-carbon, low-temperature industrial heat, and a shift from fossil fuel combustion to heat pumps would bring large environmental, economic, and public health benefits to the U.S.

LOW-TEMPERATURE INDUSTRIAL HEAT IN THE U.S.

In 2020, U.S. industrial activity was directly responsible for approximately a quarter of the country's greenhouse gas (GHG) emissions.[1] Therefore, adopting sustainable, zero-emissions manufacturing and industrial processes is crucial to achieving U.S. climate goals: a 50 to 52 percent reduction in GHG emissions by 2030 and net-zero emissions by 2050.[2]

Fossil fuels made up 73 percent of industrial energy use in 2018, excluding feedstocks[iv] (Figure 1). 40 percent of these fossil fuels heated boilers to produce steam, which is used in industries such as food processing, refining, chemical manufacturing, and paper and cardboard production. Another 44 percent heated other industrial equipment, such as steel blast furnaces, cement and ceramics kilns, and chemical reactors. Thus, 84 percent of industrial fossil fuel use is dedicated to *process heating*: heat used in manufacturing steps to produce goods.

The final 16 percent of industrial fossil fuel use serves other purposes, such as moving machines, maintaining buildings at a comfortable temperature for workers, and moving items within a facility using vehicles such as forklifts.

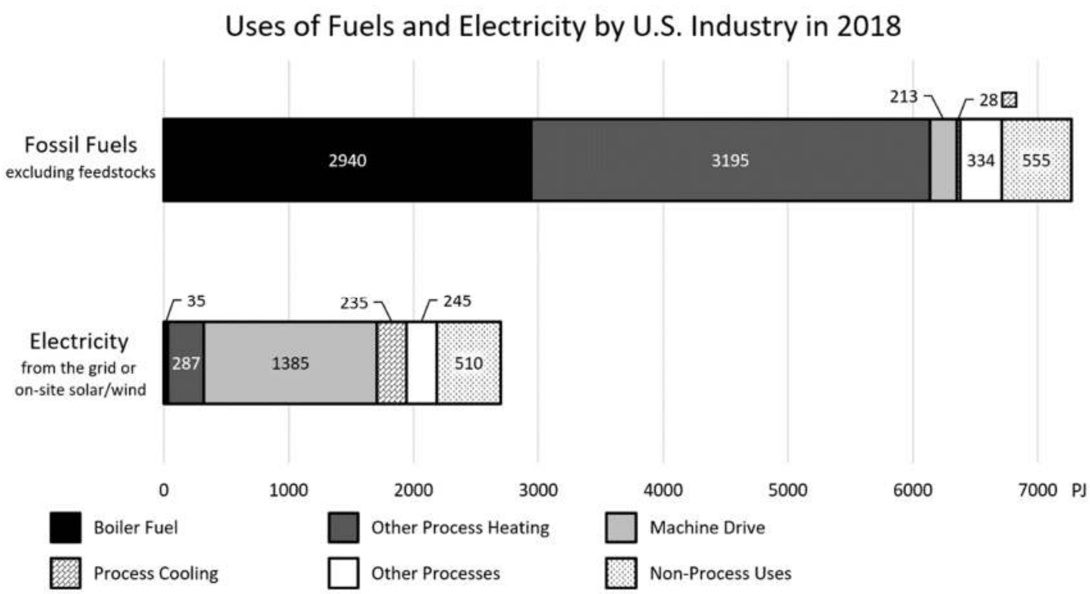

Figure 1. Energy use by U.S. industry in 2018 (in PJ), excluding feedstocks[3]

[iv] Feedstocks are fossil fuels used for non-energy purposes, such as petroleum that goes into making plastic and ammonia that goes into making fertilizers. Feedstocks typically contribute atoms to the final product, so they cannot be directly replaced with electricity (though they can be replaced with electricity-derived feedstocks, such as electrolytic hydrogen). Feedstocks are outside the scope of this report.

These uses are mostly straightforward to electrify using commercialized technologies such as electric motors, chillers, HVAC[v] systems, and forklifts, so the central challenge in achieving zero-emissions industry is decarbonizing industrial process heating.

Different industrial processes require heat of different temperatures (Figure 2). Generally, temperatures above 500°C are needed to make metals, chemicals, and nonmetallic minerals, such as cement and glass. In contrast, temperatures under 200°C satisfy most of the heat needs for producers of food, paper, textiles, wood products, and manufactured items such as appliances or machinery. Across the entire U.S. industrial sector, 19 percent of heat requirements are for temperatures under 100°C, 25 percent for temperatures from 100 to 200°C, 7 percent for temperatures from 200 to 500°C, and 49 percent for temperatures above 500°C (Figure 2).

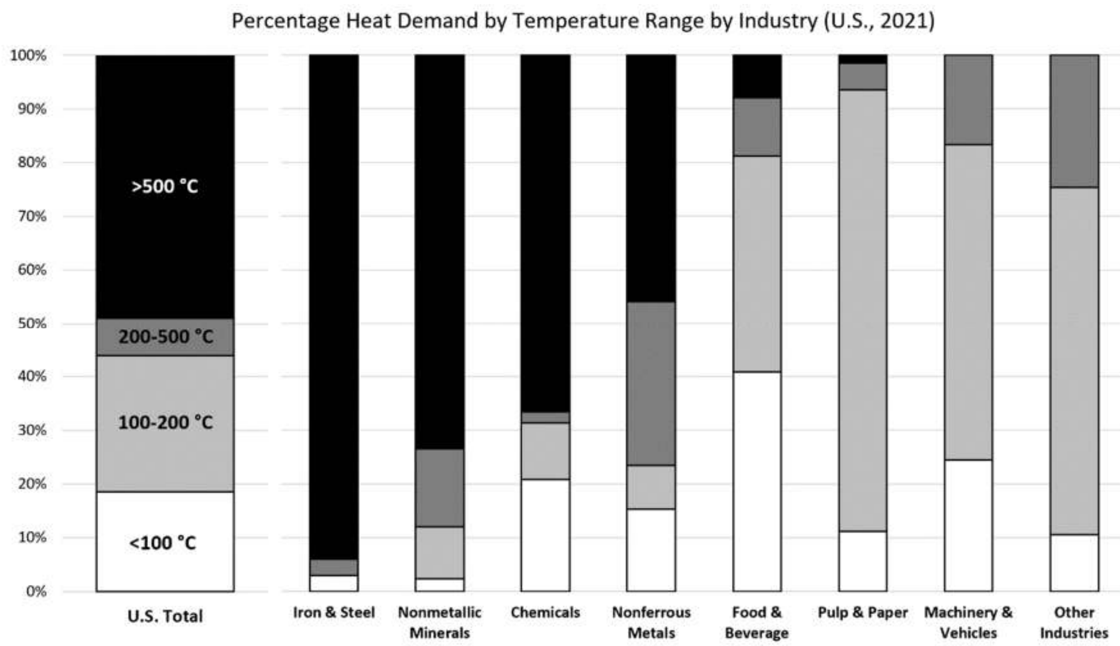

Figure 2. U.S. industrial heat demand by temperature range by industry in 2021. "Nonmetallic minerals" include cement, lime, glass, brick, tile, etc. Excludes heat for non-process uses, such as HVAC services for the comfort of workers.[4,5]

This report focuses on technologies and policies to decarbonize *low-temperature industrial heat*, which is here defined as temperatures up to 165°C. This is the maximum temperature that can be supplied by commercialized industrial heat pumps, the most important technology to supply emissions-free, low-temperature heat (discussed below). Across all U.S. industries, low-

[v] HVAC stands for heating, ventilation, and air conditioning. It refers to equipment that maintains indoor air at a comfortable temperature for workers, not equipment that provides heat or cooling to industrial processes.

temperature heat accounts for approximately 35 percent of industrial process heat demand,[vi] representing around 171 million metric tons of CO_2 in 2021, or 3.5 percent of total U.S. energy-related CO_2 emissions in that year.[4] This is the equivalent to the annual emissions from 37 million gasoline-powered cars, 22 million homes, or 430 natural-gas-fired power plants.[6] Therefore, fossil fuel combustion to produce low-temperature industrial heat is a source of considerable climate-damaging CO_2 emissions. Fortunately, it can be addressed cost effectively using technologies that are already commercially available.

Industrial Heat Decarbonization Technologies

A range of technologies and technical approaches can reduce emissions from industrial process heating.

Energy efficiency can reduce industrial energy demand at all temperature ranges. Efficiency is often considered at the scale of individual pieces of equipment, such as installing a highly efficient boiler that recovers heat from condensate. However, efficiency can also be improved by optimizing the way different machines are connected and the way material flows between them. For example, minimizing variability in material flows allows for the installation of smaller heaters that operate at their intended design capacity instead of using oversized equipment that must ramp up and down to match variations in material flows. A third approach is to alter product design to improve efficiency, such as by reducing the number of process steps required to make a product. Another energy efficiency technique is waste heat recovery: using excess heat from a high-temperature process to provide useful services, such as heating input materials or powering a lower-temperature process. Extensive technical guidance is available on how to optimize manufacturing energy efficiency.[7–9]

Material efficiency refers to making the same products while using less material. Material efficiency does not reduce product quality or functionality, and in some cases can improve products (for instance, by making them lightweight and therefore easier to handle or more fuel efficient). Researchers Allwood and Cullen reviewed engineering case studies of many common products and found that "we could use 30 percent less metal than we do at present, with no change in the level of material service provided, simply by optimizing product design and controlling the loads that they experience before and during use."[10] Digitization of products (e.g., newspapers and books) or services (e.g., videoconferencing, which reduces the need for travel, reducing demand for vehicles and infrastructure) can also reduce material demand.

Circular economy refers to putting products and materials to the highest and best use, minimizing the need to manufacture new products and materials (and associated industrial emissions).

[vi] Assuming sector-wide heat demand between 100°C and 200°C is evenly distributed between these temperatures.

Examples include designing products for longevity and repairability, facilitating resale or transfer of used products, sharing systems that enable more people to use the same product (such as tool lending libraries or car sharing), remanufacturing (reusing components from old products in new products), and recycling the materials in old products.

Energy efficiency, material efficiency, and circular economy are valuable techniques for reducing industrial emissions, including emissions from low-temperature heat. On their own, however, they cannot eliminate all industrial energy demand or emissions because demand for products cannot be reduced to zero, and the manufacturing and recycling of products and materials cannot be accomplished without energy. Therefore, industry requires a means of supplying emissions-free process heat.

Direct electrification of heat (i.e., using electricity to produce heat, without first using the electricity to make a combustible fuel) is the most efficient method of supplying process heat. This is for two reasons. First, it avoids the energy losses associated with converting electricity to hydrogen or other electricity-derived fuels. Second, electricity can deliver heat to a material or product with lower heat losses than combustion, as electrical heating does not create hot exhaust gases and does not form water vapor (H_2O), two important heat loss modes.[11]

To be emissions free, electricity used by industry must come from zero-emission generating technologies, such as solar, wind, hydroelectric, or nuclear power plants. Decarbonizing the electric grid can be done using already-commercial technologies, and the U.S. has set a goal to achieve a zero-emission electric grid by 2035, 15 years sooner than industry.[2] Due to the long lifetimes of industrial equipment, it is crucial to begin deploying electrified equipment as soon as possible rather than wait for the grid to be decarbonized. (Industries can accelerate this process by procuring clean electricity or building on- or off-site renewable generation.) This paper considers electrified industrial heat to be emissions free, with the understanding that this assumption depends on continued progress toward a zero-carbon electric grid.

There is a wide range of direct electrification technologies capable of supplying industrial heat at all temperatures. The main electric heating technologies are industrial heat pumps, electric resistance, induction, electric arcs and plasma torches, dielectric heating (with radio waves or microwaves), infrared heating, lasers, and electron beams.[vii] While each of these technologies has industrial applications, industrial heat pumps are by far the most efficient and cost-effective option for low-temperature heat.

Heat pumps are efficient because they do not need to produce new heat. Rather, they move heat from an area of low temperature to an area of high temperature, operating much like a refrigerator or air conditioner (which extracts heat from a cooler area and moves it to a warmer area). Typically,

[vii] Also, it is sometimes possible to replace heat with non-thermal, electricity-driven chemical reactions, such as curing compounds with UV light or chemically breaking down compounds with electrolysis.

an industrial heat pump will take heat from a source around 25 to 35°C and can output temperatures as high as 165°C. The efficiency of a heat pump declines with greater temperature increases. Heat pumps' efficiency is expressed as a coefficient of performance (COP), where a COP of 1 indicates a 100 percent conversion of electricity into heat, as would be expected from a theoretical, idealized electric resistance heater. Heat pumps delivering a temperature increase of 40 to 60°C often have a COP of 3 to 4, meaning they are three to four times more efficient than an idealized electric resistance heater. A heat pump configured to deliver an output temperature of 165°C, corresponding to a heat increase of about 130°C, has a COP of 1.5, or 50 percent more efficient than an idealized resistance heater (Figure 3).

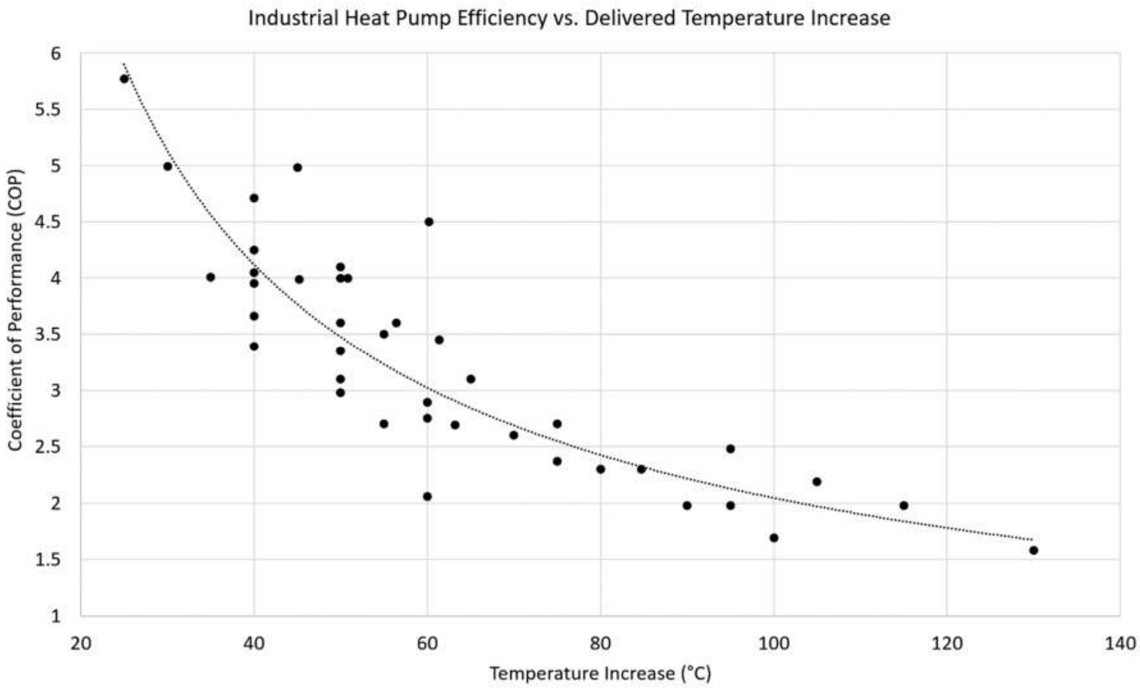

Figure 3. Heat pump efficiency (COP) for commercial heat pumps configured to deliver various levels of temperature increase[12]

No other electrical heating technology, nor fuel combustion, can supply heat at an efficiency exceeding 100 percent (meaning complete conversion of the electrical or chemical energy into heat). This makes direct electrification via heat pumps a uniquely cost-effective and appealing option for satisfying low-temperature heat needs.

Electrolytic ("green") hydrogen is produced by electrolyzing water using renewable electricity. The hydrogen can then be burned directly for heat, or it may first be transformed into other fuels, such as ammonia or methanol. Electrolytic hydrogen and its derivative fuels are not a good fit for low-temperature industrial heating because they combine high cost with low efficiency: electricity is more expensive than coal or natural gas per unit energy,[4] there are energy losses involved in forming hydrogen (and, if applicable, its conversion to a derivative fuel), and hydrogen combustion suffers the same inefficiencies as fossil fuel combustion (such as heat loss in exhaust gases). Electrolytic hydrogen and hydrogen-derived fuels are best reserved for use as feedstocks in chemicals and primary steelmaking, and for use in aircraft and perhaps long-distance shipping, where direct electrification is impossible or impractical.

Bioenergy[viii] combustion experiences the same heat loss modes as fossil fuel combustion. Bioenergy combustion may have a role to play in providing medium- to high-temperature industrial heat, particularly in regions where biomass is available at low cost. However, for low-temperature heat, bioenergy will struggle to compete with heat pumps due to pumps' great efficiency. Additionally, sustainable bioenergy supplies will be limited due to competition with other bioenergy applications, such as chemical feedstocks and transportation fuels, as well as other land uses, such as growing agricultural crops, providing ecosystem services, and protecting biodiversity. Therefore, industry should generally reserve bioenergy for feedstocks and for medium- to high-temperature heating while relying on heat pumps to provide low-temperature heat.

Carbon capture and sequestration (CCS) can capture and store CO_2 from fossil fuel or bioenergy combustion. CCS requires large infrastructure investment (to capture, compress, transport, and store the CO_2) and is best suited to facilities that produce very large amounts of CO_2. These tend to operate at high temperatures and/or have non-energy CO_2 emissions, such as cement kilns. Low-temperature heat needs often arise from smaller-scale machinery and smaller industrial facilities, where CCS investment would be too costly.

Due to heat pumps' ability to provide electrified industrial heat more efficiently than alternative technologies, the remainder of this report focuses on heat pumps.

INDUSTRIAL HEAT PUMP ABATEMENT POTENTIAL AND CO-BENEFITS

The addressable market for industrial heat pumps is large. As noted above, about 35 percent of U.S. industrial process heat demand is at temperatures heat pumps can provide, but this is a highly aggregated estimate. For more detail, Arpagaus et al. characterized many industrial processes well suited to heat pumps, their temperature requirements, and corresponding heat pumps' technological readiness (Table 1). The industries in Table 1 account for about half of U.S. non-feedstock industrial energy demand,[4] but not all of their heat demand is for low-temperature heat, so 35 percent remains a reasonable ceiling for the U.S. market.

[viii] Bioenergy includes crop and forestry residues, methane harvested from animal waste (e.g., in an anaerobic digester), and sustainably grown bioenergy crops (crops intended for conversion to energy). Some bioenergy sources, such as corn-derived ethanol, are not carbon neutral and should not be considered zero-carbon energy sources.

Table 1. Industrial heat pump applications by temperature range and technology readiness level

Sector	Process	Temperature [°C]
Paper	Drying	90 to 240
	Boiling	110 to 180
	Bleaching	40 to 150
	De-inking	50 to 70
Food & beverages	Drying	40 to 250
	Evaporation	40 to 170
	Pasteurization	60 to 150
	Sterilization	100 to 140
	Boiling	70 to 120
	Distillation	40 to 100
	Blanching	60 to 90
	Scalding	50 to 90
	Concentration	60 to 80
	Tempering	40 to 80
	Smoking	20 to 80
Chemicals	Destillation	100 to 300
	Compression	110 to 170
	Thermoforming	130 to 160
	Concentration	120 to 140
	Boiling	80 to 110
	Bioreactions	20 to 60
Automotive	Resin molding	70 to 130
Metal	Drying	60 to 200
	Pickling	20 to 100
	Degreasing	20 to 100
	Electroplating	30 to 90
	Phosphating	30 to 90
	Chromating	20 to 80
	Purging	40 to 70
Plastic	Injection modling	90 to 300
	Pellets drying	40 to 150
	Preheating	50 to 70
Mechanical engineering	Surface treatment	20 to 120
	Cleaning	40 to 90
Textiles	Coloring	40 to 160
	Drying	60 to 130
	Washing	40 to 110
	Bleaching	40 to 100
Wood	Glueing	120 to 180
	Pressing	120 to 170
	Drying	40 to 150
	Steaming	70 to 100
	Cocking	80 to 90
	Staining	50 to 80
	Pickling	40 to 70
Several sectors	Hot water	20 to 110
	Preheating	20 to 100
	Washing/Cleaning	30 to 90
	Space heating	20 to 80

Technology Readiness Level (TRL) of heat pumps:

- Conventional HP < 80°C, established in industry
- Commercial available HTHP 80 to 100°C, key technology
- Prototype status, technology development, HTHP 100 to 140°C
- Laboratory scale research, functional models, proof of concept, HTHP > 140°C

Table from Arpagaus et al.[12]

To determine the benefits associated with a transition to heat pumps for low-temperature industrial heat, modeling was performed using the U.S. Energy Policy Simulator (EPS) version 3.4.1.[13] The EPS is a free and open-source model that can predict the impacts of hundreds of energy technologies and policies relative to a business-as-usual (BAU) case[ix] from now through 2050. The modeled scenario featured a linear growth in the share of low-temperature manufacturing[x] process heat needs met by heat pumps, beginning in 2022 and culminating in a 100 percent displacement of fossil fuels (but no displacement of biomass)[xi] by heat pumps in 2050 (Table 2). All other policy settings, such as in the transport and buildings sectors, remained as they were in the BAU case.

Table 2. Share of low-temperature industrial process heat needs met via electricity in the modeled scenario.

2020	2025	2030	2035	2040	2045	2050
25.6%	36.4%	48.3%	55.4%	71.7%	83.1%	94.5%

The value for 2020 reflects historical data on actual electricity use, while data for 2025-2050 are modeled projections. The percentage does not reach 100 percent in 2050 because only fossil fuels are being displaced, not biomass. Non-heat pump electric technologies used in the BAU case (such as electrical resistance heating) remain the same; only fossil fuel use is displaced with heat pumps, so heat pumps make up the vast majority but not the entirety of the electricity use reported in this table. Due to the long lifetime of industrial equipment (i.e., slow stock turnover), achieving these results without early retirement of fossil-burning industrial equipment requires the market share of newly sold, electrified, low-temperature industrial heating equipment to reach these percentages 10-20 years sooner than the corresponding years in this table. For instance, the sales share of new, electrified, low-temperature industrial heating equipment should reach 94.5 percent between 2030 and 2040 in order to achieve 94.5 percent electricity use in 2050. (To achieve these results in early years, such as 48.3 percent electricity use in 2030, some early retirement of fossil-burning industrial equipment would be necessary.)

The shift to industrial heat pumps reduces direct industrial GHG emissions by 77 MMT (5 percent) in 2030 and by 284 MMT (16 percent) in 2050 relative to the BAU case (Figure 4). For comparison,

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[ix] The BAU case does not include the effects of the IRA. The IRA's effects have not yet been incorporated into EIA and other government datasets used to form the BAU case in the Energy Policy Simulator.

[x] The modeled industries were food and beverage, textiles and apparel, wood products, pulp and paper, refined petroleum and coke, chemicals, rubber and plastic products, glass and glass products, cement and other nonmetallic minerals, iron and steel, other metals, computers and electronics, appliances and electrical equipment, other machinery, road vehicles, nonroad vehicles, metal products except machinery and vehicles, and other manufacturing. In contrast, agriculture, forestry, mining and quarrying, oil and gas drilling, energy pipelines, waste management, and construction were excluded as non-manufacturing activities.

[xi] Some industries, such as pulp and paper manufacturing, burn biomass they obtain in the course of their operations. If these facilities did not burn this biomass, they would be obligated to dispose of it, which risks the creation of methane (a potent GHG) during decomposition. Additionally, the carbon in biomass was recently sequestered from the atmosphere by plants. For these reasons, the modeled scenario opts to continue biomass combustion where it is used in the BAU case rather than displace it with heat pumps.

modeling of the Inflation Reduction Act (IRA) conducted by nonpartisan think tank Energy Innovation® found that the IRA would reduce industry sector emissions by 86-112 MMT in 2030,[14] so an additional 77 MMT abatement from industrial heat pumps could increase this abatement by 70-90 percent. This would close 10-20 percent of the gap between the IRA abatement (across all sectors) and the U.S.'s 2030 nationally determined contribution (NDC). Industrial heat pumps are even more crucial to meeting the U.S.'s 2050 net-zero goal.

Switching to heat pumps also reduces emissions of conventional (non-GHG) pollutants, such as fine particulate matter, nitrogen oxides (NO_X), and sulfur oxides (SO_X). Industrial heat pumps prevent more than 1,000 premature deaths in 2030 and prevent more than 3,000 deaths in 2050 (Figure 4).

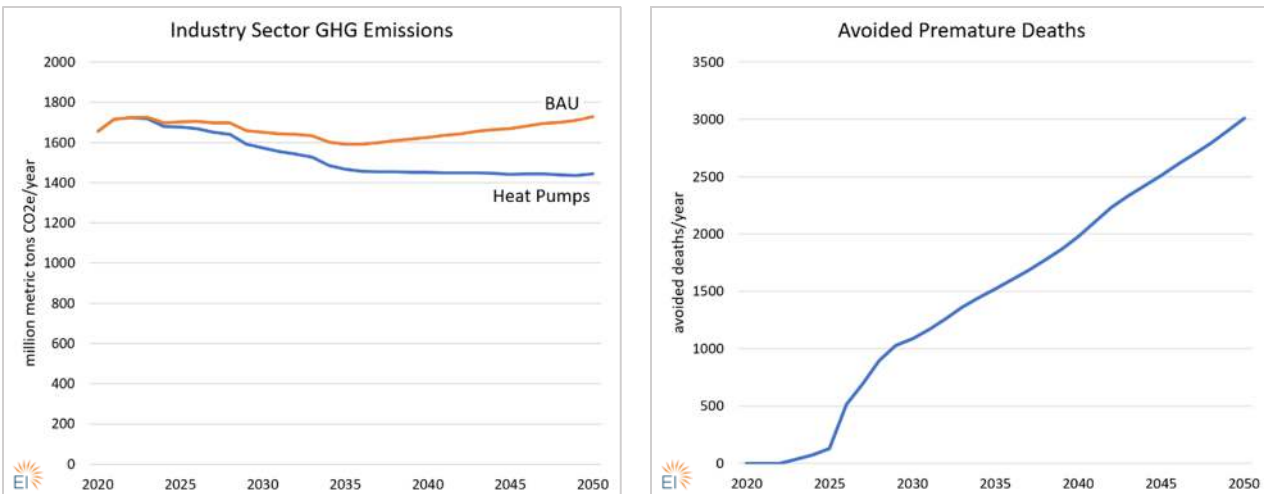

Figure 4. Industry sector GHG emissions and avoided premature deaths from industrial heat pump scenario vs. BAU

Switching to industrial heat pumps also boosts the U.S. economy. Heat pumps produce heat efficiently, plus they have lower heat losses than combustion-related technologies (which lose heat in the exhaust gases and in formed water vapor).[11] Businesses spend less on fossil fuels, leaving more money for electricity, capital equipment, and payments to workers, or enabling businesses to lower the price of their products. Buying electricity or equipment creates more jobs per dollar than buying fossil fuels, while paying workers more or reducing goods' prices puts more money in households' pockets, which is spent on various goods or services, creating additional GDP and jobs. With a transition to heat pumps, GDP is increased by over $42 billion in 2030 and $8 billion in 2050, while there are over 275,000 more U.S. jobs in 2030 and around 75,000 more jobs in 2050 relative to the BAU case in those years (Figure 5). From 2022 to 2050, 17 percent of the increases in job-years (one job worked for one year) are in the electricity supply industry, which grows to meet the increased demand and to replace retiring fossil and nuclear plants (discussed below). The construction industry accounts for 17 percent of the increases, including building and updating industrial facilities and power plants. The remaining increases are distributed as follows: 15 percent in the finance industry, which plays a role in financing new industrial equipment and power plants, 11 percent in other business services (accounting, consulting, etc.), 8 percent in wholesale and retail trade, and 5 percent in manufacturing electrical equipment and other machinery, including heat pumps. The last 27 percent of the increased job-years are spread widely throughout the economy.

There are some job-year losses. Losses are only 13 percent as large as the job-year gains (so, 7.7 job-years are created for each job-year lost). Job-year losses are overwhelmingly concentrated in fossil fuel extraction, processing, and transmission.

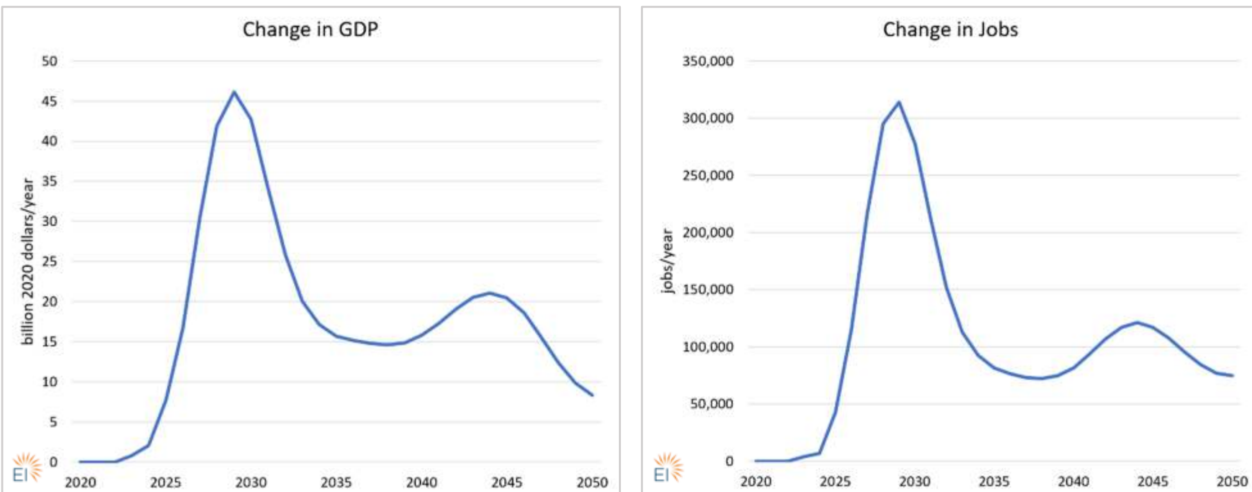

Figure 5. Change in GDP and jobs from industrial heat pump scenario vs. BAU

Using heat pumps instead of burning fossil fuels increases electricity demand relative to BAU (Figure 6). Industrial electricity demand in 2030 increases from 946 TWh to 1,059 TWh (12 percent), and in 2050, demand increases from 1,016 TWh to 1,428 TWh (41 percent). Therefore, new generation capacity and associated grid infrastructure must be constructed. Most of the new capacity is wind and solar PV because these are the most cost-effective resources, and the U.S. grid has the flexibility to accommodate a much higher penetration of variable renewables. Some natural gas peaking plants are also added to help ensure the grid meets peak power needs with a reserve margin. As noted above, the new renewables reduce the marginal price of electricity, making it harder for other plants to compete economically. As a result, the heat pumps scenario has more retirements of coal, natural gas non-peaker, and nuclear plants than the BAU scenario (Figure 6). Most of the newly constructed renewables after 2025 are built to replace fossil and nuclear capacity retirements, rather than to meet new demand from industrial heat pumps. Thus, the demand from industrial heat pumps serves as a catalyst that has a larger effect on transforming the power sector than is suggested by narrowly looking heat pumps' own electricity demand.

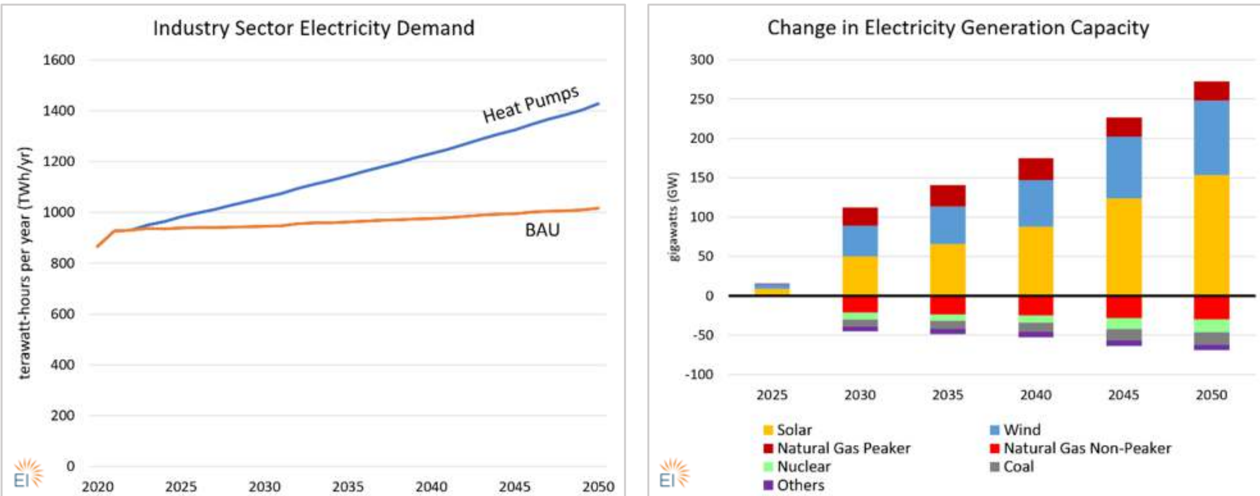

Figure 6. Change in industrial electricity demand and electricity generation capacity from industrial heat pump scenario vs. BAU. The second panel shows the difference in capacity that exists in each listed year relative to BAU, so each stacked bar effectively cumulates changes up through that year. Renewables have a lower capacity factor (share of the year when they operate at their full capacity) due to variability in wind and sunlight availability. Therefore, a larger capacity of renewables is needed to replace a smaller capacity of fossil and nuclear resources. This is the main reason why capacity additions are much larger than capacity retirements. The increased electricity demand from heat pumps also plays a role in making capacity additions larger than retirements.

INDUSTRIAL HEATING TECHNOLOGY CAPITAL AND OPERATING COST COMPARISON

Heat pumps are cost effective compared to alternative technologies, such as natural gas combined heat and power (CHP) systems or electric boilers. A tool for analyzing and comparing capital and operational costs of industrial heat pumps and alternative technologies was developed by Agora Industry, FutureCamp Climate, and Wuppertal Institute.[15] Key findings are shown in Table 3. Calculations use a U.S. electricity price of $74.8/MWh (7.5 ¢/kWh) and a U.S. natural gas price of $17.3/MWh ($5.06/MMBtu), the average prices paid by U.S. industrial energy buyers in 2021.[4]

In the U.S. in 2021, electricity was 4.3 times more expensive than natural gas per unit energy. This causes the electric resistance boiler to be the most expensive technology per unit heat output. However, the high efficiency of heat pumps compensates for the higher cost of electricity, so there is no significant difference in energy costs per unit heat output between natural gas technologies ($18-35/MWhth) and heat pump technologies ($20-34/MWhth).

Table 3. Cost and performance characteristics for industrial heat pumps and three alternate technologies in 2021

	Natural Gas Steam Boiler	Natural Gas CHP	Electric Boiler	Heat Pump (80-100°C)	Heat Pump (100-180°C)
Efficiency/COP	0.95	0.85	0.99	3.7	2.2
Full load hours (hours/year)	2000	6000	2000	6000	6000
Capex ($/kW)	234	900	175	700	870
Capex ($/MWhth)	12	12	14	19	23
Non-energy opex ($/MWhth)	6	3	3	2	3
Fuel/electricity cost ($/MWhth)	18	35	75	20	34
Total cost ($/MWhth)	36	50	92	41	60

Capex = capital expenditures (excluding installation/integration costs). Non-energy opex = annual operational expenditures other than energy, such as staffing and maintenance. CHP = combined heat and power. COP = coefficient of performance, a measure of efficiency where 1.0 is complete conversion of input energy to usable heat. MWh = megawatt hours of fuel or electricity input. MWhth = megawatt hours of thermal (heat) output. Capex and non-energy opex reflect prices in Germany, which are likely similar to U.S. prices. Electricity and natural gas prices are U.S. data from EIA Annual Energy Outlook 2022.[4,15]

Heat pumps have higher capital costs than natural gas technologies, so their total cost per unit heat output is slightly higher ($41-60/MWhth for heat pumps, versus $36-50/MWhth for natural gas technologies). This price gap is relatively small (around 20 percent) and could easily be overcome using policy measures discussed later in this report.

Even without policy measures, the price gap will likely vanish (or may have already vanished) because natural gas prices have increased since 2021. The Henry Hub natural gas spot price in August 2022 was $30/MWh ($8.81/MMBtu), almost double the value used in the calculations for the table above.[16] Figure 7 illustrates the electricity and natural gas price ranges over which industrial heat pumps or natural gas steam boilers are more cost effective. Natural gas prices are likely to remain volatile and exhibit no long-term upward or downward trend in the decades ahead,[xii] but electricity prices are on a long-term downward trend driven by deployment of low-cost wind and solar generation. Additionally, high-temperature heat pump technology may improve in the future, while natural gas technologies are largely mature. Therefore, the price comparison above can vary significantly by year, would favor heat pumps if repeated using mid-2022 energy prices, and will likely favor heat pumps consistently in the longer term even without policy support.

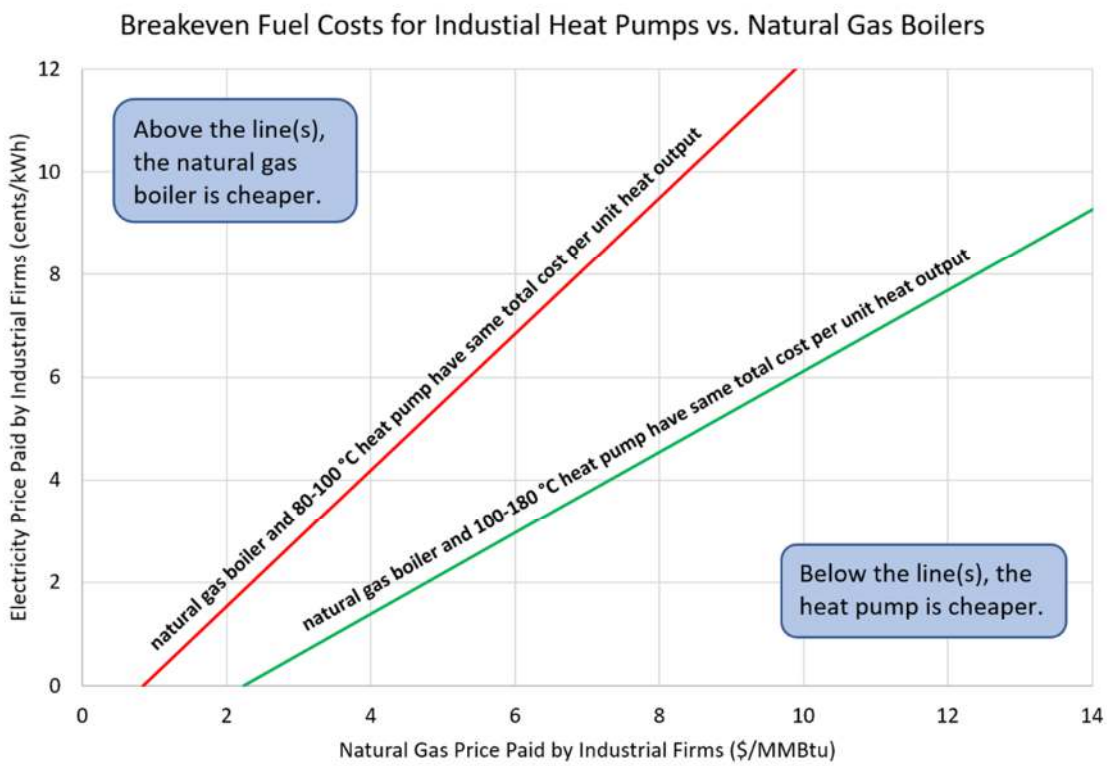

Figure 7. Input electricity and natural gas prices where total cost of heat output from an industrial natural gas boiler is equivalent to the total cost of heat output from an industrial heat pump (per unit heat output). Total costs include capital expenses amortized over the equipment's lifetime, non-fuel operational expenses (staff and maintenance), and fuel/electricity costs. Note that in the U.S., industrial firms benefit from lower natural gas and lower electricity prices than residential customers, which is why the price ranges shown in this graph may seem low to a reader familiar with residential electricity and gas prices.[15]

[xii] Natural gas prices are driven by supply and demand. Supply is reduced by depletion of proven gas reserves and is increased by discovery of new gas deposits or development of new extraction technologies. Demand is driven by domestic usage and by LNG export capacity. The net effect of these factors is volatility in natural gas prices and no clear, technology-driven trend toward consistently increasing or decreasing costs.

Industrial Heat Pump Commercial Status

In 2021, the global market for heat pumps was around $53-68 billion,[17,18] but the vast majority of these were for building HVAC systems or water heating. Industrial heat pumps (i.e., those intended for industrial process heating) accounted for $0.6-1 billion,[19,20] representing under 2 percent of the heat pump market. In 2020, a little under 4 million heat pumps were sold in the U.S., and the installed base of heat pumps in North America was around 40 million units, but these were overwhelmingly for HVAC systems.[21] No sales or stock figures specific to industrial heat pumps are available.

Our research identified 21 manufacturers of heat pumps marketed for industrial process heating, i.e., for applications such as manufacturing food, pharmaceuticals, textiles, chemicals, and printing. These manufacturers, their home countries, and whether they have U.S. operations are detailed in Table 4. We also reviewed a further 26 heat pump manufacturers who do not currently sell models intended for industrial processes, but some of these firms produce units for large commercial buildings that might be adapted to industrial process uses, and some of these firms may be well suited to manufacture industrial heat pumps in the future (Table 5). Finally, we reviewed two manufacturers who formerly manufactured high-temperature industrial heat pumps. Kobelco Compressor Corporation (Japan) produced a heat pump capable of 165°C output in 2011 and 2012, but it no longer manufactures heat pumps. Viking Heating Engines (Norway) formerly sold a model capable of 160°C output, but the company is no longer in business.

Table 4. Manufacturers of industrial heat pumps in 2022 and their headquarters countries

Carrier	U.S.	**Ochsner**	Austria
Combitherm	Germany	**Oilon**	Finland*
Danfoss	Denmark*	**Phnix**	China
Emerson Electric	U.S.	**Robert Bosch**	Germany*
ENGIE Refrigeration	Germany	**Star Refrigeration**	UK
Friotherm	Switzerland	**Thermax Limited**	India*
GEA Group	Germany*	**Trane Technologies**	Ireland*
Hybrid Energy	Norway	**Viessmann Group**	Germany*
Johnson Controls	Ireland*	**Vossli**	China
Mayekawa	Japan*	**Zhengxu New**	China
Mitsubishi Heavy	Japan*		

**Non-U.S. companies with U.S.-based facilities (including corporate offices and manufacturing facilities but excluding independent dealers and repair businesses).*

Table 5. Heat pump manufacturers in 2022 that do not sell models intended for industrial processes

BDR Thermea	Netherlands	**LIXIL**	Japan*
Daikin	Japan*	**Midea**	China*
Denso	Japan	**Moon Envr. Tech.**	China
Finn Geothermal	UK	**NIBE Industrier**	Sweden*
Fujitsu	Japan*	**Panasonic**	Japan*
Glen Dimplex	Ireland*	**Parker Davis HVAC**	U.S.
Heliotherm	Austria	**Qvantum Energi**	Sweden
Hitachi	Japan*	**Rheem**	U.S.
Huntingdon Pump	UK	**Samsung**	S. Korea*
Keling Energy	China	**Sprsun New Energy**	China
Kensa Heat Pump	UK	**Stiebel Eltron**	Germany*
Lennox	U.S.	**Swegon**	Sweden*
LG Electronics	S. Korea*	**Vaillant**	Germany

*Some manufacturers make commercial models that might be adapted to industrial process uses, and some of these firms might be well situated to manufacture industrial heat pumps in the future. *Non-U.S. companies with U.S.-based facilities (including corporate offices and manufacturing facilities but excluding independent dealers and repair businesses).*

Note that some manufacturers sell under multiple or alternate brand names. For example, Johnson Controls sells heat pumps branded as Coleman, Luxaire, and York; Carrier sells heat pumps under a dozen brands including Bryant, Comfortmaker, and Day & Night; Daikin sells Goodman and Amana heat pumps; LIXIL sells American Standard heat pumps; Rheem sells Ruud heat pumps; Parker Davis uses brand name Pioneer, etc. There are also partnerships between companies, such as Johnson Controls–Hitachi and Carrier–Toshiba. Additionally, there are numerous small makers of heat pumps intended for HVAC use, and behind the scenes, the same contracted manufacturing facilities (often in Asia) may produce similar, rebranded equipment for different companies. Due to these complexities and limits on publicly available information, it is not possible to produce a comprehensive listing of industrial or other heat pump manufacturers. However, the tables above, particularly Table 4, should give a sense of the range of companies that could ramp up production in response to increased demand for industrial heat pumps.

FEDERAL POLICY OPTIONS AND AUTHORITY

There are two promising federal[xiii] policy approaches to accelerate the deployment of industrial heat pumps in the U.S.: financial support for RD&D and for companies switching to heat pumps, and standards under DOE and/or the EPA for industrial equipment (including efficiency and CO_2 emissions standards). Standards are in theory powerful tools for accelerating industrial heat pump deployment. Federal agencies would nonetheless have to work through formal rulemaking processes, including opportunities for industry and public comment, and would need to craft the regulations to withstand judicial scrutiny. Financial support under existing legislative authority from the government to the manufacturers or users of industrial heat pumps could likely be deployed more quickly than standards could be implemented. A robust federal program that includes both financial support and standards would drive near-term adoption while also providing the benefits of long-term regulatory certainty.

Financial Support

Financial support is the most important near-term federal mechanism for increasing U.S. industrial heat pump penetration. Government financial support seeks to overcome key barriers in the commercialization and deployment of industrial heat pumps, ranging from research, development, and demonstration (RD&D) to helping businesses afford the up-front expenses of purchasing and installing heat pumps. There are several key methods of providing financial support for industrial heat pumps:

- RD&D: While industrial heat pumps are a commercial product, they represent under 2 percent of the heat pump market, as noted above, and very few manufacturers produce heat pumps capable of reaching temperatures higher than roughly 140°C. Support for RD&D could help develop heat pumps that are more efficient, are cheaper to manufacture, and can reach higher temperatures. RD&D support can come in the form of direct research grants, public-private research partnerships, research conducted in national laboratories, and coordination of research efforts across private companies, academia, and government.[22]
- Incentives and Tax Credits: Government can offer incentives that reduce the cost of purchasing industrial heat pumps, such as equipment rebates (which are commonly used to promote sales of efficient residential appliances). Equipment rebates are simple to administer and are accessible to businesses irrespective of their level of taxable income.

[xiii] Although this report focuses on federal policy, industrial low-temperature heat electrification can also be accelerated by policy at the state level and by utility-run electrification programs and incentives. The discussion of financial incentives and standards in this report may also be useful to state-level policymakers or regulators.

Retooling grants—money provided to help businesses purchase and install electrified industrial equipment—are broadly similar to equipment rebates, but often have more conditions concerning which businesses and activities qualify for the grants.

Alternatively, it is possible to subsidize clean industrial production activities, such as by paying firms per unit of goods they produce exclusively through electrified processes. This approach does not require the government to pick and choose which types of equipment should qualify for an equipment rebate, and it is better at spurring research and development of novel, zero-carbon technologies. However, it can be challenging to administer because it requires robust GHG accounting to ensure neutrality of lifecycle emissions (i.e., that emissions are not simply being moved up the supply chain, potentially outside the U.S.), and care may be needed to avoid violating trade rules on subsidizing domestic firms, at least for exported goods.

It is important that subsidies be issued as grants or refundable tax credits, to ensure they are accessible to manufacturers that do not have net income (and therefore do not have tax liability). Many businesses lack net income in particular years, especially newer, small businesses working to bring innovative technologies to market—exactly the type of businesses that government wishes to support. Nonrefundable tax credits, which only can be used to offset taxes, force those businesses to partner with large financial firms, which can take roughly half the value of the tax credit for themselves.[23] Therefore, it costs government (and taxpayers) twice as much money to provide a subsidy for a desired industrial activity via a nonrefundable tax credit versus the same level of subsidy provided via a grant or refundable tax credit.

- Lending Mechanisms and Access to Low-Cost Financing: Government may improve firms' access to low-cost financing (loans, bonds, etc.) to help pay for purchasing electrified equipment and retrofitting facilities. Rather than being a sole lender, it is generally more cost effective for government to use limited public funds to help shepherd private funds toward clean industrial projects. This can be accomplished through co-lending (where the government and a private lender share the risks and profits of a loan), aggregation (pooling multiple small, industrial projects to diversify risk and increase scale), loan loss reserves or loan guarantees (reducing private lenders' exposure to downside risk from nonrepayment of loans), industrial property-assessed clean energy (attaching the cost of upgrades to an industrial facility's property tax bill, which reduces the default rate), and selling tax-exempt government bonds to raise money for industrial electrification projects from bond markets. These mechanisms are cheaper for government than grants or tax rebates because the funds are loaned and must be repaid with interest. In some cases, government may even earn a profit. Lending mechanisms are ideal for efficient, commercialized technologies, such as heat pumps, where up-front costs can be an important barrier to adoption, but the technology is expected to perform well and enable repayment of a loan.

DOE's Loan Programs Office has experience in applying a range of lending mechanisms and financing tools.

Related IRA Provisions

Section 13501 of the IRA provides $10 billion in funding for the 48C Manufacturing Tax Credit that could be used to accelerate industrial heat pump adoption. The IRA expands eligibility for the tax credit to include re-equipping "an industrial or manufacturing facility with equipment designed to reduce greenhouse gas emissions by at least 20 percent through the installation of… low- or zero-carbon process heat systems."[24] Upgrading an industrial facility to utilize heat pumps (and other zero-emission process heat technologies) clearly meets this definition.

Section 50161 establishes an Advanced Industrial Facilities Deployment Program, which authorizes $5.8 billion to support the purchase, installation, retrofits, or upgrades to industrial facilities to use "advanced industrial technology."[24] This term is defined in the Energy Security and Independence Act of 2007 section 454(c)(1)(F) to include "technologies and processes that increase the energy efficiency of industrial processes,"[25] a definition that would encompass industrial heat pumps, as they are far more efficient than alternative heating technologies (as discussed above).

Related Federal Agency Offices

The most important federal office for providing financial support for innovative industrial and manufacturing technologies and processes has been the Advanced Manufacturing Office (AMO), within DOE's office of Energy Efficiency and Renewable Energy. The AMO has enjoyed bipartisan support, with its annual budget growing from $116 million in 2013 to $416 million in 2022.[26] Recently, DOE announced the AMO will be reorganized into two offices:

The Advanced Materials and Manufacturing Technology Office (AMMTO) will support next-generation materials (such as those with improved strength, high-temperature performance, conductivity, etc.) and clean manufacturing process technologies. It will also focus on securing a sufficient domestic supply of critical materials, including circular economy measures ranging from product design to re-use of parts and recycling of materials. The AMMTO also will support RD&D for innovative manufacturing technologies, workforce training, and entrepreneurship programs.

The Industrial Efficiency and Decarbonization Office (IEDO) will accelerate the adoption of cost-effective technologies that eliminate industrial emissions. This includes a focus on five energy- and emissions-intensive U.S. industries (chemicals, iron and steel, food and beverage, cement, and forest products), as well as cross-cutting technologies useful for many industrial sub-sectors, such as electrification of heat, hydrogen and other low-carbon feedstocks, and combined heat and power. The IEDO also will provide technical assistance to manufacturers and aid in workforce development, preparing workers for clean industrial jobs.

The AMMTO and IEDO are well suited to take the lead on financial incentives for low-temperature heat electrification. They can build on DOE's experience with related programs, including the AMO's history supporting industry RD&D and providing technical assistance (including publishing numerous "bandwidth" studies and other studies outlining industrial efficiency and decarbonization best practices),[27] the DOE Loan Programs Office's experience providing clean-energy financing, and national laboratories' work assessing industrial energy efficiency and decarbonization best practices.

Energy Efficiency Standards

Standards set performance thresholds that equipment must meet to be sold on the market. A well-designed standard is technology neutral, aims to cover as much of the market as possible, and has a built-in mechanism to self-tighten to avoid stagnation.[28] For example, an energy efficiency standard may specify that a piece of equipment such as a boiler must convert at least a certain percentage of the energy in its input fuels to useful heat. A requirement that useful heat output exceed 100 percent of the input energy would disqualify all fossil fuel boilers (and electrical resistance boilers), as only heat pumps can produce useful heat in a quantity that exceeds the input energy. A standard requiring zero CO_2 emissions could similarly prevent fossil-fueled boilers from being sold, but it would not affect equipment using non-heat pump electrical technologies, such as electrical resistance boilers. Industries then select from standard-compliant technologies based on performance and cost.

Ideally, standards are not set separately for each specific industry or process in granular detail but rather offer clear guidelines that cover the entire industrial sector. For example, it is better to regulate CO_2 emissions from widely used industrial activities (such as creating steam, heating materials, or driving chemical reactions) than separately regulating each use of steam, each material to be heated, or each chemical reaction to be driven. Regulations may make distinctions by required temperature, heat delivery rate, or other technical requirements pertaining to the service provided by the equipment.

DOE sets energy efficiency standards for commercial and industrial equipment, such as pumps, unit heaters, warm air furnaces, and commercial packaged boilers.[29] However, existing standards make distinctions for different fuel types. For example, different efficiency standards are set for gas-fired versus oil-fired warm air furnaces,[30] and the same is true of commercial boilers.[31] It is difficult to use energy efficiency or CO_2 emissions standards to drive the transition to heat pumps if weaker standards are set for fossil-fuel-using versions of the equipment. A well-designed standard is technology neutral and thus applies to all fuel types.

42 U.S.C. § 6295(q)(1), "Energy Conservation Standards," indicates that DOE "shall specify a level of energy use or efficiency higher or lower than that which applies (or would apply) for such type (or class) for any group of covered products which have the same function and intended use, if the

Secretary determines that the covered products within such group… consume a different kind of energy from that consumed by other covered products within such type (or class).”[32] This language suggests DOE must set different standards for products that use different energy sources. However, this language is in Part A of the statute, which applies only to “consumer products other than automobiles.” Industrial equipment is covered in Part A-1 of the statute,[33] which has no wording similar to that quoted above from Part A. This difference in wording suggests that DOE may possess the statutory authority to set fuel-neutral standards for industrial equipment.

That said, DOE is legally required to set standards that are “technologically feasible and economically justified.”[34] Whether the “technologically feasible and economically justified” criterion applies to a category such as “industrial boilers” or a narrower category such as “gas-fired industrial boilers” could be challenged in court. DOE would need to demonstrate that the relevant category for determination of technological feasibility is “industrial boilers” (not “gas-fired industrial boilers”) and that switching to electrified models is a technologically feasible and economically justifiable method of meeting the standard. DOE would have to thoughtfully construct its regulations to stay within the bounds of the 2022 Supreme Court ruling in *West Virginia v. Environmental Protection Agency*. This ruling blocked EPA regulations that required shifts in generation from one energy type to others (discussed more below).[35] It would also be necessary to show that industrial heat pumps are sufficiently mature and commercially available. Therefore, it may be advantageous to first use other policy tools (such as the financial incentives discussed above) to increase industrial heat pump market penetration because these incentives are more legally defensible and because widespread availability and use of industrial heat pumps will strengthen the legal case for standards.

New legislation could help clarify that the “technologically feasible and economically justified” criterion is satisfied if there exists a suitable, commercialized technology to perform a specific activity or provide a final service (such as a way to process a type of material or provide warm air), irrespective of whether there exist other technologies or fuels that cannot feasibly meet the proposed efficiency standard.

GHG Emissions Standards

Under authority granted by the Clean Air Act (CAA), the EPA has long-established standards pertaining to certain industrial emissions, but no present standards adequately address CO_2 emissions from low-temperature industrial heat. Under the CAA’s Title V and Prevention of Significant Deterioration (PSD) provisions, any facility that emits more than 250 tons per year of a single air pollutant (or 100 tons per year for some types of facilities) is considered a “major” emitter and is required to obtain an operating permit.[36] For decades, these regulations have required new or modified major facilities to employ Best Available Control Technologies (BACT) to limit industrial emissions of conventional air pollutants, such as volatile organic compounds (VOCs), NO_X, SO_X, and toxic chemicals. The EPA has also promulgated New Source Performance Standards (NSPS) regulations under the CAA that establish emission standards for conventional pollutants from certain industrial sources.

In a 2007 case brought by the state of Massachusetts to compel the EPA under a recalcitrant Bush administration to regulate GHGs, the U.S. Supreme Court held that GHGs are qualifying pollutants under the CAA and that the EPA is legally required to regulate GHG emissions.[37,xiv] Thereafter, under President Obama, the EPA developed rules to limit GHGs from industrial sources but indicated that the GHG emissions threshold triggering a Title V or PSD permitting requirement would be 100,000 tons/year, to prevent the permitting requirements from applying to large numbers of small facilities (since GHG emissions are generally orders of magnitude larger than conventional air pollutant emissions). In 2014, the Supreme Court ruled that the EPA may not use GHG emissions as a basis for subjecting facilities to Title V or PSD permitting requirements, but facilities that are subject to those requirements anyway (i.e., due to their emissions of non-GHG pollutants) may be required to also control their GHG emissions using BACT if these GHG emissions exceed a "de minimus" level that the EPA must set.[36] In 2016, the EPA proposed revisions to the Title V and PSD rules to bring them in line with the 2014 Supreme Court decision, including a proposed de minimus level of 75,000 tons CO_2-equivalent (CO_2e) per year, but the proposed revisions have not been finalized.[39]

The EPA's PSD and NSPS programs, by themselves, might be insufficient to quickly decarbonize low-temperature industrial heat because:

- Many facilities demanding low-temperature industrial heat may not be subject to the requirements because they do not emit more than 250 tons/year of a regulated non-GHG air pollutant or their GHG emissions are below 75,000 tons CO_2e/year, the thresholds for regulation under the PSD program.
- The EPA's control measures white papers specifying BACT for GHG emissions reduction focus on steps that incrementally reduce emissions from fossil fuel combustion (such as improvements to efficiency) rather than establishing order-of-magnitude reductions in emissions, or classifying heat pumps and other electrical and zero-emission technologies as BACT.[40]

The EPA should update its control measures white papers to recognize that order-of-magnitude emission reductions are possible through techniques like electrification, CCS, and electrolytic hydrogen use; emphasize true zero-carbon solutions as preferred BACT options; and indicate that technologies that offer only modest emissions benefits are not sufficient.

In a 2022 case, *West Virginia v. Environmental Protection Agency*, the Supreme Court held that the EPA could not under its NSPS require electricity suppliers to shift to different generating

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[xiv] The finding that GHGs are air pollutants and that the EPA has authority and responsibility to regulate them was later codified in the IRA.[38]

technologies as a means of complying with CAA standards.[35] While that case concerned electricity producers rather than industrial facilities, the EPA will need to be thoughtful about how it establishes GHG emission limitations so that it does not run afoul of *West Virginia v. Environmental Protection Agency*. A regulatory path with reduced legal risk would be for the EPA to establish technology-neutral emission limitations, with potential compliance options including CCS, electrolytic hydrogen co-firing, direct electrification, or a combination of these approaches, rather than relying on electrification as the only compliance option.

Finally, it is important to be aware of several related EPA programs that are relevant to industry but do not address CO_2 from fuel combustion for industrial process heat. These programs may provide important guidance or lessons when designing industrial GHG emissions standards:

- The EPA sets conventional and toxic air pollutant emissions standards for industrial facilities using several types of regulations, including National Emission Standards for Hazardous Air Pollutants, NSPS, Control Techniques Guidelines, Alternative Control Techniques, and others.[41] Rules are set separately for specific industries and industrial activities in highly granular detail.[42,43] These regulations do not cover GHGs and, as discussed above, well-designed GHG emissions standards should strive for broad applicability, clarity, and simplicity rather than making distinctions between many industries and processes.

- The EPA limits emissions from spark-ignition engines used in industrial equipment and tools, but these regulations do not cover GHGs,[44] and engines constitute only a tiny fraction of industrial-energy-using equipment.

- The EPA's Greenhouse Gas Reporting Program requires industrial facilities with annual emissions of more than 25,000 metric tons CO_2e to report their emissions, but this is merely a reporting and disclosure program and does not include GHG emissions standards.[45]

- The EPA has a final rule phasing down the use of fluorinated gases by industry and a proposed rule limiting methane emissions from the oil and gas industry, but these standards do not cover CO_2 from fossil fuel combustion.[46]

- The EPA limits CO_2 from vehicles and from electric power generation facilities, but these regulations do not apply to industrial facilities.[46]

CONCLUSION

Low-temperature industrial process heating represents roughly 35 percent of industrial heat demand and is responsible for around 3.5 percent of total U.S. energy-related GHG emissions. Electrifying low-temperature industrial heat is one of the most technologically ready and cost-effective tools for decarbonizing U.S. industry. Industrial heat pumps can deliver low-temperature heat with unmatched efficiency. They are particularly well suited to the food and beverage, textile, chemicals, wood products, and metal products industries (Table 1). An ambitious effort to electrify all low-temperature U.S. industrial heat demand by 2050 would reduce industrial emissions 77 MMT (5 percent) by 2030 and 284 MMT (16 percent) by 2050 relative to BAU (Figure 4). It would also increase U.S. GDP by more than $42 billion in 2030 and $8 billion in 2050, and it would increase U.S. jobs by 275,000 in 2030 and 75,000 in 2050, relative to BAU (Figure 5). The U.S. government can help develop the market for industrial heat pumps and expand their use through financial support (provided by DOE's new AMMTO and IEDO offices) and, potentially, energy efficiency standards (issued by DOE) or CO_2 emissions standards (issued by the EPA). These moves would contribute substantially to the U.S.'s emissions reductions commitments, support high-quality manufacturing jobs in the U.S., secure domestic supplies of industrial technology and products, and help cement U.S. technological and manufacturing leadership.

Correction

This report was updated in Jan. 2023 to correct a math error in calculating the CO_2 *emissions attributed to low-temperature industrial heat in 2021. Low-temperature industrial process heating was directly responsible for 171 million metric tons of* CO_2 *in 2021, not 344 million metric tons.*

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