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EMBRACING CLEAN HEAT

Opportunities for Zero-Emission Industrial Boilers

Trevor Dolan, Andres Restrepo, Cassandra Lopina, Melanie Law, Madison Carroll

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1. Introduction

American industry currently depends on fossil fuels for power, heat, and much more. In recent years, there has been an emerging consensus across the political spectrum that a strengthened domestic manufacturing base can revitalize many American communities that have suffered years of disinvestment and help rebuild a robust, unionized middle class. But the sector's reliance on oil and gas also means that, in the absence of clean manufacturing technologies and practices, any growth will bring public health risks, hurdles to meeting domestic and international climate targets, and threats to international competitiveness. Recent waves of increased private sector investment in domestic manufacturing may deliver tangible socioeconomic benefits, but those benefits will ultimately be counterproductive if they come at the expense of public health and a stable climate.

These are not merely theoretical concerns: Nearly three-quarters of climate-disrupting carbon dioxide (CO_2) emissions from the U.S. industrial sector derive from fuel combustion. **In addition to CO_2, these units also emit enormous quantities of other pollutants that directly jeopardize public health.** For example, according to U.S. Environmental Protection Agency's (EPA) National Emissions Inventory (NEI), in 2023, fuel combustion at U.S. industrial facilities emitted over 950,000 tons of nitrogen oxides (NO_x), the primary ingredient of smog (U.S. EPA. - a., 2024). This exceeds by about 23 percent the amount of NO_x emitted by the electric sector, a massive leap from only a decade prior when industrial fuel combustion emitted 35 percent less NO_x than U.S. power plants (U.S. EPA. - a., 2024). Moreover, NEI data show that in 2020, industrial boilers emitted over 33,000 tons of hazardous air pollutants (HAPs), which cause ailments including cancer, neurological damage, and birth defects (U.S. EPA. - b., 2020).[1] This figure is well over double the quantity of HAPs emitted by the electric power sector in that same year (U.S. EPA. - b., 2020).

Bolstering domestic manufacturing under the status quo may therefore function as a double-edged sword: It can bring jobs and investment to communities that have been hollowed out by decades of disinvestment, but can also increase pollution burdens on those same populations, who are often already suffering from the cumulative impacts of environmental contamination and socioeconomic harms. However, economic

1 The HAP data cited herein can be found using EPA's interactive NEI Exploration Tool, which is part of the online 2020 National Emissions Inventory and Trends Report (US EPA. - b., 2020).

prosperity and sustained pollution problems need not go hand in hand: Clean industrial growth is possible, but only if industry grows with a commitment to safeguard public health and address the climate crisis. Developing and adopting zero-emission technologies for manufacturing—including for industrial heating needs–will be critical to ensuring it does so.

The good news is that opportunities are already ripe to widely deploy zero-emission technologies in the transition to clean industrial heat. Over three-quarters of GHG emissions from industrial heat applications drive from low- (<130ºC) and medium- (130-500ºC) temperature processes, for which traditional fuel-combustion boilers can be replaced with clean, affordable alternatives (RTC, 2022, p. 10).[2] These include electricity-powered industrial heat pumps for temperatures up to 200ºC; conventional electric resistance and electrode boilers (among other possible options) for temperatures of 200-500ºC; and the use of thermal batteries where appropriate. By transitioning from combustion boilers to electric and thermal battery options in the near-term, industrial facilities can clean up their act today and lay the groundwork for a climate-sustainable future.

Opportunities are already ripe to widely deploy zero-emission technologies in the transition to clean industrial heat.

Regulatory agencies and policymakers—as well as the advocates who support their work—will have a critical role to play in this process, not just federally but at the state and local levels as well. Indeed, state action at the present moment will be particularly critical. The current presidential administration has signaled an unwillingness and outright hostility towards safeguarding public health and the climate: It has doubled down on fossil fuel production, worked to roll back environmental protections, and withheld billions of dollars in appropriated and contractually obligated funds for clean technology and climate projects. It has also imposed extraordinarily broad and controversial import tariffs, which are likely to cause significant economic uncertainty and may discourage investments in new industrial technology. Federal action to advance boiler electrification is therefore unlikely in the current administration, yet states retain full authority under the federal Clean Air Act (CAA) to issue air pollution standards that apply to stationary sources EPA has not yet regulated, or that are more

2 Though we generally use the term "electrification" throughout this report as a catchall for technological pathways to decarbonizing industrial boiler processes, it is also important to recognize that alternative chemistries—different ways of manufacturing the product itself to eliminate the need for heat—are another promising option for eliminating pollution at the source for industrial boilers. Alternative chemistries are currently generally at low technological readiness levels, however, and we do not consider them here as near-term solutions. Similarly, we encourage policymakers to explore policies that can generate clean industrial heat through technologies other than the two we focus primarily on—electric heat pumps and conventional electric boilers—such as thermal batteries, geothermal heat pumps, and solar thermal arrays.

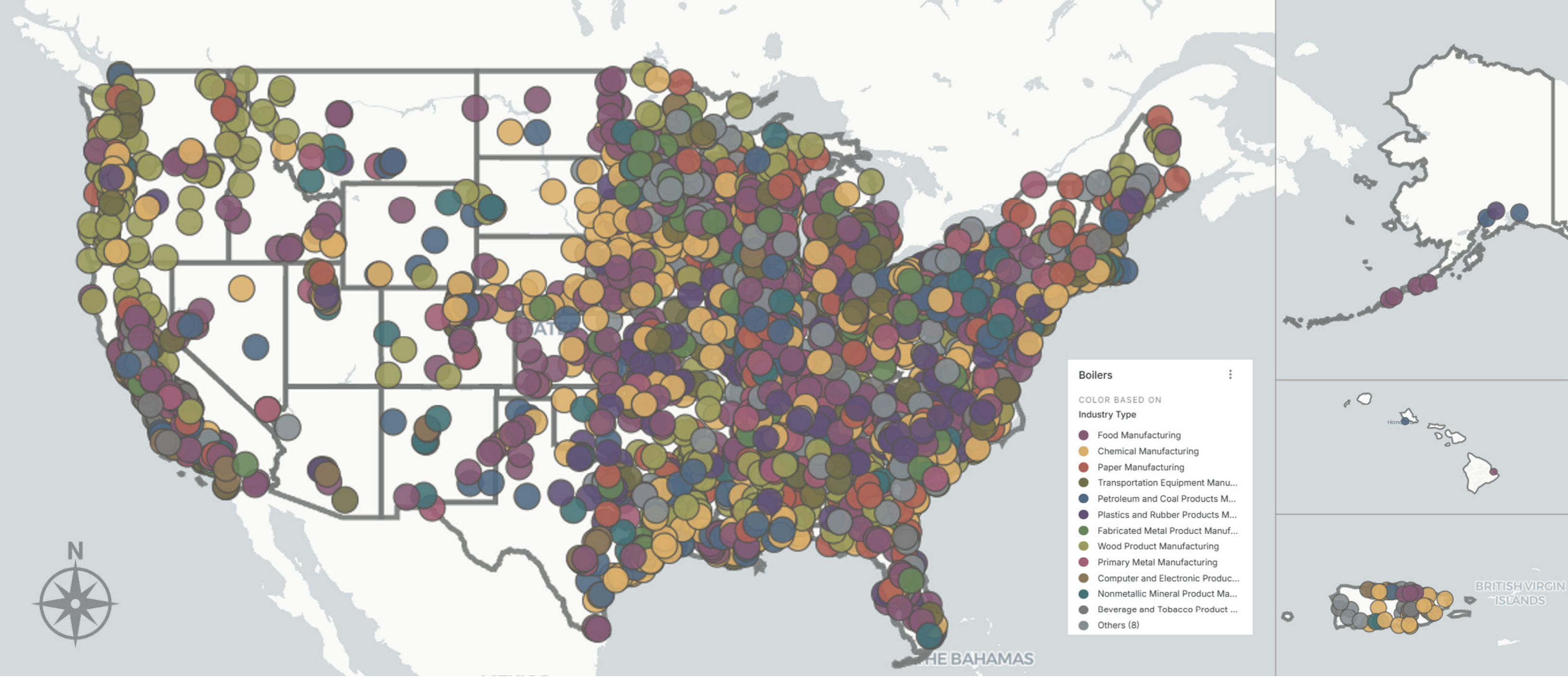


Illustration of National Map of Industrial Boilers. See page 20 for interactive map.

protective than EPA's own requirements for such facilities. Federal CAA standards will ultimately be necessary to achieve broad-scale electrification of the nation's industrial boiler fleet, but in the meantime, state regulators and policymakers can help advance clean and sustainable industrial regrowth.

In service of that vision, **this report will make the technical, economic, environmental, and public health case for aggressively pursuing accelerated adoption of low- and zero-emission alternatives to combustion boilers.** We build that argument around a first-of-its-kind National Map of Industrial Boilers, which contains nearly 14,000 boiler units with integrated data on the criteria and hazardous air pollutants they emit. While state regulators may be particularly interested in these discussions, we intend this paper to appeal to a wide audience, with sufficient technical depth to make a comprehensive case for boiler electrification and accessible takeaways for community advocates, non-profit staff, environmental justice leaders, legislators, and others.

First, we describe the urgent need to decarbonize American industry and the opportunities afforded by industrial boiler electrification. **Second,** we provide a broad overview of the current industrial heat landscape, defining the term and the processes that fit under its umbrella and identifying the ideal technological targets for an emission reduction policy. **Third,** we characterize both the conventional pollution and greenhouse gas (GHG) emissions that result from industrial heat, providing both macro-level data and an analysis of geographically distributed impacts that tend to fall disproportionately on low-income communities and communities of color. **Fourth,** we describe the commercially available technologies for mitigating that pollution. Fifth, we provide an economic analysis of these options and demonstrate that by switching from combustion boilers to electric alternatives, many industrial facilities can achieve substantial pollution reductions at a reasonable cost. **Finally,** we conclude with a discussion of different policy options that regulators, legislators, and others can implement in order to advance the spread of these technologies on the ground.

1.1 THE INDUSTRIAL MODERNIZATION IMPERATIVE

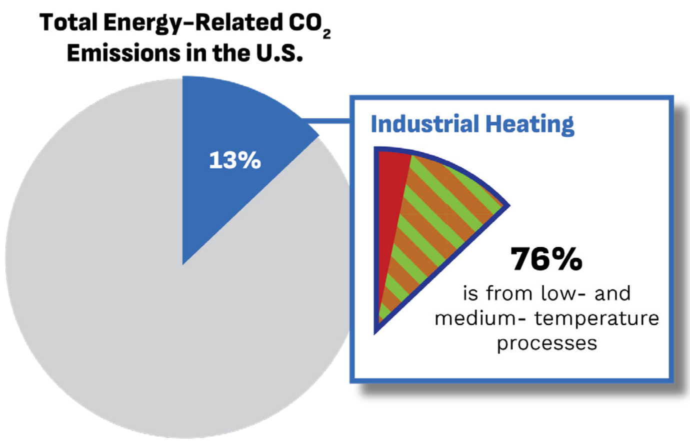
Industrial pollution, in large part a consequence of American industry's reliance on fossil fuels, is a public health crisis for countless fenceline communities. The industrial sector produces NO_x, volatile organic compounds (VOC), particulate matter (PM), and many other air and water pollutants that threaten human health. As detailed in Section 3.3, industrial air pollution is associated with higher rates of respiratory illness, cardiovascular disease, cancer, and premature death for both facilities' workers and the communities in which they're sited (Bergstra et al., 2022; Turner et al., 2020). Industrial sources pose further significant health risks due to their HAPs emissions, which in some cases can increase risks of cancer and other serious health problems even at very low exposure levels.

American industry's dependence on fossil fuels also threatens the sector's international competitiveness. Global pressures to decarbonize are mounting: Europe's carbon border adjustment will impose high tariffs on carbon-intensive American goods, while China has adopted a nationwide action plan to cut climate pollution from its own industrial sector (European Commission Taxation and Customs Union, 2025; Yin et al., 2024). Gas prices are also volatile, creating price uncertainty for American manufacturers, while electric equipment alternatives can provide price stability and higher efficiencies (Hoffmeister et al., 2024). In order to remain internationally competitive, U.S. industry must decarbonize—yet the sector has achieved only small reductions in GHG emissions to date. Since 2005, American industrial sector CO_2 emissions have declined by less than 7 percent, while electric sector emissions have declined by over 40 percent (EIA. - a., 2025, Tables 11.4 and 11.6).

Current projections anticipate that a revitalized manufacturing base, absent policy change, could offset a substantial amount of the country's progress toward cutting climate pollution thus far. Thanks to the industrial sector's growth, the Energy Information Administration's (EIA) 2025 projections indicate that direct energy-based CO_2 emissions from this sector will increase by 5.2 percent through 2035 and by 13.4 percent through 2050 (EIA. - b., 2025, Table 18). 2050 is also the year that global GHG emissions must reach net zero for our planet to have a chance of avoiding the worst impacts of climate change (Intergovernmental Panel on Climate Change, 2021, pp. 12-17).

Besides limiting America's competitiveness in a decarbonizing global market, those trends are also troubling for international efforts to mitigate climate change. The industrial sector is the third-largest source of GHG emissions in the United States after transportation and electricity generation, totaling 1,453 million metric tons (MMT) CO_2-equivalent in direct emissions in 2022 (U.S. EPA. - e., 2024, Tables 2-10 and 2-12). That exceeds the total economy-wide GHG emissions of all but four countries (*EDGAR*, 2024). Even single-digit percentage point increases in U.S. industrial pollution present an outsized burden on the global carbon budget, and on domestic public health through the emission of conventional pollutants like NO_x, PM, and scores of air toxics.

1.2 THE CASE FOR FOCUSING ON INDUSTRIAL BOILERS



While there is no silver bullet to tackle the staggering volume of pollution from American industry, **there is one process element in the sector that contributes a far greater share of GHGs and conventional pollutants than any other: heat.** The U.S. industrial sector encompasses everything from petrochemical production to paper-making. Its diverse subsectors require a myriad of feedstocks, processes, and technologies to operate—splitting hydrocarbons and boiling wood pulp, for example, are very different procedures. But across subsectors and processes, applying heat "to transform materials into useful products" is nearly universal (U.S. Department of Energy, n.d.).

The industrial heat landscape is typically broken down into three tiers: low heat (<130°C), medium heat (130-500°C), and high heat (>500°C) (RTC, 2022, p. 10). Every tier of industrial heating currently relies on burning fossil fuels, with a massive collective energy and carbon footprint in the United States. However, low- and medium-temperature processes account for a disproportionate share of that footprint: While the energy consumed for industrial heating generally accounts for about three-quarters of all energy used in industrial processes, 30 percent of industrial thermal energy needs fall below 100°C and two-thirds fall below 300°C (Hasanbeigi, 2021). From an emissions standpoint, industrial heating produces about 13 percent of the total energy-related CO_2 in the U.S.—and low- and medium-temperature processes generate approximately 76 percent of those heat-related GHG emissions (U.S. DOE. - c., n.d.; RTC, 2022, pp. 9-10). Table 1 provides a summary of common industrial equipment types by common temperature ranges, but precise temperature ranges may vary depending on the specific application, design, and material used.

Table 1: Common Industrial Heat Equipment Categorization by Temperature Profile

Temperature Category	Equipment Types	Example Equipment Subtypes
High (> 500ºC)	Furnaces	Blast, Electric Arc, Electric, Electric Smelting, Basic Oxygen Ferroalloy Arc, Glass, Pot, Dross, Reverberatory, Rotary, Smelters, Cracking Furnace
	Kilns & Calciners	Kilns, Calciner, Precalciner, Lime Kiln, Rotary
	Incinerators	Rotary Kiln Incinerator, Fluidized Bed Incinerator, Catalytic Incinerator
	Metal Processing Equipment	Pelletizing, Rolling
Medium (130ºC - 500ºC)	Chemical Reactors	Reactors
	Process Heaters	Process Heaters, Heat Exchange Systems
	Boilers	Steam, Water Heater, Combined Heat/Gas (Turbine), Waste Heat
	Ovens	Drying, Baking, and Curing Ovens
Low (<130ºC)	Distillation Equipment	Distillation, Evaporators
	Drying Equipment	Convection and Belt Dryers
	Miscellaneous Processing	Bleaching, Pasteurizing, Recausticizing, Sterilizing, Washing, Stock Steaming Preparation

Source: Adapted from RTC, 2022, p. 36

Efforts to decarbonize industrial heat should start with low- and medium-temperature processes, both because of their disproportionately large share of the market and because they present the opportunity for near-term progress due to the current availability of clean, cost-effective alternatives.[3] Encouragingly, electric technologies that emit no pollution at the point of use are already available for many of these applications.

This report focuses specifically on industrial boilers that operate at low and medium temperatures to deliver indirect process heat through steam and other heat transfer media. In a range of contexts, manufacturers can begin to replace traditional fuel-combustion boilers with cost-competitive electric equipment—including

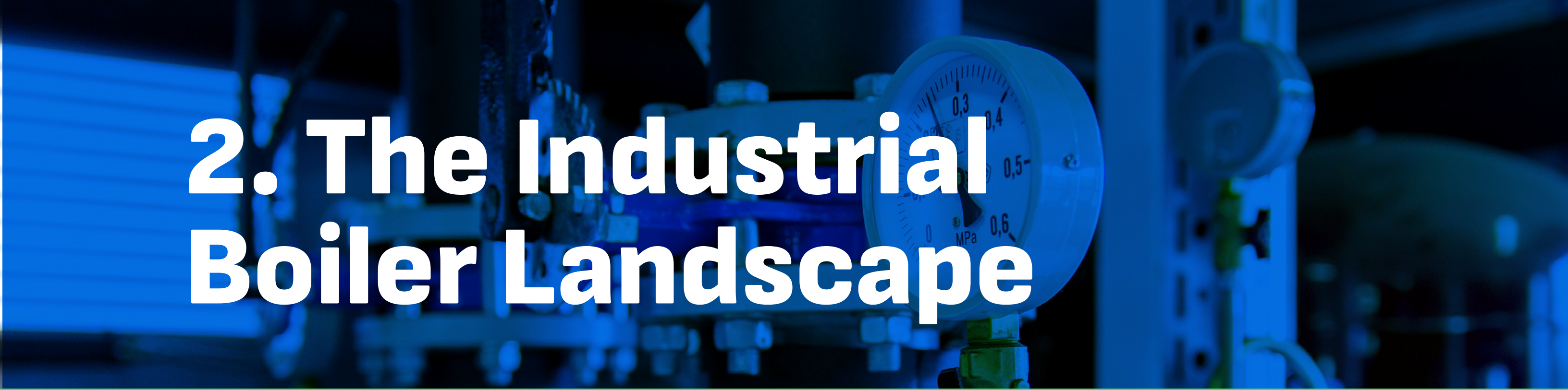
3 However, as we discuss in sections 4 and 5 below, clean and options for producing high-temperature heat–including large-scale thermal batteries powered entirely by renewable energy–are rapidly advancing and will soon be commercially scalable.

stand-alone or combined applications of industrial heat pumps for temperatures up to 200°C, conventional electric boilers for applications in the 200-500°C range (and in some cases much higher), and thermal batteries for a very wide range of temperatures (with added grid demand flexibility as a co-benefit). More information on these technologies is provided in Section 4 below.

Electrifying industrial boilers is a promising near-term opportunity to reduce emissions from the industrial sector. While boiler electrification is only one piece of the complex industrial decarbonization puzzle, it offers a practical step forward using technologies that are already on the market. These non-emitting systems could help meet a significant share of U.S. low- and medium-temperature industrial heat demand—strengthening trade competitiveness and curbing harmful air pollution in many American communities while also substantially reducing the sector's carbon footprint. The urgency to act on industrial emissions is growing, and in many states, the political and economic conditions are aligned to support long-term investments in clean, modern manufacturing systems. This report is designed to help regulators, advocates, and others help translate those conditions favoring clean industrial heat into a widespread, on-the-ground reality by providing an in-depth evaluation of several of they key elements needed to support electrification (Figure 1).

Figure 1: Pathway to Industrial Electrification

The remainder of this report outlines the pathway to industrial electrification by: identifying currently available **technology**; exploring the **emissions benefits** that drive its utilization; and recommending policy options to establish clear **regulatory signals** that promote a competitive landscape and enhance **economic viability**. While acknowledging **grid modernization** as a crucial element to effectively support and utilize new electrified technologies, this report focuses on the aforementioned aspects due to regional variations in grid infrastructure needs.



2. The Industrial Boiler Landscape

As detailed above, fossil-fueled industrial boilers in the United States are a significant source of conventional and GHG pollution, driving public health issues—particularly in fenceline communities—and contributing to the mounting climate crisis. Surprisingly, it is not a straightforward process to identify where boilers and other industrial heat equipment are operating, as most of the publicly available emissions data are summarized at the facility rather than unit level. In 2005, researchers first worked to identify and characterize industrial boilers operating across the U.S. In recent years, new research efforts have further cataloged where boilers are operating, the fuels they utilize, and associated GHG emissions. However, comprehensive and reliable data on industrial boilers, particularly with respect to emissions of conventional and hazardous pollutants, have remained incomplete, and the data that do exist have been scattered across multiple different sources using diverse methodological protocols.

This report aims to help rectify this problem. To do so, **we have expanded the data available on boilers by developing a first-of-its-kind emissions dataset for the full fleet of U.S. industrial boilers[4], with a map of nearly 14,000 boiler units and the conventional pollutants they emit**. This section is intended to describe this landscape of fossil-fueled boilers and detail past research efforts to quantify and characterize the U.S. boiler population. The following section will explain how we built a comprehensive dataset from multiple existing sources and lay out key takeaways from our emissions analysis.

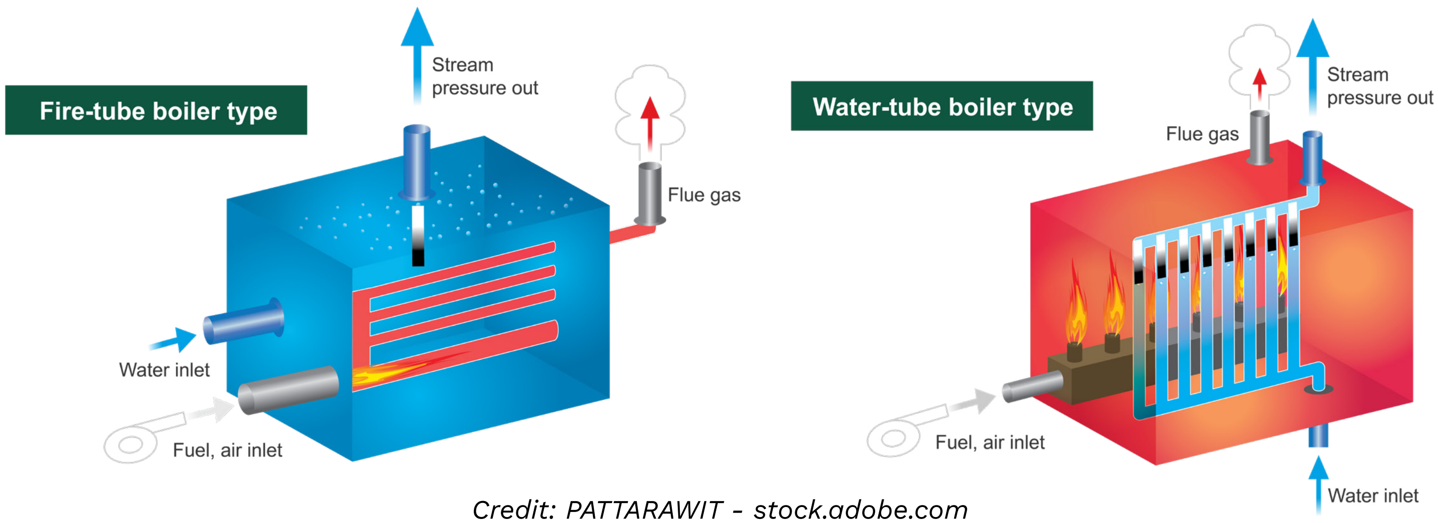
2.1 COMBUSTION BOILER TECHNOLOGIES

Boilers are the backbone of industrial heat and steam generation. While we use the term generically in this paper, there is a diverse set of boiler types operating across industries. Broadly speaking, combustion boilers can be categorized by their heat transfer mechanism, fuel type, and pressure levels. The two dominant designs are fire-tube and water-tube boilers, each optimized for different applications, as shown in Figure 2. Fire-tube boilers, a mainstay of smaller-scale heating, immerse tubes carrying hot combustion gases in a water-filled vessel, transferring heat by conduction. Their relatively simple design, lower cost, and smaller capacity of <10 million British

4 This figure includes boilers reported to EPA's NEI in 2020.

thermal units per hour (MMBtu/hr) make them prevalent in commercial heating and small industrial processes (McKellar, 2023). In contrast, water-tube boilers—used in high-pressure applications such as power generation and large-scale manufacturing—pass water through tubes heated externally by combustion gases, allowing for higher efficiency and a much greater thermal output (Carvalho et al., n.d.).

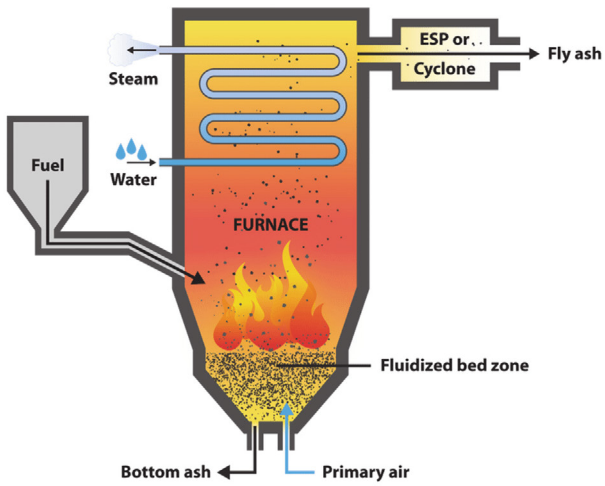
Figure 2: Combustion Fire-Tube and Water-Tube Boiler Design



Credit: PATTARAWIT - stock.adobe.com

Another key distinction lies in fuel source and combustion technology. Most combustion boilers burn purchased fuels such as natural gas, fuel oil, or coal, with varying efficiencies (Tawil, 2021, p. 3-1). Pulverized coal boilers—historically the workhorses of heavy industry—are among the most carbon-intensive, while fluidized bed boilers, which suspend fuel particles in a turbulent flow of air, offer improved combustion efficiency and lower emissions (Figure 3). Gas-fired boilers, dominant in many industrial applications, generally produce less emissions than coal or oil alternatives on-site while providing more flexible operation, particularly in condensing boiler designs, which extract additional heat from exhaust gases to improve efficiency. In addition, a substantial percentage of combustion boilers fire byproduct fuels that result from other industrial processes occurring at the facility, such as blast furnace gas at steel production facilities and black liquor, wood chips, and bark at pulp and paper mills.

Figure 3: Fluidized Bed Boiler Design



Source: Yliniemi, Juho. (2017).
Alkali activation-granulation of fluidized bed combustion fly ashes.

These traditional fuel-combustion boilers are widely used for steam production across the industrial sector. In a 2005 Energy and Environmental Analysis study—the most recent national survey available—a combined inventory of industrial and commercial boilers found that there were 43,000 boilers with a combined capacity of 1.6 million MMBtu/hour (Energy and Environmental Analysis, Inc., 2005, p. ES-1), as summarized in Table 2. Notably, over 70 percent of boilers surveyed had a capacity of < 10 MMBtu/hour, but these small capacity units accounted for only about 15 percent of total boiler capacity (Energy and Environmental Analysis, Inc., 2005, p. ES-1).

Table 2: Summary of 2005 Industrial Boiler Inventory by Unit Capacity

	Boiler units						
	Food	Paper	Chemicals	Refining	Metals	Other Manufacturing	Total
< 10 MMBtu/hr	6,570	820	6,750	260	1,850	7,725	23,495
10-50 MMBtu/hr	3,070	1,080	3,370	260	920	3,680	12,380
50-100 MMBtu/hr	570	530	950	260	330	930	3,570
100-250 MMBtu/hr	330	540	590	200	110	440	2,210
>250 MMBtu/hr	70	490	350	220	120	110	1,360
Total	10,610	3,460	11,980	1,200	3,330	12,435	43,015

Source: Energy and Environmental Analysis, Inc., 2005

Building off the results of the 2005 Energy and Environmental Analysis report, researchers from Northwestern University and UC Santa Barbara undertook a new boiler characterization study in 2022 that considered the impact of electrifying the U.S. industrial boiler fleet (Schoeneberger et al., 2022). Rather than relying upon survey results, the 2022 study utilized multiple existing datasets;[5] Schoenberger, et al.'s resulting dataset, which included 38,537 total units, characterized boiler fuel use by the number of boilers operating and the total installed capacity, as summarized in Table 3 (Schoeneberger et al., 2022, p. 4).

Table 3: Percentages of number of boilers and total installed capacity by fuel type from the 2022 Northwestern/UC Santa Barbara Boiler Analysis

Fuel Type	Proportion of Boilers	Total Installed Capacity
Gas	67.0%	41.0%
Oil Products	6.4%	10.4%
Biomass	6.1%	9.5%
Coal	1.9%	9.4%
Other Fuels	3.0%	6.9%
Fuel Not Reported	15.6%	22.9%

Source: Schoeneberger et al., 2022, p.6

As with the manufacturing sector as a whole, combustion boilers are now at a crossroads. While incremental efficiency improvements continue to accrue for these technologies, each one operates through the combustion of polluting fuels, such that even a maximally efficient boiler fleet will still be a major driver of the climate and public health crises described above—and will remain technological laggards in a rapidly evolving global industrial landscape. However, understanding the design, thermodynamic limitations, and emissions profiles of the domestic population of combustion boilers provides a necessary foundation for evaluating electrification and low-carbon alternatives.

5 The datasets Schoenberger et al. drew on included including EPA's GHG Reporting Program (GHGRP) (794 boilers), EPA's Maximum Achievable Control Technology (MACT) dataset (4,412 boilers), EPA's National Emissions Inventory (NEI) (13,988 boilers), and the National Renewable Energy Laboratory (NREL) Manufacturing Thermal Energy Use study (19,343 boilers) (Schoeneberger et al., 2022, pp. 2-4).

3. Emissions Impacts of the Existing Boiler Fleet

This section will provide new insights into criteria pollutants from U.S. industrial boilers, building upon the advancements in characterizing the U.S. industrial boiler fleet achieved in the 2022 Northwestern/UC-Santa Barbara study.[6] In this section we will also introduce our own research to further explore emissions of criteria air pollutants (i.e., those regulated under EPA's National Ambient Air Quality Standards (NAAQS) program) and HAPs from boilers.

In the two subsections that follow, we first provide a brief overview of the GHG emissions generated by the U.S. boiler fleet, relying on data from the Greenhouse Gas Reporting Program (GHGRP) as evaluated by a recent analysis issued by the Center for Applied Environmental Law and Policy (CAELP). We then offer a discussion of the conventional and hazardous air pollutant impacts from these units. Our disaggregated analysis of NEI data allows for a more precise understanding of the geographically distributed air quality impacts and public health burdens associated with these emissions, providing a crucial foundation for evaluating the benefits of transitioning to cleaner, electric alternatives discussed later in the report.

3.1 GHG EMISSIONS OVERVIEW

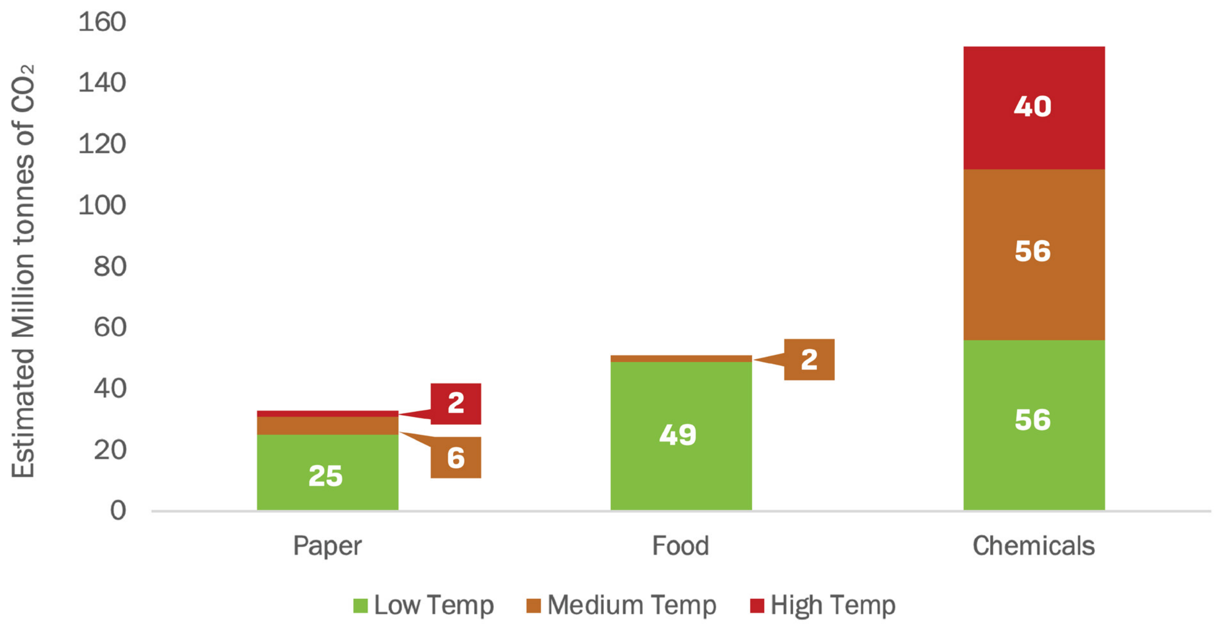
In the United States, the industrial sector is responsible for 23 percent of all GHG emissions, the vast majority of which come from fossil fuel combustion (U.S. EPA. -e., 2024, Table 2-5). Natural gas accounts for 48 percent of industrial fuel use by total heat input (Smillie et al., 2024), more than any other fuel. In recent years, analysts have thoroughly characterized GHG emissions from the U.S. industrial boiler fleet in particular. In October 2024, CAELP published an analysis that, among other things, analyzed data from the GHGRP to explore GHG emissions from industrial boilers (Smillie et al., 2024). The report's findings reflect data from industrial facilities that emit over 25,000 metric tons of CO_2 equivalent per year (and are therefore required to report their emissions to EPA through the GHGRP) (CAELP, 2024, p. 6). CAELP found

6 That study, for the first time, connected boiler locations and operational characteristics by integrating federal emissions inventory datasets. Historically, publicly available emissions data have been aggregated at the facility level, limiting the ability of interested parties—including researchers, policymakers, advocates, industry representatives, and other stakeholders—to attribute specific pollutants to individual equipment units. The 2022 study laid critical groundwork by leveraging datasets such as EPA's GHGRP and NEI to understand the distribution and fuel use of boilers. This information has informed subsequent analyses of GHG emissions, including our own.

that across the eight energy-intensive industrial sectors—chemicals, refining, cement, iron and steel, pulp and paper, food and beverage, glass, and aluminum—**combustion boilers emitted over 70 million metric tons of CO_2** (CAELP, 2024, p. 9). From a climate standpoint, this is equivalent to over 180 billion gasoline-powered vehicle miles traveled annually, or over 9.6 million homes powered for one year (U.S. EPA. - d. (2024)). Taking into account boilers at facilities that do not report to the GHGRP would reveal even higher CO_2 emissions.

CAELP also reported in a concurrent study that **thermal processes below 200°C account for 75 percent of all heat demand from industrial boilers** (Smillie et al., 2024, p. 8). As indicated in Table 1, the CO_2 emissions associated with different combustion-related temperature ranges vary significantly across each of the major industrial subsectors. The majority of combustion-related emissions from refining, iron and steel, and cement, for instance, are from high-heat equipment (CAELP, 2024, p. 11). Conversely, for pulp and paper and food and beverage, nearly all CO_2 emissions come from low-heat processes, while the ratios are more evenly divided across different temperature ranges in chemical manufacturing (CAELP, 2024, p. 11). The estimated combustion-related CO_2 emissions by subsector and temperature profiles are summarized in Figure 4.

Figure 4: CAELP Estimates of Combustion-Related CO_2 Emissions by Subsector and Temperature Profile.



Source: CAELP, 2024, p. 9.

While the recently comparatively low cost of gas and the zero marginal costs associated with byproduct fuels provide a financial incentive for manufacturers to maintain the technologies that utilize them, ongoing reliance on gas combustion for industrial heating needs is incompatible with achieving the GHG reduction goals—including net-zero by 2050—that will allow us to avoid the worst impacts of climate change.

3.2 AIR POLLUTION EMISSIONS ANALYSIS

Our analysis now turns to the critical issue of the criteria air pollutant and HAP emissions from industrial heat generation. Recognizing the absence of a comprehensive, unit-level inventory for these pollutants specifically from boilers, we drew on EPA's NEI database as a first step in this analysis. Because data in the NEI derives from state-level surveys that do not follow a single national data collection and reporting protocol—and typically provide only facility-level information—further analytic work was necessary to drill down into the NEI data to disaggregate the emissions from industrial boilers in particular and to determine where those boilers were located. By carefully examining the unit-level data and associated Source Classification Codes (SCC), we developed a unique approach to identify the average air pollutant emissions from boilers and their geographic locations.

Note on NEI Data Limitations

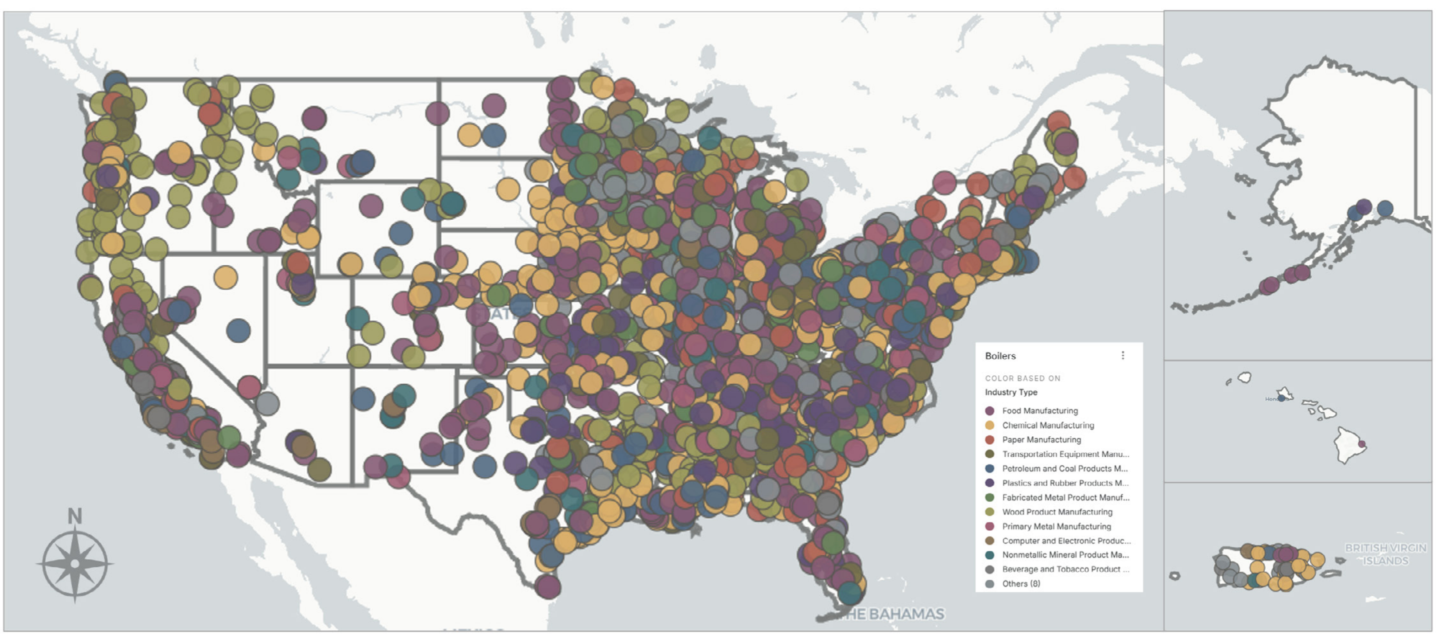
The data presented in this report utilizes information sourced from the EPA's NEI. EPA itself acknowledges the mixed nature of this inventory, which relies on data provided by state, local, and tribal air agencies, supplemented by EPA data. As such, users are advised to carefully consider the sources, scale, accuracy, and currency of NEI data, ensuring they are utilizing the most recent versions available, as stated in EPA documentation.

Several factors inherent in the NEI compilation process can affect data accuracy at granular levels, including variations in reporting requirements, emissions estimate methodologies, data aggregation, and data completeness. In some instances, multiple physical boilers at a single location are aggregated in the NEI database and reported as a single entry (row) with combined emissions data. This aggregation is often indicated in the notes field. In the process of refining the NEI data to develop our National Map of Industrial Boilers (see methodology in Appendix 3), we disaggregated those combined reporting units, which we refer to here as "reported units", to identify the number of individual boilers in the current U.S. fleet (i.e. the total number of boilers widget). However, because splitting those boilers out into individual entries would require making very rough assumptions about each unit's emissions profile, the number of rows in the National Map dataset represents the original aggregated reported units. Readers should interpret those metrics in the map accordingly.

Readers should also note that because of NEI data limitations, this report focuses on the analysis of general trends derived from averaged data rather than the evaluation of specific individual units. This approach is intended to provide a broader understanding of emission patterns while mitigating the impact of potential inaccuracies at the individual source level, aligning with a pragmatic approach to utilizing large-scale environmental datasets with acknowledged limitations. When using the data for more detailed analysis, we recommend taking additional efforts to validate high reported emissions using air permits or other documentation.

Our full analysis identified over 19,000 potential boiler units within the NEI. After applying rigorous confidence criteria based on SCC codes and unit descriptions (see methodology in Appendix 3), we determined that 13,987 units could be classified as boilers with high or medium confidence. This refined dataset is visualized in an [online interactive National Map of Industrial Boilers] (Evergreen Action. - a, 2024), designed to empower national, state, and local efforts to understand the geographically distributed environmental impacts of the current industrial boiler fleet as a first step in mitigating those emissions. The map's dynamic features allow users to filter and explore the data by various parameters such as state, fuel type, subsector industry, unit capacity, and proximity to environmental justice communities[7], facilitating targeted analysis of emission trends (Figure 5).

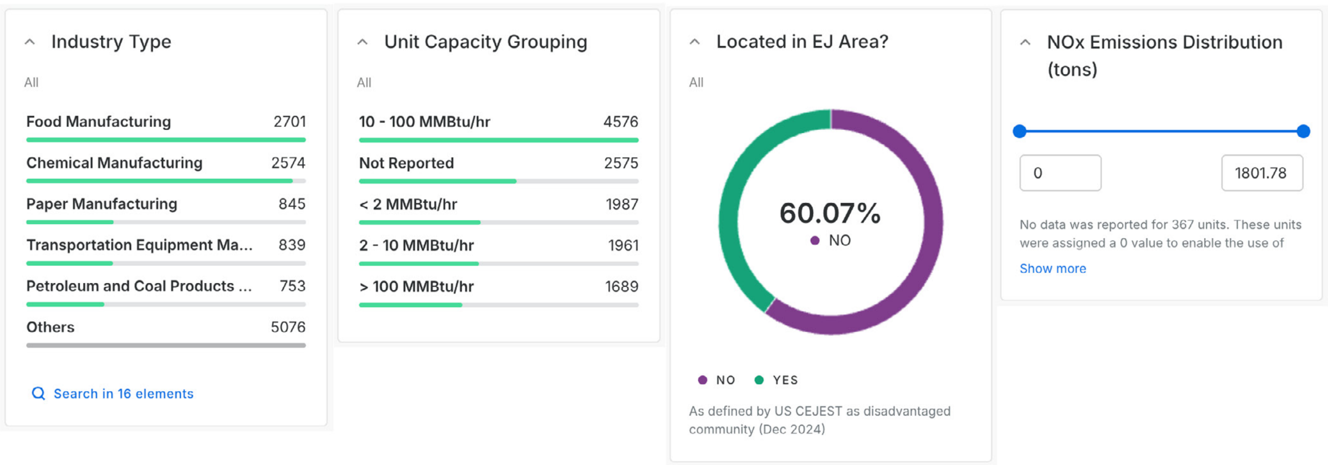
Figure 5: National Map of Industrial Boiler Locations By Subsector



7 As defined by archived data from Climate and Economic Justice Screening Tool (CEJEST) 2.0, as of December 2024.

The filtering options incorporated into this map were intentionally designed to align with existing and proposed regulatory frameworks. For instance, the unit capacity groupings (10-100 MMBtu/hr and > 100 MMBtu/hr) correspond to the applicability thresholds for EPA's federal New Source Performance Standards (NSPS) Subparts Db and Dc, which set emission standards for standard and small industrial, commercial, and institutional boilers, respectively.[8] The < 2 MMBtu/hr category aligns with recent regulatory developments in jurisdictions like the South Coast Air Quality Management District (South Coast) and the Northeast States for Coordinated Air Use Management (NESCAUM). Furthermore, the applicability criteria for National Emissions Standards for Hazardous Air Pollutants (NESHAP), which are often fuel-based, were also considered in the map's design (as shown in Figure 6). An in-depth discussion of the NSPS, NESHAP, and South Coast regulations appears in Section 6. It is important to note that in some cases multiple boilers were reported as one unit; we therefore distinguish throughout this section between the real recorded number of boilers and NEI's "reported units," as described in the NEI data limitations breakout box above.

Figure 6: Map Filters Summarizing Number of Reported Units that Meet Given Criteria[9]



Identifying specific fuel types for boilers within the NEI presented analytical challenges. While fuel information was often present in the unit description field, NEI data lacks a dedicated fuel type field. Instead, fuel is typically indicated through one or more SCC codes. This coding system does not always specify the primary fuel, although in some instances, reasonable assumptions about auxiliary fuels can be made (e.g., the co-reporting of solid fuels makes natural gas as a primary fuel unlikely).
To address the limitations in NEI data accuracy, we present the summarized emis-

8 40 C.F.R. § 60, Subparts Db and Dc.

9 Filters are shown at full extent (all boilers across continental US, Alaska, Hawaii, and Puerto Rico). The total number of boilers in the dataset may be higher than what appears in this table due to multiple units being installed in one location. However, the filters summarize the number of reported units in the data set.

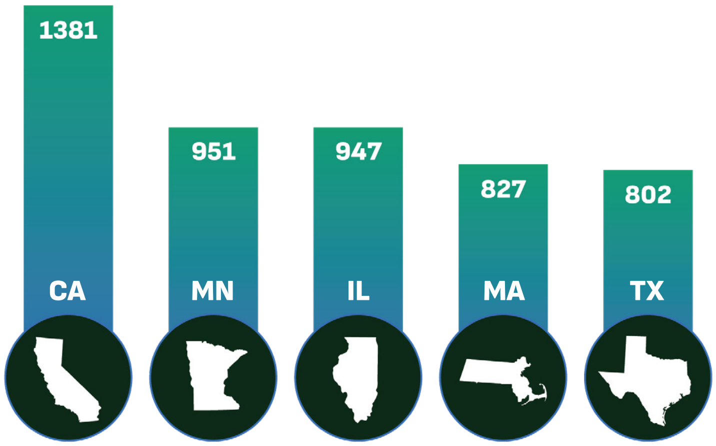
sions data in the map as averages, but also provide additional tools to allow users to further evaluate reported data on individual units or to isolate units within specific emissions ranges.

We anticipate that this interactive map will be a valuable tool for exploring specific areas of interest, such as the prevalence of different fuel types among boilers or the distribution of boiler capacities across states. For the purpose of this report, we highlight several key findings from this analysis:

Finding #1 - Boilers Generate 6 Percent of All Industrial NO_x Pollution: Comparing the cumulative NO_x emissions of the National Map dataset to NEI reporting on industrial emissions in 2020, we find that boilers produced 6 percent of all industrial NO_x pollution. That is more than the reported NO_x emissions from other major source categories, including coal-fired power plants, cement production facilities, and petroleum refineries. (U.S. EPA. – b., 2020). As detailed below, NO_x is a dangerous pollutant and potent greenhouse gas that forms ozone in the atmosphere and contributes to cardiovascular and respiratory disease. Given the diverse number of emissions sources operating at U.S. industrial facilities, it is striking that boilers contribute a full 6 percent share of that pollution.

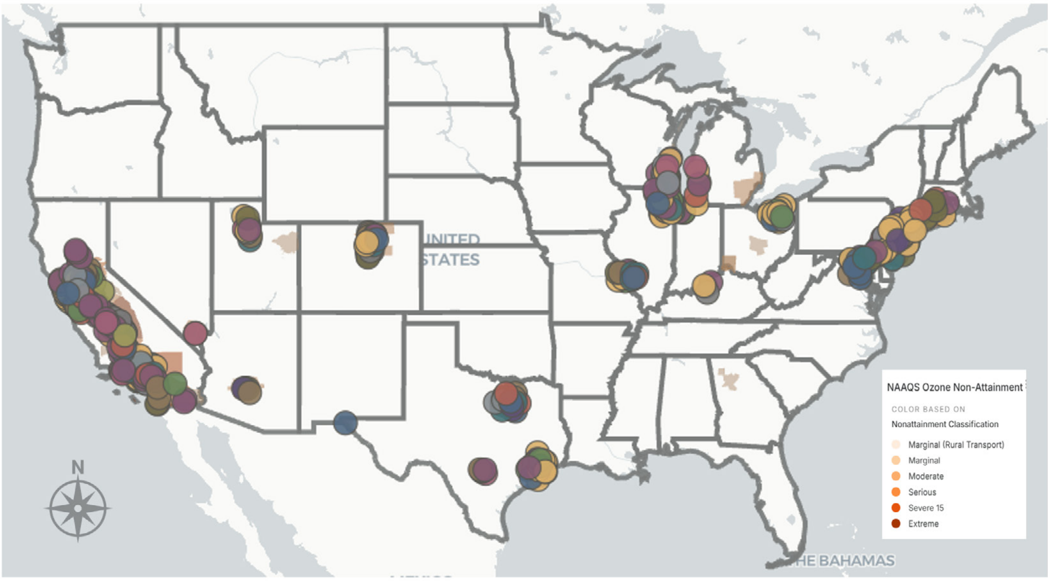
Finding #2 - Nearly 40 Percent of Boilers Across the U.S. Are Installed in 5 States: California exhibits the largest number of boilers in the U.S., with 1,386 boilers (recorded as 1,381 reported units in the NEI dataset). Minnesota has 951 boilers (same number of reported units), Illinois has 1,237 boilers (947 reported units), Massachusetts has 921 boilers (827 reported units), and Texas 802 boilers (same number of reported units). The data indicate a widespread reliance on process heat across diverse industrial landscapes (Figure 7).

Figure 7: States with Highest Number of Boilers



Finding #3 - 25 Percent of Industrial Boilers are Located in NAAQS Nonattainment Areas: Our analysis finds that a quarter of all industrial boilers are located in nonattainment areas where ozone pollution consistently exceeds the NAAQS 8-hour ozone limit, based on the 2015 standard set by EPA. As described below, combustion boilers emit major precursors that form ozone in the atmosphere, including NO_x and VOCs. The boilers in these nonattainment areas are thereby currently worsening local ozone pollution, but electrifying those units would eliminate NO_x and VOC emissions at the source; in nonattainment areas with especially high concentrations of industrial boilers, widespread electrification could meaningfully help bring ambient ozone down to within legal limits.

Figure 8: Map of Boilers Located in an 8-hour Ozone NAAQS Non-Attainment Areas



Finding #4 - Just Two Companies Operate Nearly a Third of The Nation's Highest NO_x Emitting Boilers: When producing the National Map dataset, we cleaned and standardized the reported company names in the NEI database to facilitate comparisons and identify opportunities to work with companies on targeted emissions reduction efforts. Among the set of highest-emitting NO_x boilers (top 1 percent nationally), we found that two companies—Westrock LLC (21 reported units) and International Paper (16 reported units)—operate 30 percent of the highest-emitting boilers in the U.S. Looking more broadly at the entire boiler population, 3,523 companies that operate boilers across the country. The top 10 companies with the highest number of boilers collectively operate 839 boilers and are primarily within the food manufacturing (44 percent) and paper manufacturing (27 percent) industries (Table 4).

Table 4: Top 10 Companies with the Highest Number of Boiler Reported Units

Primary Sector(s)	Company Name	Reported Units
Food & Chemical Manufacturing	Cargill	131
Food Manufacturing	Archer Daniels Midland Company	115
Paper & Wood Product Manufacturing	Georgia Pacific	92
Paper Manufacturing	International Paper	86
Paper Manufacturing	Westrock LLC	82
Food Manufacturing	Darling Ingredients	74
Petroleum & Chemical Manufacturing	Valero Refining	69
Food Manufacturing	Tyson Foods	65
Petroleum & Chemical Manufacturing	Exxon Mobil	64
Transportation Equipment & Fabricated Metal Production	Aerojet Rocketdyne	61

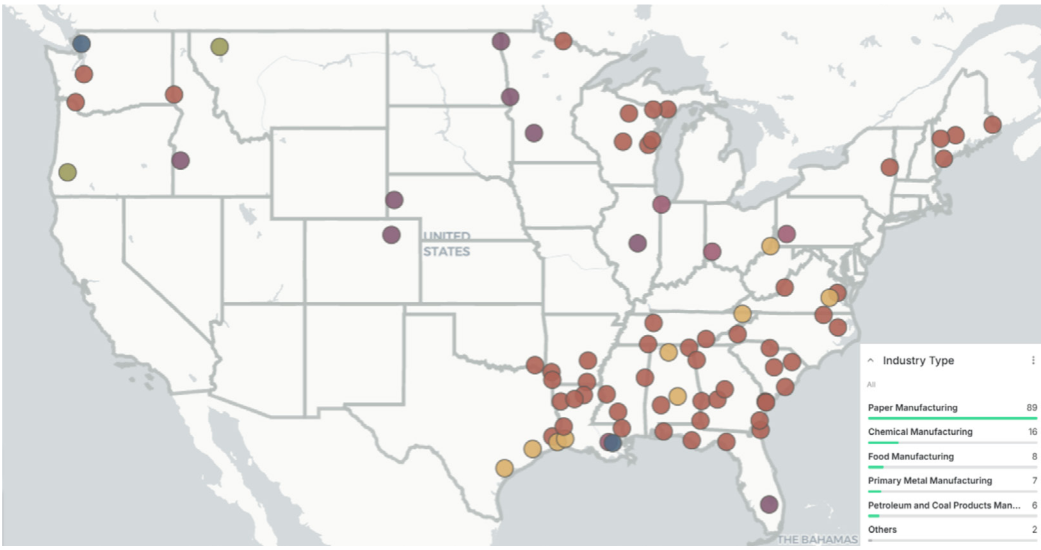
Finding #5 - NO_x Emissions Data Reported for Boilers is Heavily Skewed Due to High Emitters, and a Large Proportion of High Emitters Are Located in Disadvantaged Communities: Annual NO_x emissions were reported for 93 percent of the sources listed in the dataset.[10] In evaluating those emissions, we found that the histogram was heavily right-skewed, meaning that high-emissions units are pulling the average upwards, while the majority of data points are clustered around lower values (median of 1.0 ton and average of 15.3 tons). The standard deviation was also high (68.0 tons), indicating a wide spread in the data. The maximum value reported was 1,801.8 tons, from a single 1,230 MMBtu/hr boiler reported by Westlake U.S. Chemical in Louisiana's Cancer Alley. This number was not a single outlier: The top 1 percent highest-polluting sources reported values above 341.2 tons, meaning that 127 reported units (152 boilers) reported NO_x emissions higher than this value. The top 5 percent of polluting sources—634 reported units (688 boilers)—reported emissions above 57.6 tons.

When analyzing the highest emitting NO_x boilers in the country (top 1 percent), we found that 66 percent of the reported units were located in federally recognized dis-

10 The remaining 7 percent did not have values either due to a lack of data available or incomplete data reporting efforts.

advantaged communities (DAC)[11], with the highest concentration in Louisiana (Figure 9). In turn, a majority of these reported units (68 percent) were associated with paper manufacturing, with unit capacities typically over 100 MMBtu/hr. See Section 6.2 below for context on the existing emissions standards on industrial equipment mitigating this NO_x pollution.

Figure 9: Distribution of Highest Emitting Boiler Reported Units Across the U.S. (Top 1 Percent for Annual NO_x Emissions)

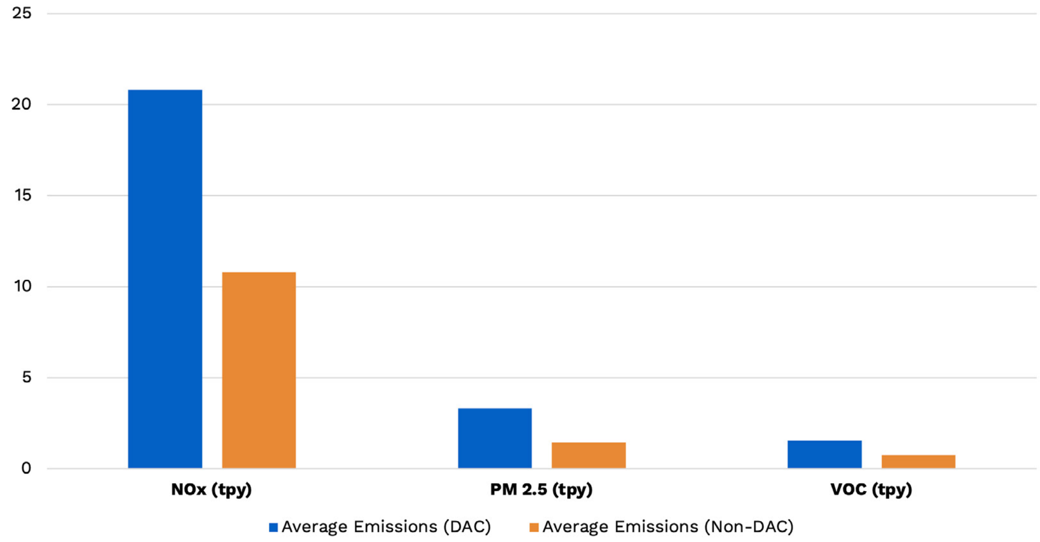


Finding #6 - Nationally, Boilers Impose Disproportionately Higher Pollution Burdens on Disadvantaged Communities: Alarmingly, over 40 percent of industrial boilers nationwide are situated within federally recognized DACs. Our analysis reveals a consistent and concerning trend: Industrial boilers (reported units) located within those communities exhibit significantly higher average emissions across all major pollutant types compared to those in non-DACs (figure 10).[12] Nationally, the average annual boiler NO_x emissions in DACs are nearly double the emissions elsewhere—20.8 tons vs. 10.8 tons. We see similarly elevated disparities for other harmful pollutants, including fine particulate matter ($PM_{2.5}$), VOCs, mercury, lead, cadmium, formaldehyde, and hydrochloric acid. This finding underscores the disproportionate pollution burden these communities face and highlights the urgent need for targeted mitigation strategies in these areas to remedy the environmental injustices that industrial boiler emissions exacerbate.

11 The White House Council on Environmental Quality has defined “disadvantaged communities” through eight criteria, including climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development (Shrestha et al., 2023). The now-retired Climate and Environmental Justice Screening Tool synthesized those criteria to develop a map of federally recognized disadvantaged communities.

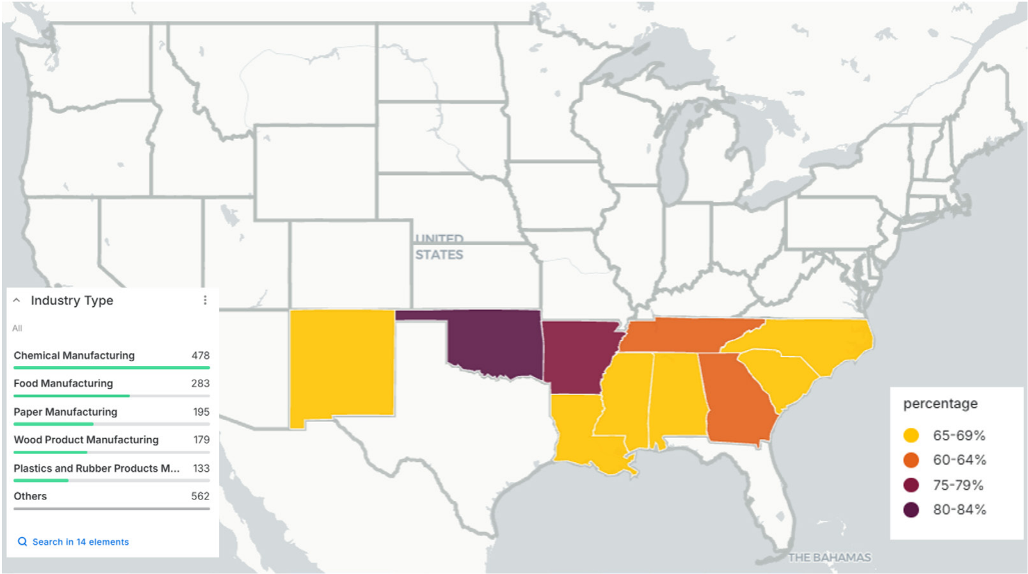
12 Trends may vary at the state or regional level.

Figure 10: Average Emissions by Boiler Location - Disadvantaged Versus Non-Disadvantaged Community



Finding #7 - Boiler Units Are Disproportionately Sited in Federally Recognized Disadvantaged Communities in the Southern U.S.: In total, we found 16 states where over half of their reported units were operating in DACs (Figure 11). These reported units are primarily associated with the chemical and food manufacturing sectors, and have unit capacities between 10-100 MMBtu/hr or over 100 MMBtu/hr. The states with the highest concentration of reported units operating in DACs are in the Southern U.S., which includes Oklahoma (81 percent of reported units), Arkansas (75 percent of reported units), and South Carolina (69 percent of reported units).

Figure 11: U.S. States with the Highest Concentration of Boiler Reported Units Operating in Disadvantaged Communities (Represented as Percent of Total State Population)



Our analysis thus demonstrates not only the substantial scale of conventional and hazardous pollution emitted by industrial boilers, but also identifies a number of concerning trends, including the disproportionate concentration of boiler facilities in particular states and underserved communities that are already heavily burdened by legacy pollution. To further explore these trends and empower localized action, the accompanying interactive map offers a dynamic tool for stakeholders at the national, state, and local levels to investigate boiler emissions within their own jurisdictions. While this analysis has highlighted specific states and emission patterns, we strongly encourage policymakers, community advocates, and the public in *all* states to utilize this resource to evaluate opportunities for targeted regulatory efforts and emission reduction strategies, ultimately working towards improved air quality and public health outcomes, the subject of our next section.

3.3 PUBLIC HEALTH IMPACTS

Our emissions analysis reveals a harsh truth: Industrial boilers are poisoning workers and fenceline communities. In the status quo, fossil fuel-based methods of generating industrial heat are producing high volumes of toxic air pollutants, causing illness and premature death—and stand to do even more harm in a period of industrial growth if we do not shift toward clean energy sources. In this section, we dig deeper into the epidemiological consequences of industrial boiler emissions. In particular, the disproportionate pollution burdens identified by our analysis underscore a critical environmental injustice, as these elevated emissions translate directly into increased risks for respiratory illnesses, cardiovascular diseases, neurological problems, and other adverse health outcomes within already vulnerable populations.

Health Impacts of Key Boiler Pollutants

In addition to huge quantities of CO_2, which threaten public health by trapping heat in the earth's atmosphere and thereby drive climate disasters and phenomena that devastate whole regions, industrial combustion boilers emit a host of other pollutants that directly impair human health. This complex mixture of criteria and toxic air pollutants include the following:

- **NO_x:** Boilers are a significant source of NO_x, a group of highly reactive gases that include nitrogen dioxide (NO_2). NO_x is a key precursor to both ground-level ozone and $PM_{2.5}$, both of which contribute to well-documented cardiovascular and pulmonary illnesses. Direct exposure to NO_x itself can also cause respiratory illness; the pollutant penetrates deep into lungs, worsening asthma and bronchitis, increasing susceptibility to infection, and, when inhaled at high levels, even triggering pulmonary edemas that fill the lungs with fluid. (American Lung Association - b., 2024; Manisalidis et al., 2020, p. 6).

- **$PM_{2.5}$:** Fine particulate matter, also emitted from boiler combustion, poses a significant threat to cardiovascular and respiratory health. Inhalation of $PM_{2.5}$ can corrode alveolar walls and lead to decreased lung function, asthma attacks, heart attacks, strokes, and premature death. In European Union countries, $PM_{2.5}$ pollution was found to decrease the average life span by 8.6 months (Orru et al., 2020, p. 3). Hospitalization rates have been shown to increase by 8 percent when daily $PM_{2.5}$ pollution increased by 10 μg/m3 (Xing et al., 2016, p. E70), and a 7-year study in the U.S. indicated that the average life span was extended by 0.35 years for every 10 μg/m3 decrease of $PM_{2.5}$ (Correia, et al., 2013, p. 3).

- **VOCs:** VOCs emitted from industrial processes and incomplete combustion in boilers can contribute to the formation of $PM_{2.5}$ and ozone, the latter being a potent respiratory irritant that can limit lung function, cause severe respiratory illness, and increase mortality rates, especially among older adults (U.S. EPA - n., 2025) . Some VOCs are also known or suspected carcinogens and can have other toxic effects (U.S. EPA - h., 2024). The Centers for Disease Control have indicated that there are no safe levels of carcinogen exposure (CDC, 2014).

- **HAPs:** Fossil fuel combustion in boilers releases a range of HAPs, which are toxic air pollutants formally recognized by U.S. EPA as substances known to cause cancer or other serious health impacts. While our boiler analysis focused on a handful of specific HAPs, over 100 toxic air pollutants were reported for boilers (inconsistently reported based on boiler location, size, and fuel). Among the most significant HAPs emitted by industrial boilers are the following:

  - **Mercury:** Mercury is a potent neurotoxin, and even low levels of exposure can cause neurological and developmental damage, particularly in fetuses and young children, and contribute to cardiovascular disease in adults (World Health Organization, 2017; Zhang, 2021).

  - **Lead:** Lead exposure causes developmental issues in children, even at low levels; encourages respiratory syndromes including asthma, lung cancer, and chronic obstructive pulmonary disease; and can cause nervous, kidney, and cardiovascular disorders (Raj & Das, 2023, p. 81). Our analysis revealed significantly higher average lead emissions from boilers in DACs.

  - **Formaldehyde:** Formaldehyde, typically used as a disinfectant and preservative, is a known human carcinogen and can cause respiratory irritation and asthma exacerbations (National Cancer Institute, 2024). Our analysis revealed significantly higher average formaldehyde pollution from boilers in DACs compared to other affected populations.

- **Hydrochloric Acid (HCl):** HCl is a corrosive substance that can irritate the eyes, skin, and respiratory tract. Long-term exposure can lead to more severe chronic issues, including respiratory disease, skin inflammation and higher sensitivity to sunlight, and even dental erosion (California Air Resources Board, 1997, p. 577). Our data indicate substantially higher average HCl boiler emissions in DACs.

Cumulative Impacts and Environmental Justice

The health burdens from industrial boiler emissions are rarely experienced in isolation. Instead, individuals are often exposed to a cocktail of pollutants from multiple pollution sources. These impacts can be cumulative, meaning the combined effect of multiple pollutants is greater than the sum of their individual effects. Regulators sometimes focus on the adverse health effects of individual air pollutant exposures (e.g. respiratory, cardiovascular, metabolic, neurological, reproductive impacts of NO_x, SO_x, PM, ozone), which encourages pollutant-by-pollutant (or category-by-category) regulatory strategies. (American Lung Association - b., 2023; U.S. EPA - k., 2025; U.S. EPA - g., 2024; U.S. EPA - l., 2025). But that regulatory approach fails to account for cumulative impacts , which are defined as the "totality of exposures to combinations of chemical and non-chemical stressors and their effects on health, well-being, and quality of life outcomes" (U.S. EPA - k.).

> **Across the United States, people of color are more likely to reside in communities with the heaviest burdens of ozone and particle pollution—nearly twice as likely as a white person**
>
> (American Lung Association, 2024, p. 12)

Consequently, many air pollution control strategies (such as EPA's processes for determining primary NAAQS for criteria air pollutants and for setting section 112 standards for for HAPs) and public risk communication tools (such as the agency's Air Quality Index, which is based on short-term primary NAAQS) do not address the true public health burden resulting from cumulative impacts. (U.S. EPA - k., 2025). Some lawmakers have acknowledged the problem of siloed regulatory approaches and have been working to develop solutions. For instance, in 2020, New Jersey enacted the Environmental Justice Law,[13] which requires the state's Department of Environmental Protection "to consider how certain facilities seeking permits to construct and/or operate in overburdened communities will contribute to environmental or public health stressors in that community in a manner that is disproportionate compared to its neighbors" (New Jersey Department of Environmental Protection, 2023, p. 2). Crucially, this process involves a consideration of the cumulative impacts to which an overburdened community may become (or is already) subject in relation to the proposed facility (New Jersey Department of Environmental Protection, 2023, p. 6).

13 N.J.S.A. 13:1D-157, et seq.

Frontline communities and the workers in polluting facilities often experience health burdens from a wide range of pollutants and pollution sources and through multiple exposure pathways. Populations in close proximity to industrial facilities, particularly the federally recognized DACs highlighted in our emissions analysis, often face additional environmental stressors from other industrial sources, transportation emissions, and waste facilities.[14] Across the United States, people of color are more likely to reside in communities with the heaviest burdens of ozone and particle pollution—nearly twice as likely as a white person (American Lung Association, 2024, p. 12). These communities frequently experience socioeconomic and sociodemographic vulnerabilities, such as limited access to healthcare and healthy foods, poor housing conditions, and diminished job opportunities, which can exacerbate the direct health effects of air pollution on the human body. Other factors such as pre-existing medical conditions, vulnerable life stages, and genetic predispositions can also contribute to cumulative impacts. The significantly higher average emissions of multiple harmful pollutants from boilers in these communities, as demonstrated in Finding #6 above, directly reflect this pattern of environmental injustice. The communities adversely affected by cumulative impacts stand in particular to benefit from industrial decarbonization writ large, including from a broader push toward boiler electrification.

Public Health Benefits of Boiler Electrification

Transitioning from fossil fuel-burning boilers to clean electric alternatives, such as heat pumps, will offer substantial and multifaceted public health benefits. By eliminating the combustion of fossil fuels at the source, electrification directly reduces emissions of NO_x, $PM_{2.5}$, VOCs, and HAPs in the communities where these boilers operate, alongside the substantial climate benefits in terms of reduced CO_2 emissions. (As we discuss in Section 5, though industrial boiler electrification may displace some pollution to fossil-fueled electricity sources, electrification will also yield lifecycle emission reductions thanks to the ongoing decarbonization of the electric grid.) These health benefits translate into:

Bay Area Air District estimates that their zero-NO_x building appliance rule alone will avoid an estimated 37 to 85 premature deaths per year and about 110 new cases of asthma each year.

(Bay Area Air Management District, 2024, p. 16).

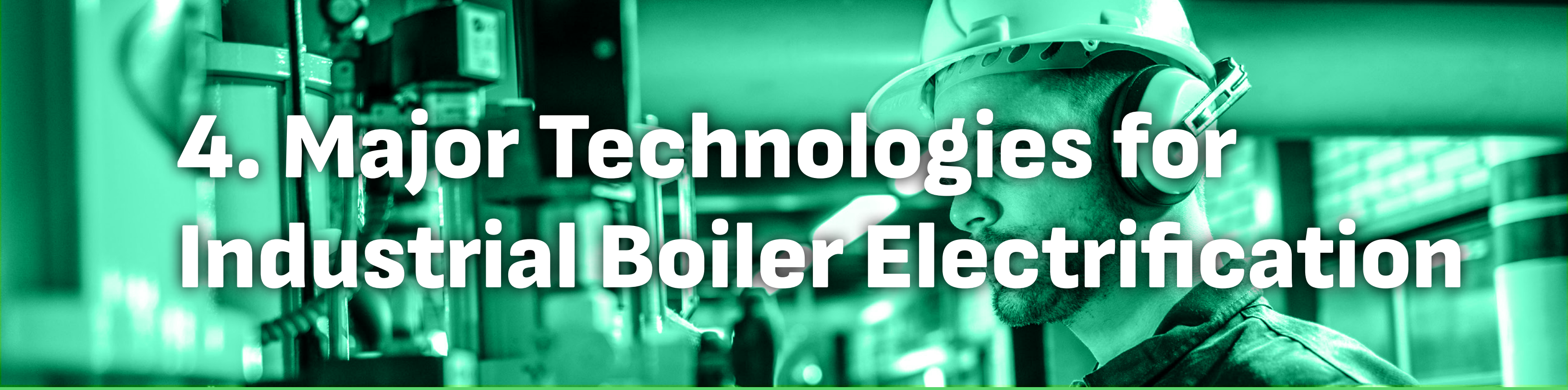
- **Reduced Respiratory Illnesses:** Lower concentrations of NO_x, $PM_{2.5}$, and ozone lead to decreased rates of asthma development and exacerbations, bronchitis, and other respiratory illness.

14 Environmental exposure is further influenced by several variables, including weather and pollutant potency (California Air Resources Board, n.d.).

- **Reduced Emergency Room Visits:** By reducing asthma exacerbations and other acute health impacts, lower concentrations of NO_x, $PM_{2.5}$, HAPs, and ozone will cut down the number of ER visits in polluted communities.
- **Improved Cardiovascular Health:** Reduced $PM_{2.5}$ and ozone exposure lower the risk of heart attacks, strokes, and other cardiovascular events, and will reduce instances of premature death.
- **Reduced Cancer Risk:** Eliminating emissions of carcinogenic HAPs like formaldehyde and certain VOCs contribute to a lower incidence of cancer in exposed populations, including workers at polluting facilities.
- **Better Neurological and Developmental Outcomes:** Phasing out HAPs like mercury and lead protect vulnerable populations, particularly children, from neurological and developmental harm.
- **Reduced Premature Mortality:** By reducing the incidence of serious disease and exacerbations, cutting criteria and hazardous air pollution across the board will directly result in fewer premature deaths.

The widespread adoption of boiler electrification, therefore, represents a significant opportunity to improve air quality, reduce the burden of respiratory and cardiovascular diseases, mitigate cancer risks, improve neurological and developmental outcomes, save lives, and advance environmental justice by alleviating the disproportionate pollution exposure and cumulative impacts in DACs. Bay Area Air District estimates that their zero-NO_x building appliance rule alone will avoid an estimated 37 to 85 premature deaths per year and about 110 new cases of asthma each year. (Bay Area Air Management District, 2024, p. 16).

While community health should be the foremost priority, it is also important to recognize the economic co-benefits of improved public health through lower healthcare costs and fewer missed work and school days. Though Section 5.2 below does not account for these co-benefits in our abatement cost accounting, forthcoming research from the American Lung Association on the geographically distributed health benefits of non-combustion boiler technologies will further strengthen the evidence base for this crucial transition.



4. Major Technologies for Industrial Boiler Electrification

As we have discussed thus far, legacy fossil-fueled boilers are a significant source of GHGs, criteria air pollutants, and HAPs, contributing to climate change, exacerbating public health problems, and worsening ongoing environmental injustices that afflict vulnerable populations. But technology exists now that can effectively mitigate this pollution while revitalizing and future-proofing the U.S. manufacturing sector. Regulators, lawmakers, and advocates must prioritize the transition to boiler electrification—the replacement of combustion-based systems with clean, electric alternatives. This section provides an in-depth analysis of electric heat pump and boiler technologies, acknowledging that the options discussed herein are only some of a larger constellation of alternatives to combustion boilers that are available on the market or currently in development.

The remainder of this section will explore the technical capabilities, technology readiness levels, availability, and capacities of two key electric alternatives to combustion boilers—heat pumps and conventional electric boilers—while also offering an overview of thermal energy storage, an emerging and crucial enabling technology for enhancing electrified heat's economic viability and grid integration.[15] Understanding the current landscape of these clean alternatives is essential to accelerating their adoption and supporting the implementation of new, stringent limits on industrial boiler pollution. This, in turn, can provide significant reductions of both climate and conventional air pollution while helping to cultivate a more modern, competitive U.S. industrial sector.

ELECTRIC HEAT PUMPS

Electric heat pumps are a mature and highly efficient technology for transferring ambient and waste heat, with widespread deployment already in residential and commercial applications. They present a compelling alternative to fossil-fueled industrial boilers, often operating up to three times more efficiently in competitive temperature ranges (60-200°C), which are estimated to cover approximately 55 percent of industrial process heat needs (Roelofsen et al., 2020, p. 5; Rightor et al., 2022, p. 2). Powered by electricity to upgrade and transfer heat from the environment or a waste

15 The technology review here is not intended to be a comprehensive survey of all alternatives to fossil-fueled industrial boilers, and omits several potentially viable technologies, such as concentrated solar power.

heat source, industrial heat pumps can achieve impressive efficiencies of 300-400 percent, delivering three to four times more thermal energy than the electrical energy consumed. Industrial heat pumps are a relatively new technology that currently contributes only about 5 percent of industrial heat globally (Bauer et al., 2024), but this figure continues to grow, and is now poised for accelerated uptake as capital and operating costs continue to decline.

Heat pumps are commonly categorized based on the two of the heat transfer mechanisms they use: mechanical vapor compression (MVC) or absorption.[16] MVC heat pumps utilize a mechanical compressor to increase the pressure of waste or ambient vapor and are often powered by electric motors and steam turbines (U.S. DOE -h., 2003, p. 4). Absorption heat pumps, by contrast, use working fluid, boiling-point elevation, and heat of absorption to achieve higher temperatures, making them more versatile across industrial applications (U.S. DOE - h., p. 4).

Successful deployments of heat pump technology have been demonstrated across various industrial sectors, including pharmaceuticals, food processing, and pulp and paper. Appendix 2 provides a table illustrating the range and availability of electric heat pumps with notable examples of their application. The proven energy efficiency and suitable temperature ranges of heat pumps, coupled with their successful global implementation and the rapid ongoing technological advancement to reach higher temperatures and capacities, clearly indicate their technology readiness to be utilized as a replacement for a significant portion of fossil fuel-fired boilers in the U.S. As of now, industrial heat pumps can achieve temperatures of up to 200°C, although researchers are actively investigating heat pump designs and technologies that can exceed this temperature threshold (Yoo et al., 2025; Pettinari et al., 2024).

CONVENTIONAL ELECTRIC BOILERS

Conventional electric boilers generate steam for process heating by passing an electric current through a medium (RTC, 2022, p. 142). In industrial settings, these boilers are primarily categorized by the method of current transfer, including resistance boilers, which generate heat through an external resistive element (similar to an electric kettle), and electrode boilers, which heat water by passing the current directly through the water itself (Zuberi et al., 2021, p. 2). Of these two configurations, electric resistance boilers typically have lower maximum thermal capacities, typically of approximately 17 MMBtu/hr—equivalent to the heat output of a medium-sized industrial boiler. Electrode boilers can achieve higher capacities, ranging from approximately 10

16 Note that other viable IHP technologies have also been developed and deployed. See ACEEE's report, Industrial Heat Pumps: Electrifying Industry's Process Heat Supply (Rightor et al., 2022).

MMBtu/hr, which is the lower applicability threshold for EPA's NSPS for small industrial, commercial, and industrial boilers, up to approximately 239 MMBtu/hr, which is well above the lower applicability threshold of 100 MMBtu/hr for EPA's NSPS for standard-size industrial, commercial, and institutional boilers (Schoeneberger et al., 2022, p. 4).[17]

Compared to heat pumps, resistance and electrode boilers can reach substantially higher maximum temperatures, and do not experience efficiency losses when operating at high temperatures (Smillie et al., 2024, p. 14). This makes conventional electric boilers well-suited for applications that would otherwise use gas-fired combustion boilers across a range of subsectors, such as food and beverage, paper products, pharmaceuticals, and small-batch specialty chemicals production. They also have significant advantages over combustion boilers: Because they have no site-level emissions, conventional electric boilers often face fewer permitting hurdles compared to fossil fuel-fired boilers. For instance, they are not subject to federal New Source Review (NSR) evaluations or permitting requirements, which apply to new or modified combustion boilers (Evergreen Action. - b, 2024, p. 44). When powered by clean electricity sources, conventional electric boilers provide entirely pollution-free (i.e., both at the site level and upstream) process heat for industrial applications (Zuberi et al., 2021, pp. 2-3).

Although they are a mature technology, conventional electric boilers in the U.S. have seen somewhat limited deployment thus far, accounting for about two percent of the country's steam generation (Zuberi et al., 2021, p. 3). This is largely because of the cost differential between electricity and natural gas or zero-marginal cost byproduct fuels, often referred to as the "spark gap." The spark gap means it is cheaper in most U.S. markets for manufacturers to use combustion rather than electric boilers, despite the former's greater efficiency (95-99 percent efficient versus 70-80 percent efficient) (Zuberi et al., 2021, pp. 2, 30-31). For these reasons, policy interventions will be crucial for reducing cost barriers and advancing the adoption of both conventional electric boilers and heat pumps. The economics of boiler electrification and policy approaches for encouraging their use are discussed in detail in Sections 5 and 6 of this report.

17 40 C.F.R. §§ 60.40b(a), 60.40c(a)).

Case Study

Rondo Energy

Rondo Energy deployed a 2MWh Rondo Heat Battery (RHB) at Calgren Renewable Fuels in Pixley, California. This facility captures intermittent renewable electricity and stores it at temperatures exceeding 1,000°C, the **RHB provides continuous, zero-carbon industrial heat without requiring changes to existing processes**. This installation replaces fossil fuel combustion in biofuel production, effectively doubling CO_2 savings per gallon. With an efficiency exceeding 90 percent and using widely available materials, Rondo's technology is scalable, fast to deploy, and capable of reducing the carbon intensity of ethanol production by 50 percent, with the potential to achieve zero-carbon fuels when paired with carbon capture.

Source: Rondo Energy

THERMAL ENERGY STORAGE

Thermal energy storage (TES) offers a valuable mechanism for storing energy in the form of heat for later use (What Is Thermal Energy Storage? – 5 Benefits You Must Know, n.d.). Unlike battery energy storage, which stores and discharges electricity itself, TES uses electricity to generate thermal energy for storage and discharge. Sensible heat storage (SHS) is a common TES technology in which materials like water, molten salts, or sand are heated to high temperatures, typically using electric resistance coils, within an insulated environment (Tawalbeh et al., 2023, p. 3). Industrial processes with high-temperature demands can then draw upon this stored heat as needed. Electric heaters can recharge SHS units during off-peak hours, capitalizing on dynamic electricity pricing to minimize operational costs and prioritizing periods of high renewable generation. While latent heat and thermochemical storage technologies also hold promise, they are currently less commercially mature than SHS.[18] These technologies can serve as standalone units or can be used in conjunction with heat pumps or electric resistance boilers.

SHS units are already commercially available and demonstrated in various industrial sectors, as detailed in Appendix 2 (RTC, 2022, p. 179). The storage capacity of SHS units varies based on the storage material and volume, with some units capable of storing heat at temperatures up to 1,500-1,600°C, potentially suitable for high-temperature industrial applications. However, industrial scale applications of this technology are still quite new, and manufacturers have not yet reached economies of scale, so relatively high initial capital costs (as well

18 Latent TES is in the demonstration and early commercial stages and thermochemical TES in the research and development stage.

as industry inertia and TES units' need for a separate heating component) remain barriers to widespread adoption (RTC, 2022, p. 179). As more companies adopt these technologies in the coming years, nth-of-a-kind effects will likely reduce capital costs substantially and help pave the way for greater market penetration of thermal energy storage units, especially for applications with high temperature heating needs and in areas with a high concentration of renewable electricity resources.

Emerging Technology: Next-Generation Geothermal Next-generation geothermal technologies, including enhanced geothermal systems, closed-loop systems, and superhot rock systems, offer another promising alternative to fossil-fueled boilers (Clean Air Task Force, 2025). Leveraging established drilling techniques, these emerging systems have the potential for rapid scaling to address industrial heat needs. They also provide a promising opportunity to create jobs, and can leverage the workforce and equipment already developed for horizontal drilling to scale more rapidly across sectors (IEA, 2024, p. 10). While currently in pilot and demonstration phases for industrial heat (having been demonstrated in the power sector), next-generation geothermal offers the prospect of continuous, reliable, 24/7 process heat of up to 150°C without the climate, time-of-day, or seasonality challenges faced by other sources of renewable energy (IEA, 2024, p. 7).

Electrification from Rejected Thermal Energy: Waste Heat to Power Waste heat from various industrial processes can be recovered and diverted to organic rankine cycle power generation equipment to produce baseload, emission-free power onsite for boiler electrification. Waste heat to power (WHP) technology is commercially deployed worldwide and uses heat exchangers to superheat a working fluid which expands through a turbine to generate power. WHP can generate meaningful electrical output with gaseous or fluid waste heat sources exceeding 250 degrees Fahrenheit and can be an effective means to electrify boilers with clean power by utilizing wasted energy from a nearby or peripheral industrial process. Waste heat to power currently qualifies

5. Emission Reductions and Economic Impacts of Industrial Boiler Electrification

In Section 3, we described the results of our dataset analysis, which describe the emission *impacts* of the existing fleet of fossil fuel-fired boilers. Here in Section 5, we will discuss the benefits of emission reductions that can be achieved by electrifying combustion boilers. We also evaluate the associated costs of replacing combustion boilers with electric technologies and compare them against those benefits. Rather than conducting our own independent quantitative analysis of emission reduction benefits and the associated economic costs, we instead compare the findings from a number of recent studies on this very topic, which all point toward a similar conclusion: the substantial majority of heat pumps installed today for industrial thermal needs will be broadly cost-effective at reducing pollution over the course of their operating lives and, in some instances, can actually reduce facilities' operating costs. The pollution abatement costs remain higher for applications that require temperatures that exceed the current capabilities of heat pumps, but we conclude that electrification in these cases is still justified, particularly where thermal batteries can serve heat storage needs alongside the use of conventional electric boilers.

From our review of the recent literature, the following top-line points emerge:

- **Electric technologies pollute far less CO_2 than combustion boilers, even accounting for upstream emissions from generating electricity.** The average lifecycle CO_2 emissions associated with newly installed heat pumps are approximately **45 to 80 percent lower** than natural gas-fired boiler emissions over the units' operating lives. For conventional electric boilers, average lifecycle CO_2 emissions are approximately **25 percent lower.**

- **Electric technologies generate far less conventional pollution than combustion boilers.** The average lifecycle NO_x emissions associated with heat pumps and conventional electric boilers are approximately **80 to 95 percent lower** than gas-fired boilers' emissions over the course of their operating lives. Adopting heat pumps in particular, rather than gas-fired boilers, can save **thousands of lives per year** through reduced criteria and toxic pollution.

- **At present, the average overall cost of generating industrial heat through electric technologies is somewhat higher than it is for combustion boilers.** The studies reviewed here found that the levelized cost of heat, which estimates the overall cost of producing thermal energy from a particular technology, most often falls in the range of approximately **$10-30/MMBtu for heat pumps**. For conventional electric boilers this figure is most often in the range of **$20-25/MMBtu** at lower temperatures and can extend into the **$30-50/MMBtu** range for higher temperatures. For gas-fired combustion boilers, the levelized cost of heat is lower—typically in the **$7-15/MMBtu** range–primarily because of the historically consistent cost differential between gas and electricity.

- **The lifetime emission reduction benefits from replacing gas-fired boilers with heat pumps already exceed any additional cost in the vast majority of cases.** Industrial heat pumps have such high efficiencies that the economic benefits of the CO_2 reductions they achieve will, over the course of their operating lives, outweigh any additional operating or capital costs compared to gas-fired boilers for **over 90 percent of units**. This projection does not even account for the additional benefits of reduced criteria and hazardous pollution and avoided upstream emissions of methane that result from boiler electrification.
- **The additional costs of switching to conventional electric boilers still exceed the monetized value of their CO_2 emission reduction benefits in most cases, but multiple factors still favor their installation over gas-fired units.** While conventional electric boilers also provide substantial environmental benefits compared to gas-fired units, their additional costs will in most cases be greater than the value of the lifecycle CO_2 emission reductions they will achieve—until the electric generation grid undergoes further decarbonization. However, the additional benefits conventional electric boilers provide by reducing other pollutants and upstream methane emissions, as well as the opportunity to reduce costs by pairing them with thermal batteries where possible, should encourage their adoption where appropriate.

As we have emphasized throughout this report, electrifying industrial heat reduces not only GHGs, but also criteria and hazardous pollutants such as NO_x, $PM_{2.5}$, and mercury. The section that follows describes the emission reduction benefits of boiler electrification based on a range of pollutants, but focuses primarily on CO_2 abatement costs and their comparison to the social cost of carbon when discussing economics. This is not because we intend to avoid or deprioritize reductions of criteria and hazardous air pollutants, but because the extensive body of research synthesized here focuses primarily on CO_2—a gap in the literature on boiler electrification that must be remedied in order to fully illuminate the immense public health benefits of transitioning to electric technology. At the heart of it, understanding the emission reduction benefits and economic implications of this transition is crucial for informing policy decisions and driving widespread adoption of clean heating technologies in the industrial sector.

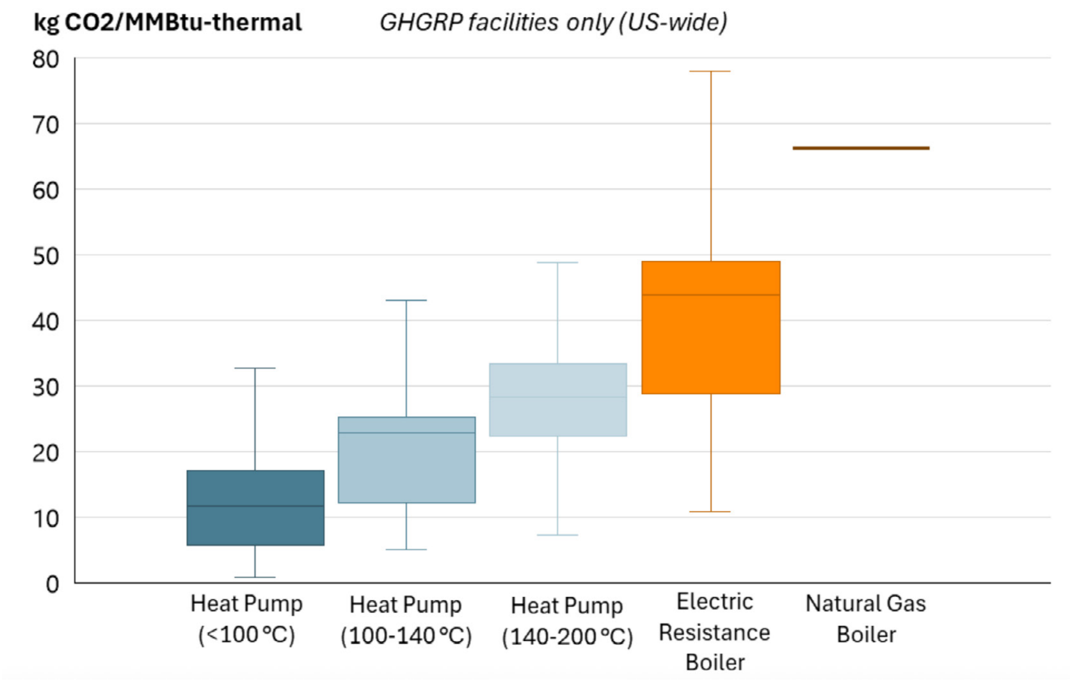
5.1 QUANTIFYING AVOIDED EMISSIONS FROM BOILER ELECTRIFICATION

To understand the emission reduction benefits of boiler electrification, let us consider a 30 MW gas-fired industrial boiler, which operates at a 50 percent annual capacity factor (generating half of its maximum heat output annually)[19] and has a thermal efficiency of 75 percent (wasting one-quarter of the heat produced) and a CO_2 emission rate of 70 kg/MMBtu. Over the course of the year, this unit can be expected to emit over 23,500 metric tons of CO_2, the climate equivalent of nearly 60 million vehicle miles traveled or the annual power usage of close to 3,000 homes (U.S. EPA. - d. (2024)). An industrial facility owner can, in theory, entirely eliminate those onsite emissions by replacing that combustion boiler with a heat pump for temperatures of up to 200ºC, or a conventional electric boiler (either resistance or electrode) to reach between 200 and 500ºC.

The amount of electricity generated in the U.S. by renewable resources such as wind and solar has expanded tremendously in recent years, and will continue to grow exponentially in the years and decades to come. However, until American electricity needs are fully supplied by renewable resources, the process of generating the electricity that powers electric heat pumps and conventional electric boilers will itself emit NO_x, $PM_{2.5}$, CO_2, and other pollutants. **But even taking into account these upstream electric sector emissions, the research indicates that switching from natural gas-fired boilers to electric options produces significant net emission benefits on average**. CAELP's October 2024 report *Decarbonizing Industrial Heat: Measuring Economic Potential and Policy Mechanisms* found that heat pumps and conventional electric boilers have significantly smaller CO_2 and NO_x footprints compared to gas-fired units, as shown in Figures 12 and 13 below.

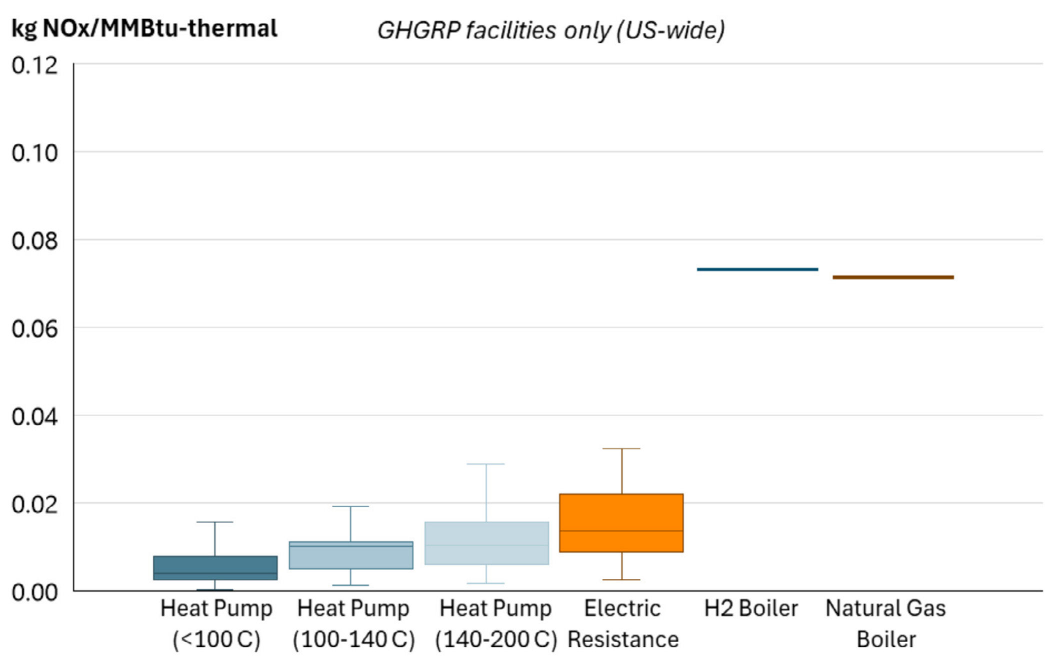
19 More specifically, capacity factor refers to the ratio of energy actually produced compared to the maximum possible energy output over a period of time. Thermal efficiency is the percentage of the source's energy input that is actually used to produce thermal output, instead of being lost as waste heat.

Figure 12: CO_2 emissions factors for different industrial steam-generating technologies



Source: Smillie et al., 2024, p. 40

Figure 13: NO_x emission factors for different industrial steam-generating technologies



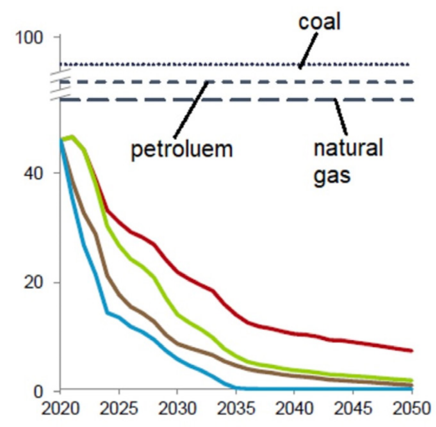
Source: Adapted from Smillie et al., 2024, p. 40

Figures 12 and 13 represent (respectively) the average lifetime CO_2 and NO_x emission factors of different technologies for producing industrial steam, taking into account the anticipated upstream emissions resulting from electricity generation and assuming a 20-year operating life for each unit (Smillie et al., 2024, p. 39). The analysis considered electric grid emission across a diverse set of 15 states and assumed that such emissions would decline 71 percent between 2025 and 2045 (Smillie et al., 2024, pp. 14-15, 26, 39).

The CAELP report's projections indicate that installing industrial heat pumps and conventional electric boilers would provide, in the vast majority of cases, meaningful net climate and public health benefits over the course of their operating lives. While the lifecycle emission factors of clean alternatives decrease at lower temperatures, the analysis demonstrates that units operating in the medium-temperature range of 200-500°C—which, under current technologies constraints, must be conventional electric boilers—also provide overall NO_x benefits across all the modeled states and grid scenarios, and overall CO_2 benefits in the vast majority of cases (Smillie et al., 2024).

The Renewable Thermal Collaborative's (RTC) 2022 *Renewable Thermal Vision Report* broadly corroborates CAELP's conclusions for industrial heat pumps. Considering four scenarios reflecting different levels of renewable resource uptake in the electric sector between 2022 and 2050, RTC found that **replacing fossil fuel-fired boilers now with industrial heat pumps would, in each outcome, result in lifecycle CO_2 reductions, and that these reductions would rapidly grow as the grid becomes cleaner** (RTC, 2022, p. 19). Figure 14 below depicts these findings, with each colored line representing heat pumps' lifecycle CO_2 emission intensity over time based on a different electric grid emission scenario. The dotted horizontal lines represent the emissions intensity of boilers fired by gas, oil, or coal.

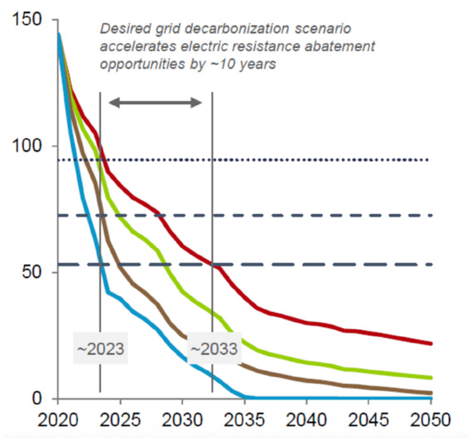
Figure 14: Electric heat pump emissions intensity v. fossil fuels (Kg CO_2e/MMBtu)



Source: Adapted from RTC, 2022, p. 19

In three of the four modeled grid scenarios, RTC further concluded that industrial heat pumps would reach zero or near-zero CO_2 emitted per MMBTu by 2050 (RTC, 2022, p. 19) . Replacing fossil fuel-fired boilers with conventional electric boiler units would also achieve net CO_2 reductions on average before 2030 in three of the four assessed grid scenarios, and by 2033 in the fourth scenario (i.e., the one least favorable to renewable growth) (RTC, 2022, p. 19). These results are depicted in Figure 15 below.

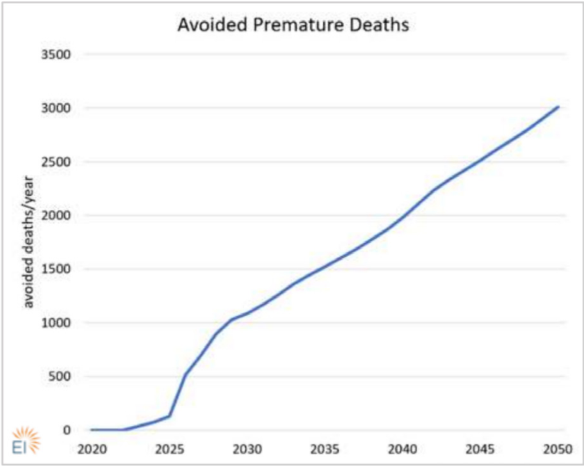
Figure 15: Conventional electric boiler emissions intensity v. fossil fuels (Kg CO_2e/ MMBtu)



Source: Adapted from RTC, 2022, p. 19

Like the *Renewable Thermal Vision Report*, a 2022 study by Lawrence Berkeley National Laboratory (LBNL) projected annual net CO_2 reductions before 2030 for medium-temperature applications of both electric resistance and electrode boilers (Zuberi et al., 2021, p. 19). Energy Innovation (EI) also found positive environmental outcomes from boiler electrification in a 2022 report. Using the U.S. Energy Policy Simulator, EI modeled the industrial sector emissions that would result from replacing combustion boilers operating at low and medium temperatures with industrial heat pumps (Rissman, 2022, p. 12). Figure 16 below displays the modeling results in terms of total lives saved due to reductions in conventional pollutants such as NO_x, SO_2, and $PM_{2.5}$ through 2050.

Figure 16: Total lives saved due to conventional pollution reduction from heat pump adoption, 2022-2025



Source: Rissman, 2022, p. 13

EI's modeling **shows that transitioning to industrial heat pumps would save over 1,000 lives in 2030 and more than 3,000 lives in 2050** through conventional pollution abatement (Rissman, 2022, p. 13). It also finds that a steady replacement of combustion boilers with heat pumps can reduce sector-wide GHG emissions by 77 MMT of CO_2e in 2030 and 284 MMT in 2050—the equivalent of removing over 18 million cars from the road in 2030 and over 67 million in 2050 (Rissman, 2022, p. 12; U.S. EPA. - d. (2024)). Moreover, because the U.S. Energy Policy Simulator had not yet been updated to reflect the effects of 2022's Inflation Reduction Act by the time EI conducted these modeling runs, the emission reduction and public health benefits of transitioning to heat pumps are likely to be greater still than EI concluded in its report.

Across these four studies, each published in the last four years, the data consistently show that **replacing fossil fuel-fired boilers with industrial heat pumps and conventional electric boilers will provide major climate and public health benefits.** These benefits provide a compelling rationale for the transition to electric boiler technologies, the economic implications of which we discuss next.

5.2 THE COSTS OF ELECTRIFICATION: FOCUSING ON CO_2 ABATEMENT

Stakeholders in this space—especially air regulators considering policies to drive boiler electrification and industry representatives evaluating these technologies—will be keenly interested in understanding the economic implications of transitioning to clean sources of industrial heat. Drawing from the same recent reports analyzed above, the following discussion considers the CO_2 abatement costs of boiler electrification and compares those costs to representative values of the social cost of carbon. We find that a significant share of the national boiler fleet can be electrified now within cost-effective parameters, particularly at temperatures that heat pumps can efficiently provide. While higher-temperature applications typically have higher CO_2 abatement costs, several factors support the economics of boiler electrification at these temperatures as well.

Heat Pumps

For industrial processes (as well as residential and commercial needs) requiring temperatures below approximately 200ºC, **industrial heat pumps offer an economical solution that can eliminate the onsite emissions—and greatly reduce lifecycle emissions—of both conventional pollutants and CO_2.** In fact, research shows that in the vast majority of cases, installing a heat pump rather than a combustion boiler can achieve CO_2 emission reductions at a cost that falls below a critical metric known as the social cost of carbon[20] over the course of a typical unit's 20-year lifetime. Consequently, low-temperature industrial thermal applications present a significant opportunity for cost-effective decarbonization and are ripe for regulatory action that incentivizes and accelerates the adoption of heat pump technology.

20 The social cost of carbon (SC-CO_2) is a set of values based on complex scientific and economic modeling that attempts to quantify in monetary terms the negative climate impacts that society experiences from each marginal ton of CO_2 emitted into the atmosphere. Regulators use estimates of SC-CO_2 to weigh the value of rulemakings that would reduce carbon emissions. As EPA has previously explained it, "SC-CO_2 is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO_2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction) (US EPA - l., 2016, p. 1).

Case Study

TINE

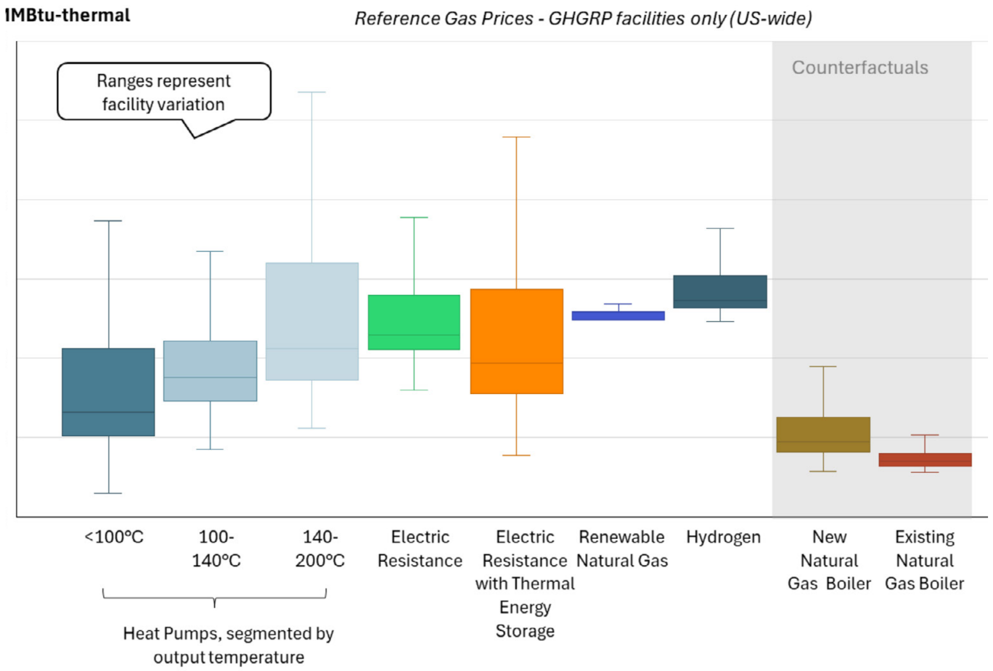
In 2017, TINE, a cooperative owned by Norwegian milk producers, embarked on constructing "the greenest dairy in Europe" as part of a greenfield project in Bergen. The project aimed for a 40 percent reduction in overall energy consumption compared to traditional dairies. To achieve this, TINE collaborated with Hybrid Energy to implement an integrated energy recovery system centered around the GreenPAC heat pump. This innovation enabled the facility to meet its entire temperature range requirements using recovered heat, with district heating as a backup, thereby eliminating the need for fossil fuel boilers and chimneys. The outcome was a dairy that not only modernized the industry but also achieved annual energy savings of approximately 4.2 GWh, making it the most energy-efficient dairy in Norway.

Source: Hybrid Energy

The economic competitiveness of heat pumps is evaluated through two key metrics. The first is the levelized cost of heat (LCOH), which averages the total costs (including both capital and operating/maintenance expenses) that a particular technology requires to produce one unit of heat output (measured in MMBtu). The second metric is CO_2 abatement cost, which determines the expenditure required by that owner/operator of technology to avoid one ton of CO_2 emissions relative to the status quo (in this case, a gas-fired combustion boiler).

Figure 17 below, which comes from the CAELP report, illustrates the LCOH ranges for various industrial thermal options based on EPA's GHGRP data. Assuming a 20-year lifespan, the ranges reflect facility variations and different natural gas-to-electricity price scenarios.

Figure 17: LCOH of Different Industrial Heat Technologies

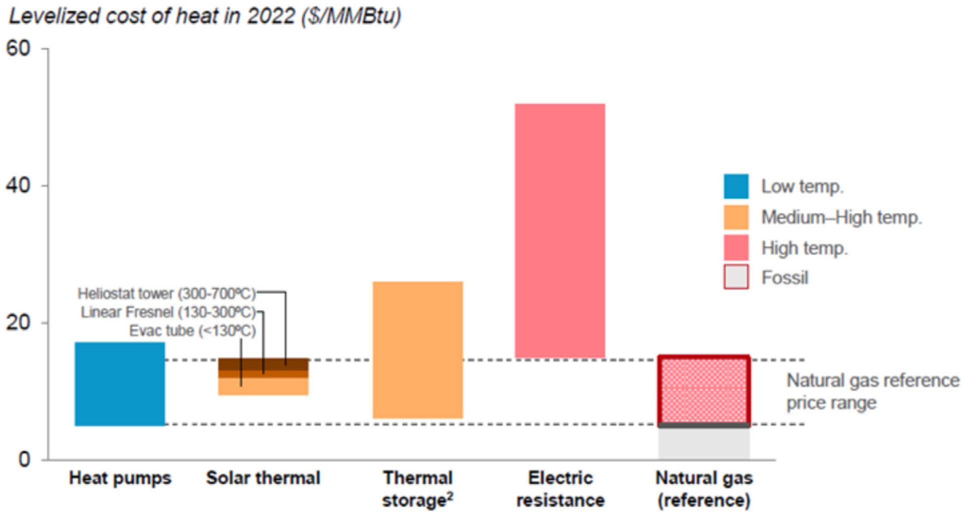


Source: Adapted from Smillie et al., 2024, p. 27

While the average LCOH for heat pumps is somewhat greater than for gas-fired boilers, particularly at higher temperatures, their cost ranges show considerable overlap. Moreover, technological advancements and economies of scale are expected to drive heat pump costs down in the future.

Other projections have similar findings, with Energy Innovation (EI) reporting a 2021 LCOH of roughly \$11/MMBtu for gas boilers, \$12/MMBtu for heat pumps below 100°C, and \$18/MMBtu for those above 100°C (Rissman, 2022, p. 4). RTC similarly found near-identical LCOH for sub-130°C heat pumps and natural gas boilers (RTC, 2022, p. 12), as seen in Figure 18, which is adapted from the *Renewable Thermal Vision Report.*

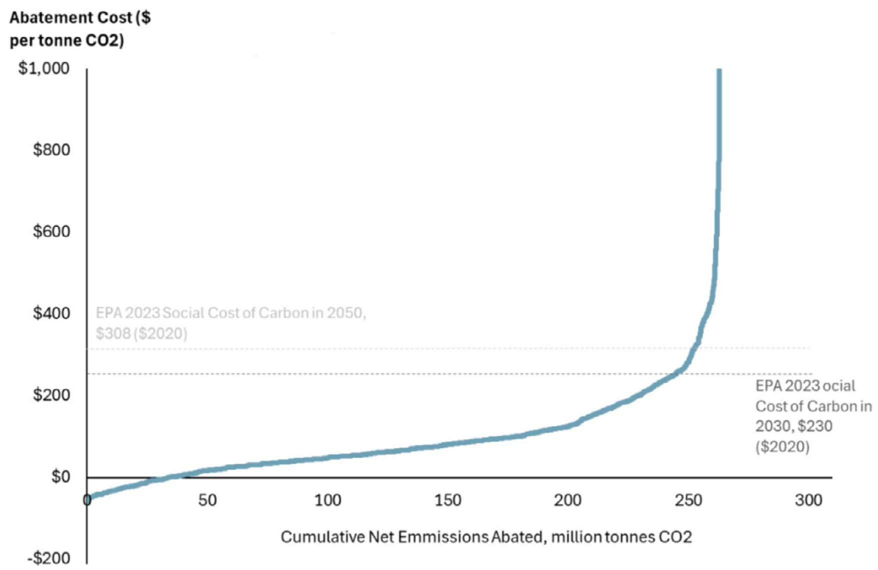
Figure 18: LCOH of Different Industrial Heat Technologies (RTC)



Source: Adapted from RTC, 2022, p. 12

On the other side of the ledger, the substantial emissions reductions achieved by replacing gas-fired boilers with heat pumps justify their somewhat higher LCOH, strongly supporting near-term policies to phase out combustion boilers below 200°C. The CAELP report, which calculates the CO_2 abatement costs for heat pump adoption, depicted in Figure 19 below, highlights this point.

Figure 19: Cost abatement figures for heat pump adoption



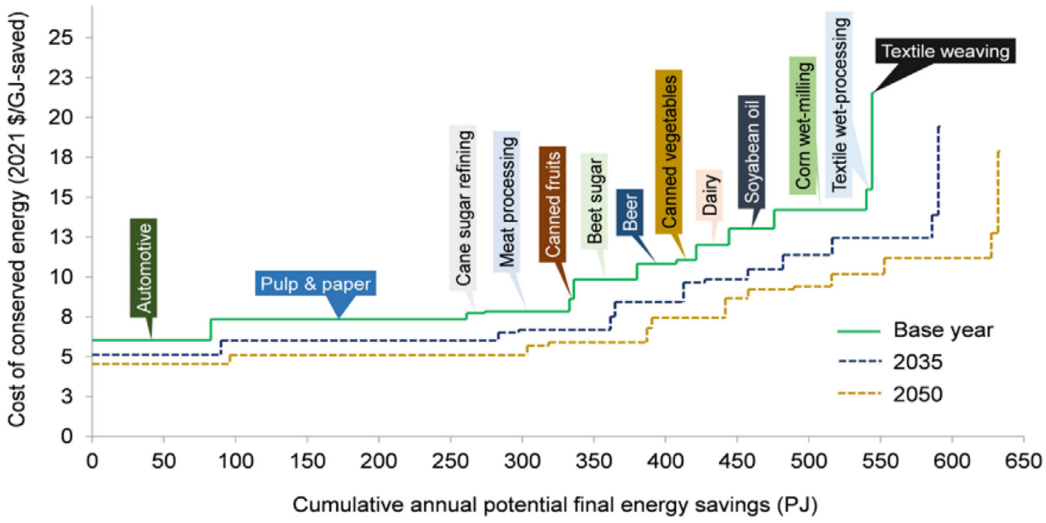
Source: Adapted from Smillie et al., 2024, p. 43

Each point on the curve depicted above, which is adapted from the CAELP report, represents a heat pump replacing a gas-fired combustion boiler in 15 selected states, with the average lifetime CO_2 cost abatement figures (on the Y-axis) and net emission reductions across all boiler replacements (on the X-axis). The data assume a 20-year unit lifetime and reflect CAELP's LCOH calculations as well as representative assumptions for gas-fired boiler emission rates and electric grid emission rate trajectories (Smillie, et al., 2024, pp. 39-43). As this graph shows, **in the substantial majority of cases, the CO_2 abatement cost for heat pump adoption is below $200/ton CO_2.**

As a reference point, in EPA's December 2023 report, which included the most updated and scientifically rigorous social cost of carbon figures yet developed, estimated a central value $230/ton in 2030 as the SC-CO_2; by 2050, this figure increases to $308/ton. (U.S. EPA - c., 2023, p. 152, Table A-5). These values are shown in the two dotted horizontal lines in Figure 19 above. CAELP's modeling shows that the **CO_2 abatement costs of heat pumps fall below the 2030 social cost of CO_2 figure in 90.2 percent of cases, and below the 2050 in 95.5 percent of cases when averaged over their 20-year operating lives.** This means that, with technology that is available now, the benefits of using heat pumps in terms of avoided CO_2 emissions and reduced climate impacts outweigh any additional costs far more often than not. Indeed, CAELP found that in some cases (i.e., where the cost curve in Figure 19 falls below $0/tonne), the compliance costs of adopting heat pumps rather than combustion boilers are negative, in which case operators reduce lifecycle CO_2 emissions while saving the operating facility money.

LBNL's analysis of annual CO_2 cost abatement for heat pump adoption across 13 industrial subsectors (shown in Figure 20) similarly found average annual abatement costs well below the 2035 and 2050 social cost of carbon, ranging from below $50/ton CO_2 to approximately $175/ton CO_2. Sectors with significant low-temperature heat needs, like pulp and paper and food and beverage, showed particularly low abatement costs (around $75/ton CO_2), making them prime candidates for heat pump-based boiler standards (Zuberi et al., 2022, p. 62).

Figure 20: Annual 2035 and 2050 cost abatement figures for heat pump adoption in different industrial sectors/subsectors



Source: Zuberi et al., 2022, p. 62

Of course, CO_2 is only one of the pollutants abated through heat pump adoption; criteria and air toxic emissions also decline as a result. And by reducing overall natural gas consumption, replacing combustion boilers with heat pumps can avoid large quantities of methane, which is released into the atmosphere during the production, processing, transmission, storage, and distribution of natural gas. Methane is a greenhouse gas that is approximately 30 times more potent than CO_2 at warming the planet over a 100-year time frame and over 80 times more powerful over a 20-year timeframe, so even a small reduction in gas demand can have a large impact (Intergovernmental Panel on Climate Change, 2021, p. 7-125).

The overall social benefit of installing these units is thus significantly greater than the CO_2 abatement figures alone indicate. The low but (in most cases, at least for now) positive CO_2 abatement costs of heat pumps make these units prime candidates to focus on through concerted policy actions. Regulations supporting these units will provide emission reduction benefits that, in most cases, outweigh their costs, but in the absence of such regulatory pressure, manufacturers are likely to underinvest in these resources. Section 6 discusses policy avenues that can help increase the market share of heat pumps for industrial heating needs.

Conventional Electric Boilers

For facilities with medium-temperature heat requirements (i.e., between 200 and 500ºC), conventional electric boilers—meaning electric resistance and electrode-equipped units— are readily available alternatives to fossil fuel-fired boilers.

Although the carbon abatement costs associated with these units operating by themselves are higher than for heat pumps, several factors make electric resistance and electrode boilers a sensible option for replacing combustion boilers at medium temperatures. Particularly given the roughly 20-year lifespan of boilers, policymakers and regulators should work to support the adoption of conventional electric boilers for medium and high-temperature thermal needs in order to avoid locking in fossil fuel infrastructure for decades into the future.

Conventional electric boilers have operating efficiencies up to 99 percent, significantly exceeding the 70-80 percent efficiency range of typical fossil-fueled boilers. (Zuberi et al., 2021, p. 2). While conventional electric units typically have lower capital costs than heat pumps, they require more electricity to provide the same heat output due to heat pumps' substantially greater efficiencies, which can reach up to 300-400 percent (Rissman, 2022, p. 4). Consequently, conventional electric boilers' average LCOH is higher than that of heat pumps, as shown in Figures 17 and 18 above. For this reason, conventional electric boilers also yield lower CO_2 reductions on average compared to heat pumps as a replacement for combustion boilers.

While most heat pumps can already achieve lifecycle CO_2 reductions[21] at abatement costs below the current social cost of carbon, it will take longer for conventional electric boilers to reach that level as the power grid becomes cleaner. LBNL projects that across 15 industrial sectors, conventional electric units will provide CO_2 reductions at an average abatement cost that falls within EPA's general range of the social cost of carbon by 2040 (which EPA calculates at $173/ton-$431/ton), and at an average cost that falls well below that range by 2050 (i.e., $202/ton-482/ton) (Zuberi et al., 2022, p. 24). However, LBNL data for 2030 shows CO_2 abatement costs for conventional electric boilers substantially higher than the social cost of carbon range in most cases (Zuberi et al., 2022, p. 24).

Despite these costs, several factors support near-term action to promote the use of conventional electric resistance boilers rather than gas-fired units for medium-temperature industrial heat. First, industrial boilers typically have operating lifetimes of at least 20 years, and so any decision an operator makes in 2030 as to what kind of boiler to install will have emission implications through 2050 or later. Over the course of its lifetime, an electric unit will achieve increasingly lower average CO_2 abatement costs as the electric grid becomes cleaner and cleaner. It is the cumulative cost figure that is most important, rather than the snapshot of a particular year.

21 Which, to reiterate, account for upstream electric sector emissions.

Second, as we have emphasized throughout this report, switching from combustion boilers to electric units (both conventional electric devices and heat pumps) reduces not only lifecycle CO_2 emissions, but also large amounts of other pollutants that are directly harmful to human health, including NO_x, $PM_{2.5}$, and HAPs. Indeed, as seen in Figure 13 above, the NO_x reduction benefits provided by conventional electric boilers are almost on par with those provided by heat pumps. Moreover, like heat pumps, deploying conventional electric units reduces natural gas usage, thereby also cutting climate-disrupting upstream methane emissions. Conventional electric units provide significantly greater benefits in terms of public health and the climate for each dollar spent than is immediately apparent from CO_2 cost abatement figures alone.

Finally, facility owners can both reduce the operational costs of conventional electric boilers and achieve greater emission reductions by pairing these units with thermal energy storage devices (Smillie et al., 2024, pp. 22, 34-35). As described above in Section 4, thermal storage units (also known as thermal or heat batteries) generate and store heat efficiently for long stretches of time and can be configured to charge when

Case Study

Diageo

Diageo's Lebanon Distillery showcases the potential of full electrification in high-heat industrial processes through the deployment of high-voltage jet electrode boilers powered by 100 percent renewable electricity. Built from the ground up in Kentucky, the facility replaces conventional natural gas combustion with a near-instantaneous, precision-controlled steam generation system that maintains constant pressure and supports traditional distilling processes such as grain cooking, ethanol separation, and grain drying. Sourced via a 15-year agreement with local energy cooperatives, the renewable electricity—primarily wind and solar—enables the facility to avoid approximately 117,000 metric tons of CO_2 emissions annually.

By eliminating the need for air permits and reducing maintenance requirements and noise levels, the electric boiler system not only contributes to Diageo's Society 2030 net-zero goals but also improves operational efficiency and safety. This case illustrates how electrification, paired with strategic renewable energy sourcing, can deliver scalable decarbonization in the food and beverage sector (RTC, 2022).

Source: Diageo

low-cost renewable energy is abundant. Using conservative assumptions (Smillie et al., 2024, p. 38), CAELP found that the average LCOH of conventional electric boilers falls to levels comparable with those of heat pumps when the former are equipped with heat batteries on site, as seen in Figure 16 above (Smillie et al., 2024, p. 27).

Consistent with these findings, RTC's *Renewable Thermal Vision Report* shows that thermal batteries have an LCOH range that overlaps significantly with those of both combustion boilers and industrial heat pumps (see Figure 17 above). RTC has also published a detailed paper describing the different ways in which thermal batteries can be used to help reduce emissions from industrial heat applications (RTC, 2022). Indeed, there is no reason thermal batteries cannot also be paired with heat pumps, and as these units fall in capital costs with nth-of-a-kind advances, they are expected to become increasingly attractive options.

Conventional electric boilers offer a significant opportunity to achieve climate and public health gains through cleaner industrial practices. Policymakers should explore strategies to increase their adoption for medium-heat applications, including emission standards. Where cost considerations pose a barrier to broad electrification mandates, policymakers should identify specific industrial sub-sectors, boiler population, or geographic regions ripe for near-term targeted regulatory action. The following section will discuss potential policy avenues for achieving more widespread boiler electrification.

6. Policy Drivers for Industrial Boiler Electrification

Thus far, this report has explored the current landscape of industrial boilers throughout the U.S. in terms of both geographic distribution and emission impacts. It has described the available non-emitting options that could replace combustion units and compared the various studies showing that these technologies can, under many circumstances, achieve significant emission reductions at a reasonable cost across a wide array of boiler applications.

In this last section, we will provide a brief survey of some of the policy avenues that regulators and lawmakers may consider (and that other stakeholders may advocate for) to help accelerate the pace of adoption of the non-emitting technologies discussed throughout this report—namely, industrial heat pumps, conventional electric boilers, and thermal batteries. This discussion is not meant to be exhaustive, nor are any of the policy options discussed exclusive of one another. Instead, we provide a survey of the kinds of regulatory or legislative tools that may help decarbonize industrial heating processes.

6.1 STATE-LEVEL EMISSION STANDARDS

State-level departments of environmental protection are, in many cases, already authorized to advance industrial boiler electrification through enforceable emission standards. Notably, the Federal Clean Air Act (CAA) expressly preserves states' authority to issue their own emission limits for stationary sources, provided that such standards are not less stringent than parallel EPA requirements issued under section 111 of the CAA. While some states have adopted laws or policies prohibiting their own state-level requirements from being more stringent than EPA's, many states have not tied their own hands in such a manner. These latter jurisdictions—particularly those with a strong commitment to reducing GHG emissions, and those that suffer from high levels of pollution that could be ameliorated through boiler electrification—may be well poised to adopt standards that permit zero measurable emissions from their industrial boiler fleet or a subset of such units (Chen et al., 2025).

Case Studies for Emissions Standards

Three potential candidate states demonstrate how those new standards could be implemented in practice: California, Illinois, and Minnesota. All three states have large boiler populations, as well as favorable statutory and regulatory environments for advancing industrial heat decarbonization. Numerous other states also show a strong potential for boiler electrification; for instance, in 2021, Colorado enacted legislation requiring a 20 percent reduction in its industrial sector GHG emissions by 2030 (relative to 2015 levels),[22] and has already adopted two sets of GHG standards for certain industrial sources pursuant to that law.[23] The California, Minnesota, and Illinois examples that we offer by no means present an exhaustive list of favorable states, but rather serve as illustrative case studies that regulators and other interested parties can draw on for further action.

California

Given its ambitious climate goals, severe ozone problems, and high number of residents living near industrial sources that emit HAPs, California is particularly well positioned to tackle boiler pollution and develop zero-emission standards. The state has, in fact, already taken steps in that direction.

The state of California is home to 42.5 million people and is divided into 35 regional air districts. Two of the largest air districts in the state are the South Coast Air Quality Management District (South Coast), governing an area that includes 17 million residents, and the Bay Area Air District (Bay Area), with 7.7 million residents under its jurisdiction. The California Air Resources Board (CARB) is a statewide agency that works to reduce air pollution alongside the air districts. All three entities have either adopted or are planning regulatory actions to establish zero and near-zero emissions standards for boilers. Table 5 below summarizes those actions.

22 Colo. Rev. Stat. § 25-7-105(1)(e)(XIII).
23 Together, these rules are codified at 5 CCR 1001-31.

Table 5: Summary of California Boiler Standards

Agency	Rule Name	Adoption Year	Sector	Applicability	New or Existing?	Standards
Bay Area	Regulation 9 Rule 6 - NO_x Emissions from Natural Gas-Fired Water Heaters	March 2023	Residential and Commercial	Boilers and Water Heaters < 2 MMBtu/hr	New	0 ng NO_x beginning in 2027 (<75,000 BTU/hr) and 2031 (75,000 - 2,000,000 BTU/hr)
South Coast	Rule 1146.2 - NO_x from Large Water Heaters and Small Boilers and Process Heaters	June 2024	Residential, Commercial, and Industrial	Boilers, Water Heaters, and Process Heaters < 2 MMBtu/hr	New & Existing	0 ppm NO_x & CO phased in from 2026-2033
CARB	Zero Emission Space and Water Heaters Rule	Expected in 2026	Residential, Commercial, and Industrial	Boilers, Water Heaters, and Process Heaters < 2 MMBtu/hr	New	0 GHG phased in from 2027 - 2033
South Coast	Rule 1146 & 1146.1 - NO_x from Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters	Expected in 2026	Industrial, Institutional, and Commercial	Boilers and Process Heaters > 2 MMBtu/hr	TBD	TBD

While the industrial boilers discussed throughout this paper are generally larger in capacity than those covered under the Bay Area and South Coast rules, which apply only to units with maximum heat input capacities of up to 2 MMBtu/hr, new rulemakings are in progress in South Coast to address emissions from larger boilers. According to our industrial boiler NEI analysis, a statewide action to address industrial boilers would impact approximately one quarter of the boilers operating in California.[24] These air districts' standards serve as critical proofs-of-concept for more broadly applicable zero-emission standards that affect larger units. They also demonstrate that currently available cost-effective, non-emitting technology can serve as the basis for regulatory programs, including in other California jurisdictions such as the San Joaquin Valley Air

24 Units that did not include a reported unit capacity were excluded from this estimate.

District, which oversees the most ozone-polluted airshed in the United States. Evidence further suggests that zero-emission standards would, on economic grounds, be better adapted to larger units than smaller ones; in analyzing zero-NO_x requirements for three boiler sizes, South Coast found that the cost of reducing each ton of NO_x was 43 percent less for a 1 MMBtu/hr heat pump and 58 percent less for a 2 MMBtu/hr heat pump compared to a 399,000 Btu/hr unit (South Coast Air Quality Management District, 2023, pp. 2-19–2-21, Table 2.5).

Ultimately, because California's regional air districts are primarily responsible for protecting air quality within their geographic scope, efforts by Bay Area and South Coast to control pollution from industrial boilers will typically focus on conventional pollution, such as NO_x, even while the districts maintain authority to regulate GHGs. The best forum in California to advance boiler electrification specifically from a climate standpoint is the statewide CARB, which the California legislature has tasked with overseeing the implementation and progress of the Global Warming Solutions Act of 2006, also known as AB 32 (California Health & Safety Code § 38510).[25] Under AB 32, CARB has a weighty responsibility: ensuring that California "[a]chieve[s] net zero GHG emissions as soon as possible, but no later than 2045, and ... achieve and maintain net negative GHG emissions thereafter."[26] Among its various directives to CARB for achieving that goal, AB 32 requires the agency to "adopt rules and regulations in an open public process to achieve the maximum technologically feasible and cost-effective GHG emission reductions from sources or categories of sources."[27]

In 2022, CARB included commitments to address residential boilers in the state's Scoping Plan for Achieving Carbon Neutrality, and in 2024, the agency began laying the groundwork for statewide zero-emission requirements for all boilers up to 2 MMBtu/hr in capacity (California Air Resources Board, 2024). In addition to its authority over climate pollutants, CARB is also tasked with adopting Airborne Toxic Control Measures (ATCMs) to establish emissions standards for toxic air contaminants. CARB is thus in a prime position to propose and adopt statewide boiler standards for at least some units reflecting zero-emission technology. It has a forceful mandate from the California legislature; readily available and cost-effective technology options; and precedents for zero-emission boiler standards adopted by Bay Area and South Coast. CARB's standards would also apply to all 35 air districts in California, which would efficiently extend the benefits of rulemaking efforts statewide.

25 California Health & Safety Code.

26 *Id.* § 38562.2(c)(1).

27 *Id.* § 38560.

Minnesota

Minnesota is likewise in a strong position to advance progress on industrial boiler electrification through regulatory standards. The National Map of Industrial Boilers shows nearly 1,000 boilers throughout Minnesota—second only to California[28]—and the true number of units in the state is likely higher. Those included in the Map dataset together emit over 5,700 tons of NO_x annually, as well as substantial quantities of other pollutants, including $PM_{2.5}$, HAPs such as lead and formaldehyde, and CO_2. Chapter 116 of Minnesota's statutes grants the Minnesota Pollution Control Agency (MPCA) very broad authority to control emissions such as these by

> adopt[ing] … rules and standards … for the prevention, abatement, or control of air pollution. Without limitation, rules or standards may relate to sources or emissions of air contamination or air pollution, to the quality or composition of such emissions, or to the quality of or composition of the ambient air or outdoor atmosphere or to any other matter relevant to the prevention, abatement, or control of air pollution.[29]

Chapter 116 thus provides MPCA with a powerful tool to limit pollution from major sources. Policies adopted pursuant to this law have already withstood legal battles; in *Minnesota Automobiles Dealers Association v. MPCA*, the Minnesota Court of rejected a challenge to the agency's Clean Cars Rule, which established both GHG and conventional pollution limits for automobiles produced, sold, or leased within the state.[30] In upholding the vehicle standards, the court cited Chapter 116 as MPCA's source of authority and affirmed that the agency was permitted to establish uniform, statewide standards under that provision for an entire source category.[31]

Minnesota has also enacted aggressive statutory GHG reduction targets that apply "across all sectors" of the state's economy: a 30 percent reduction by 2025, a 50 percent reduction by 2030, and net-zero emissions by 2050 (all relative to 2005).[32] In *Minnesota Automobile Dealers Association*, the Court of Appeals observed that MPCA had relied on those climate targets as part of its motivation for adopting its Clean Cars Rule that the court approved as lawful..[33] In particular, the court highlighted MP-

28 *Id.* § 39666.

29 Minn. Stat. § 116.07. subd. 4; *see also id.* at subd. 2(a) (directing MPCA to "adopt standards of air quality").

30 *Minnesota Auto. Dealers Ass'n v. Minnesota Pollution Control Agency,* 986 N.W.2d 225 (Minn. Ct. App. 2023).

31 *Id.* at 229, 235.

32 Minn. Stat. § 216H.02(a)(2)-(4).

33 *Minnesota Auto. Dealers Ass'n*, 986 N.W.2d at 229.

CA's finding that the rule's emissions reductions were critical in light of the fact that "Minnesota had failed to meet its statutory goal for the reduction of GHGs for 2015 and was not on track to achieve the 2025 or 2050 goals."[34]

Just as it did for automobiles, MPCA has robust legal authority to help remediate the state's shortfall in GHG reductions while also improving air quality by issuing air pollution standards for other sectors, including industrial boilers. Thus far, Minnesota has incorporated by reference EPA's sections 111 and 112 CAA standards for industrial boilers, but does not include any requirements more protective than the existing federal requirements standards, so provides neither zero-emission requirements nor limits on GHG emissions.[35] The National Map shows that over one-third of the state's boilers are in either food and beverage manufacturing, chemical production, or the pulp and paper industry, in which the majority of boiler needs are for medium- or low-temperature processes and therefore suitable for transition to heat pump technology. Minnesota's industrial landscape, therefore, provides another reason for the state to exercise its considerable legal authority to regulate industrial boiler emissions down to zero for targeted sectors.

Illinois

Per the National Map of Industrial Boilers, Illinois is home to almost as many boilers as Minnesota—nearly 950—and again, the true number of units in the state may well be higher. The Map further indicates that nearly half of Illinois's boilers serve subsectors with primarily medium- and low-heat needs, ideal for industrial heat pump installations. Under Illinois's Environmental Protection Act, the state's Pollution Control Board has authority to adopt "[e]mission standards specifying the maximum amounts or concentrations of various contaminants that may be discharged into the atmosphere."[36] Pursuant to this authority, the Board has adopted NO_x standards for industrial boilers that apply concurrently with EPA's standards and, for some units, are more stringent than the current federal requirements.[37] However, the Board's boiler standards do not apply to all units in the state, require very little for boilers below 100 MMBtu/hr in heat input, and do not establish zero-emission standards for any class of boilers.[38]

34 *Id.*

35 Minn. Stat. §§ 7011.0565, 7011.0570, 7011.7050, 7011.7055.

36 Illinois Compiled Statutes, 5/10(A)(b).

37 Ill. Admin. Code tit. 35, §§ 217.160-217.166. For instance, whereas EPA's NO_x limits for gas-fired boilers over 100 MMBtu/hr in heat input are .10 (for low-heat release rate) and .20 (for high-heat release rate) lbs/MMBtu, PCB's standards impose a limit of .08 lbs/MMBtu for boilers over 100 MMBtu/hr.

38 *See, e.g.,* Ill. Admin. Code tit. 35, §§ 217.150(a) (establishing geographic limits and potential-to-emit thresholds for determining applicability of NO_x requirements) and 217.164 (requiring only "combustion tuning" for all boilers that do not exceed 100 MMBtu/hr in heat input capacity).

In 2019, Governor J.B. Pritzker issued an executive order that aligned Illinois with “the principles of the Paris Climate Agreement,” which, for the United States at that time, entailed “reducing GHG emissions 50-52 percent below 2005 levels by 2030, and to net zero no later than 2050” (Ill. Exec. Order 19-6, 2019; United States of America, 2021, p. 1). The Illinois Environmental Protection Agency (Illinois EPA) has since issued a Priority Climate Action Plan that describes various strategies the state will pursue to meet those targets , including an effort to “[e]lectrify 10 percent of low-temperature industrial heat by 2030 and 95 percent by 2050”—noting that “[a]ll-electric technologies such as industrial heat pumps are technically capable, today, of filling this role in nearly all cases” (Illinois Environmental Protection Agency, 2024, p. 58). The state further describes a goal of “[c]onvert[ing] 30 percent of medium- and high-temperature industrial heat in targeted sectors to electricity or hydrogen by 2050” (Illinois EPA pp. 58-59).

Furthermore, Illinois’s state-level Environmental Protection Agency has received substantial federal funding to work toward achieving these goals: in 2024, the U.S. EPA awarded the state a $430 million Climate Pollution Reduction Grant under the Inflation Reduction Act (U.S. EPA - p., 2024). Among the five goals that Illinois EPA included in its grant application was “[k]ick-starting [i]ndustry [d]ecarbonization,” in part by sponsoring the creation of a “Clean Industry Concierge” to help states understand and navigate decarbonization pathways and to facilitate the retrofit of 10 industrial sites with clean technology (State of Illinois, 2023, p. 2 and p. 9). Illinois is therefore a state with a large boiler fleet, political commitments to decarbonize its economy, a government agency with the regulatory tools to act, and dedicated financial resources for cleaning up its manufacturing sector. It presents another prime opportunity to advance zero-emission standards for industrial boilers.

6.2 FEDERAL CLEAN AIR ACT STRATEGIES

In addition to state-level opportunities, the Federal CAA provides numerous avenues for advancing the installation of non-emitting industrial boiler technology instead of combustion boilers. Foremost among these programs are sections 111(b) and (d), which can extend to GHG emissions from new and existing stationary sources, respectively; section 112, which covers HAPs; and the NAAQS program, which governs contaminants like ozone and PM that persist in the lower atmosphere and degrade air quality.

In section 6.1, we will first offer a brief overview of each of these CAA programs to explain how they function in general. We then provide a question-and-answer section that describes how these programs can apply to industrial boilers and what role state agencies might play in this process. We intend for this discussion to help readers—

particularly state air regulators—better understand how the CAA can facilitate the adoption of non-emitting boiler technologies and how state-level pollution control efforts might interact with or even build upon these federal programs.

Sections 111(b) and 111(d) (Addressing GHGs and Other Pollutants)

Under Section 111(b) of the CAA, EPA directly administers standards of performance for new, modified, and reconstructed stationary source categories that the agency has determined cause or contribute significantly to dangerous air pollution.[39] These new source standards are not limited to any particular class of pollutant, and can include restrictions on emissions of GHGs such as CO_2. Section 111(d), on the other hand, applies to *existing* sources in a category subject to new source standards, and only covers pollutants (such as GHGs) which are not already regulated under section 108-110's NAAQS program or section 112's hazardous air pollution program.[40] Standards for both new and existing sources under section 111 must reflect EPA's determination of the "best system of emission reduction" that is adequately demonstrated, taking into account costs, energy requirements, and other factors.[41]

Unlike section 111(b)'s new source program, section 111(d) does not feature direct federal administration of standards for existing standards. Instead, EPA first issues emission guidelines that specify the level of reductions required from existing sources.[42] State agencies then develop and submit for EPA's approval implementation plans, which include enforceable standards of performance for existing sources within their borders.[43] These state plans must be "no less stringent" than EPA's guidelines.[44] For states that choose not to participate in the program or do not submit an approvable plan, EPA will issue a federal plan for existing sources within that state.[45]

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39 42 U.S.C. § 7411(b).

40 *Id.* § 7411(d)(1).

41 *Id.* § 7411(a)(1).

42 *Id.* § 7411(d)(1); 40 C.F.R. § 60.22a.

43 42 U.S.C. § 7411(d)(1); 40 C.F.R. § 60.23a.

44 40 C.F.R. § 60.24a(c); *see also West Virginia v. EPA*, 597 U.S. 697, 710 (2022). However, when "applying a standard of performance to any particular source under a [state] plan," states retain authority to "to take into consideration, among other factors, the remaining useful life of the existing source to which such standard applies." Under EPA regulation, states may set less stringent standards than EPA guidelines based on source-specific factors if the state can satisfy certain factors justifying such a relaxation. 40 C.F.R. § 60.24a(e).

45 42 U.S.C. § 7411(d)(1).

Table 6: Section 111 of the CAA

	Section 111(b)	Section 111(d)
Source types covered	New, modified, and reconstructed stationary sources	Existing sources in a category subject to new source standards
Air pollutants covered	Any class of pollutants	Pollutants not already regulated under section 108-110's national ambient air quality program or 112's HAPs program or section
Administering entity	EPA	EPA in partnership with states—EPA issues guidelines setting emissions reduction targets, and states develop implementation plans for compliance that are no less stringent than EPA's guidelines. Implementation plans are subject to U.S. EPA's approval, and EPA will issue federal plans for states with no approvable state plan.
Required degree of emission limitation	EPA's determination of the best system of emission reduction	EPA's determination of the best system of emission reduction

Section 112 (Addressing HAPs/Air Toxics)

Section 112 of the statute provides EPA with another pathway toward advancing boiler electrification, in this case through the regulation of HAPs. Section 112 currently lists 189 compounds or elements as regulated HAPs, which it defines as:

> pollutants which present, or may present, through inhalation or other routes of exposure, a threat of adverse human health effects (including, but not limited to, substances which are known to be, or may reasonably be anticipated to be, carcinogenic, mutagenic, teratogenic, neurotoxic, which cause reproductive dysfunction, or which are acutely or chronically toxic) or adverse environmental effects whether through ambient concentrations, bioaccumulation, deposition, or otherwise.[46]

For "major sources" in a listed category—i.e., those sources which, when uncontrolled, emit at least 10 tons per year of any one HAP or at least 25 tons per year of combined HAPs— EPA must designate the maximum achievable control technology

46 *Id.* § 7412(b)(1)-7412(b)(2).

(MACT).[47] For new major sources, this means the unit must achieve emission reductions equal to that of the single “best controlled similar source,” while existing major sources must achieve “the average emission limitation achieved by the best performing 12 percent of the existing sources.”[48] The statute also requires EPA to issue standards for HAP emissions from “area sources”—units within a listed category that fall below the emission thresholds for major sources.[49] For area sources, EPA may either issue standards reflecting MACT-levels of control, or may instead issue more lenient emissions limits based on Generally Available Control Technologies (GACT).[50]

NAAQS Program (Addressing Criteria Pollutants)

The CAA’s NAAQS program, which is found at sections 108 to 110 of the law, addresses dangerous air contaminants (commonly known as criteria pollutants) “the presence of which in the ambient air results from numerous or diverse mobile or stationary sources.”[51] Under this program, EPA first establishes maximum permissible limits on ambient concentrations of the six compounds that it currently regulates as criteria pollutants: ozone, PM (including both PM10 and $PM_{2.5}$), NO_x, sulfur dioxide, lead, and carbon monoxide.[52] Once EPA issues NAAQS limits for each pollutant, states then develop state implementation plans (SIP) to ensure that all areas of the state satisfy those limits.[53] For states that choose not to participate in the program, EPA will issue a federal implementation plan covering that state or portion of the state.[54]

If air quality in any part of a state falls short of the NAAQS level for a pollutant, the state (or EPA in its stead) must develop a nonattainment state implementation plan (NSIP) to improve air quality and come into compliance with NAAQS in a timely fashion.[55] These NSIPs must include “all reasonably available control measures [RACM]” to bring the area into attainment, “including such reductions in emissions from existing sources in the area as may be obtained through the adoption, at a minimum, of reasonably available control technology [RACT]” (§ 7502(c)(1)).[56]

While the CAA does not define RACT or RACM, EPA has for decades employed the following definition for RACT: “the lowest emission limitation that a particular source

47 *Id.* §§ 7412(a)(1), (d)(2).
48 *Id.* § 7412(d)(3)(A).
49 *Id.* § 7412(a)(2).
50 *Id.* § 7412(d)(5)); *see also U. S. Sugar Corp. v. EPA*, 830 F.3d 579, 595 (D.C. Cir. 2016).
51 42 U.S.C. § 7408(a)(1)(B)).
52 *Id.* § 7408(a)(2); 40 C.F.R. §§ 50.4–50.20.
53 42 U.S.C. §§ 7410(a)-(c).
54 *Id.* § 7410(c).
55 *Id.* §§ 7501–15.
56 *See also* 42 U.S.C. § 7511a(a)(2)(A), (b), (c), (d), (e) (describing RACT requirements for plans covering marginal, moderate, serious, severe, and extreme ozone nonattainment areas); 40 C.F.R. 40 C.F.R. § 51.1312 (describing RACT and RACM requirements for areas in violation of the 2015 ozone NAAQS).

is capable of meeting by the application of control technology that is reasonably available considering technological and economic feasibility."[57] Where EPA finds, in its technical judgment, that the RACT provisions in a state-issued NSIP are not sufficiently protective, it may reject that plan as unsatisfactory under the statute.[58] In addition, EPA may issue RACT/RACM guidance through its authority under section 108(b)(1) to provide state agencies with "information on air pollution control techniques."[59] These guidelines provide states with presumptively approvable RACT/RACM provisions that they can incorporate into their NSIPs.

QUESTIONS AND ANSWERS: HOW CAN EPA AND STATE AGENCIES ADVANCE BOILER ELECTRIFICATION THROUGH THESE CAA PROGRAMS?

- **Do states have the authority to adopt boiler standards independent of EPA's requirements? Can state-level requirements be more stringent than parallel U.S. EPA standards?**

  The answer to both questions is **yes.** The CAA expressly preserves states' authority to issue standards that are independent of, and potentially more stringent than, the agency's own pollution control requirements for stationary sources, including boilers. Section 116 of the Act provides that, apart from certain listed exceptions pertaining primarily to mobile sources, "nothing [the CAA] shall preclude or deny the right of any State or political subdivision thereof to adopt or enforce (1) any standard or limitation respecting emissions of air pollutants or (2) any requirement respecting control or abatement of air pollution."[60] While states cannot issue their emission requirements that are less stringent than parallel federal standards issued under section 111 or 112, or under a NAAQS implementation plan, they can be more stringent, provided that the state has not adopted a self-imposed law or policy (as some have) that prohibit standards that are more protective than EPA's.[61]

- **Are industrial boilers currently subject to section 111 standards?**

  New and modified industrial boilers have been subject to section 111(b) limitations for their criteria pollution for decades. In 1971, EPA's first set of section 111(b) standards included NO_x, PM, and sulfur dioxide limits for new fossil fuel-fired steam generators—including industrial boilers—with a heat input above 250 MMBtu/

57 82 Fed. Reg. 49,128, 49,128 (Oct. 24, 2017).

58 *See, e.g., Nat'l Steel Corp., Great Lakes Steel Div. v. Gorsuch*, 700 F.2d 314, 323 (6th Cir. 1983); State of Mich. v. Thomas, 805 F.2d 176, 183 (6th Cir. 1986).

59 42 U.S.C. § 7408(b)(2).

60 42 U.S.C. § 7416.

61 *Id.*

hr.[62] In subsequent years, the agency went on to establish subcategories under the broader steam generator umbrella that specifically applied to industrial, commercial, and institutional boilers of different sizes and that provided performance standards specifically for these units.[63] Thus far, however, EPA has not issued GHG requirements under section 111 of industrial boilers, nor has it designated industrial heat pumps or other non-emitting technology as the best system of emission reduction for these units.

- **Can EPA's section 111 standards for industrial boilers cover GHG emissions?**

  Yes. In *Massachusetts v. EPA*, the Supreme Court held that the CAA's statute-wide definition of "air pollutant" includes GHGs.[64] The agency also formally determined in 2009, based on massive record evidence, that six well-mixed GHGs—CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride—endanger public health and welfare by driving climate change.[65] Since that time, EPA has issued section 111 GHG standards for multiple source categories, including electric generating units (in the form of CO_2 limits), oil and gas equipment (in the form of methane limits), and municipal solid waste landfills (in the form of limits on methane-rich landfill gas).[66] While the agency's GHG standards for boilers do not currently extend to those outside the electric power sector, the agency has full legal authority—as well as a strong technical and economic basis—for issuing GHG standards, along with updated criteria pollutant limits, for industrial boilers as well. Industrial thermal emissions represent approximately 13 percent of total U.S. GHG emissions, more than any stationary source category apart from electricity generation, and a substantial percentage of those emissions result from the use of combustion boilers (RTC, 2022, pp. 7-8; U.S. EPA, 2024, p. 2-4, Table 2-1).

- **Does section 111 allow for zero-emission standards for boilers?**

  Yes. Section 111 does not impose a lower limit on the quantity of emissions that EPA may permit from regulated sources. While this provision does not specifically define what a "system of emission reduction" may be, language elsewhere in section 111 refers to "a technological process for production or operation by any

62 36 Fed. Reg. 24,876 (Dec. 23, 1971); 40 C.F.R. Part 60 Subpart D.

63 51 Fed. Reg. 42,768 (Nov. 25, 1986) established 40 C.F.R. § 60, Subpart Db, which applies to boilers above 100 MMBtu/hr and covers SO2, PM, and NO_x emissions. 55 Fed. Reg. 37,674 (Sept. 12, 1990) established 40 C.F.R. § 60, Subpart Dc, which applies to boilers between 10 and 100 MMBtu/hr and covers SO2 and PM emissions.

64 *Massachusetts v. EPA*, 549 U.S. 497, 528 (2007).

65 74 Fed. Reg. 66,496 (Dec. 15, 2009). While EPA officials recently announced intentions to "reconsider" the 2009 Endangerment Finding, any such action would be highly vulnerable to legal challenges, particularly since the 2009 Finding has already been upheld in its entirety by the D.C. Circuit and the evidence in support of its conclusions has only grown more overwhelming in the decade and a half since its release. *See Coal. for Responsible Regul., Inc. v. EPA, 684 F.3d 102, 116–25 (D.C. Cir. 2012), overturned in part on other grounds sub nom. Util. Air Regul. Grp. v. EPA*, 573 U.S. 302, (2014).

66 40 C.F.R. Part 60 Subparts TTTT-TTTTa, UUUUb, OOOOa-c, XXX.

source which is inherently low-polluting or nonpolluting."[67] Congress thus clearly contemplated that section 111 standards could reflect not only systems that merely reduce pollution relative to some baseline, but also those that simply do not pollute in the first place, such as electricity-powered processes that displace those that utilize polluting fuels. Provided that they satisfy the other factors relevant to the "best system of emission reduction," such as costs and availability, heat pumps and other non-emitting boiler technologies may be appropriate bases for section 111 standards. Indeed, EPA's section 111 methane standards for the oil and gas sector require zero emissions from process controllers and pumps, requiring both non-emitting new installations (such as controllers and pumps powered by electricity rather than gas) and retrofits for existing units.[68]

- **How much flexibility does section 111 grant EPA in terms of determining what standards are applicable to what sources?**

  Section 111 permits EPA to "distinguish among classes, types, and sizes within categories" when issuing standards.[69] Thus, just as EPA has set differing emission requirements for small versus standard-sized industrial boilers since the 1980s,[70] it could, in principle, limit zero-emission standards to boilers in the low- and medium-temperature range, and/or could focus on boilers in those particular industrial sectors (such as chemical manufacturing, pulp and paper mills, and food and beverage processing) in which low- and medium-temperature thermal applications are most widespread. The agency could also choose to limit zero-emission requirements to boilers that would otherwise fire purchased fuels, such as natural gas, coal, or oil, rather than those that burn byproduct fuels. EPA thus has substantial flexibility under section 111 to target those units for which electrification is most appropriate in the near-term, and need not apply a one-size-fits-all approach before the entire fleet of industrial boilers is ready to decarbonize.

- **Are industrial boilers currently subject to section 112 standards for HAPs?**

  Since the 1990s, EPA has included industrial boilers on its list of published source categories under section 112 for both major sources and area sources.[71] However, while the agency has issued major and area source emission limits for coil- and oil-fired boilers, it has issued no numerical major source standards for natu-

67 42 U.S.C. § 7411(a)(7). While the statute directs EPA to consider factors such as costs, nonair health and environment impacts, and energy requirements in determining the "best system," it does so in the context of the section 111 provision defining "standard of performance," *id.* § 7411(a)(1), and does not offer a separate definition for describing what kinds of measures such a system may include.

68 89 Fed. Reg. 16,923-39; 40 C.F.R. §§ 60.5390b(a), 60.5393b(a), 60.5394c(a), 60.5395c(a)).

69 42 U.S.C. § 7411(b)(2).

70 *See* 40 C.F.R. § 60, Subparts D, Db, Dc.

71 57 Fed. Reg. 31,576 (July 16, 1992) (major sources); 64 Fed. Reg. 38,706, 38,721 (July 19, 1999) (area sources).

ral gas-fired boilers, instead merely requiring "tune-ups" every two or five years depending upon the boiler size.[72]. Moreover, the agency has issued no area source standards at all for gas-fired boilers.[73] As part of its obligation to review and, if necessary, revise each listed category's section 112 standards at least once every eight years, EPA could not only update its boiler standards to fully cover gas-fired units—which, as described in Section 3 of this report, are significant sources of HAPS—but also to evaluate the applicability of electric boiler technology as a basis for such requirements. As with section 111 standards, revised section 112 standards for boilers could reflect the use of non-emitting options like heat pumps. In fact, the agency could coordinate its efforts in these two programs and undertake a single rulemaking for industrial boilers that established heat pumps or related technologies as the underlying technical basis for both updated section 111 and 112 standards.

- **What opportunities are available to EPA and states for achieving boiler decarbonization through the NAAQS program?**

  As of 2025, there are still many nonattainment areas that lack approved NSIPs for the 2015 8-hour ozone NAAQS. (And as noted above in Section 3.2, a quarter of all industrial boilers are located in 8-hour ozone NAAQS nonattainment areas.) Furthermore, EPA finalized strengthened $PM_{2.5}$ NAAQS in March 2024, which will require new NSIP submissions once EPA has completed the task of designating which areas are in attainment and which are not.[74] For these NSIPs, states may incorporate boiler electrification requirements, or measures that otherwise displace fossil fuel-based industrial heat applications with non-emitting options, as a means of reducing their ozone or $PM_{2.5}$ precursors (including t) and thus helping to achieve attainment. EPA may also issue guidance that includes industrial boiler decarbonization as a component of RACT/RACM for these sources, and may adopt a policy of only approving NSIPs that have either included such measures or that have adequately justified not doing so.

  To give an analogous example, in 2022, EPA issued a decision reviewing parts of California's NSIP for the 2012 $PM_{2.5}$ NAAQS applicable to the San Joaquin Valley nonattainment area. While EPA approved this NSIP in most regards, it disapproved the plan's failure to consider as Best Available Control Measures (BACM) to reduce emissions of building heating via "the electrification of furnaces, water heaters, and other gas-fired appliances."[75] EPA could extend this same policy to emission

72 40 C.F.R. § 63.7500(e); *id.* Part 63, Subpart DDDDD, Tables 1-3.

73 *Id.* § 63.11195(e).

74 89 Fed. Reg. 16,202 (Mar. 6, 2024).

75 87 Fed. Reg. 60, 494, 60510-12 (Oct. 5, 2022). BACM represent the same fundamental concept as RACT/RACM, but apply specifically to NSIPs for areas in "serious" nonattainment for PM. 42 U.S.C. §7513a(b)(1)(B).

reductions from industrial heat processes when reviewing future NSIP submissions for ozone and PM, and could issue formal guidance establishing boiler electrification as a formal element of RACT/RACM. Even without EPA taking action on this front, states without ozone or PM nonattainment areas could still incorporate these policies into their NSIPs, relying in part on boiler electrification to achieve attainment.

6.3 OTHER POLICY SOLUTIONS

Though emissions standards are an invaluable tool for driving industry-wide electrification efforts, they are not a silver bullet; lawmakers should work to implement these new rules alongside complementary policy initiatives to advance industrial boiler electrification. Reducing the price gap between electric and gas-fired equipment is a particularly high priority. Regulations will only indirectly reduce that gap, but other policy tools can provide more direct financial support and incentives to ensure that electrification is broadly cost-effective for industrial manufacturers.

As noted above, the current federal political environment has given states the opportunity to step up and lead on climate action. This section therefore explores several legislative and regulatory opportunities for both federal and state policymakers to support industrial boiler electrification, with an emphasis on states' ability to act (Evergreen Action, 2025). These include policies that can be defined as either providing direct financial support (i.e. directing state investments into electrifying facilities) or otherwise supporting the transition (e.g. through technical assistance). The remainder of this section is organized accordingly.[76]

Financial Support

Production tax credit (PTC)

Legislation establishing a clean heat PTC would provide a financial payment (through a refundable tax credit) to companies for each unit of industrial heat produced by non-emitting technologies.[77] This incentive would mirror federal policies that continue to support renewable electricity generators like wind and solar facilities, and that

76 Several of the policies described here—tax credits, carbon pricing, and low-interest loans—are analyzed and modeled in the CAELP report; readers are encouraged to explore that publication for a further discussion of them (Smillie et al., 2024, pp. 46-56).

77 Or, when considering upstream emissions, by low-emitting technologies.

were particularly important to advancing clean energy during the 2010s, before these clean resources were independently cost-competitive with emitting sources of electricity.[78]

Because the price of electricity relative to fossil fuels is the main contributor to the cost differential between clean and fossil-fueled industrial heat, a clean heat PTC would substantially offset the increased cost of operating low- and zero-carbon thermal technologies. The CAELP report's analysis concluded that a federal clean heat PTC emulating proven renewable energy policies could greatly enhance the cost-competitiveness of heat pumps, encouraging greater market penetration of these units and achieving up to 85 million additional metric tons of CO_2 reductions at no marginal abatement cost (Smillie et al., 2024, p. 47). The monetized benefits of this policy would exceed CAELP's projected program costs by an order of magnitude (Smillie et al., p. 48).[79]

And although a clean heat PTC would have the biggest impact at the federal level, states with sufficient financial resources could also implement their own PTC.

Investment Tax Credit (ITC)

Where a production tax credit would subsidize the production of clean heat on a per-unit-generated basis, an investment tax credit would offer payments to recoup some of the upfront capital cost of the new low-emissions thermal equipment itself (Smillie et al., p. 51). The federal ITC for renewable resources has meaningfully assisted the renewables industry by subsidizing the installed capacity of non-emitting electric generators, and current policy allows companies to deduct 24 percent of the installation cost of clean energy resources from their tax liability (U.S. Internal Revenue Service, 2025).

To understand the impacts of an analogous federal ITC for heat pumps, CAELP analyzed a series of subsidy options ranging from 10 to 50 percent of capital costs (Smillie et al., p. 52). The results showed an ITC can improve the cost-competitiveness of these units, particularly at lower rates of heat pump utilization. However, an ITC would not address the primary cost differential between heat pumps and combustion turbines—the "spark gap" between electricity and fossil fuel prices for each unit of energy—and so may be considered a lower priority than a PTC at the federal level (Smillie et al., pp. 52-53).

78 To evaluate the potential benefits of this option, CAELP considered a range of subsidies for heat pumps (from $2.50/MMBtu to $10/MMBtu (0.85 c/kWh to 3.4 c/kWh of heat), compared against reference prices for gas at combustion boilers. CAELP further a percentsumed that, "[t]o gain the full credit value, annual emission reductions considering upstream electri percent emissi percentns must meet a 60% reduction threshold relative to the initial year, and get a partial credit for reductions between 25% and 60%" (Smillie et al., pp. 52-53).

79 Using EPA's most recent 2030 values for the social cost of carbon, 85 million metric tons in CO_2 reductions translate to between approximately $12 and $32 billion in annual climate benefits. By contrast, CAELP projects that, at the highest level of subsidy ($10/MMBtu), the program would cost just $1.65 billion (Smillie et al., p. 48).

States can also implement an ITC for industrial electrification. Colorado has already done so: the Colorado Industrial Tax Credit Offering allocates "$168 million in refundable tax credits for industrial facilities to explore and implement greenhouse gas emission reduction projects" (Colorado Energy Office - a., n.d.). Many other states have implemented ITCs in other sectors, incentivizing the installation of clean energy capacity, electric vehicle chargers, and more (RSM, 2025). States with funding allocated for manufacturing development and/or climate programs can consider establishing a similar initiative for industrial electrification.

Other Grants and Incentives

The Inflation Reduction Act of 2022 (IRA) created multiple grant programs that could support industrial decarbonization, including the Industrial Demonstrations Program. States likewise have a number of policy tools for investments and incentives at their disposal in addition to PTCs and ITCs. For example:

- Pennsylvania's RISE PA initiative, is a $396 million statewide industrial decarbonization grant program (Commonwealth of Pennsylvania Department of Environmental Protection, n.d.). RISE PA is making tiered grants available to small, medium, and large manufacturers to implement a diverse range of facility retrofits to cut GHG emissions and invest in Pennsylvania's industrial economy.
- New York's Heat Recovery Program invests in waste heat recovery demonstration projects (New York State Energy Research and Development Authority (NYSERDA), n.d.). The program is currently seeking building owners interested in deploying waste heat recovery equipment—which could include industrial heat pumps—in their facilities.
- Colorado's $25 million Clean Air Program (CAP) grants are designed to offset "the direct costs of purchasing industrial air pollutant emission reduction equipment at the site where air pollutant emissions are generated and released" (Colorado Energy Office - b., n.d.). Though CAP closed its final round of applications earlier this year, it provides a valuable example of a midsized grant program for enabling industrial decarbonization.

Though this is not a comprehensive list of state grant programs for industrial decarbonization, it does demonstrate the diverse approaches states are taking to offset capital costs from new equipment installations. Other states interested in industrial decarbonization initiatives can follow their lead.

Loan Programs

Loan programs for industrial heat pumps can assist purchasers of these units by "[issuing] loans at below-market interest rates, providing longer repayment terms, offering loan guarantees to reduce the risk for lenders, requiring reduced down payments or waiving or reducing fees associated with loans" (Smillie et al., p. 54). Federal loan programs have for years assisted fledgling industries and technologies gain access to markets, usually with "minimal impact on public finances" (Mengden, 2024). The CAELP report considered the impacts of programs offering loans to heat pump purchasers at real interest rates (i.e., adjusted for inflation) ranging from 4 to 10 percent (Smillie et al., p. 54). As with the ITC, CAELP's analysis indicated that reduced-rate loans would have a relatively small impact on the cost-competitiveness of heat pumps, since they would affect the initial capital investments but not the differences in electricity rates versus fuel prices (Smillie et al., pp. 54-55). However, given the low costs associated with loan programs, legislators should nevertheless consider pairing these options with other policies described above in order to fully incentivize manufacturers to switch to cleaner thermal options.

State lawmakers have the opportunity to develop loan programs as a lower-cost alternative to capital grants and tax credits for industrial electrification (Evergreen Action, 2025). As noted in Evergreen and Rocky Mountain Institute's (RMI) recent report on state industrial decarbonization planning, several states established State Energy Financing Institutions (SEFI) over the last two years, with the intention of leveraging state dollars to bring federal funding to projects within their borders (Michigan Department of Environment, Great Lakes, and Energy, 2024; Arizona Governor's Office of Resiliency & Arizona Finance Authority, 2024). The pipelines of potential projects that these SEFIs identified can still be financed, with private investments filling the federal gap in the capital stack.

Workforce Support

Policymakers should ensure that all investments in industrial electrification, including projects to transition to clean heat, preserve and create good jobs with high wages, wraparound benefits, and the opportunity to organize a union. A number of policy levers can be attached to program funding to promote good job retention and creation, including:

- Prioritizing reinvestments in existing industrial facilities and their host communities to ensure their standing workforce is preserved through the clean industry transition.
- Partnering with organized labor to map workforce needs and develop training pathways to fill gaps and build sustainable career pipelines.

- Conditioning subsidies and incentives on protecting labor rights, providing high-road wages and benefits, and creating and/or retaining a large number of good jobs.
- Providing additional incentives for creating good jobs, modeled off of the adders in federal clean energy tax credits for paying prevailing wages and hiring a high proportion of apprentices.

Many states have already enacted some or all of these supportive policies; Washington State, for example, provided the original model for the IRA's labor adders (Washington State Department of Labor & Industries, n.d.). As states look to advance industrial electrification, they should prioritize such supportive policies to protect and provide for working families.

Other Supportive Policies

Carbon Price

A carbon price would function as a "stick" to the "carrots" of investment-based policies: It would impose a cost on sources' CO_2 emissions rather than offering them money not to emit. As CAELP describes, while there are multiple options for designing and administering a carbon price scheme, the most straightforward approach would simply impose a legal obligation on sources in certain industries to pay a fixed dollar amount for each ton of CO_2 that they emit—in other words, a carbon tax (Smillie et al., p. 49). Twenty-three countries in Europe currently assess some form of a carbon tax, with levies ranging from €1 per metric ton of CO_2 to over €100 per metric ton, with an average figure of €49.23 as of April 1, 2024 (Mengden, 2024). To help avoid giving an economic advantage to foreign exporters of goods who are not subject to such a tax for their CO_2 emissions, the European Union has established carbon border adjustment mechanism, which, as CAELP explains, "impose[s] tariffs based on the production emissions of imported commodities to level the playing field with commodities produced in regions without stringent climate policies" (Smillie et al., p. 49).

The U.S. federal government could institute similar policies, and could include industrial thermal equipment among the sources required to pay the carbon tax. CAELP's analysis of hypothetical $50/metric ton, $98/metric ton, and $150/metric ton carbon taxes in the U.S. would "significant[ly] increase … the share of heat pumps which are cost competitive with natural gas equipment," while driving down demand of gas for industrial heat purposes (Smillie et al., pp. 49-51). Individual states can also adopt either direct or indirect forms of a carbon tax, and many now do. Thirteen states currently participate in programs designed to reduce GHGs that include some form of carbon pricing; together, these states cover approximately 30 percent of the U.S.

population (Center for Climate and Energy Solutions - b., n.d.). For instance, California's program, known as AB32, applies to approximately 85 percent of the state's GHG emissions, including those from large electric power plants, large industrial plants, and fuel distributors (Center for Climate and Energy Solutions - a., n.d.).

Permitting legislation

For many years, state air regulators have largely left an important tool unused in their efforts to advance clean technology: new source permitting. State programs to implement the Clean Air Act's permitting requirements for new or modified major sources of air pollution have often operated under self-imposed constraints that originated at EPA but are neither required by law nor binding on state regulators. For example, as Evergreen Action has explained, under current EPA policy, "permit writers do not have to consider changes in fuel type or source design that, in the mind of the applicant, would 'redefine' what it wants to build" (Evergreen Action, 2024, p. 14). In other words, if a manufacturer is seeking a major source permit for a new gas-fired industrial boiler, EPA could not even consider requiring a boiler powered by a heat pump instead to fulfill the operators' statutory obligation to install the "best available control technology,"[80] no matter how advantageous a heat pump might be in this situation. Not only does this policy appear nowhere in the Clean Air Act, it is directly at odds with the statute's requirement that the permitting authority analyze the air impacts of the new proposed source and "alternatives thereto," prior to granting any permit.[81]

Notably, states are not bound by the "redefining the source" doctrine in their own air permitting programs, and at least one court has rejected a state agency's effort to adhere to such a policy at the state level without legal justification.[82] California has recently considered legislation to clarify that the state's air permitting authorities can and should consider "alternative technologies" from the applicant's preferred choice,[83] and other states could similarly follow suit. Relatedly, in states that require permits even for non-emitting sources like conventional electric boilers or heat pumps, those states could adopt accelerated or de facto permits for clean boiler technologies as compared to fossil-fueled combustion boilers. To learn more about these and other air permitting reform opportunities, readers should consult Evergreen Action's report titled *Accelerating the Clean Air Act's Innovation Engine: Opportunities to Reform Air Permitting Programs to Scale Up Clean Technology* (Evergreen Action - b., 2024).

80 42 U.S.C. § 7475(a)(4).
81 *Id.* § 7475(a)(2).
82 *Friends of Buckingham v. State Air Pollution Control Bd.*, 947 F.3d 68, 84 (4th Cir. 2020).
83 SB 318 §§ 2, 8 (Ca. 2025).

Roadmapping and Technical Assistance

As detailed in Evergreen and RMI's state industrial decarbonization report, states have a critical role to play in the clean industry transition through roadmapping and technical assistance services (Evergreen Action - b., 2025). Widespread industrial electrification will require targeted policy interventions developed with an understanding of market contexts. State leaders can engage in planning and visioning processes to help maximize the benefits and efficiency of this transition while preparing for any challenges. These efforts can include future-of-gas proceedings (in which public utility commissions or similar regulatory bodies develop strategies to move away from gas) or the issuance of comprehensive climate action plans. Programs such as these can help create informed policy toolkits and support long-term efforts to decarbonize U.S. industry.

Building on those visioning efforts, states can also implement technical assistance programs to support industrial stakeholders through the transition. For example, as discussed previously in Section 6.1, Illinois has developed a "Clean Industry Concierge" program that connects industrial plant owners and operators with technical resources and facilitates shared spaces for communication across stakeholder groups. This approach takes advantage of the state's centralized role to ensure manufacturers have the technical resources they need to effectively decarbonize and electrify their facilities. States can further provide industrial assessments, energy audit services, and many more resources to compile the technical assistance toolkit and facilitate ambitious pollution reduction initiatives.

Defense Production Act

At the federal level, the president can leverage the Defense Production Act (DPA) to strengthen domestic industrial heat pump supply chains and accelerate industrial electrification. Though such action is unlikely under the current administration, the Biden White House provides a model for future presidents to wield their DPA powers to full effect. Evergreen has detailed the full scope of executive authority under the DPA to build clean technology supply chains, including directing congressionally appropriated funds, convening voluntary agreements to coordinate sectoral growth, delegating priority access for material inputs to heat pump manufacturers, commissioning industrial studies to deliver detailed insights into heat pump supply chains, and more (Evergreen Action, 2023; U.S. DOE - f., 2023). An administration interested in advancing industrial electrification should look to the DPA as a critical, but often overlooked, policy tool in the toolbox.

Energy Storage Tariffs

As noted above, the pace of industrial boiler electrification depends in large part on the spark gap—manufacturers' cost differential between natural gas and electricity. Utility rate reform policies that are designed to take advantage of increasingly abundant clean energy and lower electricity rates for industrial customers is one of the most direct policy levers available to close that price gap.

Growing renewable deployment is transforming electricity markets by bringing gigawatts of low-cost variable resources into wholesale markets. In the coming years, for example, nearly every pricing node in the California Independent System Operator (CAISO) will experience hours every day where electricity prices drop below the price of wholesale gas currently used for industrial process heat. In places with inadequate demand or transmission capacity, that renewable power may even be curtailed—effectively wasting available solar and wind energy.

Novel utility tariff structures with time- and location-specific market pricing can allow industrial customers with flexible loads (i.e., flexibility in when they draw on the grid) to utilize these periods of excess energy and electricity price dips. Facilities with onsite energy storage—including the thermal energy storage systems described previously,, which are highly flexible and low load-factor technologies—are prime candidates to benefit from that pricing structure. Widely implementing such reforms would make electric boiler technologies more cost-competitive with fossil-fueled boilers, reduce curtailment of renewable resources, and lower the cost of clean energy deployment.

Other Utility Reforms

In addition to specialty tariffs for energy storage, state public utilities commissions can avail themselves of other policy opportunities to close the spark gap. Though policymaking at the commission level to facilitate industrial electrification is largely unexplored terrain with few proven successes, the policy tools applied for building decarbonization can provide some insight into options for the sector. Those might include:

- Authorizing utilities to provide electrification incentives for industrial customers (e.g., a rebate program for facilities converting to industrial heat pumps)(Blumsack, 2025, p. 102).
- Moving away from demand pricing for industrial customers, which applies charges based on the highest level of electricity they draw at one time during the billing period. As ACEEE explains in a recent report, Denmark has demonstrated that dynamic pricing can facilitate economical electrification, even for customers without onsite energy storage (Hoffmeister et al., 2024).

- Ending the practice of subsidizing “efficient” fossil-fueled industrial equipment, which encourages ongoing dependence on polluting conventional boilers and delays electrification.

These strategies by no means represent an exhaustive list of possibilities that legislators can or should consider to help encourage the adoption of heat pumps and conventional electric boilers for industrial thermal needs. Rather, they reflect a number of well-understood and potentially effective approaches, several of which have been adopted either in other sectors or in other countries, and thus have a real track record that can be studied and built upon. Legislators and policymakers should consider these options, and also work to innovate new pathways to help facilitate the transition to a cleaner manufacturing center that is oriented toward the future.

7. Conclusion

This report has detailed the significant opportunity and necessity for transitioning from fossil fuel-fired industrial boilers to cleaner, electric alternatives. The analysis of boiler distribution and emissions across the U.S. reveals the substantial negative impacts that these units have on both climate emissions and air quality, highlighting the urgent need for change. Fortunately, viable non-emitting technologies, including industrial heat pumps, conventional electric boilers, and thermal batteries, offer effective pathways to decarbonize industrial heating processes.

The report draws on multiple other recent publications that support the deployment of electric boiler technologies, including findings from economic analyses that demonstrate that these non-emitting technologies can already achieve cost-reasonable emission reductions in many settings, particularly when measured against the social cost of carbon and the long-term benefits of improved public health. While challenges remain in terms of upfront costs and the need for grid modernization, strategic policy interventions at both the state and federal levels can accelerate the adoption of these cleaner heating solutions.

State-level emission standards, leveraging the authority granted by the Clean Air Act, provide a powerful tool for driving near-term change. Federal Clean Air Act strategies, including those under Sections 111 and 112 and the NAAQS program, offer additional avenues for regulating emissions and promoting the deployment of non-emitting technologies. Furthermore, complementary measures, such as production tax credits, investment incentives, and various other support mechanisms and policy strategies, can further reduce the economic barriers to electrification.

Transitioning the industrial sector away from fossil fuel-fired boilers is crucial for achieving ambitious climate goals and protecting public health. The findings of this report strongly support a concerted effort by policymakers, regulators, industry representatives and other stakeholders to embrace the available non-emitting technologies and implement policies that foster a rapid and just transition to a cleaner industrial future. Continued research, technological advancements, and collaborative efforts will be essential to fully realize the potential for industrial boiler electrification and secure a healthier, more sustainable environment.

List of Acronyms

ACEEE	American Council for an Energy-Efficient Economy
ALA	American Lung Association
AQI	Air Quality Index
AQMD	Air Quality Management District
ATCM	Airborne Toxic Control Measures
BACM	Best Available Control Measures
BACT	Best Available Control Technology
Bay Area AQMD	Bay Area Air Quality Management District
CAA	Clean Air Act
CAELP	Center for Applied Envrionmental Law and Policy
CAISO	California Independant System Operator
CAP	Clean Air Program
CHP	Combined Heat-and-Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DAC	Disadvantaged Community
DOE	Department of Energy
DPA	Defense Production Act
E3	Energy and Environmental Economics, Inc.
EGS	Enhanced Geothermal System

EI	Energy Innovation
EIA	Energy Information Adminstration
EPA	Environmental Protection Agency
GACT	Generally Available Control Technologies
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Reporting Program
HAP	Hazardous Air Pollutant
HCl	Hydrochloric Acid
HSC	Health & Safety Code
IEA	International Energy Agency
IHP	Industrial Heat Pump
Illinois EPA	Illinois Environmental Protection Agency
IRA	Inflation Reduction Act
ITC	Investment Tax Credit
LBNL	Lawrence Berkeley National Laboratory
LCOH	Levelized Cost of Heat
MACT	Maximum Achievable Control Technology
MMBtu	Metric Million British Thermal Unit
MMT	Million Metric Ton
MPCA	Minnesota Pollution Control Agency

List of Acronyms cont'd

MVC	Mechanical Vapor Compression
MWe	Megawatt Electric
MWh	Megawatt Hour
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NEI	National Emissions Inventory
NESCAUM	Northeast States for Coordinated Air Use Management
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NSIPS	Nonattainment State Implementation Plan
NSPS	New Source Performance Standards
NSR	New Source Review
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 micrometers (in diameter)
PTC	Production Tax Credit
RACM	Reasonably Available Control Measures
RACT	Reasonably Available Control Technology
RMI	Rocky Mountain Institute
RTC	Renewable Thermal Collaborative
SCC	Source Classification Codes
$SC\text{-}CO_2$	Social Cost of Carbon
SEFI	State Energy Financing Institutions
SHS	Sensible Heat Storage
SIP	State Implementation Plan
South Coast AQMD	South Coast Air Quality Management District
TES	Thermal Energy Storage
TRL	Technology Readiness Level
VOC	Volatile Organic Compounds
WHP	Waste Heat to Power

Appendix 1: Sources and Additional Reading

This paper utilizes several existing reports, datasets, maps, and other sources to make policy recommendations for decarbonizing industrial heat. In Appendix 1, we have outlined key resources that informed major parts of this paper. We hope that this can be a helpful tool for policymakers and other interested stakeholders who would like to delve deeper into the topics discussed in this paper.

Source Type	Source	Brief Description
Dataset	Characterization of the U.S. Industrial/Commercial Boiler Population Published: May 2005 Author: Energy and Environmental Analysis, Inc.	Inventory of all fossil fueled boilers in the United States
Report	Decarbonizing Industrial Heat: Measuring Economic Potential and Policy Mechanisms Published: October 2024 Author: Center for Applied Environmental Law and Policy, Energy and Environmental Economics	Analyzes the cost-effectiveness of heat pumps and other technologies for higher temperatures in industrial applications
Report	Industrial Electrification in the U.S. States: An Industrial subsector and state-level techno-economic analysis Published: February 2023 Authors: Hasanbeigi, A., Kirshbaum, L. A., & Collison, B.	Identifies specific processes that could be electrified in the near term with commercially available technologies and analyzes the expected changes in energy use, CO_2 emissions, and energy costs

Report	Electrifying U.S. Industry: A Technology- and Process-Based Approach to Decarbonization Published: January 2021 Author: Hasanbeigi, A., Kirshbaum, L. A., Collison, B., & Gardiner, D.	Highlights the major barriers to scaled development and deployment of industrial electrification technologies, and potential solutions
Report	Industrial Decarbonization Roadmap Published: September 2022 Author: U.S. Department of Energy	Outlines a roadmap to identify existing and needed technology to achieve net-zero emissions in the industrial sector by 2050
Report	Renewable Thermal Vision Report Published: 2022 Author: Renewable Thermal Collaborative	Examines priority industrial sectors and their thermal energy use
Report	Decarbonizing Low-Temperature Industrial Heat in the U.S. Published: October 2022 Author: Energy Innovation (Rissman, J.)	Highlights the role of industrial heat pumps in electrifying industrial heat, and its wider economic, environmental, and health benefits
Dataset	Electrification potential of U.S. industrial boilers and assessment of the GHG emissions impact Published: February 2022 Authors: Schoeneberger, C., Zhang, J., McMillan, C., & Dunn, J. B.	Updated dataset of the industrial boiler population in the U.S. and characterizes the technical potential of boiler electrification to reduce fuel consumption and GHG emissions, based on the 2005 EEA study
Policy Brief	How to Decarbonize Industrial Process Heat While Building American Manufacturing Competitiveness. Published: April 2024 Author: American Council for an Energy-Efficient Economy (Wang Esram, N., Johnson, A., & Elliott, N.)	Identifies benefits of electrifying industrial process heat and outlines the challenges and opportunities

Report	Electrification of Boilers in U.S. Manufacturing Published: November 2021 Author: Lawrence Berkeley National Laboratory and Global Efficiency Intelligence (Zuberi, M. J. S., Hasanbeigi, A., & Morrow, W. R.)	Examines the boiler energy demand in the U.S. industrial sector, identifies potential electrification opportunities, and outlines potential barriers
Map	National Map of Industrial Boilers Published: 2025 Author: Evergreen Action, Sierra Club, and AJW Inc.	Map that visualizes our analysis of over 19,000 potential boiler units within the NEI

Appendix 2: Clean Heat Technology Manufacturers and Deployments

Identifying and evaluating alternative industrial technologies is a complex undertaking, as no single, comprehensive repository currently consolidates information on available solutions and their suppliers. This appendix offers a selection of manufacturers across various technology groups, based on publicly available technical specifications, to illustrate the diversity of options. It is not intended as an exhaustive database but rather as a starting point for further investigation.

The absence of a centralized resource underscores the need for an accessible platform that aggregates information on alternative technologies, particularly electric solutions, to facilitate broader adoption within the industrial sector. Additionally, as technology is identified there is a need to assess individual technology deployments with rigor. For our review, we attempted to focus on technology that can meet air permitting authorities' requirements to establish standards for new and modified sources. In other words, in this appendix we have attempted to identify deployments that meet the following criteria:

1. Commercially available technology that has been operated at one or more facilities for a minimum of 6 months, and
2. Demonstrated as effective and reliable on a full-scale (e.g., replaces conventional combustion unit)

We found that validating these criteria was difficult, and therefore this appendix is intended to be a first step in support of technology identification efforts, and we highly recommend working directly with technology providers to validate our claims.

Evergreen Collaborative

SIERRA CLUB

THERMAL ENERGY STORAGE MANUFACTURERS

Thermal batteries store energy as heat, offering a way to decouple energy supply and demand for various applications. Unlike electrochemical batteries, they utilize materials with high heat capacity or phase-change properties to store thermal energy, which can then be converted back to heat or electricity. These batteries can be charged using diverse energy sources, including renewable electricity or waste heat, and are particularly useful for providing high-temperature process heat or grid-scale energy storage. Their efficiency and applicability depend on the specific design and materials used.

Table A2-1: Summary of Thermal Battery Manufacturer Technology Availability

Manufacturer	Technical Specifications (if available): • Capacity Range • Charging Rate • Heat Range	Deployments, notable case studies, and funding
Antora: **2 models – Heatcore and Heatmax**	Capacity Range: Heatcore: 0.77 MMBTU/hr Hetmax: *No advertised capacity Charging rate: Heatcore: 700KWe Heatmax: *Not advertised Heat Range: Heatcore: 100-400 °C Heatmax: 1400 °C	Heatcore currently available Heatmax in development In June 2024, Antora received $14.5 million from ARPA-E's *Seeding Critical Advances for Leading Energy Technologies with Untapped Potential* (SCALEUP) program to fund commercial-scale capital investment.
Brenmiller Energy	Heat capacity: 330 KWh/m3 Storage: 10-500 MWh Discharge Temp Range: 100-530 °C Heat loss: 0.1%/hr Electrical Load: 1-100MW	Brenmiller Energy has several projects in develop (as outlined below) and has a completed demonstration project, highlighted by Renewable Thermal Collaborative in a case study: • Tempo: Heineken and Pepsi beverage plant • Partner in Pet Food (PPF): replacing NG boiler • Enel: Steam production • New York Power Authority: electricity generation • Fortlev: hot air to industrial plant • Wolfson Hospital: replacing HFO boiler

Elstor	Charging power:** 1.5 – 6.0 MW Storage capacity: 5 – 20 MWh Discharge power:** Max 4 MW * Values for a single modular 5-20 MWh unit. System can be scaled up by duplicating these units. Steam pressure: Max 20 bar / 290 psi Steam temperature Up to 250 °C / 480 °F Flexibility and reaction time	Herkkumaa Vegetable Processing plant, Tuulos, Finland (RTC)
Element16	Uses molten sulfur technology Capacity: 500kWh at 85% efficiency Charge temperatures: up to 260°C	Element16 is in early-stage development working on funding for future application projects
Malta Inc.	Material: Solar Salt Storage: 8 hr - Multi-day Power: 50-500 MW Steam Supply: 180 bar 550°C	Is a combination of thermal energy storage technology with heat pump technology using molten salt to provide high pressure, high temperature steam.

MGA Thermal	Material: Miscibility Gap Alloy Technology (proprietary) Individual block specification unknown, see demonstration projects in next column	MGA Thermal received AUD 1.26 million from ARENA for a 5 MWh Thermal Energy Storage (TES) demo using its Miscibility Gap Alloy (MGA) technology. Supported by Shell and Varley Group, the project will test TES for dispatchable power, process heat, and hydrogen production, generating data for commercialization. Key Specs: • Capacity: 5 MWh • Thermal Power: 500 kW • Discharge: 200°C steam at 7 bar for 24h • Components: ~3,700 MGA Blocks • Dimensions: 12m × 3m × 4m
Redoxblox	Storage: up to 20MWh at 95% round trip efficiency Temperature output up to 1500°C	RedoxBlox remains in development with no deployed assets. In October 2024, it raised $40.7 million in Series A funding from Prelude Ventures, Imperative Ventures, New System Ventures, Breakthrough Energy Ventures, and Khosla Ventures.
Rondo: **2 models – RHB 100 and RHB 300**	Capacity Range: Capacity: RHB 100: 100 MWh RHB 300: 300 MWh Output: RHB 100: 168MWh/day RHB 300: 480 MWh/day RHB100: Storage 100MWh Charge Rate: RHB 100: 20 MW(ac) RHB 300: 70 MW(ac) Discharge Rate: RHB 100: 7 MWh(t) RHB 300: 20 MWh(t) Discharge temp Range: RHB100/ 300: 80-1100 °C	Rondo has received 75 mil Euros in funding from Breakthrough Energy and the European Investment Bank Rondo also has several notable installations and announcements to date: • Installed thermal storage at Calgren Renewable Fuels in March 2023 with 2.3 MWh capacity. • Developed a storage system production capacity: 2.4 GWh/year with SCG (Siam Cement Group) • Diageo North America (Whiskey distiller) was selected by the U.S. DOE Office of Clean Energy Demonstrations (OCED), as part of its Industrial Demonstrations Program (IDP)) to install Rondo technology to decarbonize production operations in Illinois and Kentucky (up to $75 million in funding)

ELECTRIC BOILER MANUFACTURERS

Electric boilers generate steam or hot water by using electricity to heat a resistive element. They offer a clean alternative to fossil fuel-fired boilers at the point of use, eliminating direct greenhouse gas emissions and air pollutants. Electric boilers can be highly efficient, especially when powered by renewable electricity sources, and offer precise temperature control. While their operational cost can be higher depending on electricity prices, they have lower upfront costs, require less maintenance, and can be ideal for applications needing smaller capacities or where stringent emissions regulations apply.

Table A2-2: Summary of Electric Boiler Manufacturer Technology Availability

Manufacturer	Capacity Range (MMBtu / hr)	Notable Case Studies
Acme Engineering Products	0.0358-11.94	
AtmosZero	Awaiting spec sheet	Electric Boiler for New Belgium Brewery expected 1st Quarter 2025
ATTSU	0.00646-6.462	
Babcok Wanson	0.129 – 5.170	
Bosch	0.151 – 3.231	Sustainable package manufacturing at an Icelandic Fish Factory
Chromalox	0.00353 – 0.106	
Cleaver Brooks	9.403 – 405.9	
Fulton	0.0501-12.53	
Giconmes	0.00517-4.308	
Parat	0.09 – 1.08	Offshore Electrification in the North Sea, Flekkefjord, Norway
Pirobloc	0.01508-2.412	
Precision Boilers **(Thermon)**		Diageo Distillery

Skyven Arcturus*	11.94 – 298.5
Viessmann	0.006-0.06
WENTA	0.0215-0.646

Note: Each manufacturer provides multiple boiler options, the range in capacity and temperature represent the range across multiple models from each manufacturer.

Note: To ensure consistent units (MMBTU/hr) capacities were converted to MMBTU/hr from a variety of units provided in each company's publicly provided documents.

*This manufacturer's technology is also advertised as an electric heat pump

ELECTRIC HEAT PUMP MANUFACTURERS

Electric heat pumps are highly efficient heating and cooling systems that transfer heat rather than generate it. They work by moving heat from a cool space to a warm space, making the cool space cooler and the warm space warmer, using electricity as their power source. This process is significantly more energy-efficient than traditional resistance heating or cooling methods. Heat pumps can extract heat from various sources like air, ground, or water, and they provide both heating in the winter and cooling in the summer, offering a versatile and sustainable climate control solution.

Table A2-3: Summary of Electric Heat Pump Manufacturer Technology Availability

Manufacturer	Capacity Range (MMBtu)	Heat Range (°C)	Notable Uses
Carrier	0.682 – 8.53	85	
Hybrid energy/ Johnson Controls	1.706 – 17.06	120	1st installation was at a Norwegian Dairy with over 20 heat pumps now in operation globally
MAN Energy Solutions	341.2	280	District heating for the entire city of Esjerg, Denmark
Mitsubishi Electric	0.017-3.79	51-90	
Oilon	0.102- 3.50	120	

Ochsner Energietechnik	0.205 – 8.53	120	• Schwaz District Hospital • Ikea Innsbruck • Annecy, Wastewater Treatment plant
Piller Blowers & Compressors GmbH			Waste heat recovery Chivas Whiskey distellary (RTC)
Sabroe (Johnson Controls)	1.02-18.30	72-120	
Siemens Energy	51.18 - 153.5	100-180	• Hammarby Plant, district heating, Stockholm Sweden • Potsdamer Platz, Vattenfall Warme Berlin, District heating and cooling
Sprsun	0.143 – 0.314	60-80	
Thermax	0.853 – 136.5	90	
Viessmann	0.193 – 1.120	90	

Note: Each manufacturer provides multiple options of heat pumps, the range in capacity and temperature represent the range across multiple models from each manufacturer.

Note: To ensure consistent units (MMBTU) capacities were converted to MMBTU from a variety of units provided in each company's publicly provided documents.

Appendix 3: Criteria Air Pollutant and Hazardous Air Pollutant Emissions Inventory Analysis– Methodology

This dataset is intended to build upon the work completed in the reports *Electrification potential of U.S. industrial boilers and assessment of GHG emissions impact* (2022; Schoeneberger, Carrie, etc.) – Referred to as "Northwestern" report, and *Decarbonizing Industrial Heat: Measuring Economic Potential and Policy Mechanisms* prepared for the Center for Applied Environmental Law and Policy (CAELP) in October 2024 – Referred to as "CAELP" report. The methodology outlined below explains how the United States Environmental Protection Agency's (US EPA) National Emissions Inventory Data (NEI) was utilized to determine reported criteria and hazardous air pollutant (HAP) emissions information for individual boilers across the country. There are footnotes throughout the methodology to compare approaches with the Northwestern and CAELP studies to clearly identify where there is alignment. The creation of this new dataset was funded by Evergreen Action as part of a broader effort to comprehensively assess opportunities to reduce emissions from boilers.

METHODOLOGY

Step 1 – Request NEI Data: Requested the following data from US EPA NEI Team:

- NAICS: 31-33 (Manufacturing)[84]
- Year: Most recent (2020)
- Pollutants: All

Unit types:

Unit Type Code	Unit Type Description	Unit Group
100	Boiler	Fuel Comb. Equipment
120	Turbine	Fuel Comb. Equipment
1200	Electric Steel Shell Furnace	Mineral Wool Fiberglass
1201	Recovery Furnace - Direct Contact Evaporator	PnP unit type
1202	Recovery Furnace - Nondirect Contact Evaporator	PnP unit type
1251	Conveyor Stand Dryer	PCWP unit type
1252	Primary Tube Dryer	PCWP unit type

84 Matches NAICS codes used by CAELP and Northwestern

1253	Secondary Tube Dryer	PCWP unit type
1254	Rotary Yeast Dryer	Nutritional Yeast unit type
140	Combined Cycle (Boiler/Gas Turbine)	Fuel Comb. Equipment
150	Duct Burner	Fuel Comb. Equipment
180	Process Heater	Fuel Comb. Equipment
200	Furnace	Fuel Comb. Equipment
202	Regenerative Furnace	Mineral Wool Fiberglass
203	Recuperative Furnace	Mineral Wool Fiberglass
204	Electric Furnace	Mineral Wool Fiberglass
205	Unit Melter Furnace	Mineral Wool Fiberglass
206	Air Gas Furnace	Mineral Wool Fiberglass
207	Oxyfuel Furnace	Mineral Wool Fiberglass
208	Cold top Furnace	Mineral Wool Fiberglass
209	Pot/Marble Melt Furnace	Mineral Wool Fiberglass
210	Kiln	Fuel Comb. Equipment
211	Lumber Dry Kiln	PCWP unit type
212	Rotary Kiln	OSWRO
213	Wet Kiln	Portland Cement
214	Dry Kiln	Portland Cement
215	Lime Kiln	PnP unit type
220	Calciner	Fuel Comb. Equipment
2251	Hogged Fuel Dryer	PnP unit type
230	Coke Battery	Fuel Comb. Equipment
250	Direct-fired Dryer	Fuel Comb. Equipment
251	Softwood Veneer Dryer	PCWP unit type
252	Veneer Redryer	PCWP unit type
253	Hardwood Veneer Dryer	PCWP unit type
254	Rotary Strand Dryer	PCWP unit type
255	Dryer, unknown if direct or indirect.	Fuel Comb. Equipment
260	Indirect-fired Dryer	Evaporative Sources
261	Green Rotary Dryer	PCWP unit type
262	Dry Rotary Dryer	PCWP unit type
263	Rotary Agricultural Fiber Dryer	PCWP unit type
264	Hardboard Press Predryer	PCWP unit type
265	Fiberboard Mat Dryer	PCWP unit type
270	Incinerator	Fuel Comb. Equipment
290	Other combustion	Fuel Comb. Equipment
291	Hardboard Oven	PCWP unit type
292	Curing Oven	Mineral Wool Fiberglass
293	Chemical Recovery Combustion Unit	PnP unit type
600	Chemical Reactor	Process Equipment

700	Atmospheric Refiner	PCWP unit type
718	Evaporator	PnP unit type
999	Unclassified	Unclassified

Step 2 – Request SCC Data: Requested SCC codes associated with all the unit IDs in the NEI dataset

Step 3 – Join Datasets: Created database and joined the NEI dataset to the SCC code dataset based on facility ID and unit ID

Step 4 – Run Queries: Extracted data from the database for each of the following unit type codes[85]:

- Boiler
- Combined Cycle (Boiler/Gas Turbine)
- Other Small Combustion
- Other Process Emissions
- Unclassified (Note: Some states had high numbers of unclassified units. In fact 4 states had 58% of the total unclassified units – These states were California (32%), Kentucky (11%), South Carolina (8%), and Indiana (7%)

Step 5 – Convert Rows to Columns: Began with the unit type “boiler” data set.

Cleaned the data and spot checked for accuracy of the queries and pollutant values. In the original speadsheet each unit was duplicated many times for each pollutant and SCC code combination. To reduce duplication and allow for analysis the data was cleaned so that each row contains information on one reported unit (SCC codes and pollutants were converted from rows to columns). Over 180 pollutants were included in the dataset, but pollutants that were rarely reported are included in the “other pollutants” column. In cases where multiple SCC codes were reported, up to 5 SCC codes were stored in separate columns, and the remainder of SCCs are in the “Other SCC column” which may contain a comma delimited list of SCCs. The SCC codes were added in the order they appeared in the data, with no indication of the primary SCC code. For this reason, it is impossible to determine the primary fuel from the SCC alone.

Step 6 – Add NAICS Details: NAICS code description was added to each record for the 3 digit and 6-digit levels. In cases where incomplete NAICS were entered, the higher-level option was selected for the detailed description, unless enough digits were entered to accurately determine the detailed description.

85 Northwestern analysis utilized the same unit type codes, excluding combined cycle

Step 7 – Add Analysis Insights: Additional columns were added to provide more information on each unit. Added fields were based on a review of the unit description or SCC fields. The level of information reported in the unit description field varies, and therefore the accuracy of the new column added may range based on the completeness of the submission.

Columns added based on the unit type field:

- Unit Type Score – Confidence level that the unit is a boiler, based on the unit type field (see step 8)

Columns added based on unit description field:

- Number of Units – # of units included in the emissions estimate for the unit
- AJW Device Type - Device names were assigned using CARB's Unit Type list, which is more expansive than EPA's unit type code. In some cases, new unit type names were assigned if not included on CARB's list (the terms device and unit are used interchangeably between both agencies, with the same meaning).
- Unit Description Score – Confidence level that the unit is a boiler, based on the unit description field (see Step 8)
- AJW Design Capacity: Design capacity as reported, converted, or identified in the unit description field
- AJW Design Capacity UOM: Design capacity units of measure as reported, converted, or identified in the unit description field
- Unit Description NG: Confidence level that the unit uses natural gas, based on the unit description (see Step 8)

Columns added based on SCC field:

- Unit SCC Score – Confidence level that the unit is a boiler, based on the reported SCCs (see Step 8)
- Power Generation SCC – Flag if any of the SCCs selected were for power generating boilers (which are federally regulated differently than other boiler types)
- SCC 1 – SCC Other: Listing of SCC codes reported. The first 5 SCC codes reported are added to separate columns, however when there are 6 or more SCC codes, they appear in the SCC Other field
- SCC NG: Natural Gas is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.

- SCC Distillate Oil: Distillate Oil is flagged as a fuel if it (or diesel) is included as a fuel in any of the SCC codes reported.
- SCC Wood/Bark: Wood and/or Bark is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.
- SCC LPG: LPG is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.
- SCC Coal/Coke: Coal and/or Coke is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.
- SCC Waste/Biomass: Waste and/or Biomass is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.
- SCC Process/Refinery Gas: Process and/or Refinery Gas is flagged as a fuel if it is included as a fuel in any of the SCC codes reported.
- SCC Residual Oil: Residual Oil is flagged as a fuel if it is included in any of the SCC codes reported.
- SCC Gas: Gas (generic) or landfill gas is flagged as fuel if it is included in any of the SCC codes reported.
- SCC Animal Fat: Animal Fat is flagged as a fuel if it is included in any of the SCC codes reported.
- SCC Unknown: Unknown is flagged if the unit is a combustion unit but the SCC code does not indicate the fuel type.
- SCC All: Concatenated summary of all the fuel types reported through SCC codes
- SCC NG Score: Confidence level that the unit uses natural gas, based on the reported SCCs (see Step 8)

Other columns added:

- Unit Confidence: Calculated field used to indicate confidence that the reported unit is a boiler (see Step 8)
- AJW Capacity Grouping: Grouped design capacity categories based on key regulations (see Step 9)
- AJW Corrected Reported Value: Flag when reported design capacity field was changed in AJW design field based on unit description notes.
- NG Fuel Confidence: Calculated field used to indicate confidence that the reported unit utilizes natural gas (see Step 8)

- Other Pollutants 1 and 2: Infrequently reported pollutants and emissions levels.
- Company Name: New field added to combine EPA reported fields of company name and site name, to reflect a single entity, with names standardized across the dataset.

Step 8 – Assign Confidence Levels: Calculated score for each data entry based on the confidence level for two variables – unit type and fuel.

For unit type, a point was given for each of the following variables:

- If reported unit type field = “boiler” or “combined cycle”
- If any of the reported SCC codes were for boilers
    - This included any of the first 3 numbers for external combustion equipment:
        - 101 – Electric Generation Boilers
        - 102 – Industrial Boilers
        - 103 – Commercial/Institutional Boilers
        - 105 – Space Heater
    - Or specific 8 digit industry codes that contain boilers as the detailed unit type (level 4 SCC code):

30100510	Main Process Vent with CO Boiler and Incinerator
30301582	Miscellaneous Combustion Sources: Boilers
30600203	Fluid Catalytic Cracking Unit with CO Boiler: Natural Gas
30600204	Fluid Catalytic Cracking Unit with CO Boiler: Process Gas
30600205	Fluid Catalytic Cracking Unit with CO Boiler: Oil
30600206	Fluid Catalytic Cracking Unit with CO Boiler
30601202	Traditional Fluid Coking Unit without CO Boiler
30601203	Traditional Fluid Coking Unit with CO Boiler: Natural Gas
30700119	Salt Cake Mix Tank (Boiler Ash Handling)
31000227	Glycol Dehydrator Reboiler Still Stack
31000228	Glycol Dehydrator Reboiler Burner
31000301	Glycol Dehydrator Reboiler Still Stack
50100423	Landfill Gas (LFG) Energy Recovery: Boiler

50301023	Landfill Gas (LFG) Energy Recovery: Boiler
50410537	Combustion Unit: Boiler
50600623	Landfill Gas (LFG) Energy Recovery: Boiler
50700623	Landfill Gas (LFG) Energy Recovery: Boiler

- If the unit description was clearly referring to a boiler[86],[87]:
  - Units were determined to be a boiler without further review if the following terms, or variation of the following high value keyterms were used:
    - “boiler”, “blr”, “hot wat”, “water heat”, “cleaver”, “brooks”, “water tube”, “boil”
  - Unit descriptions were reviewed in more detail if the unit description contained any of the following low-value keyterms:
    - “ccct”, “cogen”, “tangentially-fired”, “wall-fired”, “steam gen”, “hydrotherm”, “steam”, “space heat”, “indirect”, “boil”, “combined heat”, “preheat”
  - “Preheaters” and “space heaters” are identified separately as different unit types unless the unit description specifically refers to boilers, water heaters, or process heaters.
  - “Cogen” units were identified as turbines, engines, or boilers, based on unit descriptions
  - For units that only contained the lower value key terms, the unit descriptions were searched to identify units that were ovens, furnaces, air makeup units, IC engines, etc.
    - Listing fuels, capacities, or boiler manufacturers associated with the boiler entry if “boiler” unit type and SCC codes were also entered, and these values were clearly used to identify a boiler.
  - Note: In California, the US EPA unit type code is not required and infrequently reported (only 3 units in the entire state), therefore, double points were awarded for the unit description containing boiler terms, to correct for this issue. Additionally, for unit type codes for other process units and other combustion equipment, two points were awarded for unit description if the unit was clearly a boiler and the unit would receive a “low” score without an adjusted value (used to prevent a 64 boilers from being excluded from boiler dataset).

86 Terms were added to the list after reviewing the unit description field for the units marked as “boilers” in the unit type field.

87 The same terms were utilized from the CAELP research for consistency, including: “ccct”, “cogen”, “blr”, “boiler”, “tangentially-fired”, “wall-fired”

- Confidence Ranking for boiler unit type: 3 points =high confidence that the unit is a boiler, 2 points = medium confidence level, and 1 points = low confidence level.
- All entries with a high or medium confidence level were identified as boilers in the "AJW Unit Type" field, UNLESS another unit is clearly identified in the unit description field. The AJW unit type field is used to quickly flag medium and high confidence level units as boilers, or to identify other unit types if necessary. In some cases, the unit type was marked as "unknown."

For fuels a point was given for each of the following variables:

- Each SCC code reported was mapped to the full description of the SCC. All codes were searched for fuel type, and the fuels were added to the file. Although all the fuel types reported are included in the file, it is unclear which fuels are primary vs. backup fuels. A point was added for each unit that reported natural gas use. Fuels include natural gas, distillate oil (includes diesel), wood/bark, process gas, LPG, coal, coke, waste, biomass, process/refinery gas, residual oil, gas and animal fat.
- If the unit description contained the words "natural gas", "NG" or "nat gas" a point was awarded.
- Confidence Ranking for natural gas use: 2 points = high confidence in natural gas use, 1 point = medium confidence level, and 0 points = low confidence level.

Step 9 – Refine Design Capacity Information: Design capacities were added to reported design capacities in new column for cases when the design capacity was not recorded in the appropriate field, or a different value was entered in the design capacity field than reported in the unit description field (fields changed due to differences in description field were flagged in "AJW Corrected Reported Value" field). Additionally, reported units of measure were converted to MMBTU/hr.[88] These values were added to the field "AJW Design Capacity" and "AJW Design Capacity UOM". Each unit with a reported or converted design capacity value was grouped into design capacity groupings. These groupings represent boiler regulations, including:

- <2 MMBtu/hr (to represent units that could be covered under SCAQMD's small boiler ZE rule)
- 2 – 10 MMBtu/hr (units outside of existing regulatory efforts of interest)
- 10 – 100 MMBtu/hr (Aligned with Boiler NSPS Subpart Dc)
- >100 MMBtu/hr (Aligned with Boiler NSPS Subpart Bd)

88 The conversions performed utilized the same unit conversion factors as the Northwestern report (based on the NEI GitHub script)

Step 10 – Identify Other Units: For unit types “Other small combustion”, “Other process emissions”, and “Unclassified” the units were added to the dataset if the unit type description contained any of the boiler key terms listed in Step 8 or boiler SCC codes. Each record was then cleaned, using the steps above. If the unit type description was clearly not a boiler, based on unit description or SCC, the confidence level of “none” was used. For example, in some cases a boiler SCC code was reported but the unit description clearly indicated an oven, or in other cases the description included one of the lower value key terms but no boiler SCC codes were selected.

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