Evaluation of Low- and Mid-Temperature Industrial Boiler Health Impacts

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American Lung Association.

ICF

Cover image source: The boiler room of the New Belgium Brewing headquarters in Fort Collins, Colorado, where startup AtmosZero will install its first electric heat-pump boiler. Canary Media, Jeff St. John, 27 June 2023

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Executive Summary

This study evaluates the potential health and climate benefits of replacing low- and mid-temperature, combustion-fueled industrial boilers with zero-emission heat pump (HP) alternatives at facilities across the United States. Industrial boilers are widely used for process heat and are predominantly fossil-fueled. Many operate at temperatures suitable for replacement with HPs, which are more efficient and emit no on-site pollutants. The study focuses on boilers operating below 200°C, which are common in sectors like paper processing, food processing, and chemical manufacturing.

This study is the first of its kind. It builds from recent research on industrial heat and publicly available models and datasets to create an inventory of industrial boilers across the Country. We estimate there are 33,528 industrial boilers operating across the country in our baseline period, which we take to be approximately 2020. We build a new, bottom-up emissions inventory of the criteria and climate-forcing air pollution emitted from them, categorized by fuel type, capacity, and industry. We then forecast the emissions from these boilers through 2050 under a business-as-usual (BAU) growth scenario. The BAU Scenario projects the emissions from these boilers without significant technology changes. We then develop a "Clean Heat" (a.k.a., Control) Scenario for industry where HPs replace combustion boilers in phases as the technology becomes feasible. The phase-in is based on the operating temperature of the boilers and technology readiness and evolves between 2030 and 2050. The control scenario considers the different fuels used in the BAU boilers, the different industrial sectors in which they are used, and the HP coefficient of performance by operating temperature. We compute the reduction in boiler fuel consumption due to this phased in control scenario, along with the increased electric grid load from the addition of the HP replacements. We then compute the reduction in combustion-fueled boiler emissions and the corresponding increase in electric grid emissions. We use two different forecasts for the nation's electric grid to capture a range of possibilities: a BAU grid (based on the US National Renewable Energy Laboratory's (NREL) CAMBIUM model; Scenario 1), and a highly decarbonized grid (based on CAMBIUM Scenario 7). We combine these changes in emissions to show the net benefits of the Control Scenario, both in terms of changes in criteria and greenhouse gas (GHG) emissions. While we analyze criteria pollutant emissions resulting from combustion at the boiler and at the electric generating unit (EGU) to emphasize the direct impact of combustion on public health, for GHGs we consider the full fuel lifecycle of emissions to assess a complete picture of the climate impacts of this switch with factors based on the Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. We use the EPA's Social Cost of GHG

(SC-GHG) to monetize the climate impacts that could be avoided by implementing the Control Scenario. Finally, we use the EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) to estimate the adverse public health outcomes that could be avoided by implementing the Control Scenario and monetize these avoided outcomes. This study focuses on the potential public health benefits that could be achieved in the general U.S. population from improved ambient air quality from the reduced combustion emissions this technology switch would enable. It is not a study of occupational exposure.

We find that 1.6 billion metric tons of carbon dioxide equivalent (CO_2e) could be avoided by implementing the control scenario between 2030 and 2050 assuming the BAU electric grid. This would result in $351 billion (2023$) in total climate benefits accrued, assuming a 2% discount rate. With a decarbonized grid, we find that 1.7 billion metric tons of CO_2e could be avoided by 2050, resulting in $382 billion in avoided costs from climate change impacts.

Implementing the Control Scenario with the BAU electric grid could lead to avoiding 260,000 short tons of oxides of nitrogen (NO_x) emissions, 100,000 tons of sulfur oxides (SO_2) emissions, and 29,000 tons of fine particles ($PM_{2.5}$) per year by 2050. These air pollution emission reductions would lead to tens of thousands of avoided premature deaths and billions in monetized public health gains. We predict cumulative monetized public health benefits from 2030 to 2050 range from approximately $732 billion to $1.1 trillion in the Control Scenario with the BAU electric grid and a 2% discount rate. Mortality is the main driver of monetized health benefits from emissions changes, with an estimated decrease in the number of premature deaths between 49,400 and 77,200 under the Control Scenario with the BAU electric grid. Other health endpoints, including asthma, respiratory and cardiac emergency room visits, hospital admissions, incidents of stroke and cardiac arrest, and work and school days lost all show strong positive results from implementation of the Control Scenario. Overall average $PM_{2.5}$ concentrations also show notable reductions.

We show these results nationally and by state. We emphasize the findings of the BAU electric grid, to focus on the benefits of change in industrial technologies, but we note that in the longer term, additional health benefits could be achieved by moving to the decarbonized grid. The decarbonized grid scenario yields greater long-term benefits but may show slightly higher criteria pollutant emissions in the near term due to technology mix. Finally, we note that care should be exercised when comparing the substantial monetized health benefits predicted here with those of other studies due to the methodological differences, including discount rate, inclusion of ozone health impacts, and the dollar valuation year.

1 Background and Purpose of the Study

Boilers are a mature technology used throughout the industrial sector to produce hot water and steam. Boilers are available in a wide range of capacities and, depending on individual facility requirements, can be configured to meet various process temperature needs. Some boilers operate on electricity and opportunity fuels (e.g., waste from pulp and paper processing), but many industrial boilers use fossil fuels. Based on data forecast in the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS) Industrial Demand Module (IDM) (version corresponding to the Annual Energy Outlook 2023),[1] at least 77% of the 1.8 quadrillion BTUs consumed by industrial boilers in 2020 was from fossil fuels. These estimates are uncertain due to the status of the NEMS model and fuel classifications,[2] but they are supported by other studies. For example, McMillan[3] found that fossil fuels have accounted for about 87% of all manufacturing fuel use in the United States, a value unchanged in four decades. Overall, this sector is fossil fuel-dependent and energy-intensive. This implies that the sector is likely to be a significant source of both criteria and climate air pollution.[4]

While some industrial boilers must operate at high temperatures (e.g., boilers used in petroleum refining), many industrial boiler applications occur at low or medium temperatures (e.g., food processing and chemical manufacturing). These combustion-based boilers are suitable for cost-effective, zero-emission heat pump (HP) replacements with technologies that are feasible and commercially available now, or expected to available in the near future. Switching from fossil-fueled boilers to HPs has the potential to reduce greenhouse gas (GHG) emissions associated with rapid, anthropogenic climate change; emissions of criteria air pollutants (CAP) associated with poor air quality and adverse human health outcomes; and save energy due to relatively high heat pump efficiencies.

The purpose of this study is to explore the health and climate benefits, and their associated economic value, that could be expected from relacing low- and mid-temperature, combustion-fueled, industrial boilers with zero-emission HP technology. The study evaluates a scenario where combustion, primarily fossil-fueled, boilers are replaced with HPs as the technology becomes

[1] Industrial Demand Module of the National Energy Modeling System (NEMS). U.S. Energy Information Administration (EIA). September 2022 model documentation available at: https://www.eia.gov/outlooks/aeo/nems/documentation/industrial/pdf/IDM_2022.pdf

[2] As discussed later, EIA did not release a 2024 version of AEO as the NEMS model that underlies it is being updated, including the approach to industrial boilers.

[3] Opportunities for Solar Industrial Process Heat in the United States. C McMillan, C Schoeneberger, J Zhang, P Kurup, E Masanet, R Margolis, S Meyers, M Bannister, E Rosenlieb, and W Xi. Technical Report NREL/TP-6A20-77760, January 2021.

[4] For example: Industrial Boilers Keep Burning in Areas Exceeding Air Pollution Limits, Hellen Chen, Fikayo Omotesho, and Anna Johnson. ACEEE. Available at: https://www.aceee.org/blog-post/2025/02/industrial-boilers-keep-burning-areas-exceeding-air-pollution-limits.

feasible. We focus on the health impacts of air quality improvements in the general U.S. population from the reduced combustion emissions this technology switch would enable. This is not a study of impacts from occupational exposure. The associated climate benefits are calculated globally and consider the full fuel lifecycle for both the boilers themselves and the electricity used in heat pump replacements.[5,6] We evaluate this replacement scenario primarily under a more business-as-usual projection for the national electric grid. We also consider the case of a more aggressively decarbonized national grid.

Section 2 evaluates current and projected levels of industrial boiler emissions in the United States. It explores the potential for heat pump technologies to replace the baseline, combustion boiler technology. It then envisions a scenario where heat pump technologies replace combustion boilers as the technology becomes feasible. Finally, it summarizes the change in national emissions of criteria and climate air pollution that could result from implementation of this scenario. Section 3 then explores the climate and public health benefits that could result from this reduction in air pollution.

2 Existing and Future Boiler Emissions

Section 2.1 discusses our current understanding of emissions and technologies in this sector, research feasibility of replacement technologies, and determine a national baseline of existing emissions from industrial boilers in the United States. We used 2020 as a baseline year.

Section 2.3 and 2.4 explore how these national emissions may change in the future. This includes forecasting the boiler emission sector out to year 2050 under two scenarios. The first is a business-as-usual (BAU) scenario without additional replacement of the current fossil fuel boiler fleet with zero emissions HP technologies. The second is a Control Scenario where fossil-fueled boilers are replaced with HP as the technology becomes available. The difference in these two scenarios describes the potential for reduction in emissions from the boilers themselves. Switching fuels also leads to an increased load on the electric grid to supply power for the replacement technology, and thus an increase in emissions from electricity generation to capture those impacts. We calculate this additional load considering industry, fuel, boiler capacity, required operating temperature, and the coefficient of performance (COP) of industrial HPs. This study evaluates these scenarios under two potential future cases for the national electric grid: a BAU case based on existing national policies for

[5] Lifecycle analyses are included here for GHG impacts since climate change is a global issue due to the well mixed nature and long-lived nature of CO_2 and other climate forcing pollutants. On the other hand, health impacts are computed only from direct emissions.
[6] This analysis focuses on air pollution impacts of fuel combustion in the studied sector. It does not include other potential lifecycle impacts of combustion boilers or heat pump systems, such as water and land impacts of boiler fuels or refrigerant leaks from heat pumps.

the electricity sector and a decarbonized grid case based on a 95% decarbonization by 2050 goal. Both cases are based on NREL's CAMBIUM[7] forecasts for the electric grid with corresponding criteria pollutant emissions calculated using the U.S. Department of Energy's (DOE) Argonne National Laboratory's (ANL) Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model[8].

This blend of assumptions about industrial emissions and electricity source grid emissions is combined into three evaluation scenarios:

a) BAU industry with BAU electric grid;

b) "Clean" industry with BAU electric grid; and

c) "Clean" industry with a decarbonized electric grid.[9]

Chapter 3 assesses the health and climate impacts of these scenarios by evaluating:

- Clean industry with BAU electric grid (b) relative to BAU industry with BAU electric grid (a)
- Clean industry with clean electric grid (c) relative to BAU industry with BAU electric grid (a).

2.1 Baseline Emissions in the Sector

To determine the existing national baseline emissions of industrial boilers in the United States, we first surveyed existing literature and data to determine an approach suitable for the development of this emissions inventory. This effort included research to identify the number, type, fuels, and emissions from boilers that could be feasibly replaced with lower emissions technologies. We used these findings to develop a baseline emission inventory.

2.1.1 Existing Industrial Boiler and Related Information

The first step of this analysis was a review of the available literature and data for this sector. This section summarizes our findings and key datasets reviewed for this work.

[7] Cambium datasets. National Renewable Energy Laboratory (NREL). (2023). Available at: https://www.nrel.gov/analysis/cambium.html

[8] GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model. U.S. Department of Energy (DOE)'s Argonne National Laboratory. (2024). Available at: https://www.energy.gov/eere/greet

[9] Decarbonized refers to the lower GHG emissions technology implementation scenario as defined in CAMBIUM. Note that these grid forecasts are not a custom developed for this analysis, but rather rely on potential scenarios developed by the US Department of Energy. As discussed later, a decarbonized grid is not necessarily a "cleaner" one, in the sense that additional air pollution emissions may be possible in the near term as the grid is decarbonized, depending on the technology mix employed. Note also that we do not explore a scenario that considers BAU industry combined with a decarbonized electric grid, as this work focuses on the industrial sector.

2.1.1.1 Literature Sources

We originally envisioned performing a top-down type of analysis with existing data at a national level to determine the emissions in this industrial sector. After conducting research to identify which dataset or combination of datasets could provide the most complete set of emissions to be attributed to the subsector and processes of interest, we concluded there is no perfect, existing source for all the emissions sought in this analysis.[10]

We target low- and medium-temperature industrial boilers as those suitable for replacement. As most emission databases are resolved at the sector level, rather than at the equipment level, to identify the existing emissions attributable to the portion of the industrial sector using low- and medium temperature fossil-fueled or other combustion-based boilers, we explored combining several datasets to create what is needed for the modeling. Some datasets that were explored include Energy Policy Simulator (EPS);[11] National Emissions Inventory (NEI),[12] the EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) default database;[13] EPA's National GHG Inventory[14] and GHG Reporting Program (GHGRP);[15] US EIA's Manufacturing Energy Consumption Survey (MECS),[16] the SCAQMD's Rule 1146.2 for zero emissions Boilers,[17] and the EIA's Annual Energy Outlook.[18]

The following summarizes the data we explored and incorporated in our approach.

[10] In the sense that there is not a dataset with a complete set of both greenhouse gas and criteria pollutant emissions. Both GHGRP and NEI datasets are complete representations of facilities that are required to report, and both have been evaluated in research separately. The purpose of this study is to create a dataset that included emissions sources that might not be subject to state or federal reporting requirements, which is a much broader scope than available in the existing data sources.

[11] Energy Policy Simulator (EPS). Energy Solutions. (2025). Available at: https://energypolicy.solutions/

[12] National Emissions Inventory (NEI). U.S. Environmental Protection Agency (U.S. EPA). (2020). Available at: https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

[13] Latest version is Version: 5.2 released March 3, 2025 in the Desktop Edition. https://www.epa.gov/cobra

[14] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022. U.S. Environmental Protection Agency. (2024). Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[15] GHG Reporting Program (GHGRP) data for 2023. U.S. Environmental Protection Agency. (2024). Available at: https://www.epa.gov/ghgreporting/find-and-use-ghgrp-data

[16] Manufacturing Energy Consumption Survey for 2018. U.S. Energy Information Administration (EIA). (2021). Available at: https://www.eia.gov/consumption/manufacturing/about.php

[17] RULE 1146.2. EMISSIONS OF OXIDES OF NITROGEN FROM LARGE WATER HEATERS AND SMALL BOILERS AND PROCESS HEATERS. South Coast Air Quality Management District (SCAQMD). (amended June 7, 2024). Available at: https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1146-2.pdf?sfvrsn=93cc1d61_23

[18] Annual Energy Outlook 2023. U.S. Energy Information Administration (EIA). (2023). Available at: https://www.eia.gov/outlooks/aeo/

- EIA's **NEMS** Industrial Demand Module (IDM)[19] (version corresponding to the Annual Energy Outlook 2022) generates long-term projections (through 2050) of industrial sector energy demand by energy source for 21 industries (the IndUSA database). From the energy consumption data NEMS provides for combustion boilers, we calculated growth factors to estimate how the baseline boiler inventory will change over time. Growth factors calculated and applied to the baseline boiler inventory were specific to industry (at the 3-digit NAICS code level). When data in the boiler inventory was available, growth factors calculated and applied to the baseline boiler inventory were specific to industry (at the 3-digit NAICS code level) and boiler capacity class (≤10 MMBTU/hr; >10 MMBTU/hr). There was no AEO or NEMS version 2024 released. We were in communication with NREL about the dataset and were told that it is currently being revised. The methodology is outdated and the information may not be current.
- The **Boiler Maximum Achievable Control Technologies (MACT)** Rule with the final emission standards for control of mercury, hydrogen chloride, particulate matter and carbon monoxide from coal-fired, biomass-fired, and liquid-fired major source boilers [20,21] was also reviewed for this analysis. Although it does have a database of some boilers, provides useful information, and was included in the Schoeneberger analysis, it is not employed directly in this analysis as it does not contain the emissions or activity data we need to characterize all boilers nationally.
- Mentioned previously, DOE ANL's **GREET,**[22] is a set of life cycle assessment models used to assess the environmental and energy performance of different technologies across its supply chain. This dataset provided emission factors per energy source/fuel type that were applied to the projected grid mix from the CAMBIUM dataset described below. It also serves as the basis for boiler emissions in our top-down approach. This is described later.
- EIA's **Manufacturing Energy Consumption Survey (MECS)[23]** is a national compilation of energy consumption and related data for manufacturers in the United States. The most recent, complete dataset is from 2018, including industrial boiler data by industry and fuel. MECS2022 is expected to be released sometime in 2025.

[19] Industrial Demand Module of the National Energy Modeling System (NEMS) - version corresponding to the Annual Energy Outlook 2022. U.S. Energy Information Administration (EIA). September 2022. Model documentation available at: https://www.eia.gov/outlooks/aeo/nems/documentation/industrial/pdf/IDM_2022.pdf
[20] Boiler MACT Rule. U.S. Environmental Protection Agency. https://www.epa.gov/stationary-sources-air-pollution/national-emission-standards-hazardous-air-pollutants-neshap-8
[21] https://www.epa.gov/stationary-sources-air-pollution/industrial-commercial-and-institutional-boilers-and-process-0#additional-resources
[22] GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) models. U.S. Department of Energy (DOE)'s Argonne National Laboratory. (2024). Available at: https://www.energy.gov/eere/greet
[23] https://www.eia.gov/consumption/manufacturing/data/2018/.

- The US National Renewable Energy Laboratory's (NREL) **CAMBIUM**[24] dataset contains modeled hourly data for potential projections of the U.S. electricity sector through 2050. This CAMBIUM data provided projections of the grid mix which were used in this study. We applied the percent of each energy source/fuel type of the grid to the corresponding emission factors per energy source/fuel type from GREET to calculate emissions from the grid overtime. These grid emissions were used to estimate emissions from the grid that result from HP replacement. Grid emissions were calculated under two CAMBIUM Scenarios (Scenario 1 and 7). This is described later.
- A 2005 report submitted by **Energy and Environmental Analysis, Inc. (EEA)** to the Oak Ridge National Laboratory titled, *Characterization of the U.S. Industrial/Commercial Boiler Population*, developed boiler inventories for industrial, non-manufacturing, and commercial boilers. Boilers were characterized in terms of number of units, unit capacity, primary fuel, application, and regional distribution. Industrial boilers were also broken down and characterized by industry. Trends in boiler sales and fuel consumption from 1991-1998 were also described. The approach of this report influenced the methodologies developed for this study.
- Several NREL reports were reviewed, particularly those by Colin McMillan[25] and the DOE liftoff reports on industrial decarbonization.[26] These provide useful background but are not directly used here.

2.1.1.2 Building from Current Research

Our research indicated that a top-down emissions inventory was likely to be insufficient to properly characterize the emissions and reduction potential for the specific set of industrial boilers necessary to support this analysis. Although the preceding datasets provide some emissions information, they are insufficient to build a top-down inventory for the targeted sector nationally. We overcame this lack of data by directly contacting several researchers active in the field to capture the latest work in this area and identify other datasets that could support our national baseline emissions inventory. The following were shared with us directly.

[24] Cambium datasets. National Renewable Energy Laboratory (NREL). (2023). Available at: https://www.nrel.gov/analysis/cambium.html
[25] Including Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions, C McMillan, R Boardman, M McKellar, P Sabharwall, M Ruth, and S Bragg-Sitton, November 2016; A New Understanding of Decarbonizing Industrial Process Heat, C McMillan, 2023 Fall MIT CEEPR Research Workshop, October 3,2023; and Facility-Level Industry Representation for Decarbonization Modeling, C McMillan, D Steinberg, M Brown, and C Hughes, March 2023.
[26] Including https://liftoff.energy.gov/industrial-decarbonization/ and https://liftoff.energy.gov/wp-content/uploads/2024/02/LIFTOFF_DOE_Industrial-Decarbonization_REV022724.pdf.

- We met with **CAELP**[27] and its partners to discuss datasets under development regarding industrial heat that could support this work. Three datasets were shared: a comprehensive set of data on large industrial heat sources based on the US EPA's Greenhouse Gas Reporting Program (GHGRP).[28] The second was an analysis of existing U.S. boilers to assess achievable GHG and NOx emissions reductions nationally.[29] Another dataset mentioned was the U.S. Industrial Sector Heat Emissions and Temperature Dataset (HEATset), which is an opensource, public dataset for exploring data on industrial heat and combustion.[30] The E3/CAELP dataset is included in our analysis to provide temperature and capacity information on boilers nationwide, to support identification of boilers suitable for HP replacement, and to determine our approach for temperature breakdown by NAICS of replacement technologies.

- **Energy Innovation** published the report Decarbonizing Low-Temperature Industrial Heat in the U.S. in October 2022,[31] which builds off multiple sources, including Fraunhoffer study[32] and AEO 2022.[33] Jeffrey Rissman, author of the report, provided the information we used to build off his research to address heat demand by temperature range industry, particularly isolating low and mid temperature boilers in the existing data suitable for replacement.

- **Schoeneberger** et al. (2022)[34] provides a dataset of the industrial boiler population In the United States, which does not include emissions. The dataset developed of boilers and corresponding emission data comes from the U.S. Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP), the Boiler Maximum Achievable Control Technology (MACT) Draft Emissions and Survey Results Database, and the EPA's National Emissions Inventory (NEI). The U.S. National Renewable Energy Laboratory's (NREL) manufacturing thermal energy use dataset was used for deriving the populations and characteristics of remaining boilers at the county-level. This dataset is the most comprehensive boiler inventory available, but does not include emission or

[27] The Center for Applied Environmental Law and Policy (CAELP). https://www.caelp.org/
[28] U.S. Industrial Sector Emissions: Thermal Temperature Analysis of Combustion-Related CO2 Emissions from Eight Energy-Intensive Subsectors, September 2024.
[29] S. Smillie, D. Alberga, R. Loken, S. Bharadwaj, T. Clark, A. Mahone, "Measuring Economic Potential for Decarbonization Industrial Heat," Energy and Environmental Economics, Inc., October 2024.
[30] U.S. Industrial Sector Heat Emissions and Temperature Dataset (HEATset) Analysis of Combustion-Related CO2 Emissions from Eight Energy-Intensive Industrial Subsectors, October 2024. https://energyinnovation.org/wp-content/uploads/Decarbonizing-Low-Temperature-Industrial-Heat-In-The-U.S.-Report-2.pdf
[31] Decarbonizing Low-Temperature Industrial Heat in the U.S., Jeffrey Rissman, Energy Innovation Policy and Technology LLC, October 2022.
[32] Mapping and analyses of the current and future (2020 – 2030) heating/cooling fuel deployment (fossil/renewables), September 2016.
[33] Annual Energy Outlook 2022. U.S. Energy Information Administration (EIA). (2022). Available at: https://www.eia.gov/outlooks/aeo/electricity_generation.php
[34] Schoeneberger, C., Zhang, J., McMillan, C., Dunn, J. B., & Masanet, E. (2022). Electrification potential of U.S. industrial boilers and assessment of the GHG emissions impact. *Advances in Applied Energy*, *5*, 100089. https://doi.org/10.1016/j.adapen.2022.100089

temperature data. However, it does provides fuel, Source Categorization Code (SCC), and capacity information. The Schoeneberger dataset, along with the Evergreen/AJW boiler dataset described below, were used as a basis for our national baseline boiler inventory.

- The Sierra Club and **Evergreen** Action published **Embracing Clean Heat** in May 2025.[35] Cassandra Lopina of **AJW** and Andres Restrepo of the Sierra Club provided a dataset of boilers compiled from the Schoeneberger dataset for boiler characterization, CAELP data for boiler emissions, and EPA's 2020 National Emissions Inventory (NEI) with additional procedures to validate boiler information and matches. This Evergreen/AJW dataset was a preliminary product of the Embracing Clean Heat study provided by the Sierra Club to support this research. We used this Evergreen/AJW Industrial Boiler NEI dataset as a basis for the U.S. baseline boiler inventory in this study.

2.1.2 Baseline Boiler Inventory

As no comprehensive dataset is available to support the emissions modeling needed for this project, we created a new, comprehensive dataset of industrial boilers and their emissions across the United States to fill this gap. We validated our assumptions about appropriate use of the existing datasets and approach with authors and researchers in this area. The following describes our methodology and results.

2.1.2.1 Bottom-Up Methodology

Unlike a top-down approach, a bottom-up inventory builds a result from individual assets – in this case individual boilers. We developed our baseline bottom-up boiler inventory for year 2020 using the Schoeneberger (a.k.a, the "NW") dataset of boilers that characterizes boilers operating across the nation (including boilers not subject to federal reporting requirements) and the Industrial Boiler NEI dataset created by Evergreen/AJW which contains CAP emissions for boilers required to report to the federal CAP emissions inventory. The boilers in these datasets overlap but are not identical. Our approach assumes that the NW dataset is the complete set of boilers nationwide. We then categorize each boiler in the NW dataset into either Tier 1 or Tier 2 based on their correspondence with the unique boiler identifiers in the Industrial Boiler NEI dataset. For Tier 1 boilers, where there is a direct match on boiler identifiers between the two datasets and emissions were reported to NEI, our dataset takes the emissions directly from the Industrial Boiler NEI dataset. All remaining boilers are considered Tier 2 and have their emissions imputed from data in the two datasets. To impute

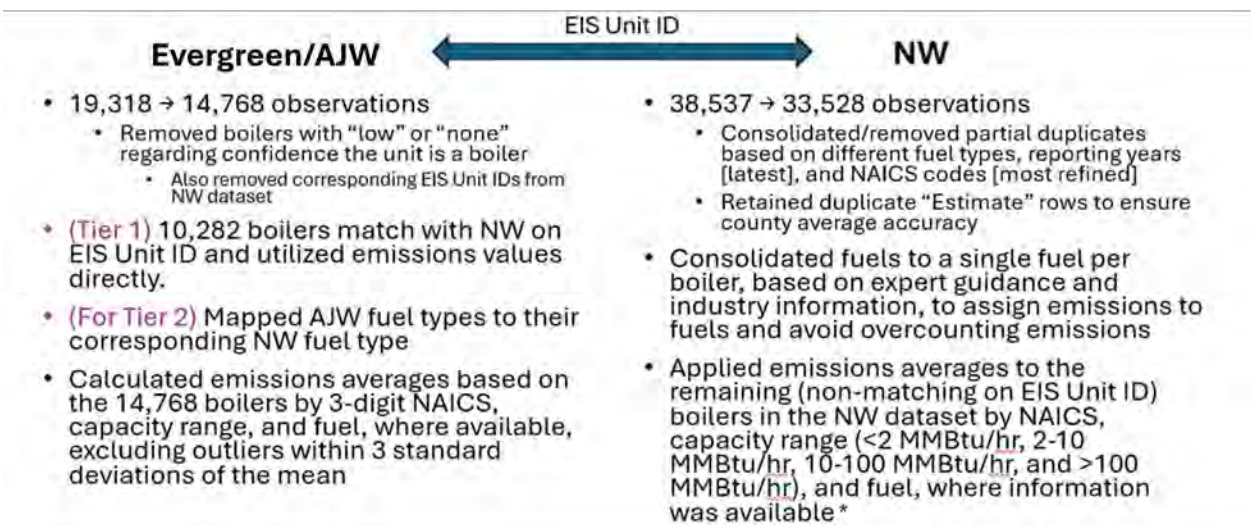
[35] Embracing Clean Heat, Opportunities for Zero-Emission Industrial Boilers, Trevor Dolan, Andres Restrepo, Cassandra Lopina, Melanie Law, Madison Carroll, May 2025. Available at: https://collaborative.evergreenaction.com/policy-hub/embracing-clean-heat.

emissions for these boilers, we applied a binned averaging approach based on data from the Industrial Boiler NEI dataset. The binned averages were based on both Tier 1 boilers, and additional boilers in Industrial Boiler NEI dataset that do not directly match boilers in the NW dataset.

We corrected both datasets to accommodate reporting issues. In the NW dataset, we removed duplicate entries. We retained only the information from the most recent year when multiple years were reported for a single boiler. We also retained the most specific NAICS code in cases where entries were duplicated, ensuring that the most precise industry information for boilers reported to operate under multiple NAICS codes was reflected. However, we kept otherwise duplicated entries that differed in reported operating hours, treating them as separate boilers per recommendation of the original author. For the Industrial Boiler NEI dataset we only considered boilers that Evergreen/AJW had assigned as boilers with high confidence to avoid polluting the dataset with other, similar sources reported in the NEI. The outcome of this analysis is our resulting baseline boiler inventory.

We estimate 33,528 industrial boilers operating in the U.S. Figure 1 summarizes our approach.

Figure 1. 2020 Baseline Bottom-Up Boiler Inventory Methods.



* These capacity ranges assigned are intended to reflect federal rule applicability, as outlined by AJW in the Industrial Boiler NEI dataset.

Many industrial boilers operate on multiple fuels. In many applications, boilers primarily operate on waste fuels, then utilize other fuels such as natural gas or other fuels as auxiliary or backup fuels. Neither the Industrial Boiler NEI nor NW dataset provided detailed information regarding the fuel hierarchy (i.e., which fuel type is primary or secondary) for individual boilers where multiple fuels were listed. For the Industrial Boiler NEI dataset, AJW also included fuels associated with SCC codes reported for individual boilers. Furthermore, the two datasets have different categories of fuel types. To combine these, we reconciled the specific fuels contained in the Industrial Boiler NEI dataset with the NW fuel type categories to align all fuel types with the overall boiler dataset (NW) to preserve emission characteristics. For example, landfill gas is mapped to natural gas because it will have emission properties more similar to natural gas than coal, even though it is considered a biofuel. However, since the CAP emissions in the Industrial Boiler NEI dataset reflects the total annual emissions from individual boilers rather than on a fuel-specific basis, we consolidated multiple fuel types into a singular fuel type to avoid overstating emissions when summarizing by fuel type. We consolidated multiple fuel types to a single fuel per boiler based on expert guidance[36] and industries comprising the boilers with multiple fuel types. Table 1 and Table 2 show the assumptions and rules we relied on for fuel mapping and reconciliation.[37]

Table 1. Mapping Evergreen/AJW Fuel Types to NW Fuels

NW Fuel Type	Evergreen/AJW Fuels			
Natural Gas	Natural gas	Liquefied petroleum gas (LPG)	Process or refinery gas	Gas, including landfill gas
Oil Products	Distillate oil	Residual oil	Oil	-
Coal	Coal	Coke	-	-
Biomass	Waste	Biomass	Animal fat	Wood or bark
Other Fuels	Unknown	-	-	-

[36] AJW indicated that when multiple fuels are reported and one is a solid fuel, that is likely the primary fuel (with natural gas as an auxiliary fuel). This agrees with other sources and ICF's internal experts and was thus used to create the hierarchies in Table 2.

[37] Note that the Evergreen/AJW approach joined the NEI dataset to SCC codes reported at the emitting unit (equipment level). This can result in multiple SCC codes per unit. For additional details, please see the Evergreen/AJW methodology for the NEI dataset in Appendix 3 of the Embracing Clean Heat report.

Table 2. Mapping NW Fuels to a Single Fuel Type

Single Fuel Type	Multiple Fuel Types
Natural Gas	Natural gas; oil products
	Natural gas; other fuels
	Natural gas; oil products; other fuels
Biomass	Biomass; coal
	Biomass; natural gas
	Biomass; oil products
	Biomass; coal; natural gas
	Biomass; coal; oil products
	Biomass; natural gas; oil products
	Biomass; coal; natural gas; oil products
Coal	Coal; natural gas
	Coal; natural gas; oil products
	Coal; natural gas; other fuels

After de-duplicating and consolidating both datasets and aligning and reconciling fuel types, we filled in the missing emissions values for Tier 2 boilers. We employed the binned emissions summarization approach based on the 14,768 boilers with emissions information in the Evergreen/AJW dataset. Our emissions averages include boilers without matching identifiers with the NW dataset to calculate binned averages to include the most available data in the average emissions values.

Furthermore, we filtered the dataset to remove outlier emissions values from the binned average calculations based on emissions values exceeding three standard deviations from the mean.[38] Our binned averages approach summarizes and applies pollutant-specific emissions based on the most available information for a specific Tier 2 boiler. We calculated and prioritized applying binned emissions averages to Tier 2 boilers based on the following categories in order from most to least refined:

- 3-digit NAICS code, capacity range, and fuel type;
- 3-digit NAICS code and capacity range;
- 3-digit NAICS code and fuel type;
- 3-digit NAICS code.

[38] This approach to remove potential outliers was developed in response to conversations with AJW, on how to deal with instances where multiple devices are reported together as a single unit in NEI. Alternatively, these high emitting units would have to be individually validated, which was beyond the scope of this effort.

We also bias-corrected our Tier 2 boiler emissions estimates. To do so, we adjusted the individual Tier 2 boiler emissions computed from the binned average results from the Evergreen/AJW dataset based on the Tier 1 boilers from the Evergreen/AJW dataset. Consistent with the binned Evergreen/AJW emissions averages we applied to the Tier 2 boilers, we removed pollutant-specific Evergreen/AJW emissions outliers exceeding three standard deviations from the mean. Then, we calculated the overall bias ratios by dividing the sum of actual, non-outlier emissions ("observed") for these boilers by the sum of what would have been predicted had these boilers used the binned average approach applied for the Tier 2 boilers ("predicted") emissions for each pollutant. This represents the geometric mean of overall bias in our prediction by pollutant. Table 3 presents the overall bias ratios. To adjust for bias, we applied these bias ratios to the individual Tier 2 boiler emissions specific to each pollutant.

Table 3. Ratio of Observed Total Emissions to Predicted Total Emissions by Pollutant.

Pollutant	Boiler Count	Total Predicted Annual Tons	Total Observed Annual Tons	Bias Ratio
CH_4	3,610	375	292	0.78
CO_2	3,554	7,660,025	7,559,174	0.99
N_2O	3,089	212	180	0.85
NH_3	5,301	1,111	1,226	1.10
NO_2	9,966	110,822	88,067	0.79
$PM_{2.5}$	9,832	15,937	12,996	0.82
SO_2	9,551	42,031	23,322	0.55
VOC	9,935	7,446	6,997	0.94

Data in Evergreen/AJW is primarily NEI. Accordingly, all GHG emissions in the Evergreen/AJW dataset are all downstream-only, or smokestack-level emissions.[39] Thus, the data sources for this inventory do not consider full lifecycle GHG emissions, while the current analysis does. After bias-correcting our predicted emissions estimates for the Tier 2 boilers, we estimated and applied lifecycle "upscale" factors to estimate full lifecycle GHG emissions associated with these boilers. We computed these factors for all three GHGs (CH_4, N_2O, and CO_2) by fuel type based on boiler fuel and feedstock emissions from the GREET2024 model. Where a boiler had no fuel type specified or the fuel type was listed as "other fuels," we applied average lifecycle factors by pollutant across all fuels that are not biomass. Biomass is not used to upscale non-biomass fuels due to carbon accounting methods between fuels and feedstocks. Table 4 presents the calculated lifecycle factors for the

[39] Similarly, The GHGRP also reports Scope 1 emissions and Scope 3 supplier emissions but excludes Scope 2 energy emissions. https://www.epa.gov/ghgreporting/what-ghgrp.

three GHGs by fuel type. We multiplied the calculated boiler emissions by these factors to estimate the full lifecycle emissions of these pollutants.

The three GHGs are combined into total CO_2 equivalent (CO_2e) values by applying the 100-year time horizon AR6 global warming potential (GWP) values[40] shown in the last line of Table 4. Note that at this point, downstream CO_2 emissions from biomass fuels are still reported. This is corrected later when all results are combined.

As with the lifecycle values, the reported units of “tons” are understood to be short tons (2,000 pounds) and are not adjusted here.

Table 4. Lifecycle Factors and Global Warming Potential Values for GHGs by Fuel Type.

Fuel Type	CO_2	N_2O	CH_4
Oil products	1.11	1.29	36.33
Natural gas	1.10	9.00	155.75
Coal	1.02	1.01	10.25
Biomass	1.00	2.39	1.54
[Blank][41]	1.07	3.77	67.44
Other fuels[41]	1.07	3.77	67.44
AR6 GWP	1	273	27.0 (non-fossil fuels) 29.8 (fossil fuels)

2.1.3 Results

Table 5 displays the ICF national baseline boiler emissions inventory summary estimates for the 33,528 boilers in ICF’s national inventory by pollutant and fuel type. These estimates result directly from applying our methodology to map, align, and fill in missing emissions values between the two datasets. Table 6 similarly summarizes emissions by the boiler tier level. Figure 2 shows the geographic distribution of boiler emissions across the country for the baseline boiler inventory. Note that this is shown at the county level, includes Tier 1 and 2 boilers, and only represents the baseline year of 2020. All values are in short tons. NOx, SO_2, and $PM_{2.5}$ are shown to represent the criteria pollutants.[42] Table 7 similarly shows the same emissions, broken down by 3-digit NAICS code to

[40] https://ghgprotocol.org/sites/default/files/2024-08/Global-Warming-Potential-Values%20%28August%202024%29.pdf

[41] For boilers without a fuel type specified or using “other fuels,” we applied the average lifecycle factor across all fuel types except biomass.

[42] Note that all results discussed in this report except the public health benefits represent the entire country (50 states plus DC). As COBRA does not include AK or HI, boilers in those states are filtered out before input into the COBRA model to produce health impacts.

indicate the industry with which these emissions are associated. In all cases, we note these are only combustion emissions from the use of industrial boilers. Process emissions are not considered here.

Table 5. 2020 Baseline Bottom-Up Boiler Emissions Inventory by Fuel Type and Pollutant, Short Tons.

Fuel Type	Boiler Count	Average Capacity Value (mmBTU/hour)	Pollutant (Total Annual Short Tons, 2020)											
			$PM_{2.5}$	SO_2	VOC	NH_3	NO_2	CO_2[a]	N_2O	CH_4	Lifecycle CO_2	Lifecycle N_2O	Lifecycle CH_4	Lifecycle CO2e[a]
Biomass	2,502	81	25,849	22,418	10,203	4,552	101,275	28,102,566	2,101	3,483	28,102,566	5,022	5,378	29,618,679
Coal	615	236	4,793	76,136	1,850	661	65,828	7,946,341	66	169	8,072,337	67	1,730	8,142,139
Natural gas	26,241	32	13,999	28,623	10,384	3,493	128,387	79,510,212	2,023	2,397	87,226,942	18,215	373,327	103,324,734
Oil products	2,430	62	3,885	12,685	1,719	483	37,434	9,230,901	148	248	10,264,150	190	9,028	10,585,133
Other fuels	725	121	2,853	2,501	1,170	547	15,978	2,636,231	16	54	2,833,810	61	3,628	2,958,581
[Blank]	1,015	-	897	1,398	505	166	6,653	2,735,298	38	74	2,940,302	141	5,019	3,128,461
Total	**33,528**	**44**[43]	**52,275**	**143,762**	**25,831**	**9,903**	**355,555**	**130,161,549**	**4,392**	**6,425**	**139,440,106**	**23,696**	**398,110**	**157,757,728**

[a] Note that downstream, biomass emissions of CO_2 are included here.

Table 6. 2020 Baseline Bottom-Up Boiler Emissions Inventory by Boiler Tier and Pollutant, Short Tons.

Boiler Tier	Boiler Count	Average Capacity Value (mmBTU/hour)	Pollutant (Total Annual Short Tons, 2020)									
			$PM_{2.5}$	SO_2	VOC	NH_3	NO_2	CO_2[a]	N_2O	CH_4	Lifecycle CO_2	Lifecycle N_2O	Lifecycle CH_4
Tier 1	10,282	62	23,754	81,734	13,152	3,886	173,689	54,404,418	2,523	2,771	58,693,437	16,729	181,114
Tier 2	23,246	36	28,521	62,027	12,680	6,017	181,867	75,757,131	1,869	3,654	80,746,670	6,967	216,996
Total	**33,528**	**44**[43]	**52,275**	**143,762**	**25,831**	**9,903**	**355,555**	**130,161,549**	**4,392**	**6,425**	**139,440,106**	**23,696**	**398,110**

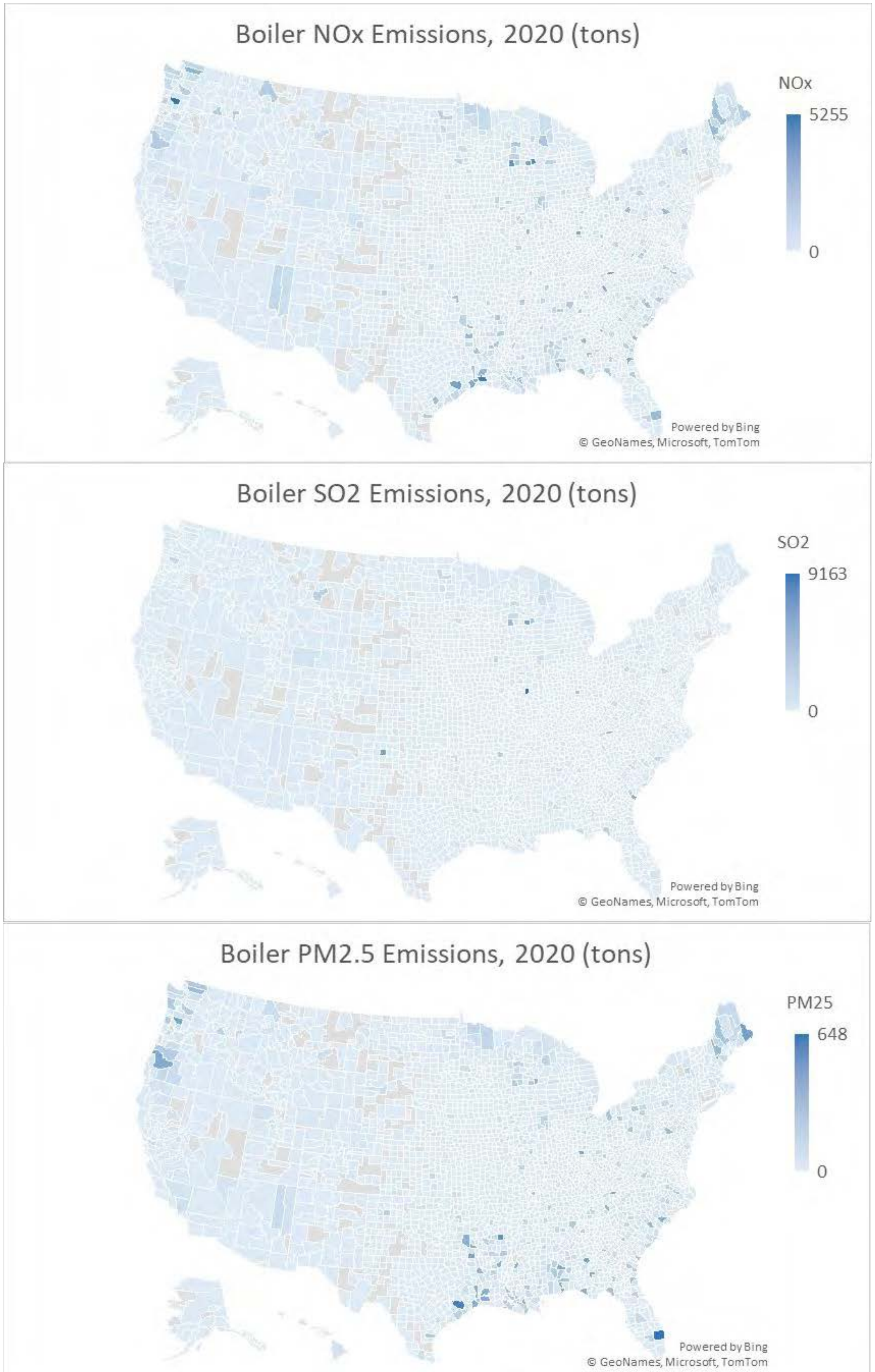
[a] Note that downstream, biomass emissions of CO2 are included here.

[43] This value is a weighted mean by boiler count of the average capacity values.

Table 7. 2020 Baseline Bottom-Up Boiler Emissions Inventory by 3-Digit NAICS Code and Pollutant, Short Tons.

NAICS Code		Pollutant (Total Annual Short Tons, 2020)										
		$PM_{2.5}$	SO_2	VOC	NH_3	NO_2	CO_2[a]	N_2O	CH_4	Lifecycle CO_2	Lifecycle N_2O	Lifecycle CH_4
311	Food Processing	4,444	25,759	2,826	2,831	37,416	17,067,593	1,533	1,044	18,537,365	13,296	145,841
312	Beverage	345	481	274	164	3,456	3,792,933	38	66	4,157,068	315	8,505
313	Tobacco	324	1,038	225	68	1,934	1,743,066	34	29	1,909,778	290	3,399
314	Textiles	211	131	263	196	4,145	4,233,042	11	72	4,642,678	94	10,408
315	Apparel	11	1	8	0	134	267,678	4	4	293,931	34	544
316	Leather	3	20	1	1	22	43,938	1	1	48,337	7	166
321	Wood	16,184	2,275	5,325	2,017	37,909	24,440,798	2,235	1,762	24,723,644	5,809	15,263
322	Paper	18,249	68,721	9,120	1,542	160,146	18,979,529	128	2,142	20,195,503	740	36,455
323	Printing	23	2	17	6	191	283,663	3	5	312,168	26	542
324	Petroleum	3,829	6,055	1,434	593	22,761	1,430,471	17	28	1,567,668	106	3,361
325	Chemicals	5,313	32,953	3,016	1,625	61,616	42,019,775	187	873	45,715,811	1,491	120,107
326	Plastics/Rubber	363	36	346	133	4,549	4,185,578	56	73	4,590,499	454	9,916
327	Stone/Clay/Glass	254	126	151	265	1,002	446,620	5	9	489,674	30	1,093
331	Metals	1,758	5,672	976	185	12,041	2,005,918	19	33	2,192,717	158	4,638
332	Metal Products	170	370	424	56	1,693	2,425,794	24	35	2,653,116	195	4,909
333	Machinery	103	21	92	46	1,316	1,562,068	19	140	1,710,929	157	21,559
334	Computer/Electronic	29	7	27	9	259	410,818	3	6	452,130	18	804
335	Equipment/Appliance	10	1	15	5	206	307,137	1	5	337,326	10	645
336	Transportation Equip	288	17	995	121	3,037	3,025,088	38	47	3,313,830	308	6,668
337	Furniture	248	73	69	11	1,052	675,656	26	34	705,434	90	1,494
339	Miscellaneous	115	5	229	28	670	814,387	9	19	890,501	67	1,795
Total		**52,275**	**143,762**	**25,831**	**9,903**	**355,555**	**130,161,549**	**4,392**	**6,425**	**139,440,106**	**23,696**	**398,110**

Figure 2. Baseline Boiler Emissions by County, Year 2020, Short Tons.



2.2 Emissions Control Technology

2.2.1 Emissions Control Technology Research

This section discusses the potential for heat pump (HP) technology to replace traditional, combustion-fueled, industrial boilers. ICF conducted research and relied on internal expert judgment to define suitable replacement technologies for the low and mid-temperature, fossil-fueled, industrial boilers. We focused on HP technologies, which are available and can be applied as replacement technology for a certain set of boilers now. As HP technology improves, there will be an expanded set of process temperatures suitable for replacement.

We also conducted research to determine whether there are other suitable zero emissions technologies that could be considered in the analysis, in addition to HP, such as other electric resistance technologies and other technologies. This is important, particularly if such a replacement technology does not get its power from the grid, such as for a fuel-cell application. Research indicated that other zero emissions technology is generally not commercially feasible in the near-term. Therefore, we focused on HP as the replacement technology for this analysis. Notably, we also only focus on replacing combustion-based boilers with HP technologies. We do not consider the benefits of replacing existing electric (non-combustion) industrial boilers with HP technologies.

We targeted a limited range of temperatures, which correspond to a subset of the processes for each industrial sector. However, as technology evolves, additional temperature ranges may be paired with HP technology. Our research showed that electric HPs have the potential to reduce pollutants associated with industrial process heating, especially in applications that require low or mid-temperature process heat. We set the definition of that operating temperature as less than 200 ˚C. It is possible that future high-temperature HP (HTHP) technologies will become more efficient and increase this upper bound temperature so that HP technologies can penetrate different industrial sectors than envisioned here. However, for this analysis, we maintain the 200 ˚C threshold throughout the projection period and vary the penetration of HPs in temperature ranges below this ceiling.

We developed coefficient of performance (COP) estimates for HPs in three process heating temperature ranges (<100 ˚C, 100-140 ˚C, 140-200 ˚C). We reviewed COP results within each of these temperature ranges from an inventory of over 3,000 boilers from the CAELP (2024) study. We determined an average COP in each temperature range to represent that temperature range, as described in Section 2.4.1.

2.2.2 Emissions Control Technology Summary

Compared to a fossil fuel boiler, an electric HP operates at a higher efficiency, especially in applications that require process heat at temperatures below our 200 °C threshold. As an example, a HP that delivers heat for a process at 65 °C will have an expected efficiency near 300% because the electric fuel is used to move heat from the source to the heated medium. In contrast, an electric resistance boiler will have an efficiency nearly 100% and a natural gas boiler will operate at a much lower efficiency, typically near 80%. When conventional boilers are replaced with HP alternatives, the end-use, on-site emissions are completely eliminated compared to the combustion boiler. The replacement HP will increase emissions associated with the additional generation of grid electricity, but not to the extent that would be required from electric resistance technologies alone, thus potentially mitigating the negative finding of Schoeneberger et al.[44]

This section provides an overview of HP technology, including operating principles (Section 2.2.2.1), design variations (2.2.2.2), efficiency (2.2.2.3), and COP estimates (2.2.2.4).

2.2.2.1 Operating Principles

A HP moves energy (i.e., heat) from a low-temperature location (referred to as a "source") to a high-temperature location (referred to as a "sink"). Ambient air is a common heat source for residential and commercial heating applications. These HPs are referred to as air source HPs. Some residential and commercial HPs are coupled with the ground or water and are referred to as ground source and water source HPs, respectively. For industrial applications, a waste heat stream is often used to capture energy that would otherwise be lost. Example waste heat streams include oven exhaust air (20 °C-100 °C), compressed air discharge (30 °C-70 °C), process wastewater (20 °C-60 °C), and cooling water discharge (20 °C-50 °C).

2.2.2.2 Design Variations

While all HPs operate on the fundamental principle of moving heat, there are multiple design variations, primarily based on the type of energy used to drive the HP and whether the cycle is closed or open.[45] One of the most common HP configurations is shown in Figure 1, which is a closed cycle mechanical vapor compression (MVC) design driven with electricity.

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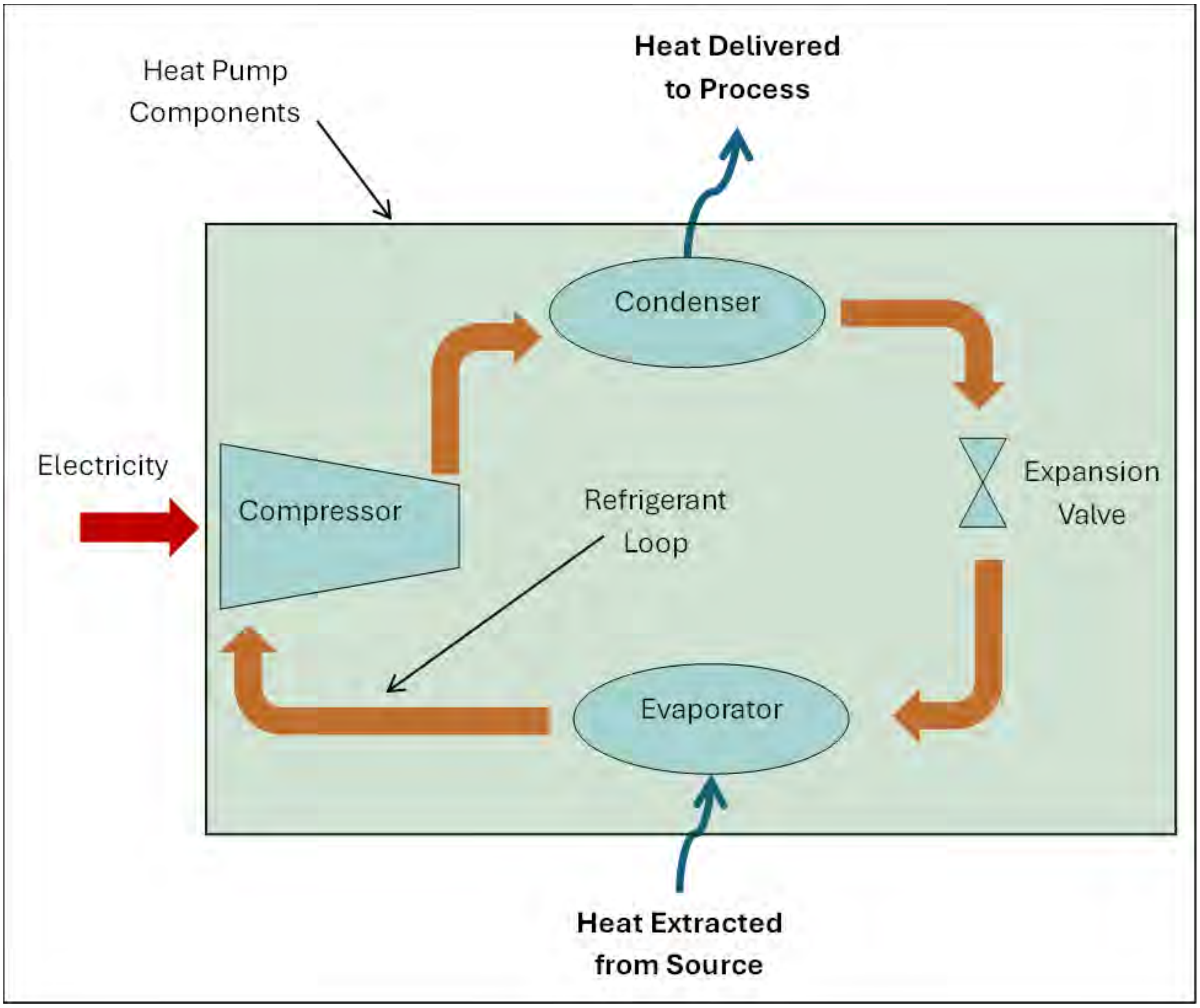
[44] Electrification potential of U.S. industrial boilers and assessment of the GHG emissions impact. C Schoeneberger, et al., Advances in Applied Energy, 2022. https://doi.org/10.1016/j.adapen.2022.100089.

[45] Rightor, Ed, Paul Scheihing, Andrew Hoffmeister, and Riyaz Papar (2022), "Industrial Heat Pumps: Electrifying Industry's Process Heat Supply," American Council for an Energy-Efficient Economy. Six industrial heat pump configurations are described in Appendix A.

Figure 3. Mechanical Vapor Compression Heat Pump Illustration.

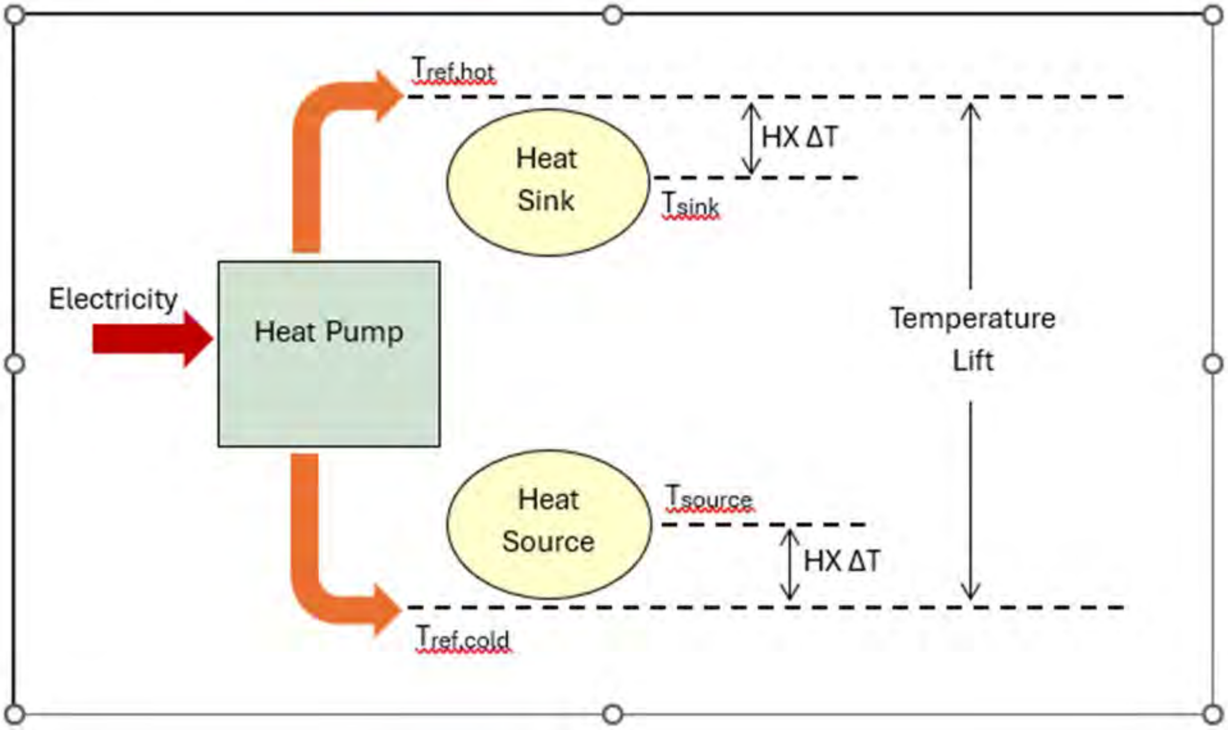


Adapted from Rightor et al., 2022. Figure A2 on p48 shows mechanical vapor compression closed cycle heat pump.

The HP condenser and evaporator are heat exchangers. To transfer heat in the condenser, the refrigerant needs to be slightly hotter than the process stream. Similarly, in the evaporator the refrigerant needs to be slightly colder than the source stream. The temperature delta in the condenser and the evaporator is referred to as the approach temperature. The total temperature difference between the cold refrigerant in the evaporator and the hot refrigerant in the condenser is referred to as the temperature lift. This is shown in Figure 4.[46]

[46] Note that all emissions here refer to combustion emissions, or those from the full fuel cycle. We do not include emissions from leaked refrigerants in this analysis. See Footnote 6.

Figure 4. Heat Pump Temperature Lift.



Adapted from Rightor et al., 2022. Figure 3 on p9 illustrates temperature lift.

2.2.2.3 Efficiency

The efficiency of an HP is greater than 100% because an HP moves heat, rather than converting energy into heat, as is done by combusting natural gas. The maximum theoretical efficiency of a HP is the Carnot efficiency, which is a function of the temperature difference between the hot refrigerant in the condenser and the cold refrigerant in the evaporator. The Carnot efficiency for a closed loop MVC HP is (temperatures on an absolute scale):

$$COP_{Carnot} = (Tsink + HX\Delta T_{cond}) / [(Tsink + HX\Delta T_{cond}) – (Tsource – HX\Delta T_{evap})]$$

In practice, HPs do not achieve the Carnot efficiency, with actual COPs often about half the theoretical maximum. Figure 5 shows HP COP with a 50% Carnot derate as a function of the process delivery temperature (sink temperature), assuming a source temperature of 20 °C and an approach temperature of 5 °C in both the condenser and the evaporator.

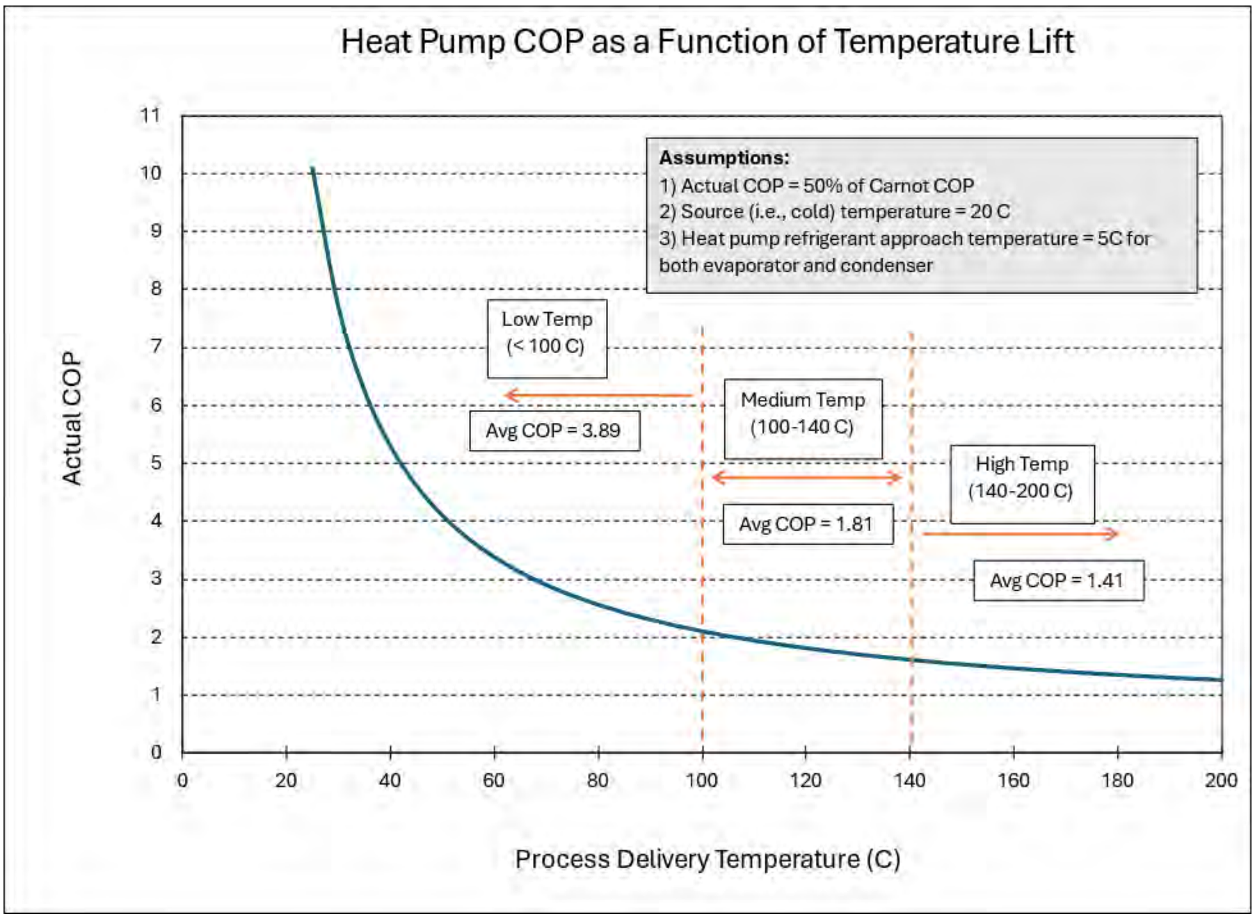
2.2.2.4 Resulting COP Estimates

For this analysis, we developed COP estimates for HPs in three process heating temperature ranges:

- Low temperature <100 °C,
- 100 °C–140 °C, and
- 140 °C–200 °C.

We reviewed COP results within each temperature range from an inventory of over 3,000 boilers.[47] The average COP values within each of these temperature bins are overlaid on the COP curve in Figure 5.

Figure 5. Average COP for Three Temperature Ranges.



[47] Smillie, S., D. Alberga, R. Loken, S. Bharadwaj, T. Clark, A. Mahone (2024), "Decarbonizing Industrial Heat: Measuring Economic Potential for Policy Mechanisms," Prepared for the Center for Applied Environmental Law and Policy, Prepared by Energy and Environmental Economics, Inc.

2.3 Projected Industrial Boiler Emissions under a Business-as-Usual Scenario

Our BAU projection accounts for anticipated growth in emissions in the baseline inventory without significant changes in the underlying technology. The BAU inventory forecasts emissions from combustion-based industrial boilers from our baseline year of 2020 through year 2050 in 1-year increments. We performed a BAU growth forecast two ways: using a top-down and a bottom-up approach.[48] Both rely on intermediate data from the 2023 EIA's National Energy Modeling System (NEMS) model, which is used to produce our *Annual Energy Outlook* (AEO). EIA did not produce an AEO in 2024. As the 2025 version was not available as of the time of this research,[49] we relied on information from the 2023 version.

2.3.1 NEMS and AEO Energy Forecasts

We contacted EIA regarding the most recent NEMS data supporting AEO for fuels and energy used in low- and mid-temperature industrial boilers in the US.[50] AEO provided ICF with the IndUSA database discussed in Section 2.1.1. This database has results for energy consumption for NEMS' boiler/steam/cogeneration component but is not solely boiler fuel. (It also includes fuel for cogeneration.) Furthermore, EIA was uncertain if the current NEMS model is correctly populating these data. EIA intends to resolve these issues in the 2025 NEMS updates, along with improved modeling of electric and HP boilers. As NEMS 2025 was not available during the analysis period, we used the 2023 data as the best available. NEMS' boiler analysis is based on the 2018 MECS. All results used here are AEO projections, which are modeled at the industry, fuel, and census region levels and carry all AEO caveats (e.g., current regulations and assumed constant economic growth.[51]) We used boiler fuel data by capacity. We expect that the general trends in these data are more accurate than absolute values, and thus are better suited for estimating emissions growth factors than emissions

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[48] Note that we found no data source that provided the information needed for a top-down, baseline emissions inventory to use in this analysis. That is, one that included operating temperature and other parameters needed to estimate control. Here we use a top-down estimate of emissions only as a check on our more detailed calculations.
[49] Statement on the Annual Energy Outlook and EIA's plan to enhance long-term modeling capabilities, July 26, 2023. https://www.eia.gov/pressroom/releases/press537.php. The 2025 AEO was released in April 2025, after the emissions technology and emissions modeling had been completed. We have not investigated if the intermediate data from NEMS supporting AEO 2025 or other information in AEO 2025 would alter these results.
[50] This data, by fuel type is not resolved either historically or in forecasts in the AEO, but is indicated as available from NEMS via the IDM documentation.
https://www.eia.gov/analysis/handbook/pdf/NEMS_Industrial_Demand.pdf
[51] More information on NEMS' boiler methodology is available in the IDM documentation starting on page 17, https://www.eia.gov/outlooks/aeo/nems/documentation/industrial/pdf/IDM_2022.pdf, and assumptions document, https://www.eia.gov/outlooks/aeo/assumptions/pdf/IDM_Assumptions.pdf, starting on page 15.

levels. We use this to estimate both an (uncertain) top-down boiler inventory and fuel/NAICS/boiler capacity-based growth factors for our bottom-up boiler inventory. This section describes both.

The IndUSA database provides energy and macroeconomic profile data for different industrial sectors for the entire US. We used the IndUSA database information on the energy consumption for boilers by fuel type and sector over time from the boiler/steam/cogeneration component for each of the 21 reported industrial sectors (crop agriculture, coal mining, oil & gas mining, food manufacturing, etc.). As this information includes energy for combined heat and power (CHP) steam generation and cogeneration, we focused on the portion of data reported for boilers in two categories: Boilers 10 mmBTU/HR and Under and Boilers Over 10 MMBTU/HR. We then mapped the different sectors in NEMS to 3-digit NAICS codes and computed total, national boiler energy consumption in different combinations of NAICS code, boiler size (in the two included capacity bins), and fuel. Table 8 summarizes our mapping from NEMS industrial sectors (listed as "Tables" in the IndUSA database) and 3-digit NAICS codes used in ICF's analysis.[52]

Table 8. Mapping of NEMS to NAICS Codes used in this Analysis.

	Reporting Table in NEMS IndUSA Database	Assigned 3-digit NAICS Code
Non-Manufacturing	Table 1. Crop Agriculture	111
	Table 2. Other Agriculture	**112-115**
	Table 3 & 5. Coal Mining and Oil AND Metallic & Non-metallic Mining	212
	Table 4. Oil & Gas Mining	211
	Table 6. Construction	**23**
Manufacturing	Table 7. Food	311
	Table 8. Paper	322
	Table 9. Bulk Chemicals	325
	Table 10 & 11: Glass AND Cement	327
	Table 12 & 13: Iron & Steel AND Aluminum	331
	Table 14. Fabricated Metals	332
	Table 15. Machinery	333
	Table 16. Computers & Electronics	334
	Table 17. Transportation Equipment	336
	Table 18. Electrical Equipment & Appliances	335
	Table 19. Wood	321
	Table 20. Plastics & Rubbers	326
	Table 21. "Balance of Manufacturing"	**Other**

[52] Note that the Evergreen/AJW and NW datasets only include Manufacturing NAICS.

For consistency, we also mapped the different fuels in NEMS to those used in this study. Table 9 shows this mapping.

Table 9. Mapping of Fuel Types in NEMS to those Used in this Analysis.

Fuel in NEMS	ICF Fuel Class
Natural Gas	Natural Gas
Coal	Coal
Residual Fuel	Oil Products
Distillate	Oil Products
Liquid Petroleum Gases	Natural Gas
Electricity	Non-combustion (excluded)
Petroleum Coke	Coal
Other	Other Fuels
Other Renewables	Biomass
Biomass	Biomass

Figure 6 and Figure 7 show NEMS-predicted total boiler fuel consumption for all years by the fuel categories used in our study for the two boiler capacity bins (less than or greater than 10 mmBTU per hour).

Figure 6. NEMS-based Forecast of Boiler Fuel Consumption for Boilers over 10 mmBTU/Hour Capacity, Trillions of BTU.

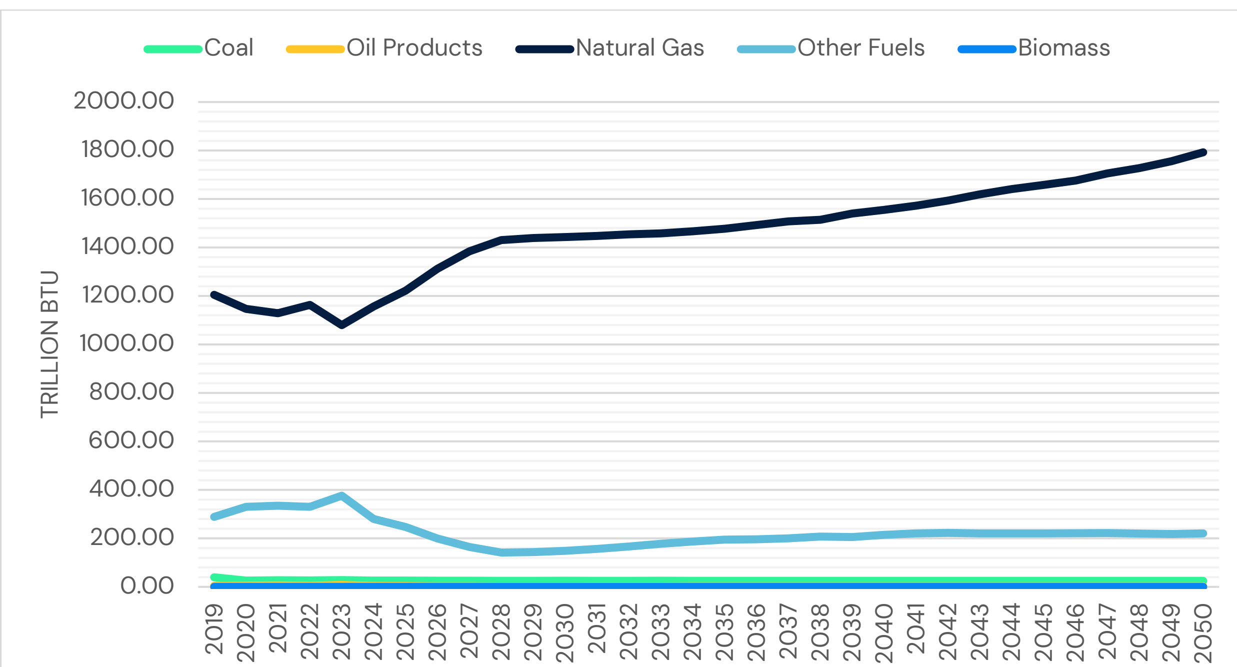
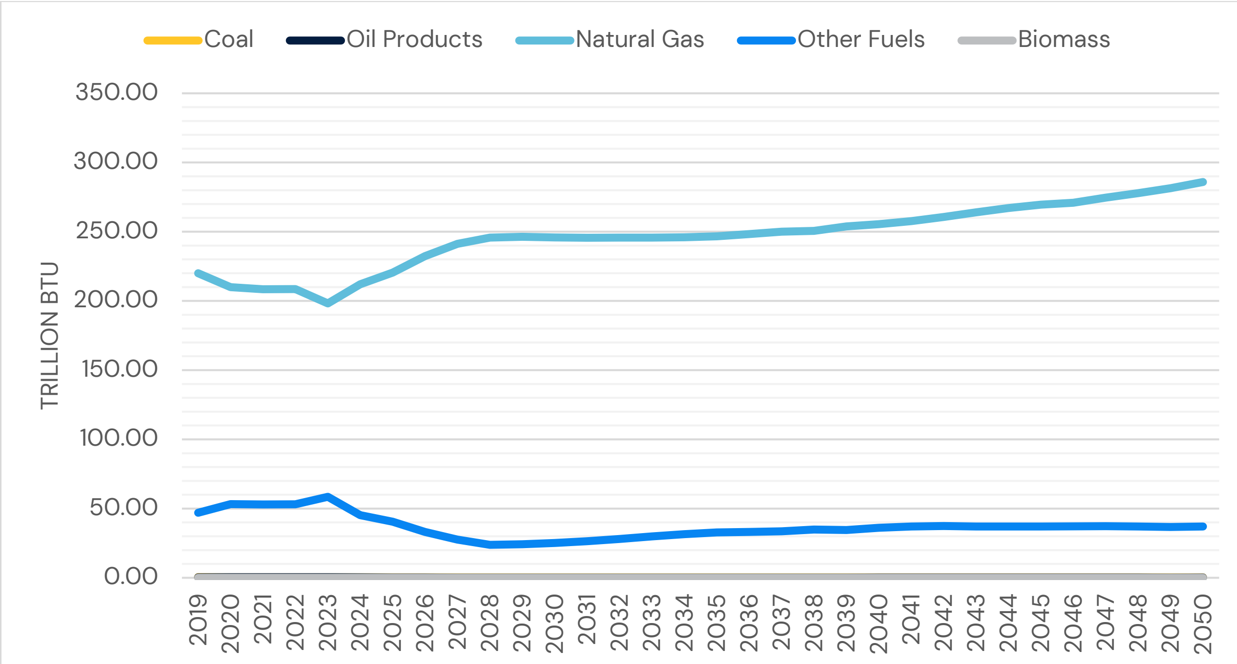


Figure 7. NEMS-based Forecast of Boiler Fuel Consumption for Boilers with Capacity less than or equal to 10 mmBTU/Hour, Trillions of BTU.



2.3.2 Top-Down, BAU Forecast Inventory

The 2023 NEMS projections represent the best, currently available estimate of future boiler fuel use by fuel type. We first generated a simple estimate of national boiler emissions in a top-down approach based on the boiler fuel consumption projections in NEMS. We coupled these with boiler emission factors derived from the GREET 2024 model.

GREET was originally included in the analysis to obtain criteria pollutant emission factors for the electric grid (See Section 2.4.2.1.). GREET is designed to support estimation of transportation emissions but includes emission factors for electricity as a fuel for many different types of generation and fuels. We modified the GREET emission factors to represent industrial boilers. To this end, we extracted emission factors from boilers used in electricity generation for residual oil, natural gas, coal, and biomass-fired power plants from GREET 2024. We used the power plant energy conversion efficiency and the predicted transmission and distribution losses in the model to estimate a conversion factor from emissions per electricity generation to emissions per fuel consumption, based on a higher heating value (HHV) assumption appropriate for these industrial sources. For biomass, the different feedstocks reported in GREET were averaged, since this is unknown for NEMS fuels. We determined both feedstock (a.k.a., upstream) and fuel (a.k.a., downstream) factors for the GHGs and downstream only for the criteria pollutants. Table 10 shows the factors used in the conversion. A 10% difference between LHV and HHV values was also applied to obtain fuel-based, industrial boiler emissions factors. Table 11 shows these.

Table 10. Electricity Generation Mixes, Combustion Technology Shares and Power Plant Energy Conversion Efficiencies for GREET Calculation.

	Power Plant Energy Conversion Efficiency (Transportation)	Conversion from gCO_2e/mmBTU electricity to gCO_2e/mmBTU fuel
Residual Oil-Fired Boiler Power Plants	32.6%	3.22
Natural Gas-Fired Boiler Power Plants	33.8%	3.11
Coal-Fired Boiler Power Plants	34.5%	3.04
Biomass-Fired Boiler Power Plants	21.7%	4.85

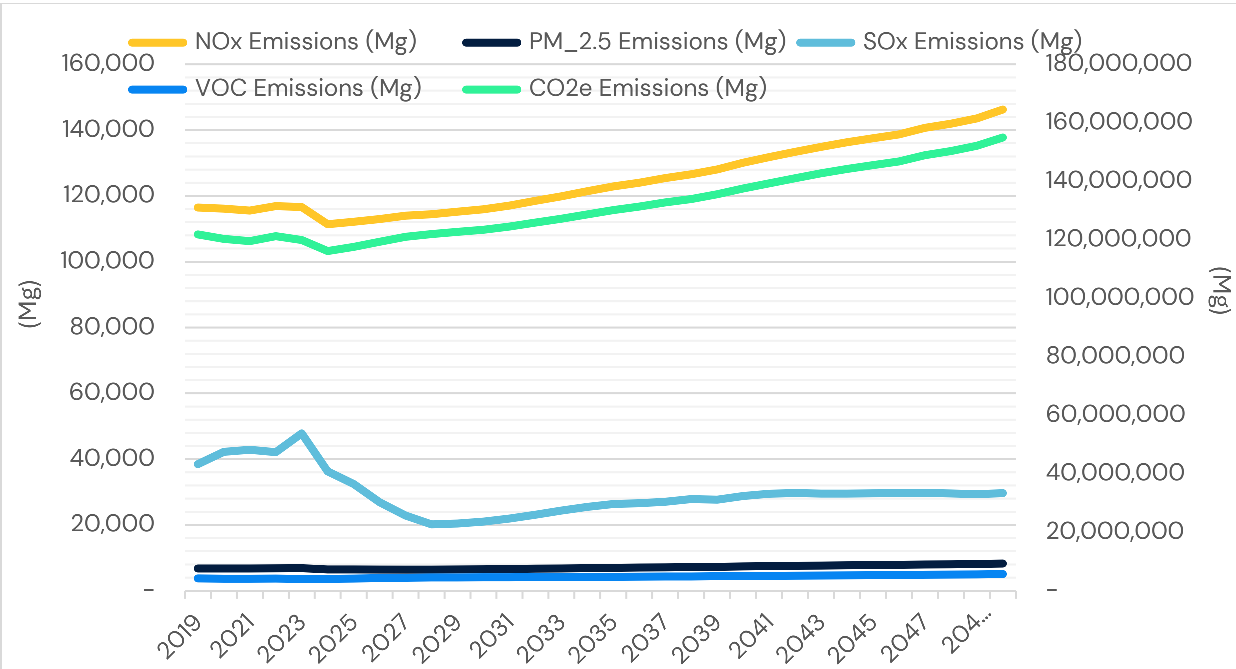
Table 11. Industrial Boiler Fuel-based Emission Factors, derived from GREET 2024, Grams per mmBTU of Fuel, HHV.

Boiler by Fuel Type	CO_2e		CO_2		N_2O		CH_4		VOC	NOx	$PM_{2.5}$	SO_2
	Feed-stock	Fuel	Feed-stock	Fuel	Feed-stock	Fuel	Feed-stock	Fuel	Fuel	Fuel	Fuel	Fuel
Oil-Fired Boiler	11,295	76,780	8,569	76,552	0.14	0.51	89.11	2.52	0.97	193.82	11.26	235.65
NG-Fired Boiler	9,559	53,520	5,184	53,414	0.71	0.09	138.15	0.89	2.24	58.36	3.17	0.92
Coal-Fired Boiler	5,418	90,999	1,426	89,954	0.03	2.09	132.92	14.37	1.22	64.55	5.42	85.84
Biomass (average)-Fired Boiler	3,705	1,112	2,284	(130)	4.77	3.43	3.51	6.45	1.82	38.77	3.93	66.94

We combined the emission factors from Table 11 with the NEMS-based boiler-fuel consumption forecasts. We consider this a useful estimate for validating our core, bottom-up projections (Section 2.3.3).

Figure 8 shows the top-down projections for national-level boiler emissions derived from NEMS with the GREET-based boiler emission factors. Note that all GHGs are reported here on a full lifecycle basis Note here that downstream biomass CO_2 emissions are effectively zero due to GREET's carbon accounting approach.

Figure 8. Top-Down, BAU Boiler Emissions Estimate based on NEMS Fuel Consumption and GREET-based Emission Factors, Mg. Criteria Pollutants on the Left Axis and CO_2e on the Right Axis.

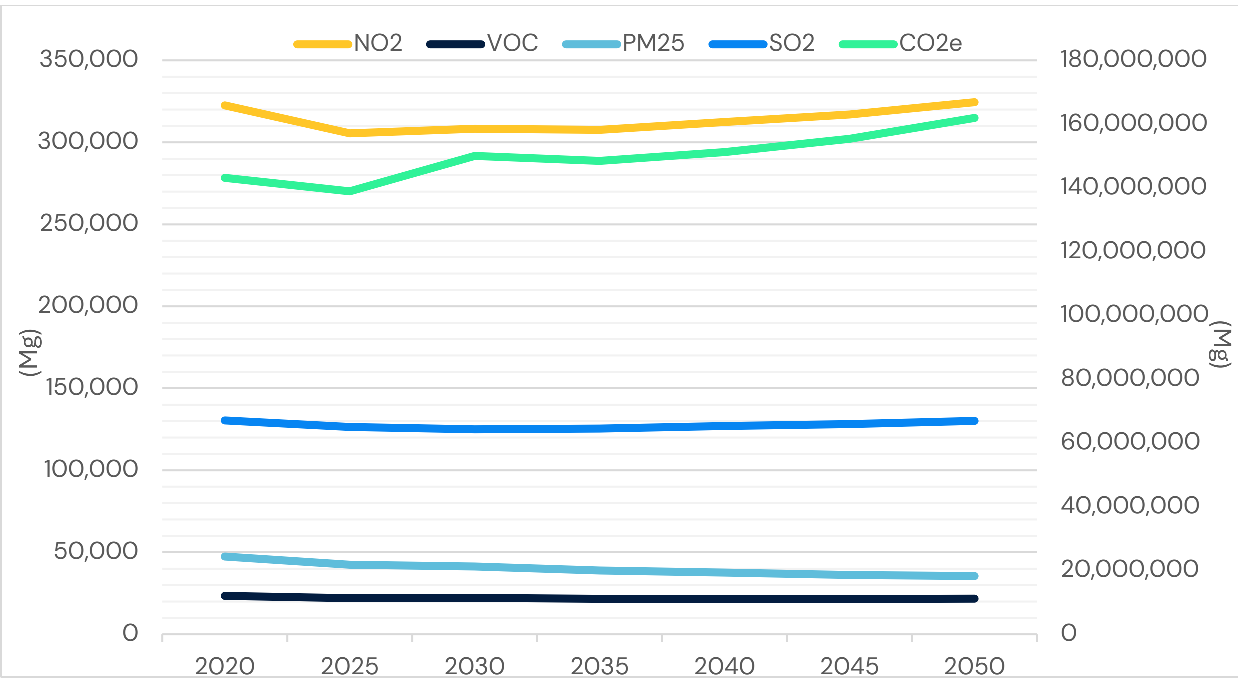


2.3.3 Bottom-Up, Projected BAU Inventory

The bulk of this work relies on our bottom-up, BAU emissions projection for the complete set of boilers in the U.S. To develop this bottom-up emissions projection, we calculated growth rates for boilers using available data from NEMS. This includes energy consumption data for combustion boilers (all fuels except electricity) by capacity range (<= or > 10 MMBTU/hour), 3-digit NAICS code, and fuel type relative to 2020. We applied the per-year growth rates to the baseline 2020 baseline inventory based on NAICS, fuel type, or capacity range to project emissions for each year through 2050. For NAICS codes in the boiler inventory without a corresponding NAICS growth ratio, we applied the "Other" NAICS code category growth ratio to capture the remaining NAICS codes. For NAICS codes without growth ratios due to a lack of energy consumption data, we applied the average growth ratio across all NAICS codes and fuel types. In addition, GHG emissions in the original data are assumed to be downstream only (see Section 2.1.2), so we also calculated full lifecycle emissions of each of the 3 GHGs and CO_2e using the fuel-specific fuel and feedstock boiler emissions in Table 11.

Figure 9 shows the BAU boiler inventory emissions projection with the bottom-up approach. This is designed to be comparable to the top-down results in Figure 8.[53] The bottom-up inventory is displayed for every fifth year of data. CO_2e (on the right axis) is the full lifecycle estimate of these emissions.

Figure 9. Bottom-Up, BAU Boiler Emissions Inventory, Mg. Results Shown for Every 5th Forecast Year. Criteria Pollutants on the Left Axis and CO_2e on the Right Axis.



[53] As above, results are reported in Mg, with the understanding that the original AJW data are reported in short tons.

CO_2e exhibits a very close match between approaches. For CO_2e on a full lifecycle basis, the top-down results for 2020 are approximately 16% lower than the bottom-up results. This is very good agreement given the completely distinct datasets involved and the uncertainty in the boiler fuel consumption values from NEMS. Since GHGs are closely related to fuel consumed, this indicates that the baseline year values are likely representing similar fuel mixes and amounts. This is complicated somewhat using full lifecycle and CO_2e values. In the horizon year of 2050, the top-down emissions forecast is only 4% below the bottom-up results. This is an excellent agreement. Recall that although the bottom-up approach relies on NEMS growth rates, it also includes fuel mapping to accommodate multi-fueled boilers and does not use absolute values from NEMS, different fuels between datasets, and missing fuel types in the original datasets. This result indicates those are reasonable.

The bottom-up approach estimates are significantly higher for all other pollutants. For NO_x and SO_2, bottom-up 2020 estimates are about three times higher than their top-down estimates. For VOC the bottom-up estimates are about six times higher than the top-down estimates. For $PM_{2.5}$, the bottom-up estimates are approximately seven times higher than the top-down estimates. These results are surprising because both estimates rely on fuel projections from NEMS. Additionally, because the top-down emissions inventory relies on fuel throughput emissions factors derived from the GREET model, it does not include any emissions controls, whereas the NEI data that underlies the baseline inventory, and thus the bottom-up projection, should capture any emissions controls at the sites. Thus, we would have expected that the top-down approach would yield higher emissions. The fact that they do not indicates that the fuel throughput-based industrial boiler emission factors derived from GREET factors (for electricity generating boilers) may not represent actual industrial boilers well. This could be due to complexities around boiler fuels, particularly for multi-fueled boilers and real-world complications of actual, installed, operating boilers that are not captured in the simple GREET emission factors, but manifest in the reported emissions of the NEI. That is, real "outlier" boilers are included in our Tier 1 dataset. Since the Tier 1 and 2 boilers each contribute approximately half the total inventory for the criteria pollutants (Table 6) and these discrepancies are much larger, we also do not think the discrepancies are due solely to our binned-average approach for Tier 2 boilers.

2.4 Projected Industrial Boiler Emissions under Control Scenario

After determining the baseline and BAU scenarios, we modeled a "Control Scenario," where the baseline combustion-fueled industrial boilers were replaced with zero-emission HP alternatives.

The level of activity for the industrial sector was treated the same as the BAU. Only the source of energy was replaced. Specifically, boiler fuel for combustion was replaced with electricity to drive

HPs. Useful energy from HPs matched useful energy from boilers. For this analysis, HP technologies were divided into three groups depending on the process temperature that could be satisfied by HPs. The three HP groups were phased in over time to demonstrate the market shift from combustion to non-combustion over the study period (low-temperature heat pump group phased in first, followed by higher temperature heat pump groups). That is, the BAU forecast includes changes in fuel consumption without technology changes, such that emissions are forecast to grow with activity. The Control Scenario forecast includes both changes in fuel consumption from the BAU projection and technology changes reducing industrial emissions. However, the phase-in of technologies is assumed to happen immediately as it becomes feasible. (See Section 2.4.1.3).

This industrial boiler replacement scenario was coupled with two potential cases for the future grid: a more BAU projection of the electric grid and decarbonized grid projection, relying on a more aggressive penetration of technologies that reduce CO_2 emissions in generation. Both were derived from the NREL's CAMBIUM dataset, coupled with GREET-based electricity emissions factors for criteria pollutants. This scenario reduces emissions from the boilers and adds additional emissions from electricity generation to support the new grid load from the HP boilers. Note that here we only present the decrease in boiler emissions and increase in grid emissions related to the boiler transition. These emissions results do not capture any change in emissions from electricity generation that would accompany shifting between the BAU and decarbonized grid nationally for other electricity uses. All electricity is assumed to represent a national average grid and longer-term average emission rates. On-site electricity generation was not considered in this study, nor was the case where boiler-driven, marginal demand is met solely from renewables (as assumed in Energy Innovation's study[54]), except as specified in the larger, national grid scenarios.

It is important to note the importance of our lifecycle approach here. For health benefits, criteria pollutants are reduced in direct proportion to the replacement of combustion boilers with zero emission technologies. For GHGs, the changing electric grid mix and the elimination of significant upstream emissions associated with fossil fuels, particularly natural gas as a fuel, all influence the results.

2.4.1 Displaced Boiler Fuel and Increased Electric Load

The control inventory consists of the BAU inventory, with combustion-fueled boilers replaced with HP technology. To develop the control inventory, we began with our bottom-up, BAU, boiler emission

[54] Decarbonizing Low-Temperature Industrial Heat in the U.S., Jeffrey Rissman, Energy Innovation Policy and Technology LLC, October 2022.

inventory (Section 2.3.3), applied a phased-in replacement schedule, and calculated the avoided boiler emissions and increased electric grid load and emissions nationally.

2.4.1.1 Capacity

Capacity is determined from the baseline inventory. These calculations begin with classifying each of the 33,528 boilers in the inventory according to the industry in which it operates, as described by the 3-digit NAICS code, and the fuel it was assigned as part of the baseline inventory development. We then summed the results to obtain the total boiler capacity according to those same metrics. Table 12 shows the resulting total boiler capacity by 3-digit NAICS code and fuel, in millions of BTU/hour. Our estimated total, national capacity for combustion-based boilers is 1.5 trillion BTU/hour.

Table 12. Boiler Capacity by NAICS Code and Fuel, MMBTU/Hour.

NAICS		Total Boiler Capacity (MMBtu/hr) by Fuel					
3-Digit Code	Description	Fuel Oil	Natural Gas	Coal	Biomass	Other	Blank
311	Food Processing	16,115	119,773	39,885	12,609	1,367	3,660
312	Beverage	4,988	31,408	1,636	531	163	458
313	Tobacco	2,561	15,137	1,213	88	13	151
314	Textiles	928	22,986	518	0	0	214
315	Apparel	466	4,178	0	0	0	4
316	Leather	184	380	0	0	0	0
321	Wood	2,911	14,803	1,248	62,253	5	1,124
322	Paper	54,352	118,953	48,822	116,531	14,928	9,272
323	Printing	476	3,500	0	0	66	59
324	Petroleum	17,811	104,287	1,880	2,546	31,568	4,322
325	Chemicals	25,622	237,698	28,807	4,957	14,990	5,604
326	Plastics/Rubber	5,398	38,521	1,056	239	0	594
327	Stone/Clay/Glass	418	7,104	20	0	845	114
331	Metals	6,470	32,460	11,929	21	20,370	647
332	Metal Products	1,412	20,420	297	620	0	415
333	Machinery	881	21,351	2,863	0	0	1,129
334	Computer/Electronic	495	2,903	0	0	1	195
335	Equipment/Appliance	379	1,417	0	0	0	57
336	Transportation Equip	8,258	41,517	3,163	22	30	1,899
337	Furniture	447	1,516	1,588	2,776	3,115	28
339	Miscellaneous	558	9,820	0	96	0	145
All		**151,132**	**850,133**	**144,924**	**203,289**	**87,460**	**30,090**

2.4.1.2 Estimating Fuel Use for Boilers

Capacity factor is a measure of the ratio of boiler output to the theoretical maximum.

Capacity Factor = Annual Energy Output / Maximum Potential Energy Output

- *Energy Output* **=** CO_2 emissions **x** fuel combustion factor (mmBTU) **x** boiler efficiency
- *Maximum Potential Energy Output* **=** boiler capacity (mmBTU/hr) **x** 8,760 hours/year

We developed capacity factor estimates for boilers grouped by 3-digit NAICS code. We used data from MECS or other fuel/NAICS combinations to fill in gaps when calculating the capacity factors. Table 13 shows the resulting boiler capacity factors by 3-digit NAICS code and fuel.

Table 13. Boiler Capacity Factors by NAICS Code and Fuel.

NAICS		Capacity Factor by Fuel					
3-Digit Code	Description	Fuel Oil	Natural Gas	Coal	Biomass	Other	Blank
311	Food Processing	14.8%	23.2%	8.5%	43.2%	20.0%	20.0%
312	Beverage	12.4%	26.6%	13.9%	17.2%	20.0%	20.0%
313	Tobacco	11.3%	16.8%	15.1%	12.8%	20.0%	20.0%
314	Textiles	14.0%	10.8%	5.1%	20.0%	20.0%	20.0%
315	Apparel	14.0%	6.1%	15.0%	20.0%	20.0%	20.0%
316	Leather	6.9%	28.6%	15.0%	20.0%	20.0%	20.0%
321	Wood	31.9%	18.7%	15.0%	35.6%	20.0%	20.0%
322	Paper	12.8%	10.1%	23.4%	14.6%	20.0%	20.0%
323	Printing	12.8%	10.1%	15.0%	20.0%	20.0%	20.0%
324	Petroleum	0.4%	15.9%	15.0%	1.9%	20.0%	20.0%
325	Chemicals	9.8%	25.5%	22.6%	22.6%	20.0%	20.0%
326	Plastics/Rubber	16.7%	16.4%	15.0%	20.0%	20.0%	20.0%
327	Stone/Clay/Glass	46.1%	12.7%	15.0%	20.0%	20.0%	20.0%
331	Metals	7.8%	17.8%	15.0%	10.6%	20.0%	20.0%
332	Metal Products	8.1%	21.4%	15.0%	20.0%	20.0%	20.0%
333	Machinery	9.6%	12.4%	15.0%	20.0%	20.0%	20.0%
334	Computer/Electronic	12.6%	12.8%	15.0%	20.0%	20.0%	20.0%
335	Equipment/Appliance	10.5%	34.5%	15.0%	20.0%	20.0%	20.0%
336	Transportation Equip	8.7%	14.4%	15.0%	20.0%	20.0%	20.0%
337	Furniture	14.0%	24.9%	15.0%	11.0%	20.0%	20.0%
339	Miscellaneous	8.3%	16.0%	15.0%	33.3%	20.0%	20.0%

Capacity factors are used to calculate annual boiler energy consumption; boiler efficiencies are then used to calculate useful energy produced. The required useful energy is assumed to be unchanged after the heat pump is installed. HP energy consumption is calculated using HP efficiency, which is expressed as a coefficient of performance (COP). The total fuel consumed annually in each NAICS category for each fuel is then computed as the product of the capacity, capacity factor, and hours in a year. These estimates were then compared to MECS data for reasonableness. We then project the calculated fuel consumption through 2050. This is based on the same NEMS data used in the top-down and bottom-up BAU emissions projections. To do so, we aggregated the IndUSA data solely by fuel type to determine year-over-year growth rates, which we then apply to the calculated fuel consumption.

2.4.1.3 Developing and Applying Boiler Temperature Bins

This analysis considers HPs suitable only for boilers that produce steam or hot water at less than 200 °C. To estimate what combustion-based boilers were suitable for HP replacement, we classified the distribution of boilers in each NAICS category into temperature bins.

We based our analysis of suitable temperature bins on that from the CAELP/E3 analysis. That study applied boiler temperatures for various industrial processes by NAICS code to estimate boiler output in temperature ranges suitable for industrial HPs. The following illustrates different boiler temperature bins, with those considered low-and mid-temperature and suitable for replacement highlighted in green.

- **> 400 C:** high-temperature heating process (e.g., refinery boilers)
- **200-400 C:** medium-temperature heating process (e.g., inorganic chemicals)
- **< 200 C:** low-temperature heating process (e.g., food processing)
  - **140-200 C:** medium pressure steam
  - **100-140 C:** low-to-medium pressure steam
  - **<100 C:** hot water

  (140-200 C, 100-140 C, <100 C) — Can be replaced by industrial heat pumps

We used this information to group boilers into three distinct temperature bins. For each boiler in the dataset, based on the NAICS code, we estimated the percentage of boiler output below 200 °C, which can be replaced by HPs in three windows. We assumed that boilers will be replaced by HPs in 5-year steps, based on technology readiness, as follows:

- Near-term (<100 °C). Phase 1 replacement. The installation year is 2030.
- Medium-term (100 °C -140 °C). Phase 2 replacement. The installation year is 2035.
- Long-term (140 °C -200 °C). Phase 3 replacement. The installation year is 2040.

Many industrial boilers produce hot water, which can be replaced with commercially available HP technologies. Some industries, such as petroleum, chemicals, stone/clay/glass, and primary metals, require higher temperatures. Table 14 below shows the resulting ranges of the combustion-based boiler heat requirements by the three temperature ranges and by NAICS.

The list above describes the HP phase-in schedule. In each case, this modeling assumes that all combustion boilers are replaced immediately with HP technologies in the year indicated. This “overnight” switch may be unrealistic, but simplifies the modeling to emphasize the benefits and reduce additional uncertainty that would be introduced from assuming a phase-in schedule without supporting data.

Table 14. Boiler Temperature Ranges by NAICS Code.

NAICS Code	Title	Heat Requirements (°C)				
		<100	100-140	140-200	>200	<200
311	Food Manufacturing	90%	9%	1%	0.0%	100.0%
312	Beverage and Tobacco Product Manufacturing	90%	10%	0%	0.0%	100.0%
313	Textile Mills	100%	0%	0%	0.0%	100.0%
314	Textile Product Mills	100%	0%	0%	0.0%	100.0%
315	Apparel Manufacturing	100%	0%	0%	0.0%	100.0%
316	Leather and Allied Product Manufacturing	100%	0%	0%	0.0%	100.0%
321	Wood Product Manufacturing	100%	0%	0%	0.0%	100.0%
322	Paper Manufacturing	76%	0%	19%	5.0%	95.0%
323	Printing and Related Support Activities	100%	0%	0%	0.0%	100.0%
324	Petroleum and Coal Products Manufacturing	2%	9%	5%	84.0%	16.0%
325	Chemical Manufacturing	25%	20%	5%	50.0%	50.0%
326	Plastics and Rubber Products Manufacturing	100%	0%	0%	0.0%	100.0%
327	Nonmetallic Mineral Product Manufacturing	0%	0%	0%	100.0%	0.0%
331	Primary Metal Manufacturing	0%	0%	0%	100.0%	0.0%
332	Fabricated Metal Product Manufacturing	100%	0%	0%	0.0%	100.0%
333	Machinery Manufacturing	100%	0%	0%	0.0%	100.0%
334	Computer and Electronic Product Manufacturing	100%	0%	0%	0.0%	100.0%
335	Electrical Equipment, Appliance, and Component Manufacturing	100%	0%	0%	0.0%	100.0%
336	Transportation Equipment Manufacturing	100%	0%	0%	0.0%	100.0%
337	Furniture and Related Product Manufacturing	100%	0%	0%	0.0%	100.0%
339	Miscellaneous Manufacturing	100%	0%	0%	0.0%	100.0%

2.4.1.4 Estimating Emissions Reduction Potential

Once the fuel consumption is determined for each fuel and NAICS, we calculate the useful heat obtained from combustion for each fuel type. This is the product of fuel consumption and boiler efficiency. Table 15 lists the boiler fuel efficiencies used in this analysis. The efficiencies in Table 2 are taken from Schoeneberger et al., other than the last two rows, which are ICF estimates.

Table 15. Boiler Efficiencies by Fuel Type.

Fuel	Efficiency (%, HHV)
Fuel Oil	83%
Natural Gas	75%
Coal	81%
Biomass	70%
Other	70%
Blank	70%

We then applied the HP phase in schedule listed above and the heat requirement table by temperature and NAICS from Table 14 to compute the useful heat that will be provided by HPs. We assume all remaining heat will continue to be provided by combustion. Useful heat is adjusted by the COP by temperature bin to yield the HP electricity consumption. This gives the amount of displaced combustion fuel and additional electricity consumed. These values are calculated for every fuel, NAICS, and year combination.

The following figures illustrate the results of these calculations using natural gas as an example. Figure 10 shows the share of useful energy from natural gas boilers versus HPs replacing them over time. Figure 11 shows the amount of natural gas consumed and avoided under the Control Scenario, along with the corresponding increase in electricity consumed.

Figure 10. Useful Energy Split between Natural Gas Boilers and Heat Pumps over Time.

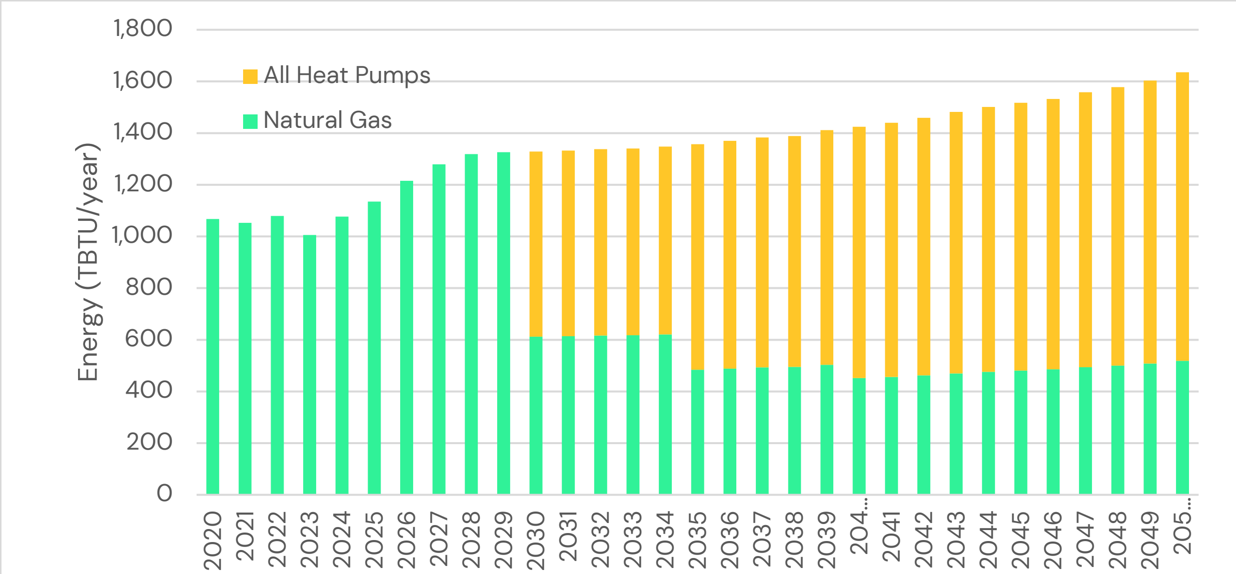
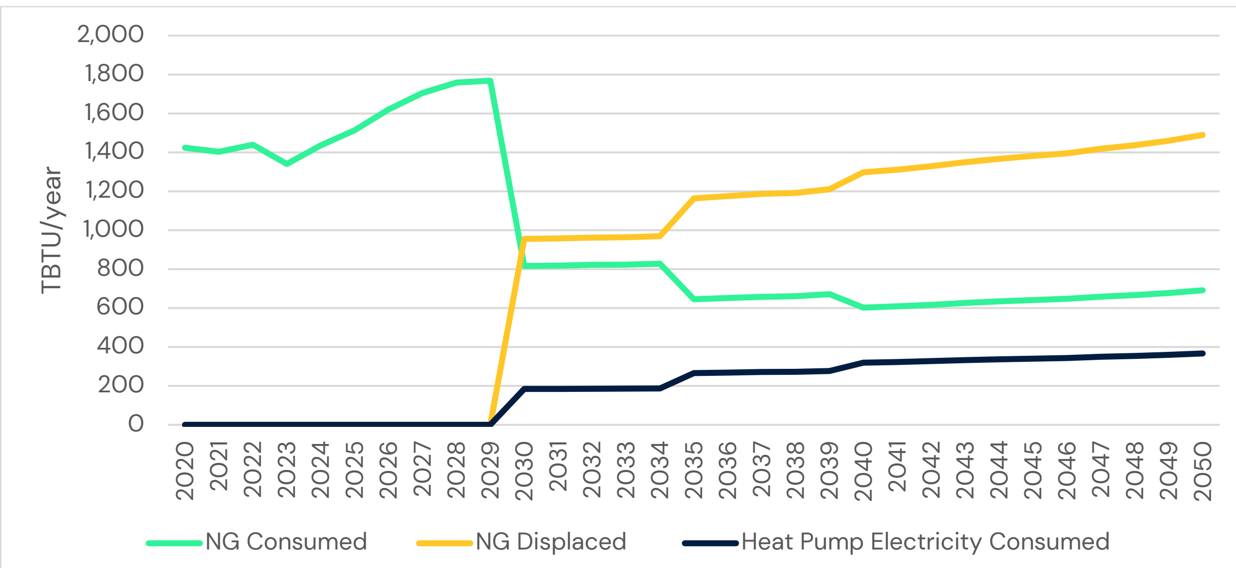


Figure 11. Natural Gas Consumed and Avoided, and Electricity Consumed, All Trillions of BTU/Year.



2.4.1.5 Results: Avoided Boiler Emissions under the Control Scenario

The outcome of the Control Scenario is the reduction in fuel and combustion-fueled boiler emissions. Because the Control Scenario applies statistical penetration estimates by temperature bins, fuel, and NAICS (Table 14) to boilers, the results of the Control Scenario are no longer reported on a per-boiler basis. Instead, we calculate the total displaced amounts for each fuel and additional annual electricity consumed. Table 16 and Table 17 show these results. Table 16 shows displaced fuel in TBTU per year. Table 17 shows the total additional electricity consumption from HP, in GWh per year.

The BAU inventory is in tons of emissions per year per boiler. It also tracks the fuel assigned to each boiler but not the amount of fuel consumed. To combine these, we normalize the total emissions from the BAU inventory by fuel to the total BAU fuel consumption by fuel as described in Section 2.4.1.2. Multiplying this ratio by the avoided fuel from the Control Scenario gives the corresponding avoided emissions.

Table 18 shows these values. Note that, as HP technology is not phased in prior to 2030, all values from 2020-2030 are zero and are shown in a single column. Table 18 presents GHG reductions in terms of CO_2e. This is done using full lifecycle values of each of the 3 GHGs and AR6 GWP values. We also remove downstream biogenic CO_2 emissions, per accounting convention that these are assigned zero values in GHG inventories. This convention is implemented here and is necessary for computing avoided damage from CO_2 emission reductions but differs from the baseline and BAU inventory results.

This scenario predicts an increased grid load of 109 TWh/year in 2030 from the penetration of HP boilers. For reference, the CAMBIUM Mid-Case predicts a total annual electricity consumption, "at the busbar", of 4,691 TWh in 2030.[55] Thus, the substitution of low- and mid-temperature industrial boilers with HP technology is expected to add an additional approximately 2% to the total load on the national grid in the near-term.

[55] For comparison, eGRID reports total generation from all fuels nationally of 4,190 TWh in 2023.

Table 16. Displaced Fuel, Trillions of BTU/Year.

Displaced Fuel	2020-2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Fuel Oil	0	28	30	34	34	35	38	38	41	41	41	50	50	50	50	50	50	50	50	50	46	48
Natural Gas	0	956	958	962	964	969	1,164	1,175	1,187	1,191	1,211	1,298	1,311	1,329	1,350	1,367	1,382	1,395	1,419	1,437	1,460	1,489
Coal	0	129	128	128	129	128	142	142	142	142	142	164	164	164	163	163	163	163	162	162	162	162
Biomass	0	827	827	827	827	827	833	833	833	833	833	980	980	980	980	980	980	980	980	980	980	980
Other	0	16	17	18	19	20	27	28	28	29	29	36	37	37	37	37	37	37	37	37	37	37
Blank	0	15	15	16	17	18	21	21	21	22	22	26	26	27	26	26	26	27	27	26	26	26
TOTAL	**0**	**1,971**	**1,976**	**1,986**	**1,990**	**1,999**	**2,226**	**2,237**	**2,253**	**2,260**	**2,279**	**2,553**	**2,569**	**2,587**	**2,607**	**2,624**	**2,638**	**2,652**	**2,675**	**2,693**	**2,711**	**2,743**

Table 17. Added Electricity Consumption from Heat Pumps, GWh/Year

Displaced Fuel	2020-2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
TOTAL	0	**108,876**	**109,187**	**109,738**	**109,998**	**110,484**	**137,537**	**138,316**	**139,355**	**139,824**	**141,090**	**181,056**	**182,170**	**183,468**	**184,895**	**186,157**	**187,197**	**188,199**	**189,867**	**191,122**	**192,416**	**194,760**

Table 18. Avoided Combustion Boiler Emissions, Short Tons/Year. Downstream CO_2 Emissions from Biomass Combustion Removed.

Pollutant	2020-2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
PM25	0	30,318	29,958	29,467	28,935	28,439	30,344	30,129	29,718	29,351	29,108	32,597	32,061	31,724	31,210	30,891	30,817	30,405	30,406	30,086	29,986	29,771
SO2	0	85,026	84,691	84,934	85,067	85,157	94,394	94,610	94,521	94,669	95,047	107,863	108,093	108,342	108,029	108,350	108,555	108,731	108,951	109,271	109,438	109,950
VOC	0	15,607	15,496	15,356	15,198	15,056	16,516	16,482	16,383	16,283	16,277	18,102	17,984	17,946	17,853	17,823	17,841	17,736	17,817	17,786	17,793	17,804
NH3	0	6,051	5,981	5,905	5,818	5,744	6,226	6,196	6,137	6,089	6,078	6,766	6,707	6,687	6,638	6,621	6,624	6,575	6,602	6,589	6,604	6,616
NOx	0	211,469	210,925	210,788	209,988	209,630	232,388	232,832	233,062	232,716	233,613	261,575	261,494	261,969	261,918	262,548	263,372	263,306	264,890	265,505	266,174	267,861
Lifecycle_CO2e (Biomass Removed)	0	79,133,545	79,291,495	79,667,748	79,797,701	80,153,522	94,996,612	95,799,276	96,589,834	96,894,900	98,169,673	106,123,309	106,976,585	108,170,947	109,448,797	110,613,051	111,570,636	112,376,980	113,896,241	115,068,558	116,409,963	118,073,412

2.4.2 Change In Electric Grid Emissions

Table 17 showed the additional electricity consumed by year due to replacing combustion boilers with HP. To compute the additional emissions associated with this additional load, we combine the additional electric load with national average electric grid emission factors.

2.4.2.1 Grid Emission Factors with GREET and CAMBIUM

We considered two future scenarios for the electric grid here. Both are based on the U.S. National Renewable Energy Laboratory's (NREL) CAMBIUM dataset.[56] We chose two, existing scenarios from this dataset to represent the future grid: the Mid-case (Scenario 1) as a business-as-usual case and 95% Decarbonization (Scenario 7) as an aggressive or "decarbonized" case.

- CAMBIUM Scenario 1: Mid-case: This case provides central estimates for inputs such as technology cost, fuel prices, and demand growth. No nascent technologies are included. Electric sector policies are as they existed in September 2023.
- CAMBIUM Scenario 7: 95% Decarbonization by 2050: This case uses the same set of base assumptions as the first scenario but employs nascent technologies and includes a national electricity sector decarbonization constraint that linearly declines to 5% of 2005 emissions on net by 2050.

The advantage of CAMBIUM is that it already has parametrized electricity supply and demand balances across the country meeting certain policy objectives and settled on a generation mix. This does not include any additional load that would be imposed by the replacement of combustion fueled with grid electricity-fueled HP boilers. We assume that the grid mix determined from both of these scenarios would also apply after this technology switch. Note that projections for the national electric grid are changing rapidly. Other forecasts made subsequent to this analysis could differ dramatically from those included here.

Both CAMBIUM scenarios were obtained through NREL's Scenario Viewer for annual values, 2025-2050 in 5-year increments. We combined data for generation by geography[57], year, and fuel source to determine the national average generation mix. Table 19 shows the resulting mix of generation technologies for both scenarios for all modeled years.

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[56] All metric definitions and scenario descriptions are available in the 2023 Cambium Documentation, available at https://www.nrel.gov/docs/fy24osti/88507.pdf.

[57] Geography here is indicated by 18 different system/distribution operators: CAISO, ERCOT, FRCC, ISONE, MISO_Central, MISO_North, MISO_South, NYISO, NorthernGrid_East, NorthernGrid_South, NorthernGrid_West, PJM_East, PJM_West, SERTP, SPP_North, SPP_South, WestConnect_North, and WestConnect_South.

CAMBIUM data includes full lifecycle GHG emissions but does not include any criteria pollutants. We determined average GHG emission factors directly from the CAMBIUM data as the ratio of the total national emissions per total user load "at the busbar", in kg/MWh, for both cases. These are full lifecycle emissions, representing both the upstream (production) and downstream (combustion) components of electricity generation.

For the criteria pollutants, we performed custom GREET 2024 modeling of power plant emissions by fuel to determine downstream (a.k.a., fuel) VOC, NO_x, $PM_{2.5}$, and SO_x emission factors for the different electricity generation technologies in the model, also "at the busbar". We then mapped these technologies to the generation types in CAMBIUM and weighted the emission factors by their share of the generation mix.

Table 20 shows the resulting national average emission factors. Note that CO_2e emission factors are based on total generated CO_2e emissions from CAMBIUM and represent full lifecycle emissions.

Table 19. Generation Mix for the Two Electric Grid Scenarios. Determined from CAMBIUM Scenarios 1 and 7.

Year	Offshore Wind	Onshore Wind	Utility-Scale PV	Hydrogen Combustion Turbine	Pumped Hydropower Storage	Oil-Gas-Steam	Nuclear	Hydropower	Geothermal	Natural Gas, Combustion Turbine	Natural Gas, Combined Cycle with CCS	Natural Gas, Combined Cycle	Distributed (behind-the-meter) PV	Concentrating Solar Power	Coal with CCS	Coal (all technologies)	Canadian Imports	Bioenergy with CCS	Biopower and Landfill Gas	Electric Batteries	Total
Scenario 1: Mid-Case																					
2025	0%	18%	12%	0%	1%	0%	17%	7%	0%	0%	0%	22%	2%	0%	0%	16%	2%	0%	1%	1%	100%
2030	2%	29%	16%	0%	1%	0%	16%	6%	1%	0%	0%	18%	3%	0%	0%	5%	2%	0%	1%	1%	100%
2035	3%	32%	21%	0%	2%	0%	13%	5%	1%	0%	0%	11%	3%	0%	0%	4%	1%	0%	0%	2%	100%
2040	3%	33%	24%	0%	3%	0%	11%	4%	1%	0%	0%	9%	3%	0%	0%	4%	1%	0%	0%	3%	100%
2045	3%	33%	27%	0%	3%	0%	9%	4%	1%	1%	0%	10%	3%	0%	0%	3%	1%	0%	0%	4%	100%
2050	2%	33%	28%	0%	3%	0%	6%	4%	1%	1%	0%	13%	3%	0%	0%	2%	1%	0%	0%	3%	100%
Scenario 7: 95% Decarbonization by 2050																					
2025	0%	18%	12%	0%	1%	1%	17%	7%	0%	1%	0%	22%	2%	0%	0%	16%	2%	0%	1%	1%	100%
2030	2%	28%	16%	0%	1%	0%	16%	6%	1%	1%	0%	17%	3%	0%	1%	4%	2%	0%	1%	1%	100%
2035	3%	31%	20%	0%	2%	0%	13%	5%	1%	1%	1%	11%	3%	0%	2%	3%	1%	0%	0%	2%	100%
2040	3%	33%	23%	0%	2%	0%	11%	4%	1%	1%	1%	10%	3%	0%	2%	2%	1%	0%	0%	3%	100%
2045	3%	35%	25%	0%	2%	0%	9%	4%	1%	1%	1%	10%	3%	0%	1%	1%	1%	0%	0%	3%	100%
2050	2%	38%	28%	1%	2%	0%	8%	4%	1%	0%	2%	4%	3%	0%	0%	0%	1%	0%	0%	5%	100%

Table 20. Grid Emission Factors at the Busbar for the Two Electricity Scenarios.

Year	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
	Scenario 1: Mid-Case						Scenario 7: 95% Decarbonization by 2050					
VOC, g / MWh	4.21	2.06	1.52	1.28	1.13	1.21	4.53	2.27	1.84	1.53	1.17	0.80
NOx, g / MWh	158.28	57.49	46.32	39.48	32.26	28.91	167.59	67.80	60.89	49.39	29.17	14.74
$PM_{2.5}$, g / MWh	15.58	6.81	5.21	4.49	3.94	4.05	16.05	7.60	6.48	5.48	3.88	2.27
SOx, g / MWh	185.31	60.47	51.46	45.54	35.90	27.81	186.80	72.13	69.21	57.57	29.98	12.77
CO_2e, kg / MWh	314.8	151.0	113.7	100.8	93.4	103.1	313.3	133.8	76.5	66.4	62.4	13.0

2.4.2.2 Results: Additional Grid Emissions

Table 22 shows the additional grid emissions resulting from replacing combustion-based industrial boilers with suitable HP technologies based on the replacement schedule assumed here and the temperature ranges of Table 14 with the more BAU projection of the electric grid described by CAMBIUM scenario 1. Table 21 shows the same but with the "decarbonized" forecast for the electric grid, corresponding to CAMBIUM scenario 7.

2.4.2.3 A Note About National Grid Emissions

It is important to note that these scenarios are different forecasts for the grid. The "decarbonized" scenario is intended to reduce CO_2 emissions. However, because of the fuel mix changes envisioned in the two scenarios, the decarbonized grid is forecast to lead to slightly higher emissions of several criteria pollutants in the medium term than the BAU grid. This can be seen by comparing values in Table 22 and Table 21 for the additional electricity emissions resulting from meeting the additional grid load from HP boilers.

To evaluate this impact, we investigated the national total emissions forecast for the two grid scenarios. This is the level of emissions anticipated without the additional boiler load. Figure 12 shows the difference in projections of national total emissions from electricity generation between the two grid scenarios. Note that CO_2e is shown in millions of metric tons (MMT) while the other pollutants are shown in short tons, so the GHG emissions avoided from the decarbonized grid are scaled down by roughly a million for display on the figure. While avoiding enormous amounts of GHG emissions, the CAMBIUM scenarios predict a modest increase in some criteria pollutants in the mid-term. This affects the predicted health impacts discussed in Section 3.2. For scale, the additional 2,700 short tons of SO2 forecast for 2035 is less than 1% of the 750,000 tons of SO_2 released nationally from electricity production in 2023 as reported by eGRID.

Figure 12 Avoided Emissions by the Decarbonized Grid.

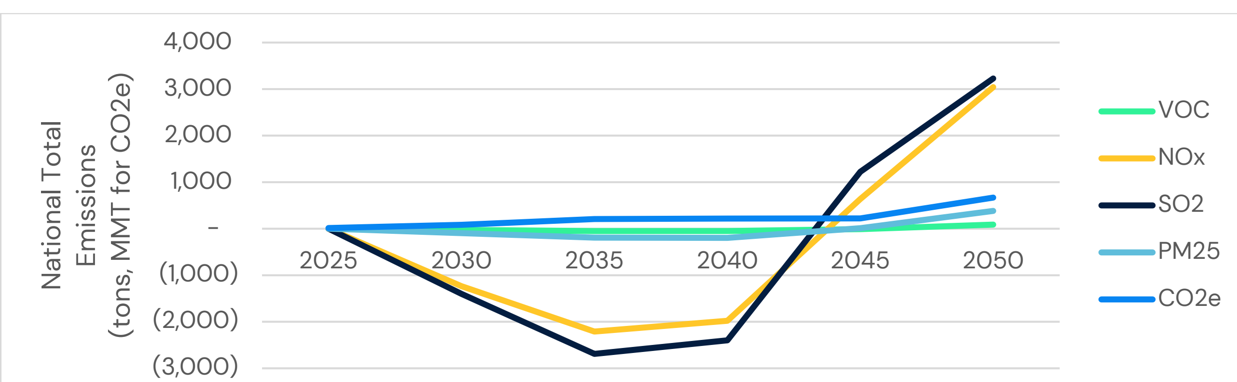

Table 21. Additional Electricity Emissions with BAU Electricity Grid (CAMBIUM Scenario 1), Mg.

Pollutant	2020-2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
$PM_{2.5}$	0	742	709	677	644	611	717	701	687	669	654	814	799	784	770	754	738	746	756	765	775	788
SO_2	0	6,584	6,406	6,241	6,057	5,885	7,078	6,954	6,841	6,699	6,593	8,246	7,945	7,648	7,350	7,041	6,720	6,451	6,201	5,933	5,662	5,416
VOC	0	224	213	202	191	180	209	203	198	192	187	231	227	223	220	216	211	215	220	225	229	235
NOx	0	6,260	6,034	5,819	5,587	5,364	6,370	6,217	6,073	5,902	5,763	7,147	6,928	6,713	6,498	6,274	6,039	5,945	5,871	5,782	5,692	5,631
CO_2e	0	16,437,441	15,669,493	14,929,538	14,144,000	13,381,881	15,632,053	15,364,302	15,120,813	14,811,470	14,582,175	18,246,550	18,090,189	17,948,480	17,815,483	17,662,529	17,485,177	17,941,808	18,467,139	18,957,808	19,457,358	20,070,047

Table 22. Additional Electricity Emissions with the "Decarbonized" Electricity Grid (CAMBIUM Scenario 7), Mg.

Pollutant	2020-2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
$PM_{2.5}$	0	828	805	785	762	741	891	869	847	822	802	993	941	889	836	783	727	670	615	557	499	442
SO_2	0	7,854	7,812	7,787	7,741	7,711	9,518	9,250	8,995	8,700	8,451	10,423	9,482	8,537	7,583	6,607	5,611	4,994	4,385	3,757	3,120	2,488
VOC	0	247	239	230	222	213	254	246	239	231	225	277	265	254	243	231	219	206	194	181	168	155
NOx	0	7,382	7,252	7,137	7,002	6,880	8,375	8,105	7,845	7,550	7,293	8,943	8,261	7,578	6,889	6,183	5,461	4,947	4,443	3,921	3,392	2,871
CO_2e	0	14,569,059	13,360,135	12,170,692	10,939,733	9,722,648	10,528,076	10,306,132	10,099,903	9,849,213	9,651,192	12,016,549	11,946,356	11,886,279	11,832,476	11,765,925	11,683,561	9,887,452	8,099,987	6,265,978	4,408,110	2,538,354

2.5 Results: Scenario Emissions Modeling

Finally, we assembled the resulting change in emissions nationally from the replacement scenario.

Table 23 through Table 25 show the resulting, national emissions from three cases:

1. **BAU industry.** This is the BAU emissions forecast for the current and default future mix of technologies, largely fossil fueled, set of combustion-based industrial boilers in the U.S. No electricity emissions are included as no replacement has occurred in this scenario. Table 23 shows these emissions.
2. **Clean industry with BAU electric grid**. This is the result of replacing the BAU industrial boilers with HP technology and assuming the more BAU forecast for the nation's electric grid. The results are derived from the BAU boiler emissions (Table 23), removing the boiler emissions avoided by replacement of combustion boilers with HP technologies (shown by Table 18), and adding the additional emissions from the electric grid to power the HP boilers, assuming the BAU electric grid (Table 21). Table 24 shows these emissions.
3. **Clean industry with decarbonized electric grid**. As with the above, this results from replacing the BAU industrial boilers with HP technology but with emissions determined from the decarbonized case for the nation's future electric grid (Table 22). Table 25 shows these results.

Note that here, we report only full lifecycle CO_2e emissions to represent GHG impacts, and that these values have had the downstream biomass emissions removed from the boiler emissions. The grid emissions also represent full lifecycle CO_2e emissions. Each table shows only every 5th year to simplify reporting. As the HP phase-in begins in 2030, prior years see no improvement. Finally, as there are no grid emission factors for NH_3, we assume no change in grid emissions for that pollutant. The net change in NH_3 emissions is due solely to reduction in the boiler emissions.

Comparing Table 23 to Table 24 shows the air pollutant emissions avoided by the Control Scenario coupled with the BAU electric grid against the BAU case for boiler emissions. All pollutants show no savings prior to 2030 when the replacement technology becomes feasible and begins to phase in. We then see a sharp increase in savings starting in 2030, reaching over 261,000 tons of NOx per year by 2050. $PM_{2.5}$ reductions rise quickly to a peak in 2040 of 31,700 tons per year avoided, then slightly lower values of annual reduction afterwards. SO_2 shows steady increase in avoided emissions from 2030 onward, reaching nearly 104,000 tons per year avoided by 2050.

Similarly, comparing Table 23 to Table 25 shows the potential for avoided air pollutant emissions from the Control Scenario coupled with a Decarbonized Grid from 2020 to 2050. NOx shows a steady increase from 2030 onward, slightly smaller than with the BAU grid until 2045, and reaches peak reduction of nearly 265,000 tons per year by 2050. $PM_{2.5}$ reductions are similar to the BAU Grid scenario but ends slightly higher, peaking at 31,500 tons per year avoided by in 2040. SO_2 also lags the BAU grid reductions until 2040, then reaches a peak of 107,000 tons per year avoided by 2050.

Table 23. BAU Boiler Emissions Nationally, Short Tons per Year.

Pollutant	Total Emissions by Pollutant and Year (Short Tons)						
	2020	2025	2030	2035	2040	2045	2050
NH_3	9,903	9,268	9,308	8,911	8,776	8,718	8,808
NOx	355,555	336,765	339,837	339,133	344,409	349,376	357,685
$PM_{2.5}$	52,275	46,744	45,569	42,889	41,476	39,927	39,163
SO_2	143,762	139,410	137,797	138,340	140,039	141,278	143,509
VOC	25,831	24,279	24,549	23,866	23,764	23,725	23,934
Lifecycle CO_2e (Biomass corrected)	129,670,219	130,465,174	144,265,661	147,112,325	153,581,008	161,689,116	171,414,386

Table 24. Net Boiler Emissions Nationally, after HP Replacement and with the BAU Electric Grid Forecast. Short Tons per Year.

Pollutant	Total Net Emissions by Pollutant and Year (Short Tons)						
	2020	2025	2030	2035	2040	2045	2050
NH_3	9,903	9,268	3,257	2,685	2,010	2,093	2,192
NOx	355,555	336,765	135,269	113,767	90,713	92,660	96,032
$PM_{2.5}$	52,275	46,744	16,068	13,336	9,777	9,922	10,261
SO_2	143,762	139,410	60,029	51,748	41,265	40,130	39,530
VOC	25,831	24,279	9,189	7,580	5,916	6,117	6,389
Lifecycle CO_2e (biomass corrected)	129,670,219	130,465,174	83,251,293	69,347,101	67,571,078	69,392,589	75,464,414

Table 25. Net Boiler Emissions Nationally, after HP Replacement and with the "Decarbonized" Electric Grid Forecast. Short Tons per Year.

Pollutant	Total Net Emissions by Pollutant and Year (Short Tons)						
	2020	2025	2030	2035	2040	2045	2050
NH_3	9,903	9,268	3,257	2,685	2,010	2,093	2,192
NOx	355,555	336,765	136,506	115,978	92,693	92,023	92,990
$PM_{2.5}$	52,275	46,744	16,163	13,528	9,974	9,911	9,879
SO_2	143,762	139,410	61,428	54,439	43,665	38,908	36,302
VOC	25,831	24,279	9,215	7,629	5,967	6,125	6,301
Lifecycle CO_2e (biomass corrected)	129,670,219	130,465,174	81,191,755	63,720,930	60,703,677	62,997,402	56,139,031

3 Benefits of the Transition

This section discusses the climate and health benefits that result from the emissions changes discussed in Section 2. Section 3.1 discusses and monetizes the avoided climate impacts that could be achieved from this transition. Section 3.2 discusses and monetizes the avoided health impacts from the same.

3.1 Climate Impacts

This section discusses the avoided climate impacts that could be achieved through implementation of the Control Scenario, monetized using the social cost of greenhouse gas values with the calculated greenhouse gas emissions.

3.1.1 Methodology

The Social Cost of GHG emissions (SC-GHG) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO_2) emissions in a given year. SC-GHG represents the estimated monetary value of the net societal harm caused by emitting one metric ton of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Correspondingly, SC-GHG, also reflects the societal net benefit of reducing emissions by that amount. The SC-GHG is intended to be a comprehensive metric that captures all future climate change impacts—both negative and positive—including changes in agricultural productivity; human health effects; property damage from increased flood risk; shifts in energy use; severity of natural disasters; disruption of energy systems; risk of conflict and environmental migration; and value of ecosystem services. However, due to data and modeling limitations, the estimates are partial and likely underestimate the total marginal benefits of reducing GHG emissions.[58]

In December 2023, the EPA updated these estimates for use in its Final Rulemaking: "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review." We used these values here.[59] All calculations here consider all three GHGs and employ the EPA's National Center for Environmental Economics (NCEE) Social Cost of Greenhouse Gas Application Workbook, v1.0.2. These updated values incorporate recent scientific advances, public feedback, and recommendations from the National Academies, and were peer-reviewed in 2023.

All values are computed using a present value year of 2024, 2023 dollars, and a 2% Near-Term Ramsey Discount Rate.

3.1.2 Results

Table 26 summarizes the results of the calculated benefits of the changes in GHG emissions expected under the Control Scenario with the BAU and the decarbonized grid scenario.

Please note that CO_2e reductions here are calculated as the sum of changes from up- and downstream activities associated with fuels used in traditionally fired boilers and in the electric grid used to power their HP alternatives. This does not include any broader benefit of the decarbonized grid over the BAU grid that is

58 https://www.epa.gov/environmental-economics/scghg

59 Note these values differ from the interim 2021 values included in previous Lung Association reports, which included different values, dollar years, and discount rates.

unrelated to powering HP boilers. This is consistent with all previous Lung Association studies on electrification but differs from the reductions used for health benefits (Section 3.2).

Under the BAU grid, $350,794,000,000 ($351 billion) in total climate benefits are accrued from 2030-2050, assuming a 2% discount rate, in 2023$, resulting from 1,561 MMT of CO_2e avoided.

Under the decarbonized grid scenario, a total of $381,572,000,000 ($382 billion) in climate benefits is accrued from 2030 to 2050, assuming a 2% discount rate, in 2023 dollars, resulting from 1,700 MMT of CO_2e avoided.

Table 26. Cumulative Climate Benefits of HP Boiler Replacement under the BAU Electric Grid, 2030-2050, Millions of 2023$.

Total Present and Annualized Values of GHG Emission Changes (Lifecycle CO_2e, Biomass Corrected) (Millions of 2023$)		
Grid Scenario	BAU Grid	Decarbonized Grid
GHG	Lifecycle CO_2e[a]	
Discount Rate	2.0%	
Present Value in 2024 (2023$)	$350,794	$381,572
Annualized Value (21 Years, 2023$)	$20,621	$22,431
[a]For Lifecycle CO_2e, upstream emissions may not occur in the same year.		

3.2 Public Health Impacts

This section discusses the potential for avoided adverse health outcomes that could be achieved through the implementation of the Control Scenario, replacing traditional combustion boilers with HP technology. We calculated these benefits and their monetized value using the latest version of the EPA's COBRA model, coupled with the modeled emissions from Section 2.

Three scenarios were considered:

a) BAU industry with BAU electric grid;

b) "Clean" industry with BAU electric grid; and

c) "Clean" industry with a decarbonized electric grid.[60]

We calculated the health impacts as Scenario (b) minus Scenario (a) for the Clean industry Scenario and Scenario (c) minus Scenario (a) for the Clean industry with decarbonized electric grid scenario.

[60] Decarbonized refers to the lower GHG emissions technology implementation scenario as defined in CAMBIUM. Note that these grid forecasts are not a custom developed for this analysis, but rather rely on potential scenarios developed by the US Department of Energy. As discussed later, a decarbonized grid is not necessarily a "cleaner" one, in the sense that additional air pollution emissions may be possible in the near term as the grid is decarbonized, depending on the technology mix employed. Note also that we do not explore a scenario that considers BAU industry combined with a decarbonized electric grid, as this work focuses on the industrial sector.

3.2.1 Methodology

We used the U.S. EPA Co-Benefits Risk Assessment (COBRA Version 5.1) model[61] to quantify and monetize changes in the incidence of adverse health impacts resulting from changes in human exposure to $PM_{2.5}$ and ozone (O_3) following the transition to HP boiler technologies. COBRA is a screening-level air quality health benefits model that provides estimates of the impact of changes in air pollution emissions on ambient $PM_{2.5}$ and O_3 concentrations, associated health effects, and the monetary value of avoidable health impacts.[62]

COBRA utilizes a source-receptor (S-R) matrix to translate changes in air pollutant (primary $PM_{2.5}$, NOx, SO_2, and VOC) emissions into corresponding changes in ambient $PM_{2.5}$ and O_3 concentrations. The S-R matrix consists of fixed transfer coefficients that relate annual average $PM_{2.5}$ concentrations at a single receptor in each county and the contribution of $PM_{2.5}$ precursors to this concentration from each emission source. For ozone, the matrix has separate transfer coefficients for NOx and VOC to calculate the ozone season maximum daily 8-hour average (MDA8) ozone concentrations. The S-R matrix is based on the Comprehensive Air Quality Model with Extensions (CAMx) and specifically uses the source apportionment feature to track the contribution of air pollutant emissions at sources to concentrations at receptors. CAMx is a photochemical grid model that comprises an open-source system for tropospheric air pollution over various spatial scales.

The COBRA model contains detailed county- and source type-specific emissions estimates for the years 2023 and 2028 in discrete categories. These estimates account for federal and state regulations as of May 2018.[63]

In addition to the health outputs, we also report the population-weighted change in annual average $PM_{2.5}$ concentrations under the scenario calculated based on COBRA's estimates of county-level changes in $PM_{2.5}$ and the total population in each county. This metric is useful as an approximation of the overall effect the Scenario will have on regional air quality.

A major change in this version of COBRA is the inclusion of ozone health effects. The health outcomes reported here are the combination of the adverse effects of PM and O_3. Note that GHGs are not relevant for COBRA and thus are not reported here.

3.2.2 Modeling Inputs and Approach

3.2.2.1 Emissions Changes

ICF adjusted emissions for the categories of emissions sources related to the emissions changes driven by the two electricity generation cases and the substitution of boilers with HP technology. We modeled three analysis years (2030, 2040, and 2050). The emission sources adjusted for the BAU and scenarios are discussed below. We did not adjust emissions for the remaining categories in the default COBRA emissions dataset.

61 https://www.epa.gov/cobra

62 COBRA relies on a suite of health impact functions and valuation functions that closely approximate what EPA used in developing the Final 2006 National Ambient Air Quality Standards (NAAQS) for PM.

63 Projected EGU emissions comply with the Cross-State Air Pollution Rule Update (CSAPR Update) finalized December 27, 2016, the Mercury and Air Toxics Rule (MATS), and the Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources.

3.2.2.1.1 Boiler Emissions

Section 2 provided the emissions changes under the control boiler scenario, with both electricity Cases. Boiler emissions do not align cleanly with a specific Tier in COBRA, capturing irrelevant industries and resulting in an overestimation of emissions attributed solely to boilers. Therefore, we identified Tiers that we determined likely more accurately reflect boiler emissions in the default COBRA emissions data. Table 27 lists the selected Tiers into which we mapped the calculated boiler emissions under the BAU and HP replacement scenarios for input into COBRA.

Table 27. COBRA Tiers used for Boiler Emissions.

Tier 1	Tier 1 Description	Tier 2	Tier 2 Description	Tier 3	Tier 3 Description
2	Fuel Comb. Industrial	1	Coal	1	Bituminous
2	Fuel Comb. Industrial	1	Coal	2	Subbituminous
2	Fuel Comb. Industrial	1	Coal	3	Anthracite & Lignite
2	Fuel Comb. Industrial	2	Oil	1	Residual
2	Fuel Comb. Industrial	2	Oil	2	Distillate
2	Fuel Comb. Industrial	2	Oil	99	Other
2	Fuel Comb. Industrial	3	Gas	1	Natural
2	Fuel Comb. Industrial	3	Gas	2	Process
2	Fuel Comb. Industrial	3	Gas	99	Other
2	Fuel Comb. Industrial	4	Other	1	Wood/Bark Waste
2	Fuel Comb. Industrial	4	Other	2	Liquid Waste
2	Fuel Comb. Industrial	4	Other	99	Other
3	Fuel Comb. Other	1	Commercial/Institutional Coal	99	Other
3	Fuel Comb. Other	2	Commercial/Institutional Oil	99	Other
3	Fuel Comb. Other	3	Commercial/Institutional Gas	99	Other
3	Fuel Comb. Other	4	Misc. Fuel Comb. (Except Residential)	99	Other

Retaining the county-level spread of boiler emissions in our inventory, we mapped the fuel-specific boiler emissions to their corresponding Tier 1 and Tier 2 levels in Table 27. We compared boiler emissions datasets by fuel type and county, updating the COBRA emissions with emissions from our boiler emission inventory when our emissions exceeded those of the COBRA defaults as this case indicates that boilers are the dominant source in any FIPS-Tier combination. When COBRA default emissions for the boiler Tiers in Table 27 exceeded our emissions for a specific FIPS and Tier, we retained the COBRA defaults, assuming other sources dominate in these county-fuel combinations. This enabled us to develop emissions scenarios focused on changes in boiler emissions.

We distributed boiler emissions for each of the three analysis years (2030, 2040, and 2050) to the Tier 3-level base case and scenario emissions, proportional to the magnitude of the default 2028 COBRA emissions subset that corresponds to the boiler-specific Tiers. We allocated the fuel-specific avoided boiler emissions at the county level based on our distribution of boiler emissions, and then to the Tier 3 levels using the default 2028 COBRA emissions subset for the boiler Tiers. The base case boiler emissions comprised the reconciled (based on the aforementioned process of prioritizing ICF or COBRA emissions) boiler emissions inventory apportioned to the county and Tier 1 to Tier 3 levels. The scenario or controlled boiler emissions comprised the reconciled boiler emissions less the avoided emissions from HP replacements, distributed at the county and Tier 1 to Tier 3 levels.

3.2.2.1.2 Electric Grid Emissions

Table 28 shows the COBRA EGU Tiers into which we mapped the calculated EGU emissions under the BAU and HP replacement scenarios for input into COBRA.

Table 28. COBRA Tiers used for Emissions on the Electric Grid.

TIER1	TIER2	TIER3	TIER1NAME	TIER2NAME	TIER3NAME
1	1	1	Fuel Combustion: Electric Utility	Coal	Bituminous
1	1	2	Fuel Combustion: Electric Utility	Coal	Subbituminous
1	1	3	Fuel Combustion: Electric Utility	Coal	Anthracite & Lignite
1	2	1	Fuel Combustion: Electric Utility	Oil	Residual
1	2	2	Fuel Combustion: Electric Utility	Oil	Distillate
1	3	1	Fuel Combustion: Electric Utility	Gas	Natural
1	3	2	Fuel Combustion: Electric Utility	Gas	Process
1	4	99	Fuel Combustion: Electric Utility	Other	Other
1	5	99	Fuel Combustion: Electric Utility	Internal Combustion	Other

For the BAU and Decarbonized EGU grids, and the additional grid emissions resulting from boiler replacements with HP, we distributed EGU emissions for each of the three analysis years (2030, 2040, and 2050) to the county and Tier 1 through Tier 3 levels, proportional to the magnitude of the default 2028 COBRA emissions subset that corresponds to the EGU-specific Tiers. We replaced all default COBRA emissions for the EGU tiers with either the BAU or Decarbonized grid EGU emissions, based on the scenario. The BAU and Decarbonized Grid Cases under the "Clean" industry scenario have the same additional EGU load due to the new HP boilers, but utilize different grid mixes and, therefore, different emission factors. This study employs an average grid approach, which applies the same emission rate (g/kWh) to both the baseline load and the new load resulting from the introduction of HP boilers. Thus, the modeled health benefits vary between the BAU and decarbonized grid due to both the changes from additional boiler load and the base load.

As noted in Section 2.4.2.3, total electric grid emissions are not needed to characterize the change in emissions from the Control Scenario or the climate benefits, but are needed to represent the health impacts. We modeled the baseline grid using the same grid emission factors and the load values from the CAMBIUM scenarios. We verified this approach by comparing the 2025 modeled grid with 2023 data from eGRID for the limited set of criteria pollutants it includes. We found our modeled 2025 BAU grid to be 19% lower than eGRID, and our SO_2

emissions to be 20% higher than eGRID. We found these differences to be reasonable and validate our approach. Note that to match our emissions to the broad COBRA Tiers, Canadian electricity imports were mapped to "other" fuel, which may slightly (<2%) increase domestic grid emissions, but maintains overall grid load, which will draw some energy from Canadian imports consistent with the CAMBIUM grid mixes.

3.2.2.2 Health incidence and impact functions

COBRA relies on baseline incidence rates for each health endpoint and health impact functions to estimate the absolute change in annual incidence of an adverse health effect. We obtained age-, health endpoint-, and county-specific incidence rates in the United States projected for years 2030, 2040, and 2050 from the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP)[64] model database.

COBRA includes several pre-loaded health impact functions that estimate the change in adverse health effects from changes in air pollutant concentrations based on epidemiological studies. Each function was developed based on data from cohort studies performed in various locations throughout the U.S. and uses different formulas and coefficients. The applicable ages for each health impact function reflect the age groups examined in the cohort studies. COBRA employs these health impact functions to assess the impact of $PM_{2.5}$ and O_3 reductions on mortality incidence (for both infants and adults), nonfatal heart attacks, hospital admissions and emergency room visits for respiratory and cardiovascular events, acute bronchitis, asthma symptoms, minor restricted activity days, and work and school loss days. For certain health endpoints, such as adult mortality and nonfatal heart attacks, COBRA employs multiple functions to obtain lower-bound and upper-bound estimates of potential health impacts. This is consistent with the methods the EPA employed when analyzing proposed National Ambient Air Quality Standards.[65]

3.2.2.3 Discount Rate

In COBRA, a discount rate is applied to express future economic values in present terms, as health effects and associated economic values are not confined to occurring solely in the year of analysis. Therefore, COBRA accounts for a general preference for present over future benefits by discounting benefits received later. COBRA Version 5.1 defaults to using a 2% discount rate to calculate monetized health benefits.

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[64] Environmental Benefits and Mapping Program-Community Edition (BenMAP-CE). BenMAP is US EPA's detailed model for estimating the health impacts from air pollution. Unlike COBRA, it relies on detailed input on air pollutant concentration changes, then applies concentration-response (C-R) health impact functions. See https://www.epa.gov/benmap For more information.

[65] U.S. EPA. (2006). Final Regulatory Impact Analysis: PM2.5 NAAQS. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards; U.S. EPA. (2009). Proposed NO2 NAAQS Regulatory Impact Analysis (RIA). Research Triangle Park, NC.: Office of Air and Radiation, Office of Air Quality Planning and Standards

3.2.2.4 Population

The exposed population is the number of people affected by the reduction in $PM_{2.5}$ and O_3 levels resulting from the transition to HP boilers. ICF obtained county- and age-specific population estimates for the 2030, 2040, and 2050 scenario years from the BenMAP model database. These are based on the 2010 U.S. Census[66] with annual population growth rates developed by Woods and Poole (2015).[67]

3.2.2.5 Valuation

The final step in the health benefits analysis is to estimate the economic value of avoided health impacts. COBRA includes several pre-loaded valuation functions for health endpoints associated with O_3 and $PM_{2.5}$ concentrations. Depending on the health endpoint being considered, valuation methods may involve estimates of willingness to pay to avoid certain illnesses, the medical costs of treating illnesses, the value of lost wages, and the EPA-estimated value of a statistical life (VSL; applicable to mortality endpoints only).

Default valuation data for all health points in COBRA are reported in 2023$. For non-mortality health endpoints, ICF did not adjust valuation data to reflect changes in willingness-to-pay values, medical costs, or lost wages in 2030, 2040, and 2050. This makes the present results more directly comparable to those from the previous studies.

Mortality, however, is typically found to be the primary driver of valuation, given the magnitude of the VSL. Following EPA's guidance for economic analysis,[68] we use the VSL ($4.8 million in 1990$)[69] to estimate the value of avoided mortality. ICF used projected income growth data from the Organization for Economic Cooperation and Development (OECD) and consumer price index data from the Bureau of Labor Statistics (BLS) to project the original $4.8 million VSL estimate in 1990$ to the 2030, 2040, and 2050 analysis years.[70,71,72]

We do not consider other consumer costs in this valuation, such as differences in boiler operation and maintenance, fuel costs, or tax revenue issues. This valuation focuses entirely on monetized health and climate (Section 3.1) benefits of reduction in combustion emissions.

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[66] Because county-level data is based on the 2010 Census, FIPS county codes may be outdated. ICF did not adjust any FIPS-level county population information for the health impacts analysis.
[67] Woods & Poole Economics Inc. 2015. Complete Demographic Database. Washington, DC. http://www.woodsandpoole.com/index.php.
[68] U.S. EPA. 2010. Guidelines for Preparing Economic Analyses. EPA 240-R-10-001.
[69] Our approach is consistent with EPA regulatory impact analyses which use this value for VSL and adjust it for inflation and changes in income over time.
[70] OECD (2020), "Long-term baseline projections, No. 103", OECD Economic Outlook: Statistics and Projections (database): https://www.oecd-ilibrary.org/economics/data/oecd-economic-outlook-statistics-and-projections/long-term-baseline-projections-no-103_68465614-en
[71] Bureau of Labor Statistics, 2025 (Series ID: CUUR0000SA0,CUUS0000SA0): https://data.bls.gov/pdq/SurveyOutputServlet
[72] Because ICF adjusted VSL for the mortality endpoint, but not other health endpoints, results may have a minor downward bias.

3.2.3 Results

3.2.3.1 Analysis Year-Specific Impacts

Table 29 and Table 30 present total, national, annual estimates of the number of avoided adverse health outcomes and the corresponding economic value of these health risk reductions at a 2% discount rate for the BAU and Decarbonized EGU grid, respectively. These economic values reflect the US population's willingness to pay to reduce risks of premature mortality or certain illnesses.[73] As such, these economic values represent monetized U.S. public health benefits.

At a 2% discount rate, total monetized public health benefits range from approximately $28-45 billion in 2030 to $39-57 billion in 2050 under the BAU electric grid. Under the decarbonized EGU grid, benefits range from approximately $21-33 billion in 2030 to $56-83 billion in 2050. Mortality is the main driver of monetized benefits from the reduced emissions, with an estimated decrease in the number of premature deaths between 2,470 and 3,710 under the Control Scenario in 2050 with the BAU grid and between 3,560 and 5,450 under the Control Scenario in 2050 with the Decarbonized grid case. As discussed earlier, the decarbonized grid in this case produces slightly less emissions reductions and health benefits than the BAU grid in the intermediate term, but greater reductions by 2050 due to the technology mix in that grid scenario. Note that here, mortality attributed to $PM_{2.5}$ and O_3 is summed together.

On a national level, there are reductions in population-weighted, annual $PM_{2.5}$ concentrations under both the BAU and Decarbonized grid cases. The annual concentration reductions under the BAU Case are 0.067 $\mu g/m^3$ in 2030, 0.076 $\mu g/m^3$ in 2040, and 0.072 $\mu g/m^3$ in 2050. The annual concentration reductions under the Decarbonized grid Case are 0.050 $\mu g/m^3$ in 2030, 0.053 $\mu g/m^3$ in 2040, and 0.108 $\mu g/m^3$ in 2050.

[73] For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

Table 29. Estimated National Total Annual Health Benefits of the Control Scenario with the BAU Electric Grid, for Years 2030, 2040, and 2050.

Health Endpoint	2030		2040		2050	
	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]
Mortality, low estimate[c]	2,010.00	$26,000,000,000	2,480.00	$33,800,000,000	2,470.00	$35,800,000,000
Mortality, high estimate[d]	3,280.00	$42,500,000,000	3,870.00	$52,700,000,000	3,710.00	$53,900,000,000
PM, Infant Mortality	8.43	$109,000,000	9.27	$126,000,000	8.60	$125,000,000
Asthma Symptoms	1,280,000.00	$300,000,000	1,650,000.00	$401,000,000	1,760,000.00	$441,000,000
Asthma Incidence	7,820.00	$597,000,000	10,100.00	$773,000,000	10,900.00	$831,000,000
Rhinitis Incidence	50,100.00	$55,800,000	64,900.00	$72,300,000	69,800.00	$77,700,000
Respiratory ER Visits	2,950.00	$4,800,000	3,850.00	$6,260,000	4,120.00	$6,700,000
Hospital Admits, All Respiratory	220.00	$5,260,000	282.00	$6,690,000	291.00	$6,850,000
PM, Nonfatal Heart Attacks	864.00	$72,600,000	1,070.00	$90,200,000	1,060.00	$89,300,000
PM, Minor Restricted Activity Days	820,000.00	$103,000,000	999,000.00	$126,000,000	1,010,000.00	$127,000,000
PM, Work Loss Days	139,000.00	$43,900,000	169,000.00	$53,500,000	172,000.00	$54,300,000
PM, Incidence Lung Cancer	82.80	$3,710,000	102.00	$4,580,000	102.00	$4,570,000
PM, Hospital Admits, Vascular Disease	173.00	$4,960,000	215.00	$6,170,000	213.00	$6,110,000
PM, Hospital Admits, Alzheimers Disease	593.00	$13,300,000	732.00	$16,400,000	724.00	$16,200,000
PM, Hospital Admits, Parkinsons Disease	81.10	$1,930,000	101.00	$2,400,000	99.60	$2,380,000
PM, Stroke Incidence	74.80	$4,720,000	93.10	$5,870,000	92.40	$5,830,000
PM, Non-Hospital Cardiac Arrest	16.80	$1,040,000	20.70	$1,280,000	20.80	$1,280,000
PM, ER Cardiac Visits	360.00	$776,000	444.00	$957,000	444.00	$957,000
O3, Asthma ER Visits	11.60	$9,590	15.40	$12,800	16.90	$14,000
O3, All Cause School Days Lost	484,000.00	$821,000,000	645,000.00	$1,100,000,000	711,000.00	$1,210,000,000
Total, low estimate		$28,100,000,000		$36,500,000,000		$38,600,000,000
Total, high estimate		$44,600,000,000		$55,400,000,000		$56,800,000,000
Population-Weighted Average Delta $PM_{2.5}$ (ug/m3)		0.0669		0.0757		0.0715

Notes:

[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.
[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.
[c]Low estimate based on Wu et al. (2020)
[d]High estimate based on Pope et al. (2019)

Table 30. Estimated National Total Health Benefits under the Control Scenario with the Decarbonized Electric Grid, for Years 2030, 2040, and 2050.

Health Endpoint	2030		2040		2050	
	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]
Mortality, low estimate[c]	1,490.00	$19,300,000,000	1,800.00	$24,500,000,000	3,560.00	$51,600,000,000
Mortality, high estimate[d]	2,430.00	$31,400,000,000	2,760.00	$37,700,000,000	5,450.00	$79,000,000,000
PM, Infant Mortality	6.17	$79,900,000	6.34	$86,400,000	13.20	$192,000,000
Asthma Symptoms	955,000.00	$226,000,000	1,210,000.00	$305,000,000	2,520,000.00	$607,000,000
Asthma Incidence	5,860.00	$447,000,000	7,500.00	$572,000,000	15,400.00	$1,180,000,000
Rhinitis Incidence	37,500.00	$41,800,000	48,000.00	$53,500,000	99,000.00	$110,000,000
Respiratory ER Visits	2,220.00	$3,610,000	2,880.00	$4,670,000	5,790.00	$9,410,000
Hospital Admits, All Respiratory	164.00	$3,900,000	205.00	$4,810,000	421.00	$10,000,000
PM, Nonfatal Heart Attacks	637.00	$53,500,000	749.00	$63,000,000	1,600.00	$134,000,000
PM, Minor Restricted Activity Days	610,000.00	$76,700,000	704,000.00	$88,600,000	1,530,000.00	$192,000,000
PM, Work Loss Days	103,000.00	$32,700,000	119,000.00	$37,700,000	259,000.00	$81,800,000
PM, Incidence Lung Cancer	61.70	$2,760,000	72.30	$3,240,000	153.00	$6,830,000
PM, Hospital Admits, Vascular Disease	128.00	$3,680,000	151.00	$4,350,000	319.00	$9,170,000
PM, Hospital Admits, Alzheimers Disease	427.00	$9,560,000	502.00	$11,200,000	1,110.00	$24,700,000
PM, Hospital Admits, Parkinsons Disease	60.00	$1,430,000	71.20	$1,700,000	149.00	$3,560,000
PM, Stroke Incidence	55.60	$3,510,000	65.80	$4,150,000	138.00	$8,710,000
PM, Non-Hospital Cardiac Arrest	12.50	$770,000	14.60	$901,000	31.10	$1,920,000
PM, ER Cardiac Visits	266.00	$573,000	309.00	$667,000	672.00	$1,450,000
O3, Asthma ER Visits	8.72	$7,230	11.80	$9,810	23.00	$19,100
O3, All Cause School Days Lost	364,000.00	$619,000,000	490,000.00	$833,000,000	976,000.00	$1,660,000,000
Total, low estimate		$20,800,000,000		$26,500,000,000		$55,700,000,000
Total, high estimate		$33,000,000,000		$39,700,000,000		$83,100,000,000
Population-Weighted Average Delta PM2.5 (ug/m3)		0.0497		0.0533		0.108

Notes:
[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.
[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.
[c]Low estimate based on Wu et al. (2020)
[d]High estimate based on Pope et al. (2019)

3.2.3.2 Cumulative Impacts

We also post-processed health benefits results from COBRA to illustrate the cumulative impacts of the proposed scenarios, covering the entire modeled period from 2030 to 2050. We calculated cumulative impacts using piecewise linear interpolation of the discounted monetized health benefits between the modeled years: 2030, 2040, and 2050. This analysis assumes there are no benefits until year 2030 when HP boilers begin to phase in.

Table 31 and Table 32 present cumulative estimates of the total national number of avoided adverse health effects and the economic value of these health risk reductions at the 2% discount rate from the Control Scenario with the BAU and Decarbonized electric grid cases, respectively. These economic values reflect the US population's willingness to pay to reduce risks of premature mortality or certain illnesses.[74] As such, these economic values represent monetized U.S. public health benefits.

At a 2% discount, cumulative monetized public health benefits from 2030 to 2050 range from approximately $732 billion to $1.1 trillion in the Control Scenario with the BAU electric grid. Under the Control Scenario with the Decarbonized grid, cumulative benefits from 2030 to 2050 range from approximately $686 billion to $1.0 trillion. Cumulative monetized public health benefits from 2030 to 2050 under the Control Scenario with both electric grid cases are shown in Figure 13. Note that this figure shows cumulative values from 2030 through the charted year. That is, the values corresponding to 2035 in these charts represent cumulative impacts from 2030 through 2035. As noted above, the decarbonized grid shows lower benefits than the BAU grid in the intermediate term but greater benefits in the longer term. As a result, the cumulative benefits under the decarbonized grid case only approach those of the BAU grid in the later years. If this analysis had extended past 2050, the decarbonized grid's cumulative benefits would likely exceed that of the BAU grid.

Mortality is the main driver of the benefits of emissions changes, with an estimated decrease in the number of premature deaths between 49,000 and 77,000 under the Control Scenario with the BAU electric grid, and between 46,000 and 71,000 under the Decarbonized grid case.

Note that here, mortality attributed to $PM_{2.5}$ and O_3 is summed together. For this reason, along with the different discount rate, the new version of COBRA, the reporting dollar-year, and other factors, these results are not directly comparable to those of previous Lung Association studies.

[74] For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people's willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available, and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

Table 31. Estimated Cumulative Health Benefits of the Control Scenario under the BAU Grid Case from 2030 to 2050.

Health Endpoint	2030-2050	
	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]
Mortality, low estimate[c]	49,400.00	$678,000,000,000
Mortality, high estimate[d]	77,200.00	$1,060,000,000,000
PM, Infant Mortality	186.00	$2,550,000,000
Asthma Symptoms	33,200,000.00	$8,090,000,000
Asthma Incidence	204,000.00	$15,600,000,000
Rhinitis Incidence	1,310,000.00	$1,460,000,000
Respiratory ER Visits	77,400.00	$126,000,000
Hospital Admits, All Respiratory	5,630.00	$134,000,000
PM, Nonfatal Heart Attacks	21,300.00	$1,790,000,000
PM, Minor Restricted Activity Days	20,100,000.00	$2,520,000,000
PM, Work Loss Days	3,400,000.00	$1,080,000,000
PM, Incidence Lung Cancer	2,040.00	$91,300,000
PM, Hospital Admits, Vascular Disease	4,260.00	$123,000,000
PM, Hospital Admits, Alzheimers Disease	14,600.00	$326,000,000
PM, Hospital Admits, Parkinsons Disease	2,000.00	$47,700,000
PM, Stroke Incidence	1,850.00	$117,000,000
PM, Non-Hospital Cardiac Arrest	414.00	$25,500,000
PM, ER Cardiac Visits	8,860.00	$19,100,000
O3, Asthma ER Visits	310.00	$257,000
O3, All Cause School Days Lost	13,000,000.00	$22,100,000,000
Total, low estimate		$732,000,000,000
Total, high estimate		$1,110,000,000,000

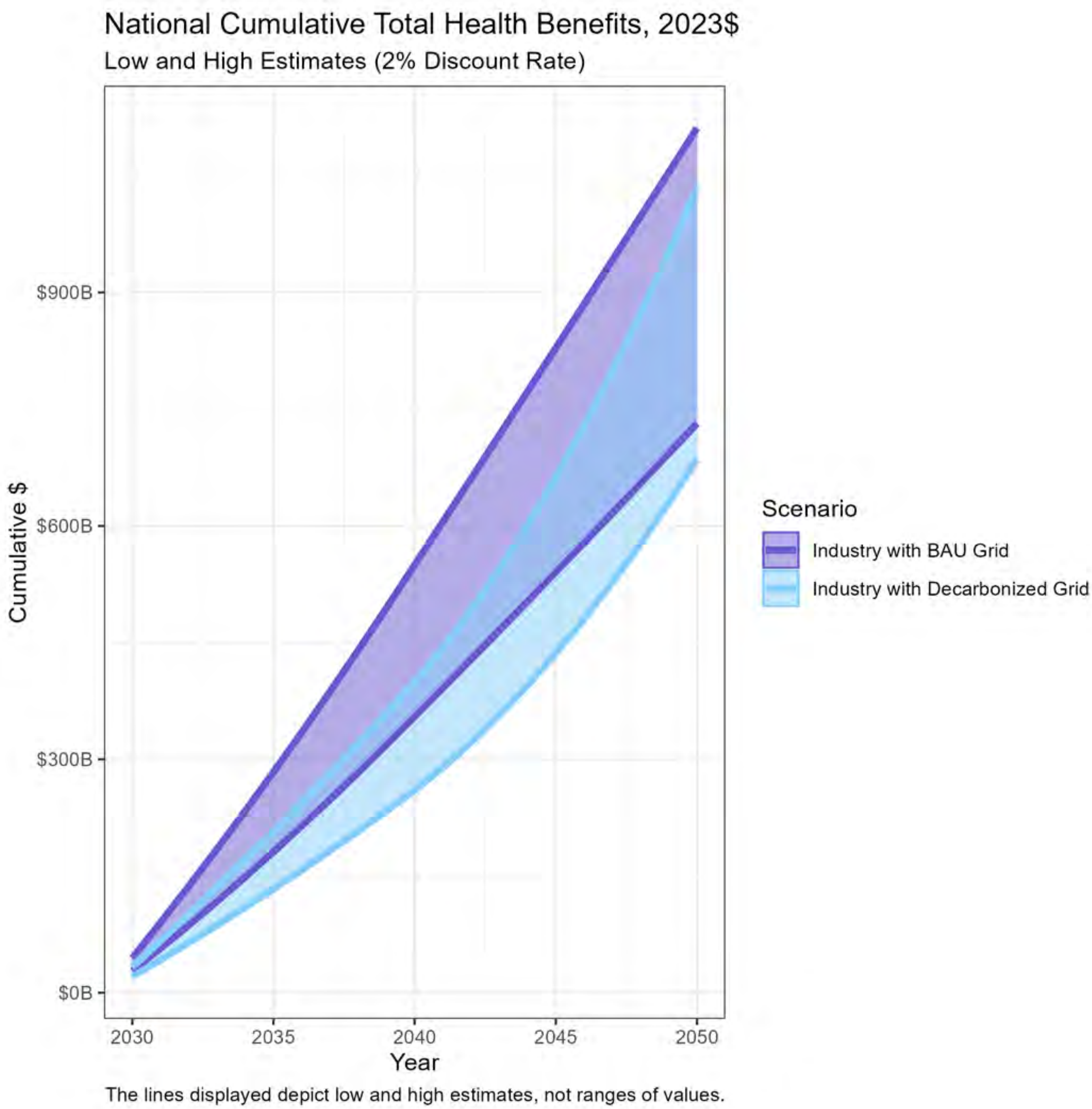
Notes:
[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.
[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.
[c]Low estimate based on Wu et al. (2020)
[d]High estimate based on Pope et al. (2019)

Table 32. Estimated Cumulative Health Benefits from the Control Scenario with the Decarbonized Grid from 2030 to 2050.

Health Endpoint	2030-2050	
	Change in the Number of Cases	Monetary Health Benefits (2023$)[a,b]
Mortality, low estimate[c]	45,700.00	$635,000,000,000
Mortality, high estimate[d]	71,000.00	$984,000,000,000
PM, Infant Mortality	170.00	$2,360,000,000
Asthma Symptoms	31,200,000.00	$7,630,000,000
Asthma Incidence	192,000.00	$14,700,000,000
Rhinitis Incidence	1,230,000.00	$1,370,000,000
Respiratory ER Visits	72,800.00	$118,000,000
Hospital Admits, All Respiratory	5,270.00	$125,000,000
PM, Nonfatal Heart Attacks	19,800.00	$1,660,000,000
PM, Minor Restricted Activity Days	18,800,000.00	$2,360,000,000
PM, Work Loss Days	3,180,000.00	$1,010,000,000
PM, Incidence Lung Cancer	1,900.00	$85,200,000
PM, Hospital Admits, Vascular Disease	3,970.00	$114,000,000
PM, Hospital Admits, Alzheimers Disease	13,500.00	$301,000,000
PM, Hospital Admits, Parkinsons Disease	1,860.00	$44,500,000
PM, Stroke Incidence	1,720.00	$109,000,000
PM, Non-Hospital Cardiac Arrest	386.00	$23,800,000
PM, ER Cardiac Visits	8,250.00	$17,800,000
O3, Asthma ER Visits	293.00	$243,000
O3, All Cause School Days Lost	12,300,000.00	$20,800,000,000
Total, low estimate		$686,000,000,000
Total, high estimate		$1,030,000,000,000

Notes:
[a]The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.
[b]Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.
[c]Low estimate based on Wu et al. (2020)
[d]High estimate based on Pope et al. (2019)

Figure 13. Estimated National Cumulative Health Benefits of the Control Scenario with the BAU and Decarbonized Grid from 2030 to 2050.



3.2.3.3 Geographic Distribution of Impacts

Figure 14 and Figure 15 provide examples of the distribution of potential impacts of the scenario across the Country. Figure 14 shows the high estimate of avoided mortalities that could be achieved by state resulting from the cumulative emission reductions over the 2030-2050 period of the Control Scenario. Health impacts result from emission reductions, and are also strongly correlated to adjacent population and demographics such as age and underlying health conditions. All results are computed at the county scale and summed here to states. Note that public health benefits are not calculated in Hawaii and Alaska, as these are not included in the COBRA model. Similarly, Figure 15 shows the state by state avoided respiratory ER visits that could be achieved through the 2030–2050 period from the Control Scenario. Both are derived with the BAU electric grid.

Figure 14. Avoided Cumulative Mortalities (High Estimate) by State under the Control Scenario with the BAU Grid, 2030-2050.

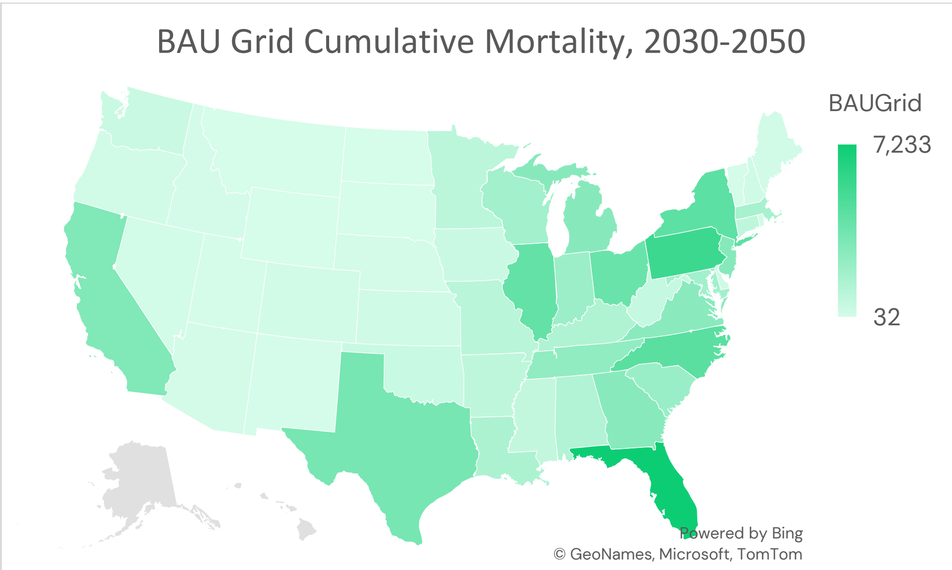


Figure 15. Avoided Cumulative Respiratory Emergency Room Visits by State under the Control Scenario with the BAU Grid, 2030-2050.

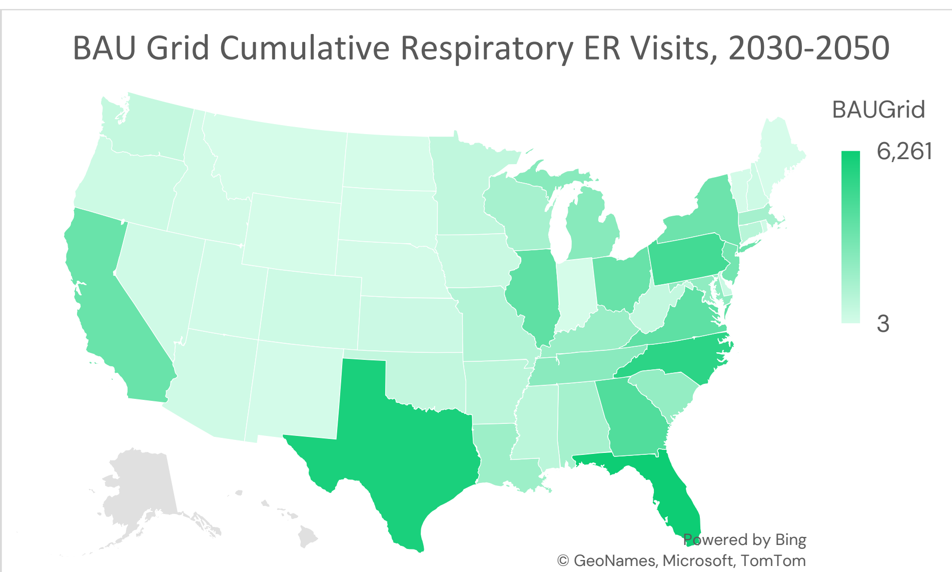


Figure 16 and Figure 17 show estimated cumulative health benefits by state from 2030 through 2050 for the Control Scenario with the BAU and Decarbonized electric grid cases, respectively. In both cases, Florida experiences the greatest monetized health benefits, with a cluster of other states including Pennsylvania, New

York, North Carolina, Ohio, and Illinois showing high but slightly lower benefits. Note that these results are not per-capita.

Figure 16. Estimated Cumulative Health Benefits by State for the Control Scenario under the BAU Grid Case by 2050.

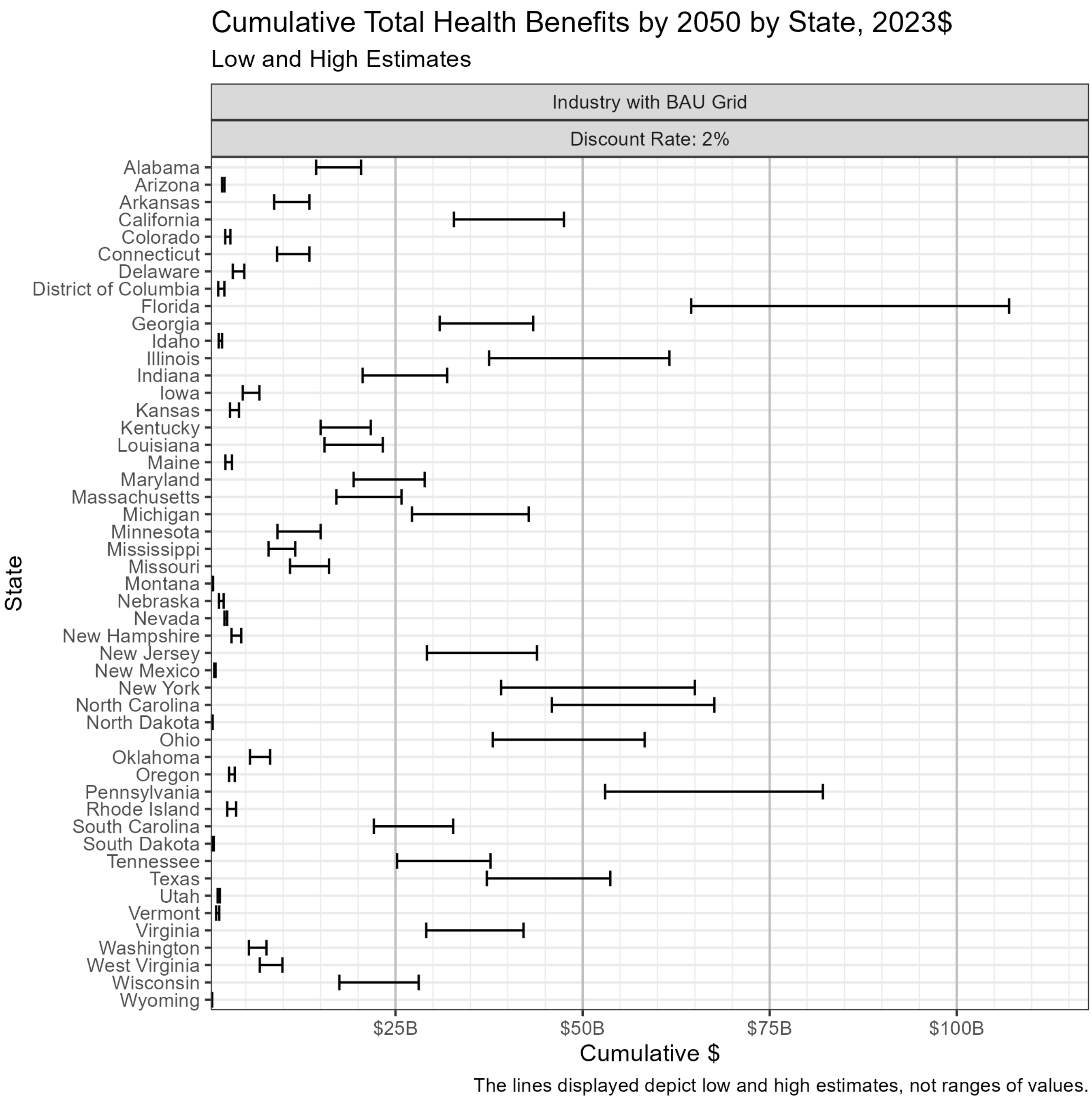
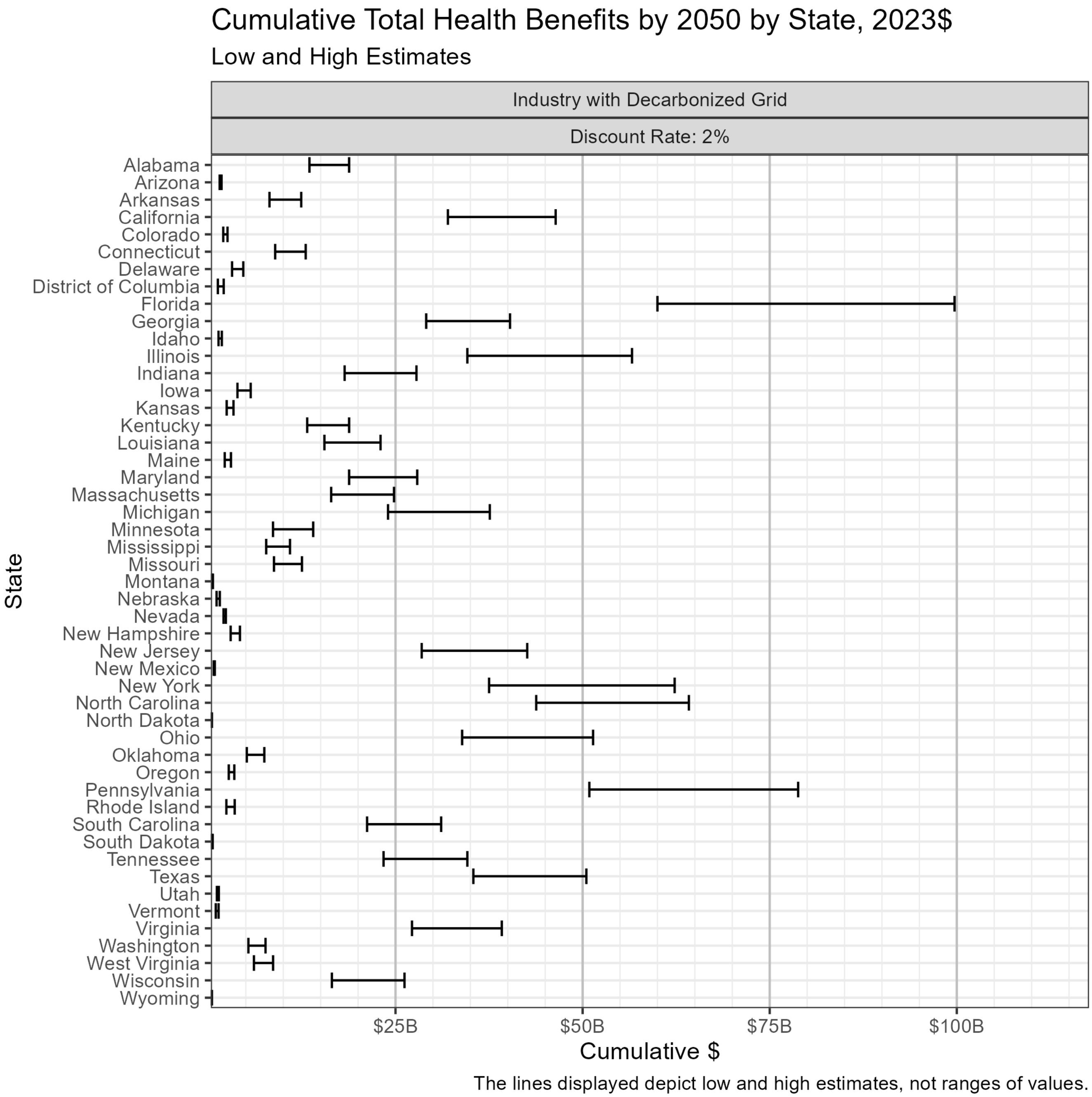


Figure 17. Estimated cumulative health benefits by state for the Control Scenario with the Decarbonized Grid Case by 2050



Appendix: COBRA Health Endpoints

Health Endpoint	Air Pollutant	Metric	Author (Year)	Age
Mortality, All Cause (high estimate)	$PM_{2.5}$	Annual	Pope et al. (2019)	18-99
Mortality, All Cause (low estimate)	$PM_{2.5}$	Annual	Wu et al. (2020)	65-99
Acute Myocardial Infarction, Nonfatal	$PM_{2.5}$	Daily	Wei et al. (2019)	65-99
Asthma Symptoms, Albuterol Use	$PM_{2.5}$	Daily	Rabinovitch et al. (2006)	6-17
Minor Restricted Activity Days	$PM_{2.5}$	Daily	Ostro and Rothschild (1989)	18-64
Emergency Room Visits, All Cardiac Outcomes	$PM_{2.5}$	Daily	Ostro et al. (2016)	0-99
Emergency Room Visits, Respiratory	$PM_{2.5}$	Daily	Krall et al. (2016)	0-99
Hospitalization, Cardio-, Cerebro- and Peripheral Vascular Disease	$PM_{2.5}$	Daily	Bell et al. (2015)	65-99
Hospitalization, Alzheimer's Disease	$PM_{2.5}$	Annual	Kioumourtzoglou et al. (2016)	65-99
Hospitalization, Parkinson's Disease	$PM_{2.5}$	Annual	Kioumourtzoglou et al. (2016)	65-99
Hospitalization, All Respiratory	$PM_{2.5}$	Daily	Bell et al. (2015)	65-99
Hospitalization, All Respiratory	$PM_{2.5}$	Daily	Ostro et al. (2009)	0-18
Incidence, Stroke	$PM_{2.5}$	Annual	Kloog et al. (2012)	65-99
Incidence, Out of Hospital Cardiac Arrest	$PM_{2.5}$	Daily	Silverman et al. (2010)	0-99
Incidence, Out of Hospital Cardiac Arrest	$PM_{2.5}$	Daily	Rosenthal et al. (2008)	0-99
Incidence, Out of Hospital Cardiac Arrest	$PM_{2.5}$	Daily	Ensor et al. (2013)	18-99
Incidence, Lung Cancer	$PM_{2.5}$	Annual	Gharibvand et al. (2016)	30-99
Incidence, Hay Fever/Rhinitis	$PM_{2.5}$	Annual	Parker et al. (2009)	3-17
Incidence, Asthma	$PM_{2.5}$	Annual	Tetreault et al. (2016)	0-17
Infant Mortality	$PM_{2.5}$	Annual	Woodruff et al. (2008)	0
Work Loss Days	$PM_{2.5}$	Daily	Ostro (1987)	18-64
School Loss Days	O_3	Daily	Gilliland et al. (2001)	5-17
Asthma Symptoms, Cough	O_3	D8HourMax	Lewis et al. (2013)	5-12
Asthma Symptoms, Shortness of Breath	O_3	D8HourMax	Lewis et al. (2013)	5-12
Asthma Symptoms, Chest Tightness	O_3	D8HourMax	Lewis et al. (2013)	5-12
Asthma Symptoms, Wheeze	O_3	D8HourMax	Lewis et al. (2013)	5-12
Emergency Room Visits, Asthma	O_3	D8HourMax	Mar and Koenig (2009)	0-17
Emergency Room Visits, Asthma	O_3	D8HourMax	Mar and Koenig (2009)	18-99
Mortality, long-term exposure	O_3	D8HourMax	Turner et al. (2016)	30-99
Mortality, short-term exposure	O_3	D8HourMax	Katsouyanni et al. (2009)	0-99
Mortality, short-term exposure	O_3	D8HourMax	Zanobetti and Schwartz (2008)	0-99