Net-zero industry by 2050: a scenario analysis of boiler replacement with industrial heat pumps

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Summary: industrial equipment replacements and technology availability need to scale rapidly to reach goals

With U.S. industry contributing 1,453 million metric tons of CO_2e emissions annually (EPA 2023), remaining competitive in the global, clean energy economy and meeting domestic economy-wide net-zero goals will require quick adoption of low- to zero-emission equipment. Process heat accounts for over 50% of U.S. industrial emissions, of which about 40% falls into the low-temperature category (McMillan 2019). There are several electrification technologies that can address this portion of emissions, one of which is an industrial heat pump (IHP). IHPs are a highly efficient and scalable technology that can help decarbonize low-temperature (typically less than 150°C) processes today and are quickly advancing to reach higher temperatures and capacities. Additionally, IHPs provide numerous co-benefits such as process modularity, reduced pollutants, future proofing, cost savings, and enhanced product quality. Replacing all fossil fuel boilers with IHPs and other electrified technologies will be necessary to reach the U.S. Long-Term Strategy goal of net-zero greenhouse gas (GHG) emissions by 2050, which includes a net-zero goal for industry (White House 2021).

However, based on the current capabilities of IHPs, a continuous rate of improvement, and assuming that boilers are not replaced before end-of-life, we found that many industrial facilities are on track to still be using fossil fuel-burning boilers in 2050. Our analysis assumed that any future installation or replacement of industrial indirect heating equipment would use an IHP system if it was available to reach the needed temperatures and capacities.

Our findings reveal that even if boiler lifetimes are as short as 10–15 years, fossil fuel boilers will still be operating in industrial facilities by 2050 (see figure 1, which includes analyses for the overall industrial boiler inventory and for key industrial subsectors). To learn about our methodology, please see Appendix A.

Therefore, supportive policies and programs are critical to expand the capabilities of IHPs and other innovative electric technologies and rapidly scale replacements before end-of-life. This brief lays out near-, mid-, and long-term solutions that include renewables, storage, and hydrogen as well as recommendations for policymakers at every level, agency decision makers, utilities and regulators, vendors and equipment manufacturers, and (most importantly) industrial managers.

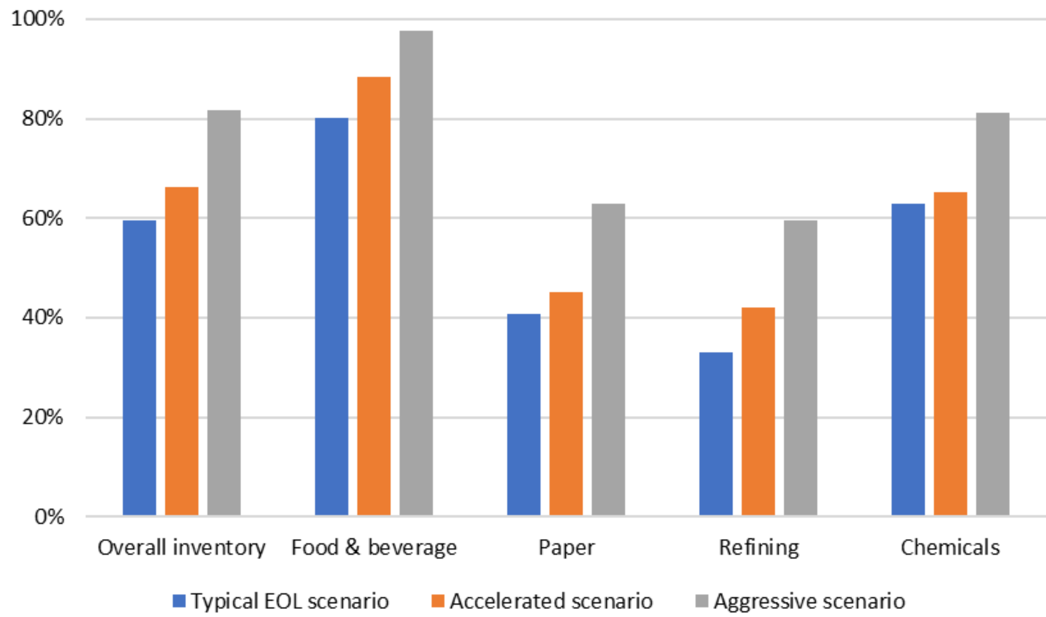

Figure 1. Cumulative percentage of overall boiler inventory and key industrial subsector inventories replaced by IHP systems by 2050, from replacement at end-of-life using typical lifetimes, in accelerated manner, and a more aggressive timeline.

Introduction: IHP technology is ready and available to reduce industrial emissions

Boilers, the workhorse of industrial heating processes since the Industrial Revolution, continue to provide the heat and pressures needed for thermal processes in myriad applications. However, in the United States, only 2% of boilers are electric, while the rest are still fossil-fuel fired (Zuberi, Hasanbeigi, and Morrow 2021). About 44% of industrial heat requires low temperatures (<80°C to 150°C); industrial boilers that power these applications can be replaced by IHP technologies that exist today. [1]

Higher temperature IHPs are currently being developed. For the industries and facilities that use large boilers with capacities, temperatures, and pressures above what is currently reachable by IHP systems, a combination of technologies could be deployed to bridge the gap, including electric boilers with renewable energy, storage, and hydrogen. [2]

We selected industrial heat pumps for this analysis, rather than electric boilers, due to the high efficiency of IHPs—coefficients of performance (COPs)[3] are typically above 2.5 whereas electric boilers have efficiencies only up to 0.95. IHP efficiency generally maximizes the heat output of each kWh from

[1] IHPs applications with sink temperatures between 100°C and 150°C have high readiness levels and are in pre-commercial demonstration stages, and those that reach higher temperatures are continually being developed. Generally, the efficiency of an IHP reduces with a higher temperature lift. For more information on the efficacy of and temperatures delivered by IHPs, consult the International Energy Agency's High Temperature Heat Pump Annexes (IEA 2014, 2021).

[2] For more information on electric boiler decarbonization potential, please read Schoenberger et al. 2022 and Zuberi, Hasanbeigi, and Morrow 2021 in the "References" section. For more information about industrial electrification and policy recommendations, please read Esram, Johnson, and Elliott 2024.

[3] COP refers to the ratio of process heat delivered, that is, output heat energy to input energy required.

the grid, leading to lower overall investment across the energy system and, most likely, to cost savings for many facilities. Of course, in practice, the industrial sector will employ a portfolio of heat pumps, electric boilers, and other technologies to meet the specific requirements at each facility and industrial decarbonization goals.

U.S. goals and role in the clean energy transition

The United States has committed to industrial and economy-wide decarbonization goals with emissions reduction targets by 2050, including the U.S. Long-Term Strategy of net-zero GHG emissions by 2050 (White House 2021). Industry accounts for almost 25% of total U.S. emissions, representing a large portion of the economy that will need significant attention and reduction strategies (EPA 2024). Additionally, some projections indicate that the industrial sector is on track to become the highest emitting sector, replacing transportation, by as soon as 2030 (Rhodium Group 2024).

The United States currently trails European and Asian countries in IHP deployments. For the U.S. industrial sector to remain competitive, it is critical to continue investment in electric technologies and other innovative solutions as presented by the recent Department of Energy's National Blueprint to Enhance a Clean and Competitive Industrial Sector (DOE 2024b). Otherwise, U.S. manufacturers risk falling behind foreign industrials who will continue to deploy emerging electric technologies, and in turn miss out on opportunities to reduce costs and pollutants, save energy, and create long-lasting jobs.

How much can IHPs decarbonize industrial process heat, and by when?

We simplified our analysis to model only the number of industrial boilers replaced with IHP systems by 2050 rather than the emissions reduced from replacing boilers. This choice was due to the lack of data availability and discrepancies between emissions values from industrial boilers (see Appendix B). For industry to reach net zero, industrial processes where boilers are currently in use need to be completely decarbonized—or in other words, every fossil fuel boiler needs to be replaced with a non-emitting alternative. Therefore, we assumed that displacing all boilers with IHPs is the way to shift boiler-reliant industrial processes towards net zero, especially as grids decarbonize.

We looked at three scenarios to reach the 2050 net-zero goal by replacing current industrial boilers with IHP systems using different lifetimes: (1) typical end-of-life, (2) accelerated, and (3) aggressive.

Our analysis looks at the potential for IHP systems to replace all boilers retired as well as those being sold new to manufacturing within an applicable range of capacities (small to medium boilers) and temperatures, **starting with capacities around 240 million British thermal units per hour (MMBtu/hr) and temperatures up to 150°C**. That is, for small boilers (defined as ≤10 MMBtu/hr), we assumed an increasing proportion of new boiler installations could be replaced by IHPs based on improvements in technologically reachable temperature ranges by that year. Similarly, for medium to large boilers (>10 MMBtu/hr), we assumed an increasing proportion of these boilers to be replaced by IHPs based on both temperature and capacity range improvements of IHP systems. We used five-year bands from 2030 to 2050 to simplify the analysis. Note that our model is based on idealized replacements at end-of-life and is not addressing retrofit (processes in which thermal redesign or facility upgrades may be needed) nor economic[4] considerations.

Our scenarios cover projected inventories for boilers across industry and boilers specific to four subsectors with a high percentage of low-temperature processes: food and beverage, paper, refining, and chemicals. For more details, please read our methodology section in Appendix A.

Scenario 1: Typical end-of-life boiler replacements with IHPs

If installed in all workable configurations, we project that replacing industrial boilers with IHP systems once they reach normal end-of-life could help offset **59%** of the overall boiler inventory by 2050. For the four key subsectors, IHPs could replace **33–80%** of their respective inventories by 2050 (range is due to subsector-specific growth projections). This scenario assumes typical lifetimes of 20 years for small boilers and 40 years for medium to large boilers.

However, we are not even close to reaching the technical potential of typical end-of-life replacement because boilers are still being replaced like-for-like rather than with lower-emitting alternative systems.

Scenario 2: Accelerated lifetimes slightly increase potential

Given the limited displacements from the typical end-of-life scenario, we need to go beyond the normal replacement of boilers to meet decarbonization goals. Assuming shorter service lifetimes of 15 years for small boilers and 30 years for medium to large boilers, we developed an accelerated scenario to model a path for quicker electrification. An accelerated scenario increases the displacement of boilers to **66%** by 2050. For the key subsectors, IHPs could replace **42–88%** of their respective boiler inventories by 2050.

However, even that accelerated replacement scenario is not sufficient to displace all industrial boilers by 2050 to meet industrial and economy-wide climate goals.

Scenario 3: Aggressive lifetimes reach ~80% of 2050 targets

We then analyzed the maximum potential if small boilers were replaced after only 10 years and medium/large boilers were replaced after 15 years in an attempt to reach the net-zero targets. This aggressive timeline brings the replacement of boilers with IHPs to **82%** of the overall boiler inventory and **60–98%** in the subsector inventories by 2050.

Economy-wide decarbonization goals require more action

Even an aggressive timeline for replacement of boilers with IHPs will not achieve net-zero goals for industrial boilers due to applications that require higher temperatures and larger capacities than current IHP technology can support. To reach 2050 goals, not only do we need to replace boilers when they are just 10–15 years old, but we also need to invest significantly in research and development (R&D) of IHP systems and other electric technologies to expand their reach: that is, beyond replacing low-temperature boilers. Additionally, domestic production of IHP components must increase to match the

[4] To overcome economic barriers, electric rate structures are important, but so too are the potential for a carbon price and industrial incentives that will make electrification projects more favorable. For more information on IHP economics, specifically for food and beverage applications, see EPRI 2024.

demand for IHPs to more rapidly replace boilers. More forceful actions will be needed to achieve wide-scale replacements of fossil-fuel boilers with carbon-free heat technologies:

- In the near term (2025–2027), industry needs to identify the applications for which IHPs that are available today can replace boilers, especially for industrial processes that have simultaneous heating and cooling. Due to limited product availability, these will likely be pilot projects that act as proving ground for the technology's ability to both decarbonize and improve the performance of industrial heat processes. Greenfield facilities and new construction provide great opportunities to design for an IHP system instead of a fossil fuel boiler, whereas retrofits may require reassessment of heat needs to more efficiently use heat (e.g., de-steaming processes that only need hot water) in each facility. Energy efficiency with optimized thermal design and application of IHPs will save money now, as well as ensure that any new systems are right sized for production needs (Chen, Elliott, and Hoffmeister 2024).
- In the mid term (2027–2030), IHP product manufacturers must work on further development, demonstrations, and deployment of steam-generating heat pumps in facilities that cannot de-steam or that cannot afford downtimes required for de-steaming. Although steam-generating heat pumps are currently expensive and have lower efficiencies than hot-water heat pumps, industry will need cost-effective steam heat pumps as packaged, drop-in replacements for steam boilers to achieve net zero by 2050. We expect increased production of steam-generating heat pumps, such as those being funded by the Department of Energy (DOE 2024a).
- In the long term (2030 and beyond), facilities should look to future-proof investments by adopting electric technologies like IHPs more rapidly, while further reducing emissions through thermal redesign and integration of complementary technologies such as renewable energy and thermal or energy storage. This is also the time horizon when we expect IHP technology to start reaching higher temperatures and capacities.

Who can act to further accelerate replacement of fossil-fuel boilers?

Public policy, private investment, and activities undertaken by leaders in the electric technologies supply chain will all play key roles in transforming their respective markets, including for IHPs. This transformation is critical for the market to reach the potential we have outlined and grow beyond it with wide-scale retrofits. To help drive greater momentum, we suggest some potential actions for key stakeholders (see infographic on page 6).

Workforce development requires collective movement

Collaboration between all stakeholders is essential for driving the market forward. For example, curriculum, training, and workforce development for electric technologies will require support from policymakers, regulators, and vendors, as well as educational institutions, trade associations, and nongovernmental organizations. Workforce development should be focused on both retraining seasoned workers like boiler engineers and technicians, and teaching new generations how to integrate and maintain electrified systems like IHPs. Process engineers could be trained in pinch analysis to enable the systematic integration of IHPs in energy intensive facilities. To help workers transition smoothly, learnings should be disseminated from new and retrofit electrification projects that have become successful. Case studies from facilities that have simply switched from fossil fuel to electric boilers must also be shared via accessible media.

Public policy:

Regional, state, and local policymakers can

- Create new financial assistance (tax credits, grants, enhancements) for accelerated IHP deployments and retrofits of existing systems with IHPs.
- Ensure integrated resource planning timelines allow for rapid adoption of electric technologies.
- Pass air quality regulations that encourage adoption of electrified technologies.
- Develop cross-agency programs.

Federal decision makers can

- Work strategically on policies and programs that highlight the benefits of electric technologies, mitigate uncertainty, and provide pathways for the growing IHP market.
- Continue expanded funding for programs that increase domestic IHP supply and demand.
- Prioritize IHP training and technical assistance through implementation programs, national labs, and educational institutions.

Utility investment:

Utility program designers, particularly those in states with ambitious decarbonization targets and regions with cleaner grids, **and regulators can**

- Work with facilities on accelerated project timelines.
- Advocate for programs to support IHP adoption, including assistance for facilities that are required to obtain a permit to remove boilers and other legacy equipment.
- Partner with engineering services companies to streamline IHP implementation.
- Design programs to help customers manage peak demand growth along with electrification.

Vendors and end users:

IHP vendors and equipment manufacturers can

- Expand production domestically and work with utilities to coordinate resource and project timelines.
- Share case studies of successful IHP implementation, especially in retrofit scenarios.
- Highlight to potential end users the full set of benefits enabled by IHPs to improve their value proposition against conventional fossil fuel equipment.

Industrial managers, including sustainability officers and facility managers, can

- Prepare packages of phased efficiency and electrification projects to reduce initial payback.
- Create workforce development programs and educational materials that focus on electric technologies.
- Provide data and share cases studies to encourage other firms to adopt electrification strategies.
- Institute policies that accelerate projects with strategic decarbonization goals such as an internal price of carbon on energy projects.

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References

Chen, Hellen, Neal Elliott, and Andrew Hoffmeister. 2024. “Stop the Waste: Using Industrial Heat Pumps to Rethink Thermal Loads.” Washington, DC: ACEEE, February 27. www.aceee.org/topic-brief/2024/02/stop-waste-use-industrial-heat-pumps-rethink-thermal-loads.

DOE (U.S. Department of Energy). 2024a. “Industrial Demonstrations Program Selected and Awarded Projects.” Washington, DC: DOE Office of Clean Energy Demonstrations, March. www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects.

———. 2024b. “The National Blueprint for a Clean & Competitive Industrial Sector.” Washington, DC: DOE, November. www.energy.gov/sites/default/files/2024-11/20241114-National_Blueprint_to_Enhance_a_Clean_and_Competitive_Industrial_Sector_1.pdf.

EEA (Energy and Environmental Analysis, Inc.). 2005. *Characterization of the U.S. Industrial/Commercial Boiler Population*. Oak Ridge, TN: Oak Ridge National Laboratory, May. www.energy.gov/sites/prod/files/2013/11/f4/characterization_industrial_commerical_boiler_population.pdf.

EPA (U.S. Environmental Protection Agency). 2023. “Greenhouse Gas Inventory Data Explorer.” Washington, DC: EPA. cfpub.epa.gov/ghgdata/inventoryexplorer/#industry/entiresector/allgas/category/current.

———. 2024. “Inventory of U.S. Greenhouse Gas Emissions and Sinks.” Washington, DC: EPA, April. www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

EPRI (Electric Power Research Institute). 2024. “Technical Report on Opportunities for Demonstrating Industrial Heat Pumps in the United States: Prototype Examples in the Food and Beverage Sectors.” www.epri.com/research/products/000000003002031135.

Esram, Nora Wang, Anna Johnson, and Neal Elliott. 2024. “How to Decarbonize Industrial Process Heat While Building American Manufacturing Competitiveness.” Washington, DC: ACEEE, April 23. www.aceee.org/policy-brief/2024/04/how-decarbonize-industrial-process-heat-while-building-american-manufacturing.

IEA (International Energy Agency). 2014. Application of Industrial Heat Pumps—Final Report Part 1, Annex 35/13. Borås, SE: IEA Heat Pump Centre. www.ieaindustry.org/app/uploads/annex-xiii-part-a.pdf.

——— . 2021. "High-Temperature Heat Pumps, Annex 58." www.heatpumpingtechnologies.org/annex58/.

IHP Alliance. 2024. industrialheatpumpalliance.org.

McMillan, Colin. 2019. "Manufacturing Thermal Energy Use in 2014." NREL Data Catalog. Golden, CO: National Renewable Energy Laboratory. Last updated: July 24, 2024. doi: 10.7799/1570008.

Rhodium Group. 2024. "Expanding the Industrial Decarbonization Toolkit." rhg.com/research/taking-stock-2023/.

Schoeneberger, Carrie, Jingyi Zhang, Colin McMillan, Jennifer B. Dunn, and Eric Masanet. 2022. "Electrification Potential of U.S. Industrial Boilers and Assessment of the GHG Emissions Impact." *Advances in Applied Energy* 5 (100089): 2666-7924. www.sciencedirect.com/science/article/pii/S2666792422000075.

White House. 2021. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. Washington, DC: U.S. Department of State and U.S. Executive Office of the President, November. www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

Zuberi, M. Jibran S., Hasanbeigi, Ali, and Morrow, William R. 2021. *Electrification of Boilers in U.S. Manufacturing*. Berkeley, CA: Lawrence Berkeley National Laboratory, November 30. doi.org/10.2172/1867393.

Appendix A: Overview of Methodology

To project the technical potential of IHPs to offset boiler replacements and new sales, we estimated boiler retirement timelines and projected new manufacturing installation (including a factor for expected growth resulting from funding provided in the Infrastructure Investment and Jobs Act of 2021, also known as the Bipartisan Infrastructure Law, and the Inflation Reduction Act of 2022).

We drew upon *Electrification Potential of U.S. Industrial Boilers and Assessment of the GHG Emissions Impact* report (Schoeneberger et al. 2022) and *Characterization of the U.S. Industrial/Commercial Boiler Population* report (EEA 2005) as primary data sources for this work, both of which include data on industrial boilers inventory, boiler capacities and data by sector, boiler count by fuel source, and so on. We analyzed the three replacement scenarios based on different equipment lifetimes (see table A1) for key subsectors in which we see IHPs as a critical near-term decarbonization solution: food and beverage, paper, refining, and chemicals, and for the overall boiler inventory, for a total of five unique results. We combined food and beverage because we assumed EEA 2005 includes both food and beverage inventories.

With EEA 2005 as our base inventory for the year 2000, we extrapolated their database using five-year bands to match Schoenberger et al. 2022's inventory, which we assumed to be equivalent to a 2020 inventory. That is, based on the number of boilers and their assumed ages in 2005, we applied a retirement rate to the inventory to match the number of boilers to Schoenberger's number of industrial boilers. We then projected the anticipated market growth in the subsectors (or lack thereof) and overall industry out to 2050, again using five-year bands to simplify the forecasting. We estimated the full impact of potential IHP deployment and determined the extent of transformation in industry investment practice beyond end-of-life replacements and new sales to reach national targets. Our analysis assumed, based on engagement with industry experts

- The delivered temperatures reachable by IHPs are up to 150°C.
- IHP systems can reach and replace boilers with capacities under 70 MW[5] (approximately 240 MMBtu/hr or about 94,000 boiler-horsepower).
- Reachable temperatures and capacities by IHP systems will increase as we approach 2050.
- Another IHP system will be installed when the previous IHP needs to be replaced within the scenarios.

Table A1 shows the lifetimes assumed for small and medium to large boilers for each scenario.

Table A1. Boiler lifetime assumptions

Boiler size	**Scenario 1** Typical end-of-life	**Scenario 2** Accelerated	**Scenario 3** Aggressive
Small (≤10 MMBtu/hr)	20 years	15 years	10 years
Medium/large (>10 MMBtu/hr)	40 years	30 years	15 years

[5] Several high temperature heat pump manufacturers make products up to 70 MW capacity today. IHP *systems* can also be configured to reach higher capacities. *Source*: Personal communications with industry experts, 2023–2024. Additionally, for the purposes of this analysis, we assumed that temperature and capacity assumptions served as an adequate proxy for pressure limitations in industrial processes: that is, the IHP system replacing the boiler meets the pressure requirements for that process.

Results: new sales and replacements with IHPs are not enough

Quantities of boilers replaceable by IHP systems and percentage of those replacements over the total inventory in five-year bands are shown in table A2, that is, anticipated figures between the start of the previous five years by the end of that fifth year. We started with 2030 because we anticipate implementation before 2025 to be mainly pilot and demonstration projects due to limited market availability. We analyzed three different scenarios for the key subsector inventories and overall boiler inventory to project the IHP replacement potential based on decreasing boiler lifetimes:

1. The first scenario, Typical end-of-life (EOL) replacements, reveals cumulative potential of 26,031 IHP systems installed by 2050 for the overall inventory, replacing 59% of industrial boilers.
    - Refining has a low replacement percentage at 33%, followed by paper at 41%. These lower values are due to boilers at higher capacities and temperatures than current IHP technology can reach. Replacements of boilers with IHP systems in the chemicals subsector is at 63% by 2050 in the typical EOL scenario, while food and beverage is at 80%. These higher percentages are due to a higher portion of the boilers within these subsectors being below 240 MMBtu/hr and/or having process heat temperatures below 150°C.
2. The second scenario, Accelerated lifetime replacements, yielded 28,968 IHP systems and 66% of boilers displaced by 2050.
    - The order of lowest to highest percentage of boilers displaced in the key subsectors are refining at 42%, paper at 45%, chemicals at 65%, and food and beverage at 88%.
3. The third scenario, Aggressive lifetime replacements, uses the shortest lifetimes for boilers to see how much of the goal to replace all industrial boilers with IHPs could be met with our analysis. Even with an extremely aggressive timeline, 35,827 IHP systems are expected to be installed by 2050, replacing only 82% of the overall boiler inventory.
    - The order of lowest to highest percentage of boilers displaced in the key subsectors are refining at 60%, paper at 63%, chemicals at 81%, and food and beverage at 98%. The food and beverage figures almost reach total displacement of the boilers within these subsectors, because almost all of the heating processes within these subsectors are low temperature.
    - Also note that by 2030, this third scenario calls for about 8,500 boilers to be replaced by IHP systems for the overall inventory, revealing that in an aggressive replacement scenario, major production must be in place by 2030 to put us on track to reach net zero by 2050.

The results of our analysis of the various scenarios are clear: Even an aggressive timeline for replacement of boilers with IHPs will not achieve net-zero goals for industrial boilers. This is the case due to applications that require higher temperatures and larger capacities than can now be served by IHPs. Additionally, for the typical end-of-life and accelerated scenarios, the long life of large boilers also limits how much of the stock is replaced by 2050. The recommendations outlined in the above sections are essential to rapidly scale production and retrofits to reach both industrial decarbonization goals and economy-wide net-zero targets.

If you would like to learn more about our IHP boiler replacement analysis (assumptions, methodology, etc.) or see the data set and results, please reach out to Hellen Chen (hchen@aceee.org) or Andrew

Hoffmeister (ahoffmeister@aceee.org). For more information about IHPs, please visit the Industrial Heat Pump Alliance (of which ACEEE is a founding member) website for resources.

Table A2. IHP technical potential to replace industrial boilers

		2030	2035	2040	2045	2050
Total projected boiler + IHP inventory for **all** industrial subsectors		41,085	41,748	42,422	43,107	43,803
Overall Typical EOL	Number of IHP systems installed cumulatively	2,448	4,893	8,754	13,900	26,031
	Percentage of IHPs over total inventory for the year	6%	12%	21%	32%	59%
Overall Accelerated	Number of IHP systems installed cumulatively	4,294	7,079	14,733	21,557	28,968
	Percentage of IHPs over total inventory for the year	10%	17%	35%	50%	66%
Overall Aggressive	Number of IHP systems installed cumulatively	8,462	12,156	17,027	24,336	35,827
	Percentage of IHPs over total inventory for the year	21%	29%	40%	56%	82%
Total projected boiler + IHP inventory for the **food and beverage** industrial subsectors		7,963	8,112	8,264	8,419	8,576
Food and Beverage Typical EOL	Number of IHP systems installed cumulatively	973	1,716	2,650	3,683	6,878
	Percentage of IHPs over total inventory for the year	12%	21%	32%	44%	80%
Food and Beverage Accelerated	Number of IHP systems installed cumulatively	1,665	2,581	4,804	6,852	7,572
	Percentage of IHPs over total inventory for the year	21%	32%	58%	81%	88%
Food and Beverage Aggressive	Number of IHP systems installed cumulatively	3,841	5,153	6,925	7,341	8,365
	Percentage of IHPs over total inventory for the year	48%	64%	84%	87%	98%
Total projected boiler + IHP inventory for the **paper** industrial subsector		2,471	2,471	2,471	2,471	2,471
Paper Typical EOL	Number of IHP systems installed cumulatively	108	216	367	571	1,009
	Percentage of IHPs over total inventory for the year	4%	9%	15%	23%	41%
Paper Accelerated	Number of IHP systems installed cumulatively	198	305	583	797	1,115
	Percentage of IHPs over total inventory for the year	8%	12%	24%	32%	45%

		2030	2035	2040	2045	2050
Paper Aggressive	Number of IHP systems installed cumulatively	337	471	621	951	1,557
	Percentage of IHPs over total inventory for the year	14%	19%	25%	38%	63%
Total projected boiler + IHP inventory for the **refining** industrial subsector		2,608	2,608	2,608	2,608	2,608
Refining Typical EOL	Number of IHP systems installed cumulatively	63	135	274	506	862
	Percentage of IHPs over total inventory for the year	2%	5%	11%	19%	33%
Refining Accelerated	Number of IHP systems installed cumulatively	118	208	547	707	1,097
	Percentage of IHPs over total inventory for the year	5%	8%	21%	27%	42%
Refining Aggressive	Number of IHP systems installed cumulatively	269	432	531	869	1,556
	Percentage of IHPs over total inventory for the year	10%	17%	20%	33%	60%
Total projected boiler + IHP inventory for the **Chemical** industrial subsector		5,943	6,070	6,200	6,332	6,467
Chemicals Typical EOL	Number of IHP systems installed cumulatively	307	558	1,033	1,623	4,063
	Percentage of IHPs over total inventory for the year	5%	9%	17%	26%	63%
Chemicals Accelerated	Number of IHP systems installed cumulatively	508	884	1,870	3,586	4,223
	Percentage of IHPs over total inventory for the year	9%	15%	30%	57%	65%
Chemicals Aggressive	Number of IHP systems installed cumulatively	1,158	1,652	3,076	3,716	5,256
	Percentage of IHPs over total inventory for the year	19%	27%	50%	59%	81%

Appendix B: GHG emissions avoided from IHP replacement of industrial boilers

Data issues

Certain data gaps limited our ability to accurately predict the impact of boiler replacements on emissions reductions for the industrial sector. There is a substantial discrepancy in the emissions attributed to conventional boilers in the 2018 MECS data (91 MMT of CO_2e) and the emissions we estimated from our forecasts of boiler inventories, using averages of operating hours and fuel intensity emissions factors (470–566 MMT of CO_2e). There are also differences in the estimated GHG reductions from electrifying boilers (Zuberi, Hasanbeigi, and Morrow 2021) or replacing boilers with IHPs in low-temperature processes only. Our baseline estimates attribute 1/3 of overall industrial sector energy emissions (1,453 MMT of CO_2e per year) just to boilers, which is unlikely. Discrepancies between industrial energy databases point to the need for an extensive reevaluation of the current emissions data from the variety of national sources.

Despite these data issues, we know rapid replacements and concerted electrification efforts are still critical in helping us reach net-zero goals. We conducted a preliminary emissions analysis, in which we set our own baselines and used average emission intensities based on capacity bands (i.e., averages across ≤10, 10–50, 50–100, 100–240, >240 MMBtu/hr)—see the next section for more details. Table B1 shows the avoided emissions and percentage of net-zero emissions goal reached by 2050 for the aggressive scenario.

Table B1. Avoided emissions from replacing boilers with IHPs by 2050 (aggressive scenario only)

	MMT CO_2e avoided	% of net-zero goal
Overall industry	270–326	48–69%
Food and beverage	56–64	66–83%
Paper	51–61	48–64%
Refining	30–40	35–51%
Chemicals	69–88	47–69%

Please note that these values are based on a preliminary analysis.

Calculations and methodologies

We estimated emissions reductions for a scenario in which every boiler within our range is replaced with an IHP system using a net emissions reduction factor of 85% (to accommodate unknown grid mixes[6]) either because it reaches end-of-life, is replaced before end-of-life in our accelerated/aggressive scenarios, or is a new installation. For 2050 baseline calculations, we used an average emissions intensity of the projected 2050 boiler inventory based on boiler capacities as well as a line-by-line

[6] While carbon free electricity is growing, it was beyond the scope of this analysis to account for projected mix and subsequent upstream emissions from the grid that the IHP system would be connected to when replacing a boiler within a facility. We also do not account for low-carbon fuels as they are currently scarce and expensive, demanding further research that was out of scope for our analysis.

calculation from Schoenberger et al. 2022's data multiplied by a growth factor (from 2020 to 2050). We used a simplified equation to calculate emissions from a single boiler per year, where the emissions intensity comes from EPA:

$$CO2e\ emissions = boiler\ capacity * operating\ hours\ per\ year * emissions\ intensity * subsector\ (or\ overall\ manufacturing)\ boiler\ efficiency$$

These estimates may be somewhat conservative in determining industrial emissions reduction potential because we

- Did not account for ability of facilities to de-steam and redesign thermal systems, which would increase the emissions reduction potential (i.e., the net reduction factor)
- Did not include the emissions reduction from combining technologies (e.g., electric boilers or hybrid systems with IHPs), with which increased reductions are likely
- Assumed the boilers with missing fuel type data were also fired by natural gas, due to the fact that natural gas boilers accounted for approximately 85% of the boilers that had data; we also used zero emissions intensity for biomass, but the true impact of biomass on carbon emissions may be higher
- Used the lower value between averages of operating hours in each sector and different boiler capacities for boilers with missing operating hours data

For these reasons, we think it is more likely that we underestimated the potential emissions attributable to industrial boilers based on our data inputs and we do not believe that calculation methods can account for the gap in our findings, compared to other baseline datasets. Discrepancies are more likely to be the result of variation in the number and type of facilities included in different national datasets. Our results should be treated as a preliminary analysis due to lack of a clear way to compare the comprehensiveness of available datasets.

Modeling should be done beyond our replacement approach to incorporate information from more recent datasets such as the Environmental Protection Agency's National Emissions Inventory (NEI). Further efforts could also provide better emissions and pollution reduction projections; for example, showing more granular reductions by type of emission down to the county level to project local impacts.

Call to action for better data

For emissions impact calculations to be accurate, we must have better and more comprehensive data across sources so that consistent baselines can be formed, and comparisons can be more easily made across data sources. We urge national agencies and Congress to set aside more resources and establish standard practices to address data gap issues in the industrial sector, especially given the historical context of industrial energy data. We believe the United States can maintain its industrial competitiveness in not only tracking emissions through transparent reporting and data collection but also in accurately and confidently accounting for progress toward our net-zero goals.