Toward Carbon-Free Hot Water and Industrial Heat with Efficient and Flexible Heat Pumps

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Glossary and key abbreviations

BTU or Btu – The "british thermal unit," a commonly used measure for a quantity of thermal energy. One BTU is equal to 0.293 watt-hours. In cases with large numbers, prefixes may be added, e.g., kBtu for one thousand Btu, MBtu for one million Btu, TBtu for one trillion.

CO_2e – Carbon dioxide equivalent. A metric that accounts for the sum total greenhouse gas impacts from emissions of multiple gases that have various warming effects, represented in terms of the equivalent carbon dioxide (CO_2) emissions for the same amount of warming.

Curtailment – The reduction in output of renewable energy generation due to an inability by grid operators to safely or economically use the electricity.

District heating – District heating systems involve using a central plant to produce heat that is distributed to multiple buildings through a network of hot water or steam piping.

HPWH – Heat Pump Water Heater

MMT CO_2e – Million metric tons of carbon dioxide equivalent emissions. 1 metric ton is 1,000 kilograms.

Wh – "Watt-hour," a commonly used measure of electrical energy. In cases with large numbers, prefixes may be added, e.g., kWh for one thousand Wh, MWh for one million, GWh for one billion, and TWh for one trillion.

Unitary – An integrated water heater "unit" that includes a storage tank and heat source.

Quad – A term to describe one quadrillion Btu of energy (10^{15} Btu).

Executive summary

Hot water and industrial heat are critical energy services. Washing our hands, taking a shower after a long day at work, cleaning the kitchens that feed us, and drying bricks and processing foods all require hot water and heat. These services have historically been provided primarily by burning fossil fuel in water heaters and boilers, leading to significant costs, greenhouse gas, and local air pollution. There is a different pathway available: high-efficiency, cost-saving heat pumps powered by carbon-free electricity.

Decarbonizing American homes, businesses, farms, and factories with heat pumps can save money, reduce carbon emissions, and support jobs.

This study describes the **scale of the opportunity** for efficient and "flexible" electric heat pumps to serve residential, commercial, and industrial hot water and process needs. This notion of flexibility--heating and storing water during times when renewables are abundant for later use--is key to the opportunity. We also identify **federal policy pathways** to accelerate a transition to low-carbon energy for hot water.

THREE BIG IDEAS: EFFICIENT, CLIMATE-FRIENDLY, AND FLEXIBLE

Heat pumps are **efficient, climate-friendly, and flexible**. With high performance, commercially-available technology, customers could save $30 billion per year on energy bills in the applications and sectors we assessed (out of $72 billion in current-day spending). These systems, powered by carbon-free energy, could cut 520 million metric tons of CO_2e emissions annually, 10% of the U.S. energy sector total. Finally, flexible heat pumps on a decarbonized grid could productively utilize 120 additional terawatt-hours of renewable energy per year by avoiding curtailment (equivalent to 30% of current solar, wind, biomass, and geothermal power), shifting as much energy as battery systems that would cost $130 billion.

High performance technology

High performance heat pumps are available now to serve a range of important applications. In addition to standard sized unitary heat pump water heaters (HPWH) for residential and small commercial buildings, heat pumps are also being produced at enormous sizes and with very high temperature output, creating exciting opportunities for large commercial and industrial applications.

Currently heat pumps are reaching a coefficient of performance (COP) of three (or higher) in practice, meaning they provide three units of useful heat for every unit of electricity input. This translates to "300%" efficiency or more, dwarfing the efficiency of conventional fossil fuel combustion (60-97%) or electric resistance heating (90-95%). With this level of performance, most customers could enjoy lower energy bills, even though electricity typically costs more than fuel per unit of energy. We estimate that with today's heat pump performance and energy prices, 80% of residential customers, 60% of commercial customers, and 70% of industrial customers would pay less, with total potential savings of $30 billion per year across these sectors.

The high efficiency of heat pumps flips the conventional wisdom that gas, coal, and fuel oil tend to be cheaper than electricity for heating. As heat pump performance improves, and energy prices adapt to incentivize use of low-carbon sources, even more will benefit with a switch.

Carbon-free heat pathway

High efficiency heat pumps can decarbonize a range of applications. We consider these in this report:

- Domestic water heaters for residential and small commercial buildings
- Large commercial, district heating, pools, and similar applications
- Industrial heat up to 150°C / 300°F: boilers, combined heat and power (CHP), and process heat

These applications collectively produce 520 million metric tons of CO_2 emissions annually, about 10% of the annual CO_2 emissions in the United States energy sector, which totals 5,400 MMT CO_2e (EPA (2021b). The total footprint for heat in general (shown in Figure 1) adds up to a total of 1,410 MMT CO_2e. High temperature industrial heat (above 150°C) and space heating make up the other key segments of total heat. Electrification with heat pumps will lead to immediate emissions reductions with today's electricity mix; 90% of the potential sites for replacement we assessed would have lower emissions with a heat pump with a COP of 2 or better (and nearly 100% with a COP of 3 or better). As the grid gets cleaner the scale of the emissions reduction opportunity will only increase.

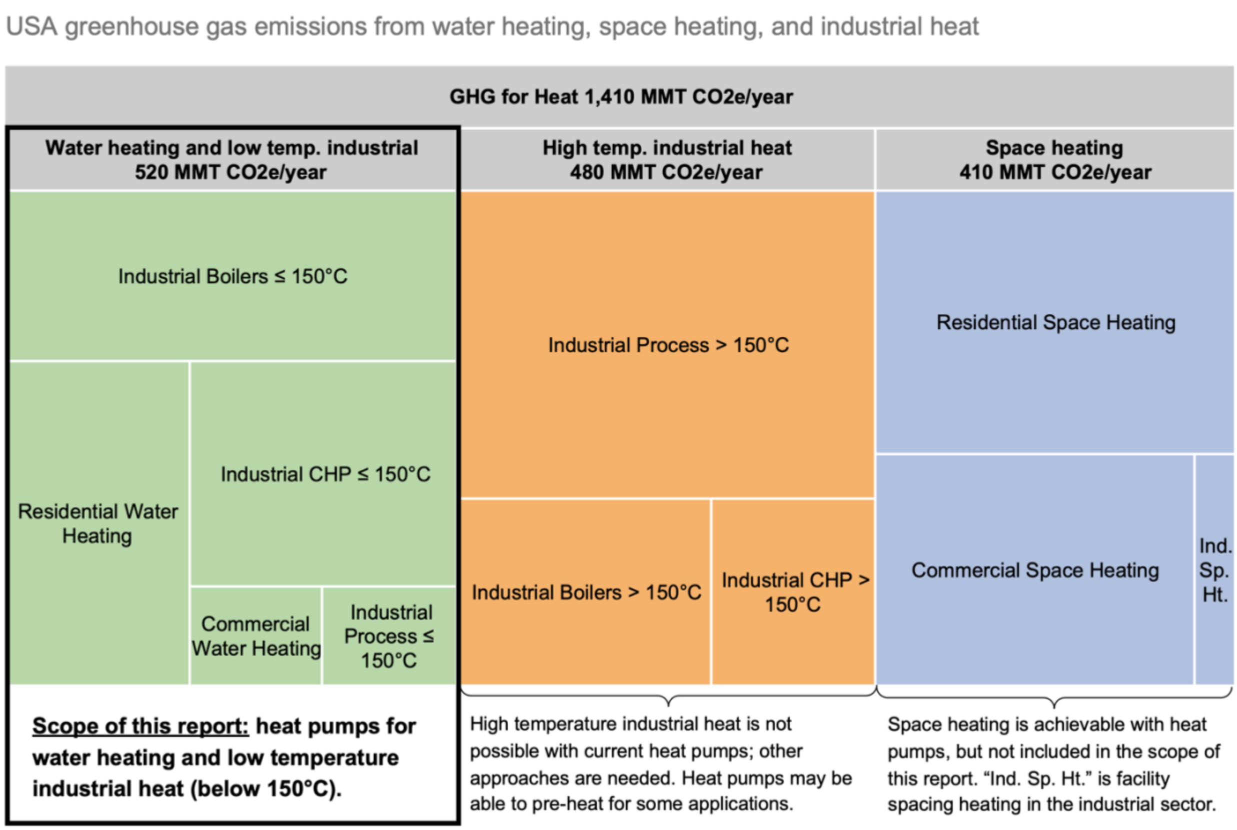

Figure 1. *Estimated greenhouse gas emissions related to providing heat across the residential, commercial, and industrial sectors. The data sources and specific values for each portion of the treemap are summarized in Table A10 and Table A11.*

Flexible for the next generation grid

Heat pumps deployed now and in the foreseeable future will be powered with electricity grids that are in a period of rapid change, as hundreds of gigawatts of new solar and wind power come online. As we build more renewables, there are increasingly predictable and frequent periods of time when these variable energy resources are in surplus. This introduces challenges for grid operators who need to balance generation and loads, and drives the need for investment in energy storage and dispatchable resources. This dynamic also creates new opportunities for flexible loads, and particularly those that have intrinsic storage. HPWH fit the bill more than almost any other end use. The storage tank of HPWHs is key to their flexibility, essentially acting as a thermal battery. They can pre-heat and hold hot water for multiple hours, with enhanced capabilities for units with larger storage tanks and/or mixing valves that enable higher temperature storage. Flexible HPWH can also be managed to avoid critical peak demand times, reducing stress on the grid.

The match between new loads and renewable energy is a critical factor for cutting electricity costs with the future grid. Across the sectors we assess, a full transition from fossil fuel to heat pumps with an average COP of 3 could result in building new electric load totaling approximately 500 TWh annually. This is a 9% increase in the total annual electricity demand, similar in scale to all of the current-day total non-hydroelectric renewable power generation. Without flexibility, we estimate about half of the new load would be coincident with renewable generation based on the typical timing of hot water demand. The other half would require storage (e.g. electrochemical batteries or pumped-storage hydroelectric projects) to match demand with renewable generation (which raises the cost of serving load by 2-3x compared to coincident demand (Lazard 2020)).

End-use flexibility and load shifting can help bring down the cost of serving new loads by making better use of renewable generation when it is available without the need for additional storage.[1] If 25% of the new heat pump load is flexible[2] and responsive to the needs of a decarbonized grid, it could result in 300 GWh of daily avoided renewable energy curtailment (about 30% of today's total non-hydroelectric renewable generation). It would cost $130 billion to procure battery systems that achieve the same level of renewables integration support[3].

Our analysis suggests that flexible operation of heat pumps to match the timing of available renewable power on the future grid could add to the bill savings customers experience by 10-100%. For example, an average residential customer currently using a gas water heater can boost their potential savings with a HPWH from $40/year to $80/year with gains from flexible operation[4]. The overall fraction of customers in the residential and commercial sector who would experience savings with a switch to heat

[1] https://www.salon.com/2021/07/04/the-humble-water-heater-could-be-the-savior-of-our-energy-infrastructure-woes/

[2] This assumption is on par with estimates of the flexible portion of residential hot water systems with storage tanks and appropriate controls and systems in place (BPA 2018, Carew et al. 2018, Cui et al 2019).

[3] We assume current-day battery pricing, with an estimated cost of $400/kWh for grid-interactive large-scale systems.

[4] The assumptions for this analysis as described in the main report. A key requirement for these savings is the availability of appropriate retail electricity price signals ("real-time" pricing, etc.) to incentivize load shifting.

pumps for hot water rises from 60-80% to 95% with flexible operation and appropriate pricing or incentives available.

These gains from flexibility come with relatively modest costs, e.g., under $100 per residential water heater at scale if the required communications, control, and mechanical systems are included at the time of manufacturing. With focused planning and support for market transformation, there is an opportunity to build a fleet of efficient water heating that is flexible to match the new renewable generation being built to power it.

TRANSFORMING THE MARKET

Developing carbon-free electric hot water and heat could involve investments at nearly every household, public building, and business in the country, supporting economic stimulus through job creation and long-term energy cost savings.

We worked to identify **how federal policy could accelerate this transformation.** Our research into what has worked in local- and state-level programs and other countries identifies a policy roadmap that includes a range of actions, including updating codes and standards, targeting procurement, providing incentives to spur market demand, and investing in R&D.

Some activity is already underway. A recent announcement by the Biden Administration[5] describes a range of federal actions that are planned to support decarbonization and heat pumps, building on the foundational goals of reaching a zero-carbon electric power sector by 2035 and a net zero overall economy by 2050. These policies and programs are a start on the long and sustained effort that will be required to accelerate adoption of low-carbon heat on a timeline consistent with climate stabilization.

Federal leadership is critical for overcoming decades of stagnation in market adoption of heat pump water heaters and larger heat pumps for commercial and industrial applications.

Codes and standards

State and Local building energy codes are important to get right since they can significantly amplify or impede uptake of new technologies, even if their use is regulated nationally. Although building codes are not set federally, policymakers can have impact by working with local code officials to mitigate barriers, harmonize between jurisdictions, and maximize synergies with complementary federal policy. U.S. leadership is also needed internationally in the International Code Council, to align its code development with building decarbonization.

[5] https://www.whitehouse.gov/briefing-room/statements-releases/2021/05/17/fact-sheet-biden-administration-accelerates-efforts-to-create-jobs-making-american-buildings-more-affordable-cleaner-and-resilient/

Department of Energy appliance standards and Environmental Protection Agency ENERGY STAR ratings are also critical regulatory arenas for advancing high-performance heat pump technology. Minimum efficiency standards and labeling allows consumers to make informed purchasing choices. Public and private energy users alike routinely defer to ENERGY STAR for purchasing guidance because of the complexity of technology choices, which is even more true with technology not yet widely in use, such as heat pumps.

The ENERGY STAR program should consider:

- Requiring grid-connected functionality
- Ceasing endorsement of fossil fuel fired products
- Increasing focus on large-scale heat pump systems

Leadership by example

The well-established Federal Energy Management Program (FEMP), as well as agency-based energy management offices, energy-oriented procurement protocols,[6] and other initiatives provide vehicles for leading by example. FEMP also issues internal standards for its own equipment purchases, and these could be fortified to emphasize heat pumps. Little effort has been made in this regard to-date.

Incentives

The upfront costs of equipment and installation for HPWH are currently a major barrier to adoption. Through rebates, tax incentives, and other mechanisms that reduce these costs, it is possible to accelerate progress on technology development and reach scale. Seasoned program administrators indicate the need to have deep incentives in place in the absence of minimum efficiency standards. Existing incentive levels for the residential sector, averaging about $400 per heat pump water heater, are insufficient to achieve market transformation.

Deeper incentives for residential and small commercial customers should be scaled to cover the full incremental project cost in order to move the needle on accelerating HPWH. We recommend the following amounts be considered:

- Incentives that result in $1,000 - $1,500 retail savings per unit for HPWH equipment, depending on size, applied at the manufacturer ("upstream") or distributor ("midstream") levels. The actual incentive amount may be lower since supply chain markup adds to the retail impact of lower wholesale prices. Incentive structures should be nuanced enough to avoid steering consumers towards lower performing products to avoid dissatisfaction and market spoiling.
- $1,000 - $2,000 in additional installation support applied as a midstream incentive to installers or downstream refundable tax incentive (or other similar mechanisms) with a streamlined and simple process. This support could be targeted for the many customers who require costly electrical panel and/or building circuit upgrades to power HPWHs.

[6] See https://www.energy.gov/eere/femp/purchasing-energy-efficient-residential-electric-storage-water-heaters

Large commercial and industrial customers would benefit from a significant expansion of tax incentives. Similar to the residential sector, initial incentive amounts should approach the full incremental project cost (equipment plus labor) to de-risk early adopters and support market development. We recommend favorable structures such as refundable tax credits and accelerated depreciation. Incentives should be performance-based (e.g., based on avoided emissions) since projects in these sectors are typically bespoke.

Historically, utilities have been the primary source of incentives and have achieved very low market penetration in the household sector (with very little attention to commercial and industrial customers). While participation rates are increasing, overall penetration rates--the ratio of HPWH units rebated each year to number of customers--are very low according to the latest national review (from 0 to 0.15% in most cases, with the best at 0.4%) (Rosenberg 2016). We recommend that utility efforts be augmented with federally directed campaigns, some of which could focus on particularly promising opportunities such as in the hospitality and food-products industries. Opportunities not deemed attractive to utilities (e.g., pools) could also be emphasized. Some efforts could be carried out in cooperation with states and cities, e.g., in decarbonizing district heating systems or coupling heat pumps to municipal waste infrastructure. Finally, merging utility rebates with federal incentives should be explored to amplify impact and reduce the transaction costs for accessing these programs.

Supporting infrastructure

For many existing buildings, particularly in the residential sector, the cost of electrical infrastructure upgrades to switch to a HPWH can approach thousands of dollars, sometimes doubling or more the cost of heat pump upgrades. Similar dynamics are present in the commercial and industrial sectors to varying degrees. These one-time service upgrades to enable high-power electric loads to replace fossil fuel are critical infrastructure investments to support decarbonization, not just for heat pumps but also for fast-charging electric vehicles, electric cooking, and space heating. Similar to the need for new transmission lines to support large-scale renewable integration on the bulk power system, upgrading the wires and circuits in households and businesses to accommodate decarbonized loads is a vital need. The federal government should include support for these infrastructure upgrades in incentive programs for heat pumps and should consider programs to make buildings zero-carbon ready.

Improving low-income housing performance

A just and clean energy transition requires special attention to ensure low-income households benefit. Our analysis indicates that among the ~50 million households where income is lower than $40,000 per year, spending on hot water represents 1-2% of *total* income (10x the fraction of the highest income households). While 80% of these lower income households stand to lower their bills with HPWHs, less than half own the building where they live and there are well-known upfront cost barriers facing households with low levels of liquid income. Focused public sector support (e.g. targeted incentives for rental properties, etc.) is vital to help ease the energy poverty burden facing these households and ensure broad decarbonization.

There are also existing federal programs that could be leveraged by significantly increasing their budgets to reach more households, and including targeted funding for HPWH and other electrification work. HHS's $3.3 billion/year Low-Income Heating Energy Assistance Program (LIHEAP)[7], DOE's $200 million/year Weatherization Assistance Program, HUD's $650 million/year Indian Housing Block Grant Program, and HUD's $6.4 billion/year utility allowance subsidies programs[8] could all deliver HPWHs that save money and cut carbon. Currently, 35 million households are eligible for LIHEAP but only 20% receive assistance due to budget constraints.[9] After an initial investment of one-time capital payments for the installation of HPWHs, per household energy subsidy requirements would be reduced, in turn making LIHEAP more financially efficient, thus enabling the program to support more households.

Industrial R&D

Heat pumps are likely to be a key competitive frontier, and U.S.-based companies are largely trailing behind their international peers in developing the technology that will be used to decarbonize the heating sector. This is the case in the residential and commercial sectors and even more so in industrial applications, where overseas companies already manufacture diverse lines of high-output heat pumps across Europe and Asia. *Proactive industrial policy* can help U.S. manufacturers, installers, and deployment programs catch up as the market grows. Some of the R&D work should be focused on technology. This could include supporting advances in low-carbon refrigerants, and development and demonstration of controls and thermal storage that enable heat pump systems to make the best use of renewable power. There is also a need for application-focused R&D to support scale-up and accelerate technological learning rates. This could include research partnerships with installers to identify and eliminate barriers to widespread HPWH adoption in key sectors, supporting development of engineering design standards, technical training for building trades, and manufacturing scale-up support.

STIMULUS WITH LOW-CARBON HOT WATER

Accelerating heat pump deployment is a three-pronged opportunity to support jobs, help customers save money on energy bills, and cut carbon emissions. We estimate that **each 1 million HPWH installed could:**

- **Stimulate about 20,000 jobs** in manufacturing and installation[10].
- Provide $1.6 billion in total customer bill savings over the first 10-years of use, an **average of about $1,600 in savings per household**.
- Lead to a reduction of 15 million metric tons of CO_2e over the equipment's lifetime compared to the status quo.

Broader approaches beyond HPWH incentives are also needed to achieve decarbonization across the economy at a pace consistent with climate stabilization. Codes and standards, regulatory work, and R&D

[7] See https://liheapch.acf.hhs.gov/Funding/funding.htm
[8] See https://www.hud.gov/program_offices/economic_development/eegb/utilities
[9] See https://www.eei.org/issuesandpolicy/Pages/liheap.aspx
[10] Combining our estimates for costs with employment impact multipliers for the relevant sectors (Bivens 2019)

pathways are all vital. Federal support programs should be both broad and deep, and should reach all sectors with dedicated approaches that meet the nuanced needs of the applications and economics. In the main report below we trace the outlines of many market stimulus opportunities and suggest pathways for policy.

A TIMELINE FOR ACTION

Time is of the essence. Every fossil fuel water heater and industrial boiler has an expected lifetime of over a decade, locking in future emissions and higher costs for customers. Another path is possible. The next 5, 10, and 15 years are critically important for heat pumps to contribute towards significant progress towards clean energy by 2035 (Table 1). Flexible end uses like heat pumps, aligned with renewable power production, can not only cut direct emissions but also help balance the grid over the coming years and decades.

Table 1. *Possible timeline for federal action on low-carbon hot water and heat*

TIMEFRAME	MARKET TRANSFORMATION ACTIONS	INDICATORS OF SUCCESS
5 years 2021-2025	● Deep incentive programs for HPWH ● Targeted procurement programs ● Begin sustained R&D effort ● Codes and standards development	Clear market signals lead to a scale-up of the HPWH industry and installation workforce. Millions of HPWHs are deployed.
10 years 2026-2030	● Continued incentive programs ● Codes and standards fully revised, including incorporating flexibility ● Deployment scale-up R&D for C&I	R&D efforts lead to breakthroughs and accelerated transition in all sectors. A growing fleet of flexible heat pumps saves billions of dollars annually, with codes and standards support.
15 years 2031-2035	● Revise incentive as market matures ● Refocus R&D on emerging needs and harder-to-reach sectors ● Int'l codes and standards harmonized	The typical new or replacement hot water heater is a flexible and highly efficient heat pump. U.S. firms enjoy a vibrant technology export business serving global markets.

MEETING THE MOMENT

The United States could play a leading role in developing and deploying low-carbon heating technology, creating tens to hundreds of thousands of jobs. There is a need for low-carbon heat and hot water around the world, and the U.S. could be a leader in this important 21st century technology.

Each dollar invested in market transformation will help advance towards these goals and also lead to a dollar in the pockets of households and the budgets of businesses who benefit from lower energy costs[11]. This clean energy annuity effect can ease the burden of energy poverty for lower income households and provide a long-term, durable, and persistent stimulus effect.

Carbon emissions from fossil fuel have pushed our planet to the brink of a climate emergency. Replacing the millions of direct combustion appliances and equipment we use for heat with low-carbon alternatives is a necessary step for stabilizing greenhouse gas that should be taken as soon as possible.

Finally, the grid is already faced with more frequent times of renewable electricity surplus that will only accelerate as more clean energy generation is added. Flexible heat pump systems can make productive use of this valuable renewable energy, helping balance the grid and cutting the cost of the overall clean energy transition.

Efficient and flexible heat pumps meet the moment by creating jobs in an important 21st century sector, lowering customers' energy bills, cutting carbon emissions, and easing integration of renewable energy.




[11] Based on an approximate midpoint of our recommended combined equipment and installation incentive, $1,500.

Study scope and objectives

This study asks, "what is the potential for heat pumps to support decarbonization of hot water and industrial process heating, and what are the policy pathways to accelerate the transition?" The technology scope includes residential hot water, commercial hot water, and industrial heat up to 150°C (300°F), which is near the upper limit for what today's heat pumps can deliver. Within these sectors there is a great diversity of building types and hot water applications.

Our approach to answering these questions combines a national-scale analysis of demand for heat with in-depth historical, institutional, and policy research on domestic and international experience with heat pumps for water heating.

The details of the methods and data sources for our analysis are in the Appendix. In short, we used national-level surveys (the well-known "RECS, CBECS, and MECS" data from the U.S. Energy Information Administration) to establish baseline demands for heat. In the industrial sector, we leveraged a unique dataset produced by researchers at the National Renewable Energy Laboratory, which estimates demand for heat at a granular level by delivery temperature (McMillan 2019).

For each sector, we focused on identifying the following:

- **Baseline expenditures and greenhouse gas emissions** from incumbent technology that provides hot water and industrial heat.
- **Potential future expenditures (and savings) from switching** from incumbent technology systems to modern heat pumps, and estimated costs to install them.
- **Alignment between the estimated load shape for heat and the net generation** of renewable energy on a future grid with net zero carbon electricity;
- **Potential cost savings from flexible operations** of heat pumps to better align with renewable generation.
- **Pathways for federal policymakers** to accelerate a transition to low-carbon heat.

Background

HEAT PUMP FUNDAMENTALS

Heat pumps use refrigerant cycles to pull heat from the ambient environment and deliver it where it is needed. They use the same mature technology as refrigeration and air conditioning, except towards a goal of providing useful heat (instead of useful "coolth"). The diagram below (Figure 2) illustrates the basic concept and pictures several examples of equipment.

The fundamental idea is to move heat from one location to another using a refrigerant fluid. The refrigerant evaporates (from liquid to gas) at one location, "absorbing" heat, and then condenses (from gas to liquid) at the location where the heat is "delivered." At the heart of the heat pump is an electric compressor. It pressurizes the evaporated refrigerant, pushing it through the condenser and around through the rest of the cycle. Air conditioning and refrigeration work the same way, just with the opposite aim: pulling heat out of a building or refrigerated space and dumping it to the ambient environment.

In some applications (e.g., hotels, dairies, and food processing industries) there are needs for both heating and cooling on any given day. These ideal sites for heat pumps can use both ends of the cycle, amplifying energy savings. At a dairy, for example, heat pumps can simultaneously provide heat to pasteurize milk and chill refrigerated storage[12].

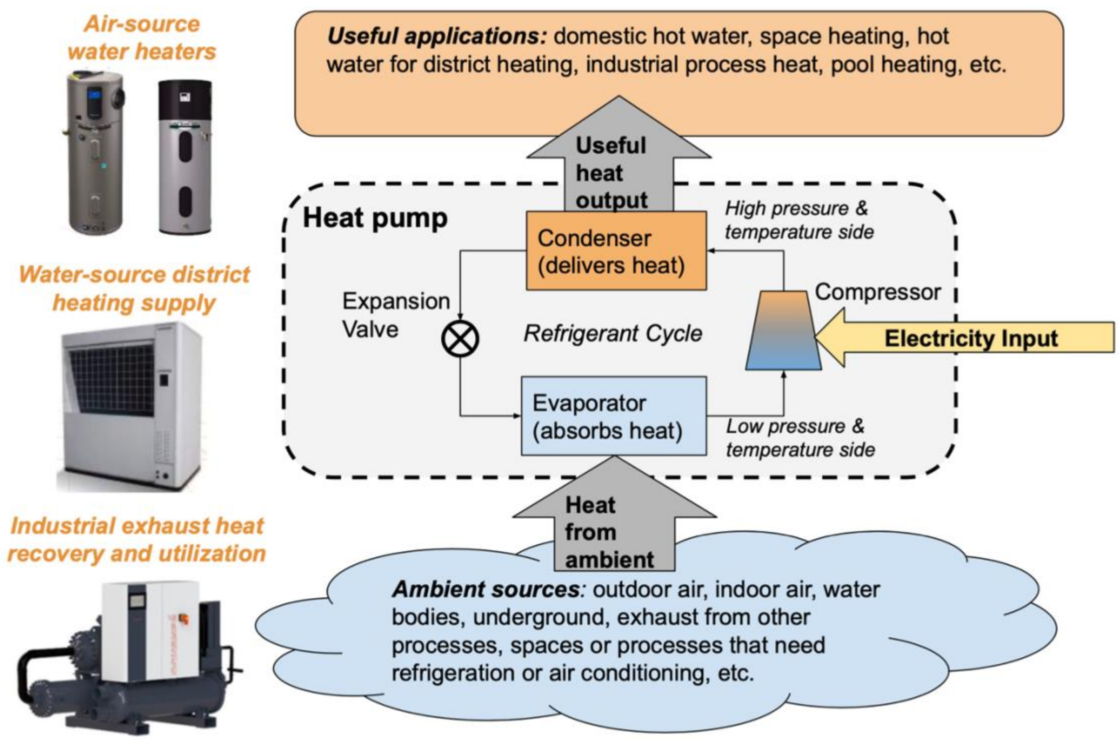

Figure 2. *Heat pump refrigerant cycle diagram with illustrative applications noted and pictured*

Thanks to the refrigerant process, and how little electricity it takes to run the compressor, the quantity of heat that is transferred by a heat pump can be much greater than the electricity input, meaning the **systems typically have apparent efficiency greater than 100%**. This outcome is due to clever application of the thermodynamic properties of refrigerants, which evaporate and condense at different temperatures when the pressures are changed, allowing these cycles to move heat from one place to another, and importantly from lower temperature sources of heat to higher temperature outlets.

The performance of heat pumps and refrigeration systems is measured and defined by a metric called **coefficient of performance (COP)**, which is defined as the quantity of heat delivered divided by the electricity needed to drive the refrigeration cycle. The **Uniform Energy Factor (UEF)** is another metric in

[12] https://iifiir.org/en/news/an-award-winning-industrial-dairy-using-an-integrated-heat-pump-system

common use that is closely associated with COP; it is based on the overall performance of a water heating system operating through a defined test cycle meant to mimic typical use. COP and UEF can be applied to heat pumps and also to other water heating technology, including electric resistance and conventional fossil fuel combustion systems. The key difference between COP and UEF has to do with how they are defined. UEF is defined by a particular test method (maintained by the U.S. Department of Energy) and is meant to be applied to multiple technology types for comparison. COP is used for measuring and describing heat pump or refrigeration cycles in general, and can apply to instantaneous or long-run performance. “Seasonal COP” is a term used to describe long-run performance in real-world conditions; this metric is useful for estimating average energy use, costs, and emissions.

COP or UEF = (Quantity of heat absorbed or delivered) ÷ (Electricity input quantity)

There are a range of COP and UEF performance factors for systems in use today, and for heat pump systems that could replace them. For example, Table 2 summarizes these values for water heating technologies in residential and small commercial applications. The key takeaway is that most fuel-based water heating systems have a UEF or COP around 0.6-0.8, based on the limits of combustion efficiency and storage losses. Instantaneous gas water heaters avoid storage loss, and have higher efficiency than storage water heaters. Electric resistance water heaters achieve relatively higher COPs, approaching 0.95, as there is no need for an exhaust flue (a significant source of thermal losses for combustion-based storage water heaters). Heat pump water heaters have a range of performance, with an average around 3.0 (based on lab testing) but some with significantly lower or higher. Even relatively lower performance HPWHs with a COP of 2.0 are twice as efficient as their electric resistance counterparts.

Table 2. *Typical performance for a range of residential and small commercial water heating technology. Summarized from report by Navigant Consulting (2018). UEF: “Uniform Energy Factor,” based on standard test procedure; COP: “Coefficient of Performance,” which depends on operating conditions. Both UEF and COP represent energy output:input ratios.*

Technology Type	**Typical UEF or seasonal COP**
Conventional natural gas storage water heater	0.58 - 0.65
High efficiency natural gas storage water heater	0.66 - 0.81
Instantaneous natural gas water heater	0.81 - 0.97
Electric resistance storage water heater	0.88 - 0.95
Heat pump water heater	2.0 - 4+

COST AND CARBON SAVINGS

Reducing costs and avoiding greenhouse gas emissions are the primary reasons for deploying efficient heat pumps instead of fuel-based or electric resistance devices. Ultimately, these cost and carbon comparisons come down to differences in COP, energy prices, and the carbon intensity of electricity.

Figure 3 below illustrates this for two water heating options, a heat pump water heater versus a conventional natural gas storage water heater.

For any two energy sources (e.g., electricity vs. natural gas), each customer faces different prices and carbon intensities. These alternatives can be framed as price and carbon ratios. In order for **an electric heat pump option to be lower cost (or lower carbon) than the status quo, the ratio of its seasonal COP (or UEF) compared to the competing alternatives needs to be larger than the price ratio or carbon ratio.** In the example shown below, the national-average price ratio between electricity and natural gas is ***3.1:1*** ($40/MMBtu divided by $13/MMBtu) (EIA 2021a). The national-average carbon intensity ratio is ***2.3:1*** (124 kg/MMBtu divided by 53 kg/MMBtu) (EPA 2018, EPA 2020). Since the ratio of UEF for the heat pump vs. natural gas is ***4.6:1*** (UEF 3 / UEF 0.65), the heat pump water heater comes out ahead on both dimensions of comparison. These are not speculative numbers; this illustrative example is for a typical residential comparison using commercially available technology and today's average energy prices and carbon intensity for the residential sector. As the carbon intensity of the grid falls and the true cost of fossil fuel is reflected more in prices, the balance will tip further in the favor of electric options.

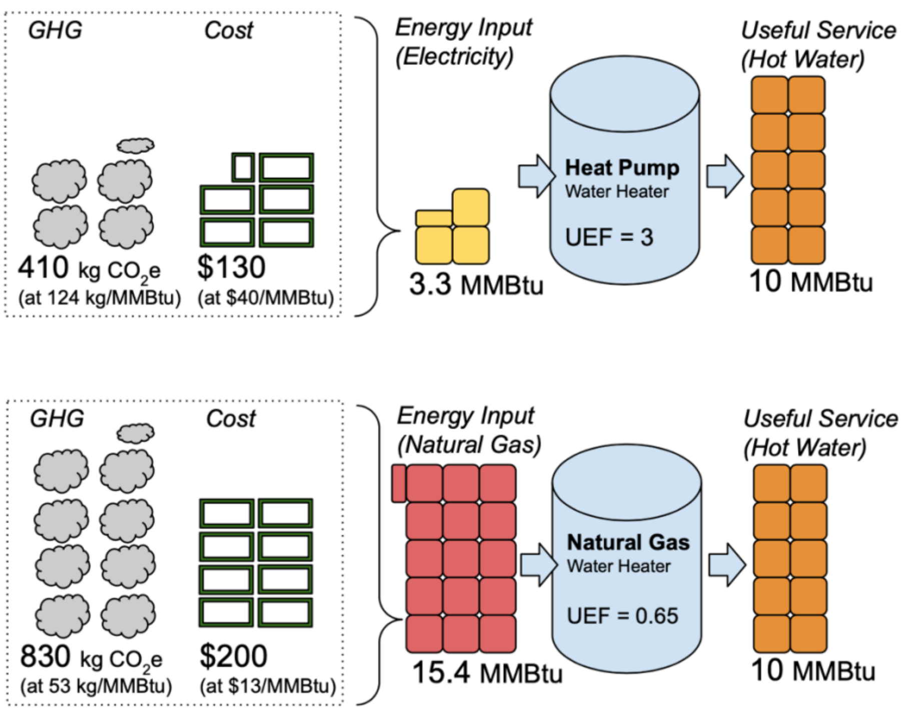

Figure 3*. Greenhouse gas and cost comparison between two illustrative water heating technology systems that both provide 10 MMBtu of useful energy service, with fuel costs, efficiency, and carbon intensity representative of commercially available systems in 2021 operated on the national average natural gas and electricity grid in terms of cost (based on RECS survey (EIA 2021a) and carbon (based on EPA factors documented in point source emissions inventory (EPA 2018) and average grid emissions (EPA 2020): (Top) Heat pump water heater with a UEF of 3, (Bottom) Natural gas water heater with a UEF of 0.65, an estimated average of currently-installed systems (Navigant 2018).*

HEAT PUMPS AND THE NEXT-GENERATION GRID

A combined effort of fuel-switching and cleaning up the grid is foundational for fighting climate change and transitioning to a fully decarbonized energy system (Larson et al. 2020, Williams et al 2012).

The transition of the grid to low-carbon energy generation is already well underway. Electrified water heating will be powered by an electricity grid with increasing fractions of energy provided by zero-carbon generation. Driven by forward-looking policies and rapidly falling costs for solar, wind, and battery storage, a tipping point has been reached in the cost of renewable power in recent years, with the cost of building most new renewable generation in 2020 being lower than the operating cost of existing coal-fired power plants (IRENA 2021).

As clean energy costs continue to fall, 100% clean electricity will be in reach. Indeed, the Biden Administration announced a goal of a fully carbon free grid by 2035[13], a timeline that is both consistent with the pace needed to avoid the worst impacts of climate change and is technically and economically feasible given the pace of progress on the cost and performance of clean electricity generation and storage technology (Phadke, et al. 2020). Heat pumps and other flexible loads can aid the transition by using renewable energy when it is generated, avoiding the need for additional storage.

An improving carbon profile

A cleaner grid means expanding opportunities to switch to electric water heating and reduce emissions compared to the status quo. At present, the EPA eGRID tool estimates electricity used by customers in the U.S. has an average emissions rate of 880 lb CO_2e/MWh[14]. This is significantly cleaner than coal (2,200 lb/MWh) and about the same as natural gas (890 lb/MWh). At this average level, heat pumps only need to have a COP of about 1.5 to break even with conventional storage tank water heating (assuming these operate at an energy factor of 0.65). **The grid is already clean enough for 80% of the country to reduce emissions by switching to heat pumps with a COP of 2 or better.**

A look at regional variability paints a picture that is broadly in favor of decarbonization with heat pumps across most of the country. The map below (Figure 4) shows average electricity-related emissions from eGRID. Regions like the Pacific coast, New York, and New England have electricity that is already clean enough on average--at or below 500 lb/MWh--that replacing a conventional water heater with an electric resistance water heater that has a UEF of ~0.9 could still result in break-even emissions. High efficiency heat pumps, of course, have significant carbon savings in these relatively clean electricity regions. The highest emissions regions--like portions of the midwest and mountain west with an average of 1,500 lb/MWh or slightly more--require a COP of 2.5 up to 3.5. This is challenging but achievable by many heat pumps already on the market. As more solar and wind power come online across the country, the carbon savings potential of heat pumps will continue to grow.

[13] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

[14] This figure and others in this paragraph based on eGRID (https://www.epa.gov/egrid/data-explorer)

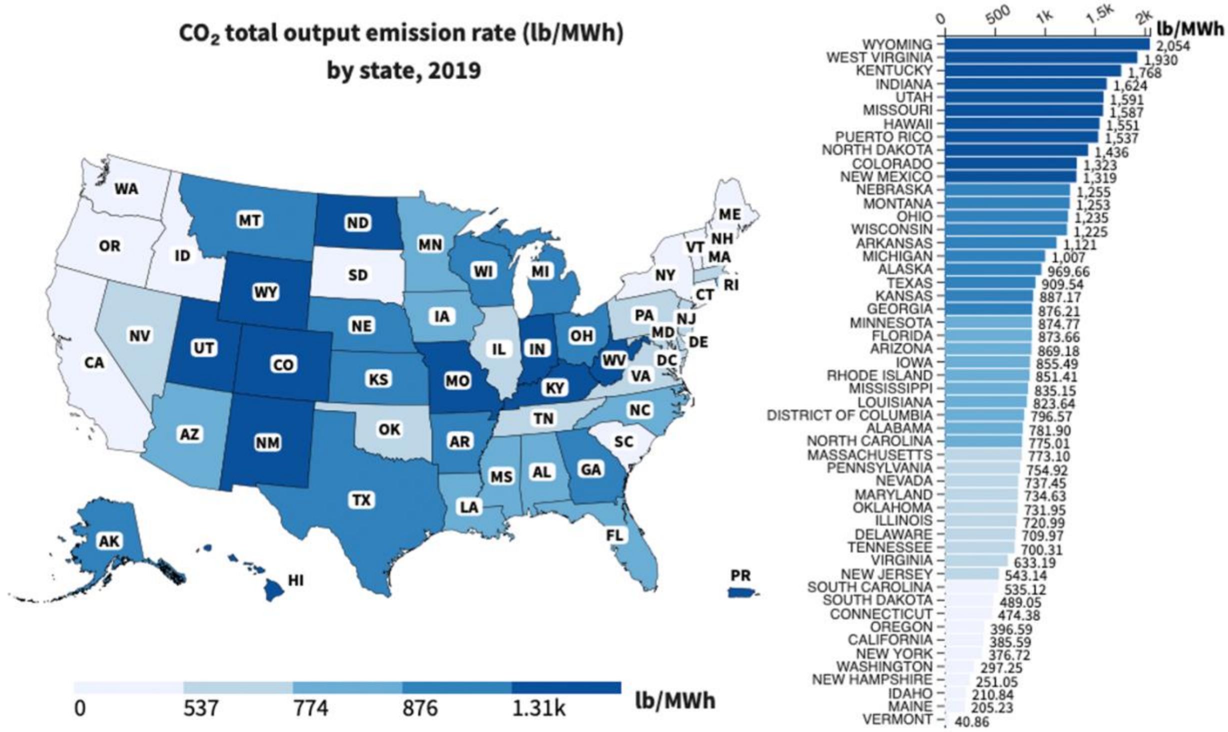

Figure 4. *Average electricity emissions rate by state for 2019. (from https://www.epa.gov/egrid/data-explorer) Data available in Table A25.*

Real-time dynamics and opportunities for flexibility

The dynamics of renewable-dominated power systems are changing in important ways due to the day-to-day and seasonal variations in available supply from solar and wind (Gerke et al. 2019). Since many water heating applications have flexible timing or include built-in storage (e.g., the hot water in storage water heaters), these new electric loads could be used to balance the variability of renewable generation. The experience on the California grid, where renewable generation already serves over one third of the demand (CEC 2021), is emblematic of what will emerge throughout regions that rely more on renewable power in the future. Figure 5 below shows the balance of generation and demand for a recent spring day in California, when solar energy was abundant but temperatures were relatively mild, and thus air conditioning loads were low. On this day, there was a nearly 10-hour period when more solar energy was available than could be effectively utilized; in total 32 GWh of renewable energy was curtailed (i.e., turned down to balance the grid), representing 13% of the total potential renewable generation that day (red striped area in Figure 5). In hours like these when renewable energy is being curtailed, strategic increases in load could soak up the available solar energy at zero marginal cost (and zero marginal carbon). Similar dynamics can also occur with wind power in surplus (typically at night), which happens frequently in places like Texas with high penetrations of wind power.

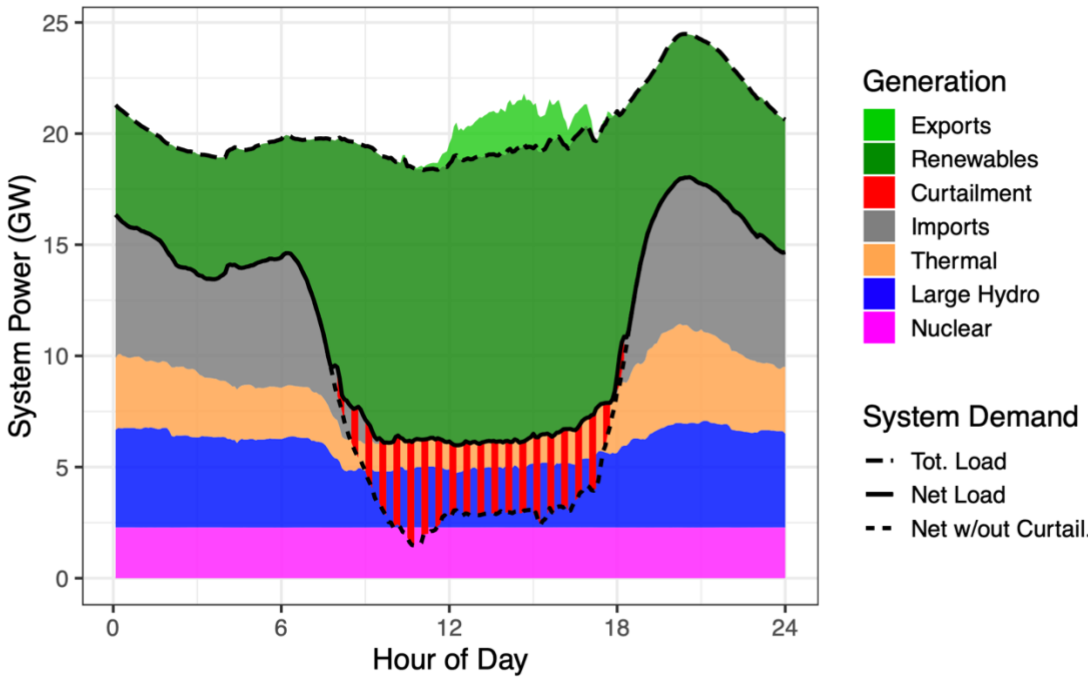

Figure 5. *Balance of generation and demand on April 21, 2019. The total load minus contributions from renewable generation defines the net load. A stack of generation sources to meet the load are in the shaded areas of the plot, matching demand. Curtailment of renewable energy due to system-level constraints (e.g., the need to keep dispatchable generation online) is shown as a red vertical striped area. Based on data from California Independent System Operator public website.*

The upshot for heat pumps with hot water storage is that these times of *marginal renewable power* are when it is beneficial to use more electricity to utilize already-built clean power. When renewables are "on the margin," the wholesale price of energy is typically zero (or even negative if there are production tax credits available to renewable generators). These are also times when using additional electricity does not require additional fossil fuel use or discharge from battery storage. While most retail customers do not currently have access to real-time prices, such tariffs will likely be used in the future along with demand response programs to incentivize alignment of loads with renewable energy. Loads that can be conveniently flexible, like heat pump water heaters, stand to benefit from reduced costs of operation if they can capture more renewable energy by aligning with times when it is available.

Storage hot water heaters (and other similar systems that have "built-in" thermal storage) are excellent candidates for flexible operation, which can be enhanced by incorporating a mixing valve on the outlet of the tank (Cervantes 2020). These "tempering valves" regulate the temperature of outgoing domestic hot water down to safe temperatures (e.g., 120°F). With the valve in place, it is possible to heat the stored water in the tank up to much higher temperatures, essentially using it as a thermal battery. During a typical day, the water heater can be controlled to heat the tank up to 140°F or more during the hours when surplus renewable power is available, then to let the tank temperature drift down in the subsequent hours. With highly insulated tanks, it is possible to use hot water hours after it was "made." From a customer perspective, hot water is always available and at a safe temperature.

Grid Flexibility Analysis Approach

In this study, we use data from current-day grid operations to estimate the possible value to customers from synergy between heat pumps and a future grid with high levels of renewable power. Our approach to estimating the value of flexibility for heat pumps is based on a simplified framework for grid interactivity illustrated in Figure 6 below. The overall concepts of the methods are described below, with more details on the data sources and estimation methods described in the Appendix.

The goal of our flexibility analysis is to estimate possible savings to customers with heat pumps that are able to shift the timing of use to match renewable generation patterns. Achieving these savings would require water heating systems to be able to be controlled to match the needs of the grid, and access for customers to an appropriately strong price signal and/or demand response program incentives.

First, we project future renewable generation impacts on the net load profiles for each interconnected region (the Eastern, Western, and Texas grids) in order to estimate times of renewable curtailment, when additional load would be served by renewable power directly instead of dispatchable generation. The assessment is based on operations data from 2019. In this analysis we "turn up" the renewable generation by scaling up the actual 2019 data for solar and wind power so the sum total balances out with the elimination of most high-carbon energy from the dataset: all of the current-day coal and oil power generated and 75% of all natural gas generated energy. The resulting net load profiles are then used to develop illustrative real-time prices to estimate the benefits of flexibility from heat pumps.

Based on the grid status, we use the average retail price paid ($/kWh) for each customer or customer group as a basis for developing a hypothetical real-time price profile, with low prices at times when intermittent renewables (solar and wind) are marginal and high prices at other times, when dispatchable generation is marginal. Holding the average retail price the same, the low vs. high prices are adjusted to match a given ratio. The price ratios (high to low) we include in this report are 1:1 (flat), 2:1, and 3:1. This range is in line with the approximate ratio of expected costs for building new renewable generation versus renewables plus storage (Lazard 2020).

Finally, using a baseline assumed load shape for each sector or sub-sector, we simulate the baseline costs and savings from shifting a fraction of the energy consumption from high-price to low-price times. Overall, this analysis finds for each customer at various price ratios: the costs of serving water heater loads before and after shifting, cost savings from operating a heat pump load flexibly, and the average shifted energy per day (kWh).

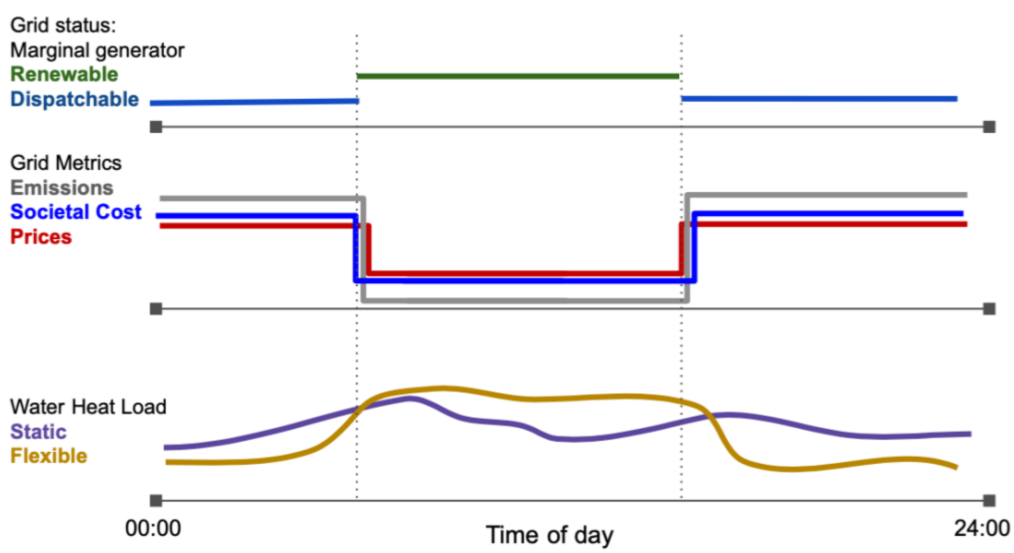

Figure 6. *Simplified framework for price response savings estimates. The times of water heater use is unchanged, but times of heating the water are shifted in the "Flexible" case.*

Heat pump technology landscape

HOT WATER AND INDUSTRIAL HEAT ACHIEVABLE WITH HEAT PUMPS

Homeowners spend $35 billion each year on energy to heat water, businesses spend another $5 billion, and industry spends $30 billion on “low-temperature” heating applications below 150°C / 300°F. All of these applications could, in principle, be met with heat pumps. The overall landscape we considered in this study is mapped in Figure 7, showing how the consumption equates to primary energy requirements of nearly 8 EJ. This results in about 520 million metric tons of greenhouse-gas emissions (CO_2 equivalent) annually (Figure 1). To maximize this opportunity for efficient heat pumps, however, requires a nuanced mapping and strategy for reaching the disparate hot water ‘market segments’, which occur in many sectors and settings. Each segment has its own constraints, technology pathways, delivery costs, consumer dynamics, and institutional decision-making processes. In subsequent sections we describe the scale, market status, and key factors in major sectors that could be a focus for policymakers and implementers.

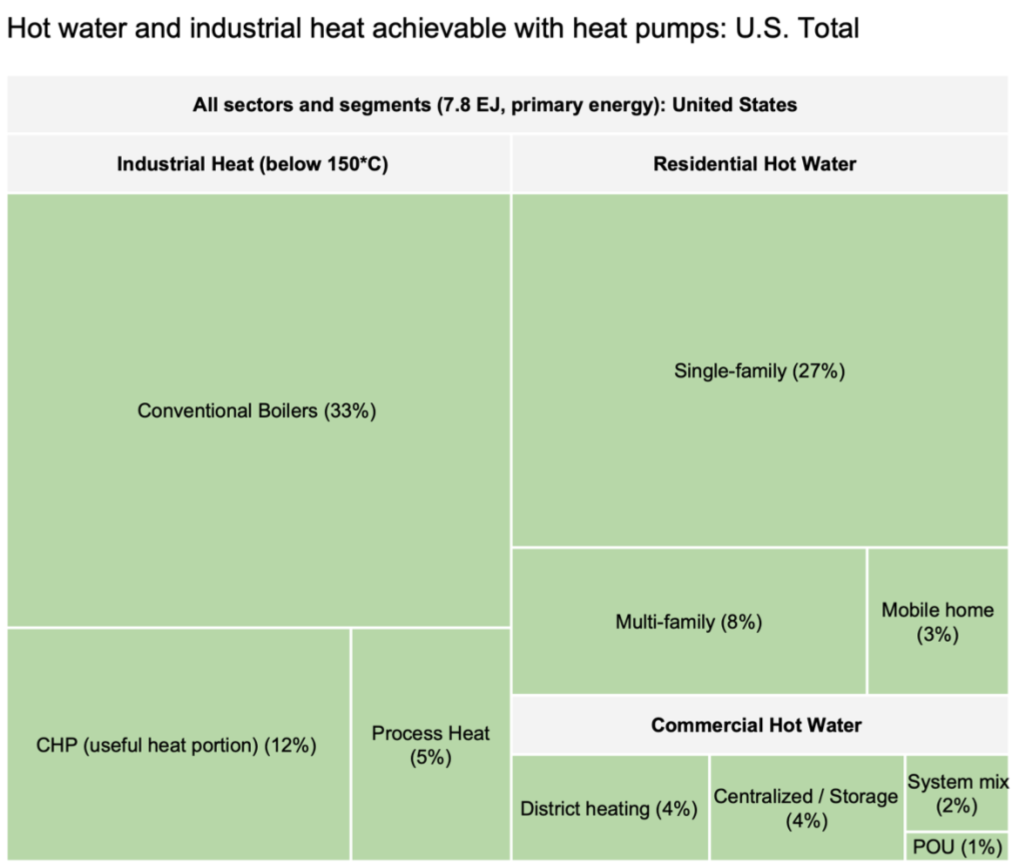

Figure 7. *Estimated primary energy consumed for hot water and industrial sector heat in applications that are technically possible to replace with heat pumps. POU = “point-of-use,” also known as “demand” or “instantaneous” water heating. Data source: authors’ synthesis of CBECS, RECS, and MECS data (see Appendix for more information on data sources, and Table A12 for summary data shown in this figure).*

COST AND GREENHOUSE GAS SAVINGS FROM HEAT PUMP WATER HEATERS

What is the opportunity to save money and cut emissions with a switch from conventional (primarily fuel-based) water heating and industrial heat to heat pumps?

In all of the sectors we analyzed there are significant possible greenhouse gas reduction opportunities. As we described above, the grid is already clean enough in most regions to have "carbon ratios" that are quite favorable for decarbonization with heat pumps. The prices for energy, however, are not fully aligned with these greenhouse gas savings.

The energy price ratio -- the price of electricity divided by the price of conventional fuel--is a critically important factor for determining the economic favorability of heat pumps. Fundamentally, the ratio helps define the average seasonal COP that needs to be reached by a heat pump to break even with a fuel-based option. A common example might be a heat pump replacing a fuel-based system with a seasonal average efficiency of 75%. If the price ratio is 4:1 (electricity is 4x as expensive as natural gas), this means that it will take a heat pump with a COP of at least 3 to break even on cost (in this case, by finding 75% of 4). If the COP is higher than this breakeven point, savings will accrue.

Figure 8 below presents a high-level analysis of the energy price and emissions outcomes across residential, commercial, and industrial customers, considering those who use natural gas and those who use other fuels separately. This analysis omits customers with electric water heaters, who would all use less electricity (and pay lower bills with lower emissions) with a switch to heat pumps. With current-day prices, natural gas customers in the residential and commercial sector will break even on cost with a COP of 2.8 or better. Industrial customers, who pay comparatively less for natural gas, have a median break even COP of 3.3. Users of "other fuels" (often fuel oil, kerosene, propane, and industrial byproducts) tend to pay more, and thus have lower break even COP levels: a median of 1.7 for the residential sector and 1.4 for commercial and industrial customers. All of these median COP values are within reach for modern heat pump systems. The highest-performance heat pumps, with COP 4 or higher, would lead to savings for over 80% of buildings we assessed.

Importantly for decarbonization efforts, the break-even COP on a greenhouse gas basis is lower in general, about half that of the cost basis. Across all three sectors, the median site currently using natural gas would break even on greenhouse gas with a COP of approximately 1.5, and for other fuels the median breakeven COP is near 1 for residential and industrial customers and 1.4 for commercial customers. Over 75% of sites would have lower operational CO_2 emissions with a heat pump that has a COP of 2 or better, and over 95% would have lower emissions with a COP of 3.5 or better.

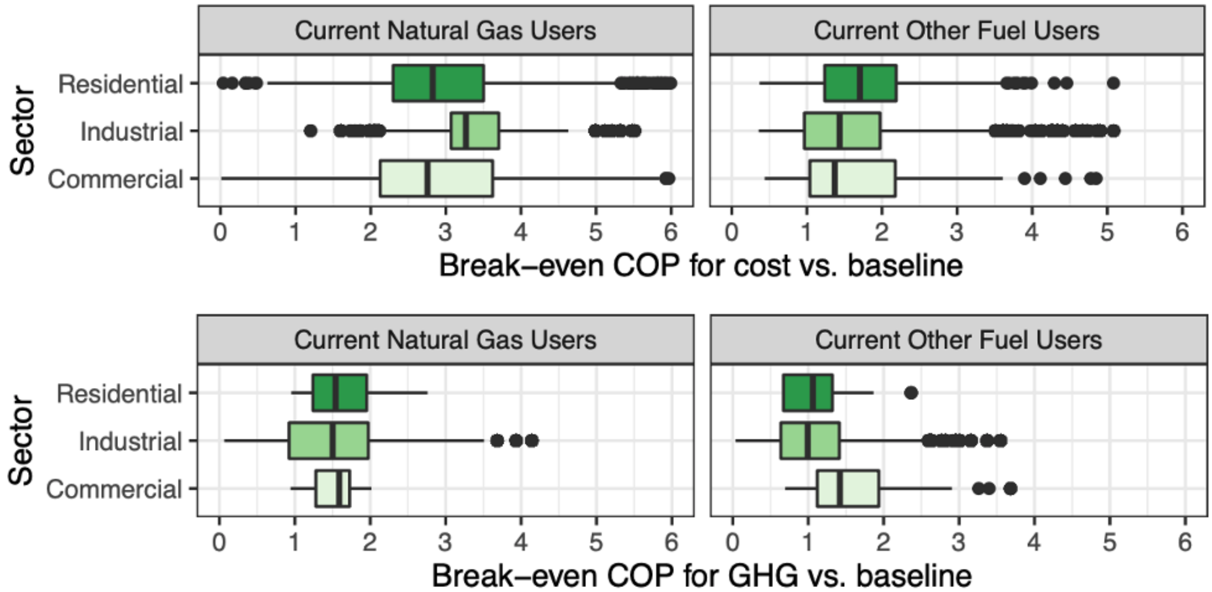

Figure 8. *Break-even coefficient of performance for* ***energy cost (top)*** *and* ***greenhouse gas (bottom)*** *given current-day energy prices (electricity given current prices vs. baseline fuel prices) and carbon intensity (electricity emissions with circa 2020 grid vs. emissions from baseline fuel). Within each plot, current natural gas users vs. current other fuel users are shown separately; sites where electricity is used for water heating are omitted. The quantiles are weighted based on the total heat served at each site. (Data based on synthesis of national electricity and fuel prices from Residential Energy Consumption Survey, Commercial Building Energy Consumption Survey, and Manufacturing Energy Consumption Survey, as documented in Appendices.). Summary statistics for the same data views are in Table A13 and A14.*

The overall opportunity for heat pumps to provide hot water and industrial process heat is clear, based on the picture presented in Figure 8. HPWH with a COP of 2 or more will result in lower carbon with today's grid in over three quarters of sites across all sectors. As the grid gets greener with more and more low-carbon generation, the opportunities for beneficial electrification will only deepen. The break-even COP on a cost basis is already in the realm of achievable performance for HPWHs for most customers.

While there is clear potential to cut emissions and costs, our analysis of the data, historical market trends, and current-day efforts to accelerate HPWH market penetration indicates there is much to do in order to achieve a transition. High incremental total project cost, installation complexity, and lack of education remain as significant barriers to adoption. **In the sections below we explore the major sectors in more detail, describing the economics, technology options, and context for each.**

Residential water heating

Water heating is the second highest energy user in homes, after space heating. As homes become energy optimized, water heating can become the primary user of energy if its efficiency is not also improved (Dean et al., 2012). Even in today's conventional apartment buildings, water heating can be the single largest use, representing a third of the total nationally.[15] Residential energy users spent $35 billion to heat water in 2015 (the most recent survey year) or 16% of their total energy expenditures and primary energy consumption. For single-family homes, about 14% of total energy use is for water heating, whereas the value is 24% for mobile homes and apartments. Water heating was 14% of total electricity consumption by homes and 24% of direct fuel consumption.

There are 118 million homes with water heaters in the U.S. (about 46% of which currently heat water with electricity). Table 3 summarizes the sector overall in terms of which energy source is primarily used to heat water. Due to the relative inefficiency of electric resistance water heaters that are commonly in use--in terms of source energy inputs required--electric water heating represents about 60% of the primary energy used (and spending) for residential water heating in the country.[16] HPWHs hold the promise to replace these inefficient units and switch the rest off of fossil fuel.

Table 3. *Summary of residential sector water heating based on RECS survey (EIA 2021a)*

Primary energy source	Number of sites	Average annual hot water demand per site (MMBtu/year)	Average annual spending per site ($/year)	Total spending across all sites ($/year)
Electricity	54 million	10	$380	$21 billion
Natural Gas	56 million	11	$200	$11 billion
Other Fuels	7 million	12	$380	$2.8 billion

Greenhouse Gas from Residential Water Heating

Among the 118 million households across all the residential building subsectors, approximately 54 million are served by electric water heaters, 56 million by gas water heaters, and 7 million by other fuels. The single-family detached house is the largest subsector in the residential building stock with estimated emissions of 90 million metric tons CO_2e per year (Figure 9). Homes with existing electric storage water heaters are prime targets for HPWHs. Figure 10 displays greenhouse gas emissions per site by energy source, with the data divided into four regions. Electricity (using resistance water heaters) tends to lead to higher emissions except in the Northeast. The South region has a significant number of households using electricity as an energy source for water heating.

[15] All stats in this paragraph from https://www.eia.gov/todayinenergy/detail.php?id=37433 Full detail in the RECS survey, https://www.eia.gov/consumption/residential/data/2015/index.php?view=consumption

[16] The most recent national data is for 2015. See https://www.eia.gov/consumption/residential/data/2015/c&e/ce4.1.xlsx\

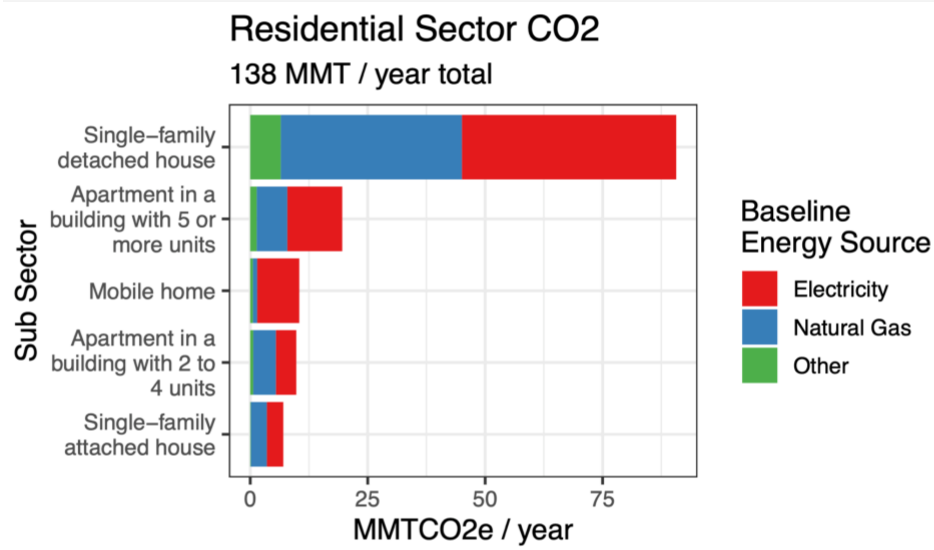

***Figure 9**. CO_2e emissions per year from water heating by residential building subsector. Data source: RECS Survey (EIA 2021a) with EPA emissions factors (EPA 2018, EPA 2020). Detailed summary data from chart are in Table A15.*

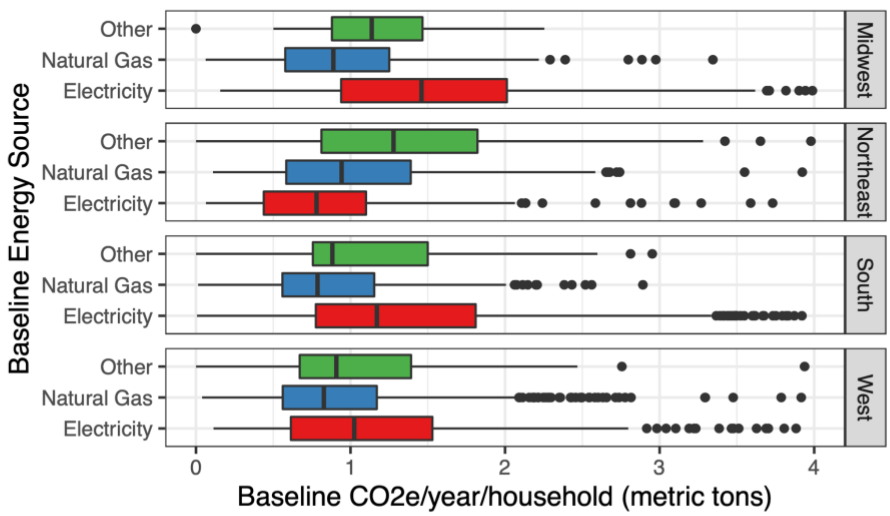

***Figure 10**. CO_2e emissions per year per household from water heating, divided in four national regions. Data source: RECS Survey (EIA 2021a) with EPA emissions factors (EPA 2018, EPA 2020). Detailed summary data from chart are in Table A16.*

To meet the needs of the residential sector with decarbonized clean energy, two distinct technology options are appropriate. First are **unitary heat pump water heaters** (in which the heat pump and storage tank are combined)**.** These systems are appropriate for replacing the numerous storage and instantaneous water heaters that are typically used in single family homes, mobile homes, and multifamily housing where each unit has a separate water heater. For large, multifamily housing with shared hot water services, there are also options for larger, **centralized heat pump hot water** systems. To a lesser degree, municipal district heating systems can also provide household's with hot water.

UNITARY HEAT PUMP WATER HEATERS

Market Dynamics for HPWHs

Between eight and nine million residential storage water heaters are purchased each year, roughly half of which use gas and the other half use electricity (Figure 12). Most (~80%) are for the replacement market (meaning they go into existing buildings, replacing a failed or end-of-life water heater). A small, but growing share of the market is on-demand “tankless” water heater that do not have storage.

Hot water heaters don’t get a lot of attention in the market, especially from homeowners who tend to view them as “mysterious” (Parker 2011), and do not typically consider them to be amenities. They are also cumbersome products for the industry, heavy and difficult to move and inventory, with low prices and low profit margins for manufacturers. The people who specify water heaters (plumbers, builders, property managers, specifying engineers) are not typically the ones who use them (or pay for their energy). This is slowly beginning to change, as zero net energy buildings become the goal and consumers become more interested and proactive.

With national sales of roughly 52,000 units, HPWHs achieved a 1% share of national residential storage water heater sales in 2016 (based on current rules, essentially all HPWHs are ENERGY STAR certified). At that time, the market penetration in terms of the share of the existing installed base was about 0.4%. While national market penetration has been poor, there have been pockets of quite successful local deployment program activity. The scale and approaches of these programs is described in the section on market transformation below.

Figure 11. *An assortment of residential HPWH, from Higbee et al. (2020).*

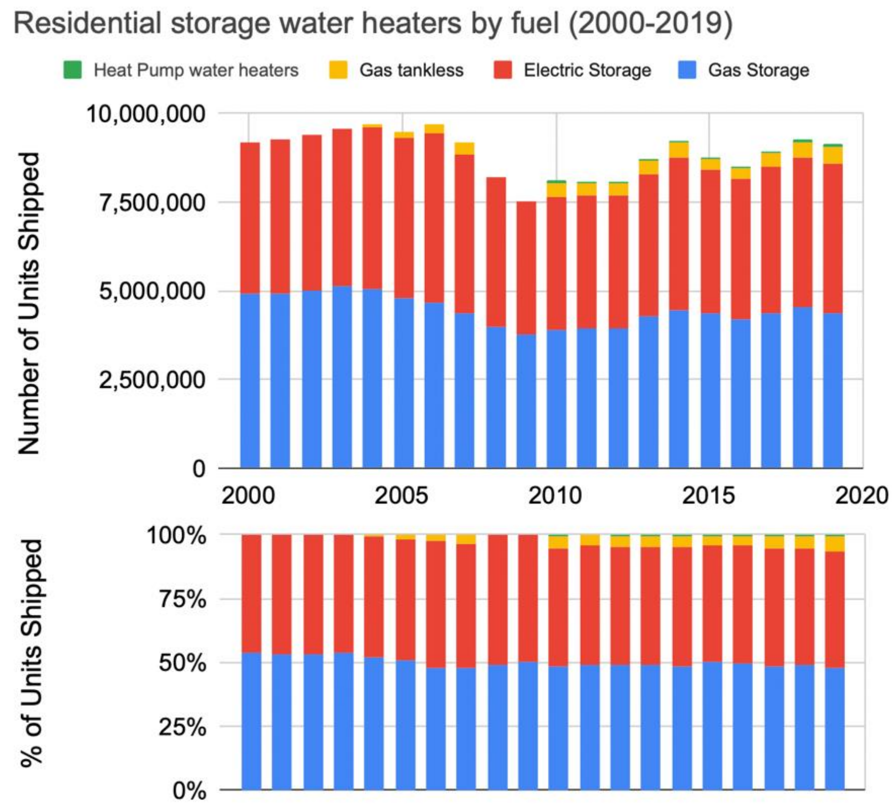

Figure 12. Shipments of residential water heaters over time. *There were a small number of oil-fired storage tanks in the early 2000s (approximately 35k units/year) but current data are not provided by AHRI. These sources provide no tankless unit data for 2008 and 2009, or before 2004. Sources: Gas and Electric storage: AHRI (2020); 2004-2007. Instantaneous gas water heaters: (EERE 2006) and ENERGY STAR Unit Shipment and Market Penetration Report (2010-2019); HPWH data also from ENERGY STAR (2010-2019). For detailed summary data from this figure see Table A17.*

Heat pump water heaters for domestic hot water are applicable across all of the residential sub-sectors: single-family, multifamily, and mobile home housing types. Within these sub-sectors there is a growing set of technology options for HPWHs:

Integrated Unitary HPWH - These combine a storage tank with an integrated air source heat pump in a single unit, with the heat pump typically on top of the tank. These are the most commonly installed systems. They can be installed indoors, in conditioned spaces or unconditioned spaces like garages and basements. They are essentially a drop-in replacement for a conventional gas or electric resistance storage water heater. Most require a dedicated 240 volt electrical circuit, but some emerging options on the market only require a typical 120 volt circuit. Because integrated HPWHs extract heat from the ambient indoor air around them, they can lead to local “cool spots” where they are installed. If the unit is located in conditioned space, during the winter some of the cool air generated by the HPWHs will need to be made up with more heating by the HVAC system, and during summer the cool air can reduce the cooling loads on air conditioners. If the room where the HPWH is located is too small or the cool air would lead to comfort issues, it is possible with many integrated HPWHs to install ducting to access attic or outdoor air (at an additional cost). HPWHs also dehumidify the air around them, which is often a selling point for humid climates, basements locations, etc.

Split HPWH - These have indoor storage tanks that are heated by a heat pump system that is located outdoors and is connected by hot water or refrigerant lines. A key benefit to split HPWHs is that heat is harvested from outdoors, underground, or some other source outside the thermal envelope of the home. This prevents cool spots indoors. It also opens up possibilities to combine water heating with space heating through hydronic systems. These combined systems are available and widely used internationally. Existing fuel-fired hydronic heating systems (e.g., those using radiators) are particularly good candidates for retrofit with these combined water and space heating systems.

Add-on HPWHs - These are designed to be installed alongside existing conventional fuel-based or electric resistance storage water heaters. Add-on units have existed since the earliest dates of integrated heat pumps (Gehring 1986) and were available in the U.S. market until at least 2012[17], if not longer, although none are offered at present and ENERGY STAR does not have a category for them. U.S. agencies have had their eye on these types of systems since trials in the early 1980s, if not longer (Harris 1983); DOE even evaluated some in the late 1970s (Dunning et al., 1978).

HPWH Performance

Residential HPWH efficiency is highly variable. Figure 13 displays values for individual units found in the literature, as well as clusters of ENERGY-STAR-qualified products in 2010, 2015, and 2020. Important caveats are that test procedures vary by country and time, and field-test data reflects user behaviors not captured in lab testing. This analysis shows that while the average ENERGY STAR value of HWHPs has increased significantly since 2010, the causal connection to the program is not known. Every model in the market likely qualified for the ENERGY STAR ratings in the three years shown. Setting aside the early models temporarily marketed in the 1950s, and increasingly better performance of the highest efficiency units (with COP of 3 to 4, and up to 5 at best), there is not much discernible improvement in best-in-class efficiencies over this very long time period. Even within the measured and rated cohorts, efficiencies today range widely. The range of COP including both lab and field test results in the last five years is from about 1.5 to 4, with an average around 3.

[17] See https://www.greenbuildingadvisor.com/article/getting-into-hot-water-part-2

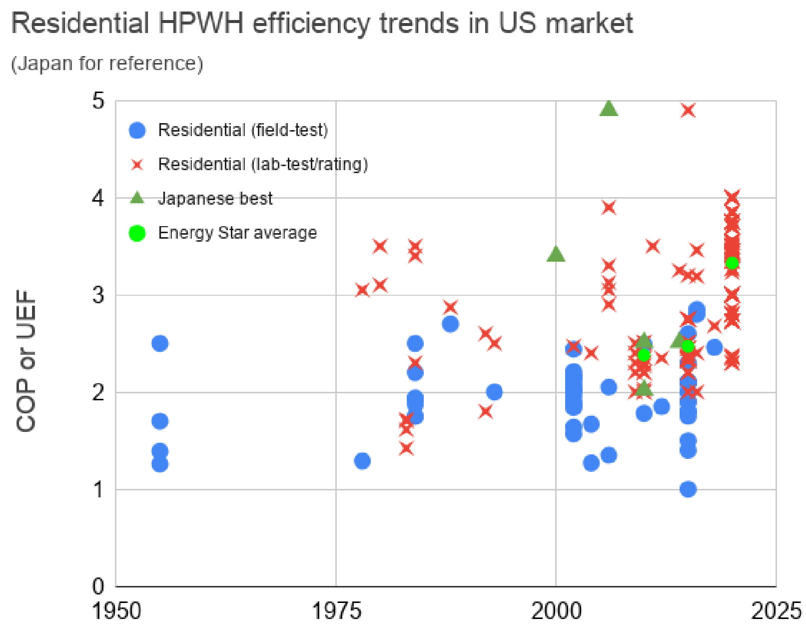

***Figure 13**. Efficiencies of residential HPWHs over time (higher is better). Shown are products identified in the literature and available on the U.S. market (with the exception of the two Japanese data points, provided for reference), with a mix of lab-tested and field-tested performance (see legend). Test procedures and metrics vary by country and time. Location on x-axis is the year of published measurement, not necessarily that of product manufacture. Note: Poorest performer (2015) is GE's GeoSpring unit, which was presumably set or stuck in electric-resistance mode during the test period. Sources: Dunning et al., (1978), Wan (1983), Harris (1983), Calm (1984), Usibelli (1984), Ashdown et al., (2004), Hashimoto (2006), U.S. DOE (2009); Franco et al., (2010), Sharaf-Eldeen, et al., (2010), Shapiro and Puttagunta (2016) (p 14), Butzbaugh et al.,(2017), WHEC et al., (2019), ENERGY STAR Product List (9/2020).*

Grid-enabled units

Grid-control of water heaters dates back 50 years, using FM radio signals (Krause et al., 1987). GE introduced one shortly before it withdrew entirely from the HPWH market. Utilities have been deploying controlled resistance water heaters in their load-management programs for some time, along with remote disconnect switches for standard electric water heaters.

Today's approaches are more diverse, sophisticated, and flexible. We identified 23 grid-enabled water heaters on the market, from six manufacturers. Most of these are electric-resistance units. EPRI embarked on development of a grid-enabled HPWH about a decade ago (EPRI 2012), with two brands of HPWHs on the market currently (Rheem[18] and AO Smith) and many more expected shortly due to California's incentive programs. The tanks range in size from 78 to 111 gallons. Data available on manufacturer websites is generally unclear on the specific modes of communication and capabilities of these units, with ports and protocols including CTA-2045 (a standardized port), WiFi / IEEE 802.11, Bluetooth, Zigbee, Cellular, FM Radio, and Open ADR.

[18] See https://www.rheem.com/hybrid-builder

CENTRALIZED MULTIFAMILY HEAT PUMP HOT WATER SYSTEMS

Large apartment complexes, while technically residential buildings, have commercial- or industrial-scale water-heating system needs, often with centralized provision of hot water. Individual, "single-family type" unitary HPWH units may be applicable in some apartment buildings. However, small apartment sizes mean that the noise from HPWHs can be an issue, as well as the lack of adequate heat sources, and/or access to condensate drainage options.

Armstrong et al., (2019) document applications of heat pump hot water systems serving a total of 1265 living units in buildings, including five centralized systems serving 50- to 102-unit complexes and individual systems in the others. Centralized heat pump hot water systems have an added potential of serving hydronic space heating needs with the same systems.

Other than case studies, there is very limited data on the deployment of heat pump water heating for these larger residential applications, and few if any utilities have promoted them for these types of customers. However, there are a number of qualitative factors that suggest this segment could be an important area of growth:

- The emergence of high-temperature, high-efficiency heat pumps (described below in the Industrial section) provide a range of options for heating water at a scale matched to multifamily building demands.
- Large building owners have concentrated decision-making and maintenance authority over many housing units. They and their energy managers may be more sophisticated buyers of heat pump systems than many single-family residential customers who face more diffuse incentives to invest effort in a technology transition (i.e., multifamily building owners may save thousands rather than hundreds of dollars annually).
- Multifamily buildings may have enhanced opportunities to use heat sources other than ambient air since the systems are large enough to benefit from site-specific design. These include ground-source (often referred to as "geothermal"), water bodies, sewer drains, laundry exhaust, and other sources of ambient heat that are commonly used in large-scale district heating applications of heat pumps (David *et al.* 2017).

BILL SAVINGS AND COSTS OF HPWHS

Based on the prices of electricity and conventional fuels for water heating, many residential customers could experience savings from switching to heat pumps. All current users of electric resistance heaters would benefit. Based on the energy prices residential customers pay today (for electricity and fuels), the average break-even COP for HPWHs replacing fuel-based systems is 3.0 for single family detached housing (which accounts for 65% of the baseline emissions in the sector). Mobile homes stand out as a sub-sector with both favorable price ratios for electrification, with a lower break-even COP of 2.4. For HPWHs with COP of 3--which is readily attainable with modern equipment and is approximately the average of ENERGY STAR lab-based test performance--a vast majority of customers (over 75%) would save money compared to the status quo.

Given current-day use patterns and prices, there is a wide range of economic favorability of operating a HPWH versus incumbent technology. Figure 14 below shows the expected distribution in outcomes among customers who hypothetically adopt a HPWH with a COP of 3 across regions, by fuel type (two key variables). The average customer in this analysis saves \$150/year compared to their conventional water heater (out of an average spending of \$300/year), with significant variability between customers. Customers who currently use electricity stand to benefit most with an average savings of \$260/year out of \$380/year baseline spending. Customers who use fossil fuels other than natural gas (e.g., fuel oil, propane, kerosene) also have high baseline spending (\$380/year) and relatively high average savings (\$180/year). Natural gas water heating customers tend to spend much less as a baseline (\$200/year) than those using electricity or other fuels; the average savings from a switch to a HPWH are more modest as well, approximately \$40/year. There are important regional differences to consider as well. In the South region, the average savings switching from gas to a HPWH are \$80/year, while they are less than \$10/year in both the Midwest and Northeast regions due to regional differences in energy prices and hot water utilization.

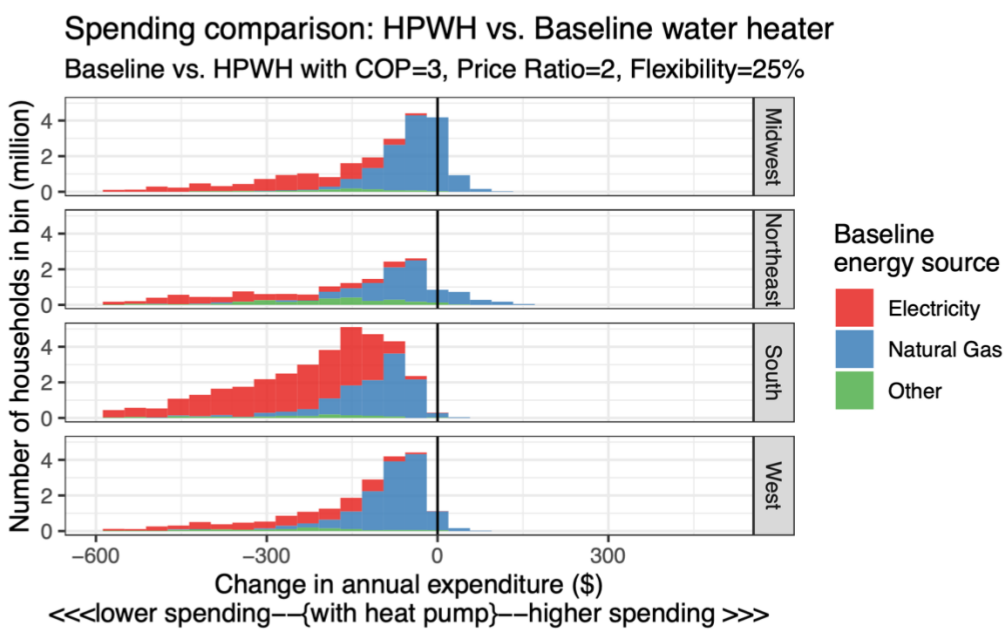

***Figure 14**. Distribution in savings for residential customers replacing baseline water heating technology with a HPWH with a COP of 3.0. This analysis does not consider any additional savings possible from flexible operation to provide grid service or respond to dynamic real-time prices. Summary data for this figure are in Table A18.*

For average customers who save ~\$150/year using a HPWH, the implied undiscounted total savings over a ~13-year lifetime of the system is \$2,000. While these savings are significant, they are not overwhelming compared to the differences in cost for HPWH equipment and installation compared to replacement of a conventional water heater. Table 4 summarizes the range of up-front costs customers who are replacing[19] a water heater face. Heat pump water heater equipment and installation tends to be more costly. In total, the increased cost ranges from a few hundred to thousands of dollars depending on the baseline technology, whether professional installers are hired, and the complexity of the replacement. Installation costs increase significantly if an electric panel upgrade is required, if the condensate drain installation is challenging where the water heater is located, or if the existing water heater is located in a confined or frequently occupied space, requiring ducted ventilation for the inlet and/or outlet on the air side.

Table 4*. Synthesis of equipment and installation costs for residential water heating options. Data are primarily taken from ranges provided in Navigant (2018), with additional installation cost for HPWHs added based on additional research and case studies. These costs are for "retrofit" of existing buildings, not new construction.*

Equipment Type	Equipment Cost	Installation Cost	Total Cost
Gas storage water heater (UEF range: 0.60 - 0.80)	\$700 - 2,000	\$600 - 2,000	\$1,300 - 4,000
Gas instantaneous water heater UEF range: 0.8 - 0.97)	\$700 - 1,700	\$800 - 1,600	\$1,500 - 3,300
Electric resistance water heater (UEF range: 0.92 - 0.95)	\$300 - 900	\$300 - 600	\$600 - 1,500
Heat pump water heater (UEF range: 3.2 - 3.5)	\$1,200 - 2000+	\$500 - 3,000+	\$1,700 - 6,000+

The differences in spending and savings among customer segments, regions, and baseline fuel types are important for considering pathways to incentivize and support HPWHs. Current electric resistance customers could be key early adopters since 100% will experience savings with a high average amount saved, and the required high-power electrical circuits and panel space is already in place to support their existing systems. While the emissions associated with electric resistance water heating are expected to go down as the grid is cleaned up, this can be accelerated through adoption of HPWHs that are 3x as efficient as resistance heaters. About 90% of customers using fuels other than natural gas will experience savings, and at an average level that is significant. Most of these "other fuels" customers are in the Northeast region; they could be an important focus for change-out programs. In addition, supporting customers who use natural gas water heaters to switch to HPWHs is an important goal for climate mitigation since 40% of the GHG emissions in residential water heating are associated with this group. About 70% of these customers will save money with a HPWH that has a COP of 3, but the average savings are only \$40/year. The relatively lower baseline spending and therefore fewer opportunities for savings mean that this will require more nuance and effort. In the section on market transformation

[19] Most water heaters are replaced on failure, creating "panic purchase" situations in which there is little time for homeowners or landlords to deliberate and consider options beyond a simple replacement of the previous model with equipment that is in stock and familiar.

below, the dynamics of customer adoption and programs that have been designed to support transitions to HPWHs given these realities are described in more detail. In addition to programmatic support, an additional technical pathway for improving the value proposition will be through flexible operation of HPWHs in response to emerging needs on the grid (and opportunities to save money through real-time electricity price arbitrage).

FLEXIBLE WATER HEATING TO INTEGRATE WITH RENEWABLE ENERGY

Heat pump water heaters can operate flexibly to match the availability of renewable power, if enabled with the right communications, control equipment, and price or demand response signals from grid operators. The features needed to make HPWHs flexible include:

- **Pricing and incentives:** Demand response programs or real-time retail pricing are needed to incentivize shifting and shedding of water-heating load at the right times for the grid. As more renewable energy comes online, grid operators may increasingly look to real-time pricing to incentivize customers to make use of solar and wind power that would otherwise be curtailed.
- **Communications and control:** HPWHs need to have a reliable way to receive and respond to prices and other signals from grid operators. There are emerging standard communications ports and modules (e.g., CTA-2045) that are being built into some water heaters at the factory and can be updated as needed at low cost by customers. Furthermore, standards and certifications are being developed (e.g., NEEA Advanced Water Heater Specificaiton[20] and California JA-13[21]) that could be models for national programs.
- **Enhanced storage:** The storage tank of HPWHs is key to their flexibility. By pre-heating water for later use, a HPWH can essentially act as a thermal battery. The installation of a mixing valve can increase the effective capacity by enabling "overheating" of the tank beyond typical temperatures (e.g., up to 140°F). The valves mix in cold water on the outlet of the tank to bring the temperature down to a target suitable for domestic hot water use (typically 120°F). These valves are costly to retrofit (several hundred dollars), but similar to communications modules, they can be incorporated at the factory for relatively low costs (less than $100).

The technical capability to shift the timing of heat pump water heater load has been shown in a range of pilots and case studies. The largest field-based study so far of flexible, grid-interactive water heaters was run by the Bonneville Power Administration and published in 2018 (BPA 2018). This study involved deployment, operation, and monitoring of these HPWHs for nearly 300 customers through a number of demand response and price events. The study concluded that a standardized communication interface (CTA-2045) is a viable method for cost-effectively controlling water heaters, with the cost of communications enablement expected to drop from $100 to $20 per unit if significant scale were achieved.

[20] https://neea.org/img/documents/Advanced-Water-Heating-Specification.pdf
[21] https://www.energy.ca.gov/rules-and-regulations/building-energy-efficiency/manufacturer-certification-building-equipment/ja13

A model-based study by Carew et al. (2018) indicated that managed operation in response to a range of potential pricing profiles resulted in ~20% of load being shifted on average (reducing bills by $30 per year compared to unmanaged operation). This study also found that utility cost savings were much higher (2x or more) than customer bill savings from the load shifting that was modeled, indicating it may be possible to provide additional incentives or more aggressive pricing to increase the value proposition.

We modeled the potential increased savings for residential customers using hypothetical but plausible real-time retail price ratios and fractions of load that can be flexible.[22] Figure 15 shows the average outcomes for a range of possible COP values (1-4), electricity price ratios (between 1:1 to 3:1), and fractions of HPWH energy use that is flexible (0-30%). At COP levels that are expected for near-term technology (2.5-3.5), the additional value of flexibility is $40/year for the average customer, with similar savings across all of the baseline energy sources (electricity, natural gas, and other fuels). These added savings increase the fraction of customers whose bills are lower with HPWHs, particularly for natural gas customers. Without flexibility, ~75% of natural gas customers would be better off with a HPWH that has a COP of 3; with 30% flexible load this fraction rises to 95% (assuming a 3:1 price ratio between low and high price periods). The added value of flexibility is somewhat ironically much higher for water heaters operating at lower efficiency, since there are more kilowatt-hours to shift.

[22] See text box earlier in report for details. In summary, the real-time price ratios refer to the difference in price between low-price times (when renewable energy is in surplus) and high-price times (when additional energy is served by discharging batteries or other dispatchable generation). The timing, frequency, and duration of these events is based on expected future grid conditions with high penetration of renewable power. The HPWHs in the model can respond by shifting some fraction of their daily load from high- to low-price times (the “flexibility fraction”).

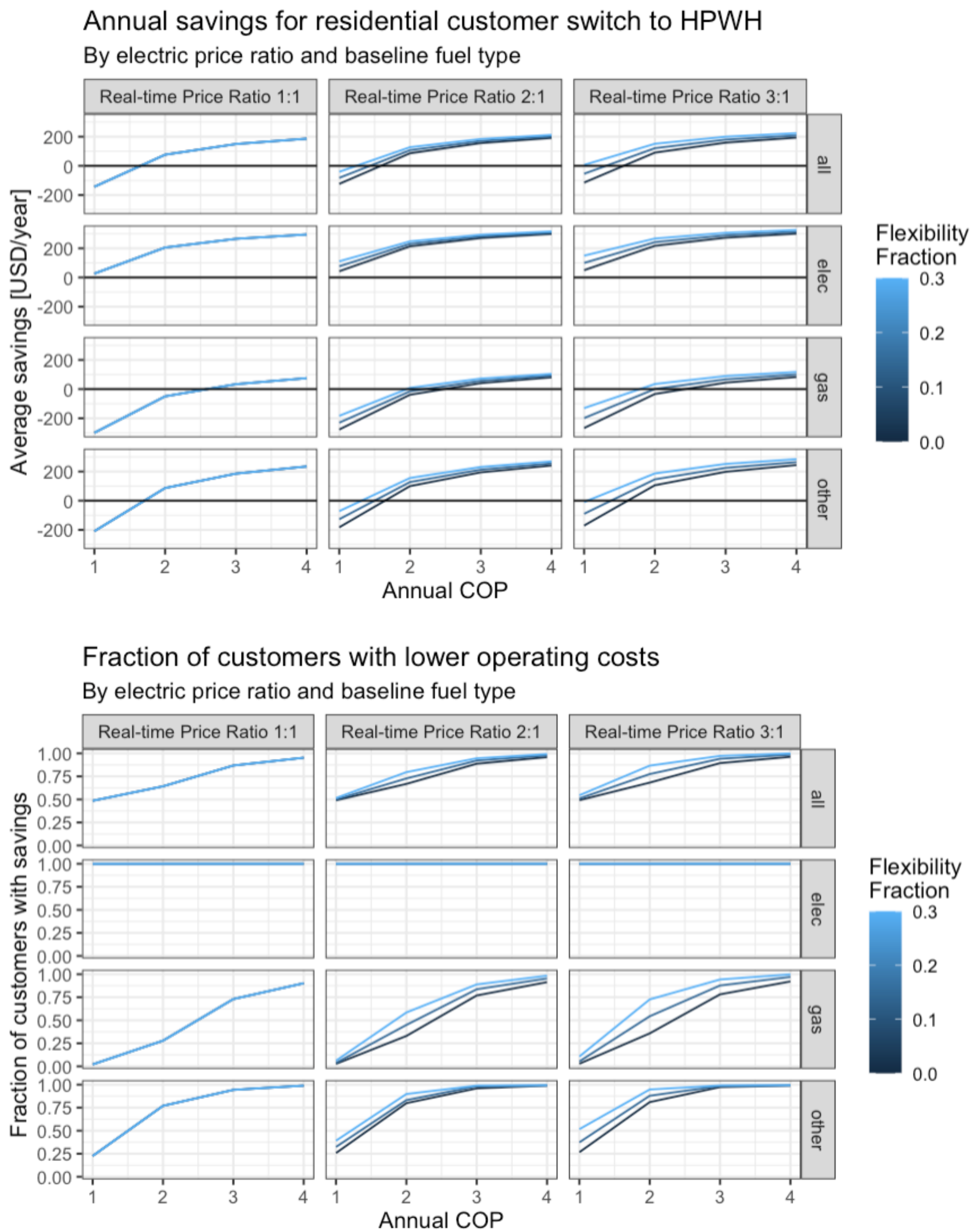

***Figure 15**. Average residential customer outcomes for a range of scenarios for HPWH performance (COP), retail "real-time" electricity price ratios, and the fraction of load that can be shifted from high-price to low-price times. Each row in the plot corresponds to different groups of "baseline" current technology in use: all customers, followed by those using electric resistance water heaters, natural gas water heaters, and other fossil fuels. **Top:** average annual savings in operating costs for HPWH compared to status quo. **Bottom:** fraction of customers with savings.*

Takeaway points from analysis

The **efficiency of heat pumps is the most important factor for cost effectiveness.** At a COP of 2.0 or better, most customers experience savings. There are significant returns for achieving a COP of 3.0 or 4.0. After that, returns diminish as the savings reach a plateau (since it is not possible to save "more" than one was originally spending). However, while the savings can be significant in aggregate (adding up to billions of dollars in possible savings across the economy), at any one site savings are relatively modest, often on the order of $50-$200/year. Across the approximately 10 to 15-year lifespan of HPWHs, this adds up to $500-$3,000. This may not be sufficient to overcome the initial cost differences however, particularly at households where electrical or other infrastructure upgrades are needed.

Adding demand flexibility capability can add value for the customer. Across the scenarios we modeled, savings of an additional $20-50 per year are expected at sites where 15-30% of demand is flexible, compared to sites without load flexibility. These savings are likely to be well worth the added expense of adding communications capabilities to water heaters (e.g., through emerging CTA-2045 or JA-13 standards). The cost of communications modules is currently $100 but expected to fall to $20 per unit at scale (BPA 2018).

Additional value could be possible from peak load reduction and other demand response services, including increased resilience and reduced incidence of blackouts during times of grid stress. However, the customer savings levels alone are not likely to spur market demand for this feature, and the cost of retrofitting existing water heaters is hundreds of dollars more than if the features are included as part of manufacturing. Given the importance of demand flexibility at the system/society level, policies may be needed to ensure widespread adoption of this feature. California's proposed Self Generation Incentive Program requires demand flexibility capability and implementation as conditions for incentive eligibility. Policies like these could spur significant market adoption of grid flexibility features, which could be important to assist in cost-effectively integrating electric water heating at millions of sites.

RESIDENTIAL MARKET TRANSFORMATION

The analysis above, showing significant potential for reducing greenhouse gas and achieving ongoing cost savings, needs to be tempered with the reality of customer behavior. Studies tracing back nearly 40 years describe the persistent gap between economically "rational" energy efficiency investments and actions of real consumers. These findings underpin policy measures ranging from information programs to utility rebates to appliance standards. A useful metric used to quantify the extent of the gap between actual and optimal choices of increasingly efficient appliances has typically been the implicit discount rate (Ruderman et al., 1984), which is essentially the discount rate that equates the net present values of efficient and inefficient alternatives. This of course is not a consciously applied discount rate, but, rather, a number that integrates all of the inertia in the market into a numerical value. Rational real discount rates used in energy policy analysis (and public sector and corporate decisions) are typically on the order of 3 to 7%. Higher values reflect an undervaluation of future energy savings. Water heaters are an ideal consumer good for implicit discount rate analysis, thanks to their relative uniformity, high capital and operating cost, and general lack of amenity beyond the actual energy service provided. **The**

range of implicit discount rates found for efficient water heater purchases spans 19% to 816%, with electric water heaters having significantly higher rates than gas-fired ones. This is higher than other energy-using household goods studied (Kim and Sims 2016). With these practical discount rates, few customers will actually invest in more efficient water heaters (which is reflected in market data).

In many cases there is not even a basis for economic analysis, evidenced by the particularly intractable so-called landlord-tenant problem, wherein **property owners tend to see no benefit in spending more to purchase energy efficient devices when tenants are paying the energy bills**. Water heaters are particularly susceptible to this issue, as they are part of the building and virtually never tenant-owned. More than one-third of housing in the U.S. is rented.[23]

For these and other reasons, a number of program designers and evaluators have come to the conclusion that in order to achieve their goals in the residential sector, they **need to essentially give away HPWHs**, or require them once costs come down sufficiently and complementary funding is available to cover electrical upgrades. Table 5 summarizes a range of current "deep incentive" programs for residential water heaters. Note that the values in the table do not include the $300 federal tax credits that may also be claimed by program participants.

Seasoned program operators also conclude that "upstream" incentives (to manufacturers) or "midstream" (to distributors, wholesalers, retailers, plumbers) are much more effective than "downstream" incentives that require customer effort and paperwork to access.[24] Furthermore, upstream and midstream incentives can be less costly due to avoiding markup in the supply chain (Lekov et al. 2000). Noting the meager HPWH offerings from big-box retailers (a survey of website offerings in October 2020 found only 14 HPWH out of over 1,000 available models online through home improvement store websites); offering a sales-based incentive to these midstream sellers may be particularly productive.

In the process of planning for future demand-response residential water heating programs, Bonneville Power Administration found that full participation could require a *recurring* incentive of $200 or more per year, distinct from the incentive needed to install grid-enabled energy using equipment. Bill credit, cash rebate, and discounted electricity rates were found equally attractive as incentive structures. (BPA 2018).

[23] See https://www.eia.gov/consumption/residential/data/2015/hc/php/hc9.1.php

[24] NEEA per personal communication, Geoff Wicke, October 23, 2020. See also SMUD per Cox (2020).

Table 5. *Deep incentives for HPWH uptake.*

Sponsor	Incentive (excluding tax credits)	Participation rates	Equip. only or all costs	Recipient
BayREN - 9 Bay Area jurisdictions	$1,000			
Boulder	$1,450			
Con Edison	$1,000		Equip.	
Efficiency Maine	up to $750 (together with bulk-purchasing price reductions at retailer level)	34% of retail/distributor electric storage sales in 2019	Equip.	Distributors, retailers, or consumers
Efficiency Vermont	Up to $800 (including $200 for low-income participants), plus incentive to distributor.	~12% of all water heater purchases. (60% of electric-to-electric conversions.)	Equip.	Distributors or consumers
Electrify San Jose	$1,000 HPWH, plus up to $4,500 without panel upgrade and $6000 with panel upgrade		All costs	Consumer
Energize CT	$750			
NEEA - new and existing	$250-$600	Fraction of <u>electric storage</u> water heaters: 9% (average, ID, MT, OR, WA).		
NEEA - new construction	$250-$600	Fraction of <u>electric storage</u> water heaters: 33-44% (average, ID, MT, OR, WA). Approximately half of total WH sales in the region are electric.	Equip.	Consumer and upstream
NEEA - replacement	$250-$600	Fraction of <u>electric storage</u> water heaters: 1% (ID, MT) to 9% (OR) and 10% (WA) - variation primarily due to proximity to large cities). Approximately half of total WH sales in the region are electric.	Equip.	consumer and upstream
NYS Clean Heat	Up to over $2000 per unit**			
Palo Alto	$500 (existing electric WH) $1,200 (<80 gal gas WH) or $1,500 (80 gal+ gas WH) (up from $300 in 2016)	0.4% participation rate. 15,800 eligible households and 60 systems installed as of 29-Oct-2020.		
SCE	Up to $1,000 for equipment Up to $1,500 for electrical upgrades			Upstream
Silicon Valley Clean Energy	Up to $2,000 for equipment (UEF 2.9 or greater); Up to $1,500 for electrical upgrades, Up to $1,500 for CARE/FERA customers		All costs	Consumer
SMUD	Up to $2,500 for equipment (plus $2,500 for electrical service upgrades if entire home electrified)			Consumer

Reaching low-income customers

As policies and programs are planned to incentivize HPWH, it is important to account for differences in the incomes and abilities of potential users to pay for upgrades. Table 6 summarizes the average spending and value proposition for residential customers by income category (as defined in the RECS survey). Several key trends related to income emerge from this: first, while higher-income households tend to use more hot water, there is relatively little difference in the average spending, i.e., low variability in demand based on income. Most income groups spend $300/year +/- 10% to heat water. In the context of total household budgets, however, there are striking differences in the burden of hot water spending. The lowest income households spend nearly 2% of *total* income on hot water, while the highest income households spend only 0.02%. This dynamic exacerbates poverty and inequality.

Our analysis also suggests that high percentages of households across income levels would have lower energy bills with HPWH. In table 6 we show the percentage with lower bills assuming a COP of 3.0. Notably, a slightly higher fraction of lower income households (~80%) would benefit compared to the fraction of the highest income households (~70%). This potential to save and reduce the burden of spending on household incomes is hampered by two factors: a low level of home ownership among lower income households and low levels of liquid cash available to spend on more costly HPWH. Given this gap between an opportunity to ease the burden of energy poverty and barriers to adoption, there is a clear need for public sector support. Targeted programs for the tens of millions of lower income households who could benefit will be needed to ensure progress on overall decarbonization and a just clean energy transition.

Table 6. *Heat pump water heater adoption outcomes by income category. Data from RECS Survey (EIA 2021a)*

Income Category	Number of HH (millions)	Current spend on hot water $/year	Approx. % of Income currently spent	Percent renting their home	Percent with lower bills with HPWH (COP = 3.0)
Less than $20,000	23	$274	1.8%	65%	82%
$20,000 - $39,999	27	$281	0.9%	45%	79%
$40,000 - $59,999	18	$295	0.6%	34%	81%
$60,000 to $79,999	15	$310	0.4%	29%	78%
$80,000 to $99,999	10	$302	0.3%	22%	76%
$100,000 to $119,999	8	$317	0.3%	17%	76%
$120,000 to $139,999	5	$340	0.3%	16%	72%
$140,000 or more	11	$315	0.2%	15%	70%

JOBS AND ECONOMIC IMPACT OF ACCELERATED ADOPTION

A program to incentivize heat pump water heaters at the national level would require deep incentives like those currently in use across utility areas and regions where they are active. Through tax incentives or other means, it may be possible to accelerate progress on the technology, and to help reach a market scale where costs of the equipment and installation are competitive on their own. A starting point for a credible incentive to “move the needle” would be $1,000-1,500 per unit, with additional support likely required (e.g., $1,000-2,000) for customers who need costly electrical panel upgrades. These panel upgrades would also be relevant for supporting home EV charging, electric space heating, and electric cooking.

Based on our analysis of the costs for water heating and simple “input-output” estimates of the jobs impacts from induced manufacturing and installation work[25], we estimate that **the following would be the impact from each 1 million units deployed**:

- 20,000 jobs in manufacturing and installation
- Reduction of 15 million metric tons of CO_2e over the lifetime of the equipment. If the average incentive paid was $1,500 per unit, this equates to a ~$100/ton cost of carbon abatement overall without accounting for any of the energy bill savings customers experience.

The vast majority of customers will save money on their energy bills in a switch to HPWH as well (e.g., see Figures 14 and 15), with an average savings of approximately $160/year for a HPWH with a COP of 3.0. These savings represent an ongoing and persistent benefit to household incomes; this *clean energy annuity effect* is a secondary pathway for long-run stimulus and economic impact.

The workforce implications of widespread residential water heating could include additional jobs in several categories:

- **Manufacturing**: Jobs to produce HPWHs. (While there is possible job reshuffling from reduced demand for conventional electric resistance and gas water heaters, the increased complexity of HPWH is likely to require more manufacturing jobs).
- **Installation labor**: Jobs in plumbing, electrical, and general contracting trades, with an initial boost in employment related to building and electrical upgrades to accommodate HPWH.
- **Supply-side energy development**: Jobs in solar, wind, and other renewable energy sectors to build generation and associated grid infrastructure serve the new loads from electrified water heating.
- **Planning, design, and programs**: Programmatic support jobs to identify and aid eligible households, R&D jobs to support scale-up, and others.

[25] Based on Bivens (2019) https://files.epi.org/pdf/160282.pdf

Commercial water heating

Commercial-building energy users across the U.S. spent $5 billion to heat water in 2012 (the most recent data) or about 3% of their total energy expenditures and 4% of their primary energy consumption. The potential of water-heating decarbonization through existing electric-water heating systems is relatively small for most commercial buildings, with electricity consumption less than 1% of total electricity use in these buildings. In contrast, water heating is 18% of direct fuel consumption, spread roughly equally between district heating and natural gas (oil is less than 1%). The most water-heating-intensive building subtypes are Lodging (~15% of total primary energy) and Public Order and Safety (~11%), the latter presumably driven by prisons.

Two major differences between commercial and residential water heaters are the size of the storage tanks and the energy input levels. Single-premises residential heater tanks are typically no larger than 100 gallons, while commercial storage units range from very small (for handwashing) up to 250 gallons (or more) depending on the application. These unitary storage water heaters are similar in construction to those that are used in the residential sector (Figure 11). Many commercial applications call for larger systems as well that have separate heat pumps and storage tanks. A representative view of larger heat pumps is shown in Figure 16.

Figure 16: *An assortment of large-scale commercial heat pump systems, from Armstrong et al. (2020).*

As of 2012, there were 6 million commercial sites with hot water services (based on survey data from CBECS (EIA 2021b)). Table 7 summarizes the number of sites, demand for heat, and spending for five primary fuel/energy sources in use. While nearly half of commercial buildings use electricity as a primary energy source for hot water, the total energy demand at these sites is comparatively small, with about half of the annual spending as a typical residential site. The main expenditures for hot water in the commercial sector are for natural gas (at 1.7 million sites, totaling $3.3 billion/year), and the use of district heating[26] systems. While there are only ~24,000 district heating systems serving various commercial buildings and campuses, these use a large amount of energy at each site. The table below

[26] District heating systems involve using a central plant to produce heat that is distributed to multiple buildings through a network of hot water or steam piping.

only represents estimated energy use for hot water; additional district heating energy for hydronic space heating may also be an important target for heat pump replacement, which would expand the reach of these decarbonized systems (there is a dedicated section later in the report on district heating as an application for heat pumps).

Table 7: *Summary of commercial sector water heating based on CBECS survey (EIA 2021b)*

Primary energy source	# of sites	Average annual hot water demand per site (MMBtu/year)	Average annual spending per site ($/year)	Total spending across all sites ($/year)
Electricity	2.4 million	7	$200	$470 million
Natural Gas	1.7 million	160	$1,900	$3.3 billion
Mixed Sources	1.3 million	2	$40	$57 million
Fuel Oil / Kerosene	70 thousand	7	$220	$15 million
District Heating	24 thousand	2,400	$47,000	$1.1 billion

COMMERCIAL EMISSIONS PROFILE

There is great diversity in the needs and uses of hot water in the commercial sector, with spending and greenhouse gas emissions concentrated on natural gas and district heating. Lodging is the largest sub-sector, with total emissions of 5.5 MMT CO_2e/year. Hospitals and Education are other big sectors (***Figure 17***), along with Shopping malls and Food service. Figure 18 displays CO_2e emissions by number of commercial buildings and energy sources, the data are divided into four regions. A large number of commercial buildings use electricity as a primary energy source for water heating, but with relatively low use at each site compared to natural gas or district heating (which does not appear significantly on Figure 18 due to the small number of sites). Emissions from natural gas sources account for approximately 23 MT CO_2e/year of the 30 million total for all commercial sub-sectors.

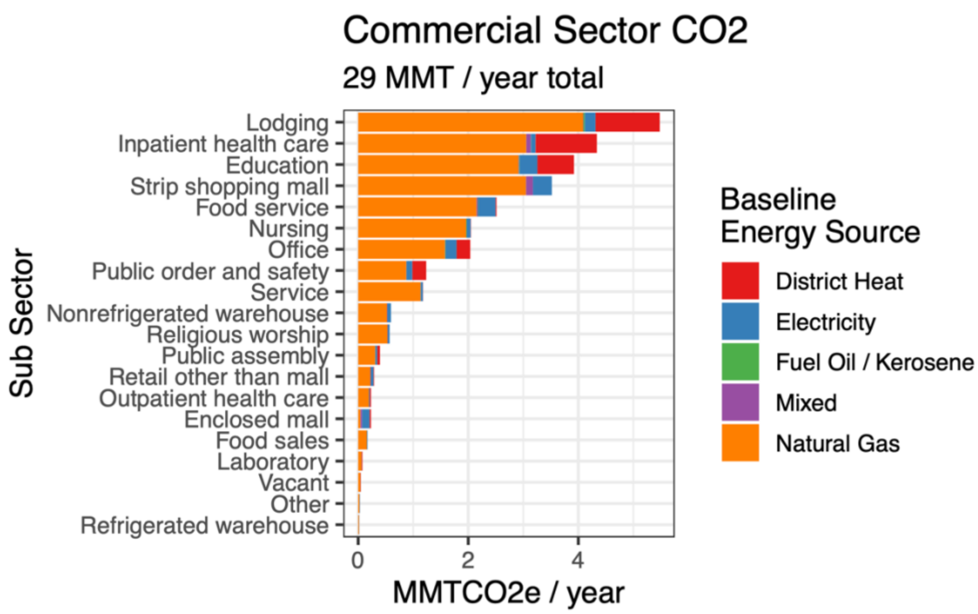

Figure 17. *CO_2e emissions per year from water heating by commercial building subsectors. Data from CBECS survey (EIA 2021b) with emissions intensity from EPA (EPA 2018, EPA 2020). Detailed summary data from this figure are in Table A21.*

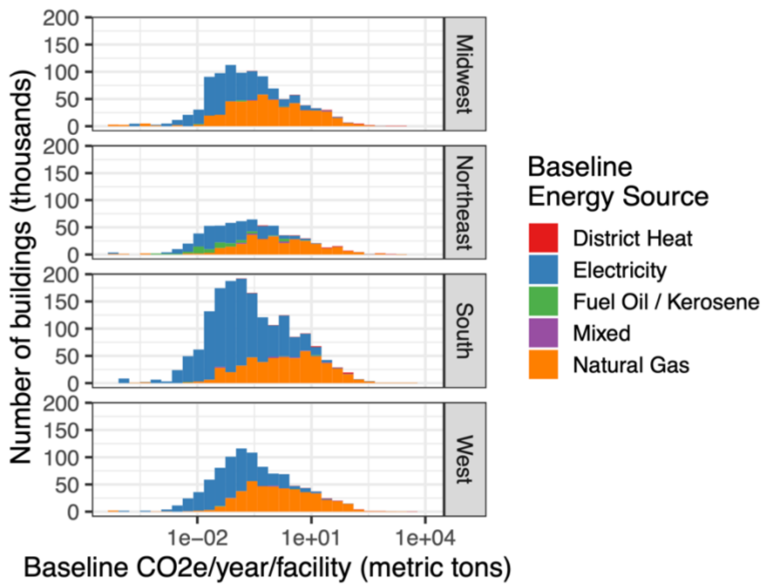

Figure 18. *Greenhouse gas emissions per facility per year from water heating per commercial building, divided in four national regions. Data from CBECS survey (EIA 2021b) with emissions intensity from EPA (EPA 2018, EPA 2020). Detailed summary data from this figure are in Table A22*

COMMERCIAL SECTOR MARKET DYNAMICS

Approximately 250,000 commercial storage water heating systems are shipped each year (Figure 19). As in the residential sector, most replacements happen under urgent circumstances when there is little time for research.[27] There has been a dramatic transition from a strong preference for fuel-based commercial storage water heaters during the 1990s (~80% of shipments), to an almost equally strong preference for electric water heaters today (~60% of shipments) (Figure 19). It has been estimated that only 10% of commercial water-heating systems are tankless (Ryan and Daken 2014). Over the same period, the overall number of units shipped has doubled. The installed base has thus been transitioning to electric (resistance) storage, including large numbers of small, point-of-use, electric resistance water heaters (e.g., those installed under bathroom sinks for hand washing). We have not identified recent data on the role of HPWHs in overall shipments. Nor have we identified a source of information on the fraction of HPWHs in the existing installed base.

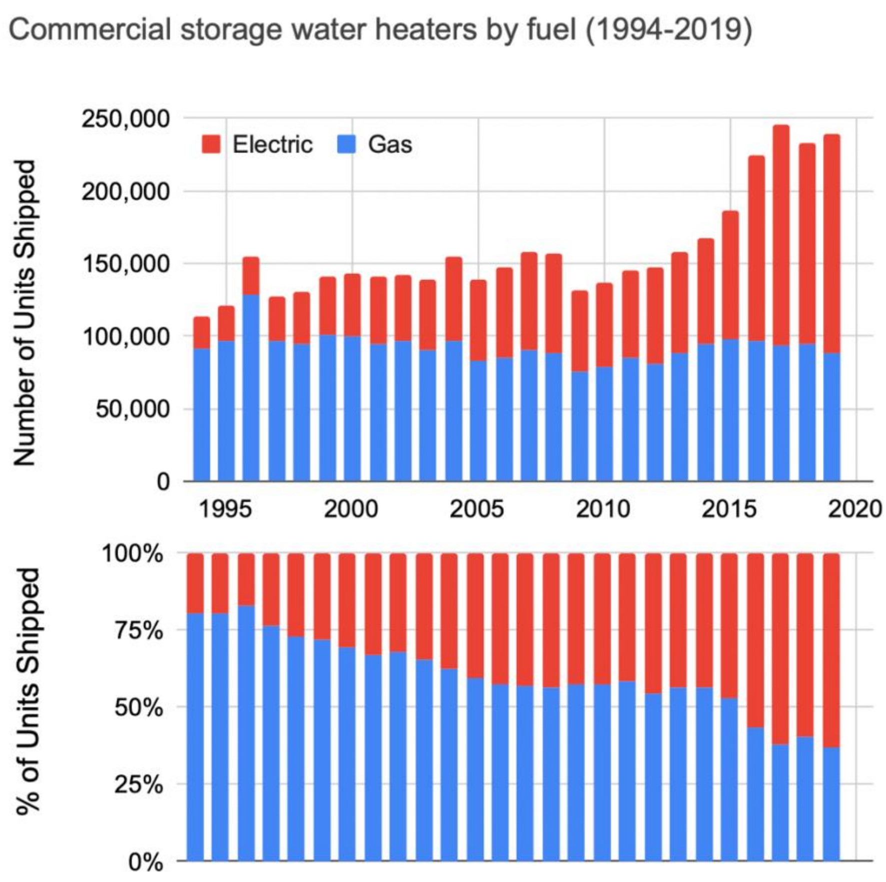

Figure 19. *Trends in sales of commercial storage water heaters, by fuel. Sources: Heater Shipments: 1994-1999 from U.S. DOE 2010, and 2000-2019 from AHRI (2020). Unfired storage tanks and boilers used for water heating are not included here. Detailed data from this figure is available in Table A23.*

[27] See https://www.regulations.gov/document?D=EERE-2014-BT-STD-0042-0041

Radcliff et al., (2007) state that commercial HPWHs have been in the market since the 1960s, with sales in the range of 1,000-1,500 units per year in the late 1990s--falling precipitously thereafter--with more than half the units sold in Hawaii due to the presence of incentives.

A recent national assessment states that HPWHs "have not been deployed in substantial quantities" in the commercial sector (Jadun et al., 2017) and that "add-on" units to existing fossil-fired systems are more common, although no primary source is provided for this somewhat surprising statement. The national buildings energy survey (CBECS) does not tabulate numbers of HPWH systems in the installed base, or specific types of equipment, but the surveys indicate that about 40% of U.S. commercial floorspace (over 30 billion square feet) is served at least in part by "distributed" water-heating systems[28]--presumably referring to smaller tanks serving local loads such as bathrooms--making them potential candidates for residential-type HPWHs.

As indicated above, HPWHs for commercial applications are not well documented, although they have been in use even longer than for households. Even in the 1990s, they were available in an enormous range of capacities, ranging from 10 to 800 kBTUh, and over 50,000 installations were said to exist in the U.S. at that time, with sales of 2,000-4,000 units annually, and 14 manufacturers serving the market (FEMP 1997). The number of manufacturers dropped to approximately 2 by 2002 (Sachs 2002). At that time, sales were stagnant (~2,000 units per year) (Nadel et al., 1998). A report five years later noted sales potentially below 1,000 units per year, and that several of these manufacturers had exited the market (AD Little 1992), with several others only building units to order (Sachs 2002); most of the market appeared to be concentrated in Hawaii at that time. A few years later, Zilio (2007) noted that Carrier had entered the market and developed a series of commercial units, but no units were displayed on Carrier's website in 2020. At present there appear to be six manufacturers offering central commercial heat pump water heating systems in the U.S. market.[29]

There are clearly many attractive applications for HPWHs in commercial settings, in spite of poor availability of data and apparent stagnation in the market. Their co-benefits of free cooling and dehumidification are also more commonly welcomed and useful in this sector, and DOE reports have long recognized them as promising (FEMP 1997; Radcliff et al., 2007; Gupta and Smith 2019). They have been used for decades in applications such as restaurants, hotels, hospitals, nursing homes, commercial laundries, carwashes, pools, and health clubs. These tend to be settings where there are needs for service hot water as well as space cooling or refrigeration, and/or dehumidification. Sources of waste heat streams (either water or air) are also often available. For example, in a laundry or linen-service setting, heat can be obtained from dryer exhaust air and/or drain water, and the cool-air exhaust has value for climate control in the buildings while the laundry is in use. Humidity levels are high in these spaces, which can also be managed by the HPWH system. Sachs (2002) identified particularly promising market segments for the State of New York, which were validated through expert interviews. Bonneville Power conducted successful field tests in three underground car garages located below apartment

[28] As of the 2012 CBECS survey, 12.7 billion square feet of commercial floor area is served by distributed water heating systems, with an additional 18.8 billion served by a mix of central and distributed systems. https://www.eia.gov/consumption/commercial/data/2012/bc/cfm/b42.php

[29] Colmac, Nyle, Lync, Mayekawa, Mitsubishi, and Sanden.

buildings (with stable year-round temperature) in Seattle, WA (Heller and Oram 2015). Field studies conducted in the 1990s yielded positive results, e.g., 45 installations in restaurants and laundries yielded simple payback times ranging from 9 months to 5 years (FEMP 1997).

Larger units (typically split systems) are offered for commercial-buildings also, including CO_2 units from Japanese manufacturers (Sullivan 2017). A.O. Smith has six air-source models and 14 water-source models.[30] In 2010, A.O. Smith, the largest manufacturer of residential integrated HPWHs, launched seven "Commercial" models to the market (A.O. Smith 2010). A decade later, the company announced an ENERGY STAR compliant model, with COPs of 4.2 (A.O. Smith 2019). They note that these units can be manifolded together to serve progressively larger loads. These are the only integrated models under the ENERGY STAR program. It is not clear why more integrated systems are not available or included.

A detailed analysis conducted for NREL in 2017--based on a manufacturer with many decades in the market--concluded that "the technology is still not mature" (Hoeschel and Weitzel 2017). As with residential units, this is hard to fathom given three-quarters of a century of R&D and use in practice (Zogg 2018).

Hoeschele and Weitzel (2017) note that very little is documented about the field performance of central HPWHs. They describe one such application (earlier-generation c. 2011), with 12 residential dwelling units served by a single HPWH connected to two storage tanks, where the performance is substantially below rated levels.[31] However, they also note the potential for more disaggregated water supply in large buildings, along with drain-water heat-recovery. A NYSERDA project installed four large (10-ton) HPWHs to recover heat from a kitchen serving a 100,000 square foot New York hotel, which was monitored in detail (Sachs 2002). Radcliff et al., (2007) modified and installed a number of CO_2 heat pumps originally produced for the European market.

We have gathered limited third-party field-measurements or test data on units applicable to commercial buildings (split or integrated systems rated "commercial") (Figure 20). Efficiencies tend to be higher than those achieved in residential models and settings.

[30] See https://www.hotwater.com/Water-Heaters/Commercial/Water-Heaters/Heat-Pump/Split-System-Heat-Pumps/
[31] Observing measured COPs ranging from 1.7 to 1.9, much lower than rated performance of 3.0 to 4.0.

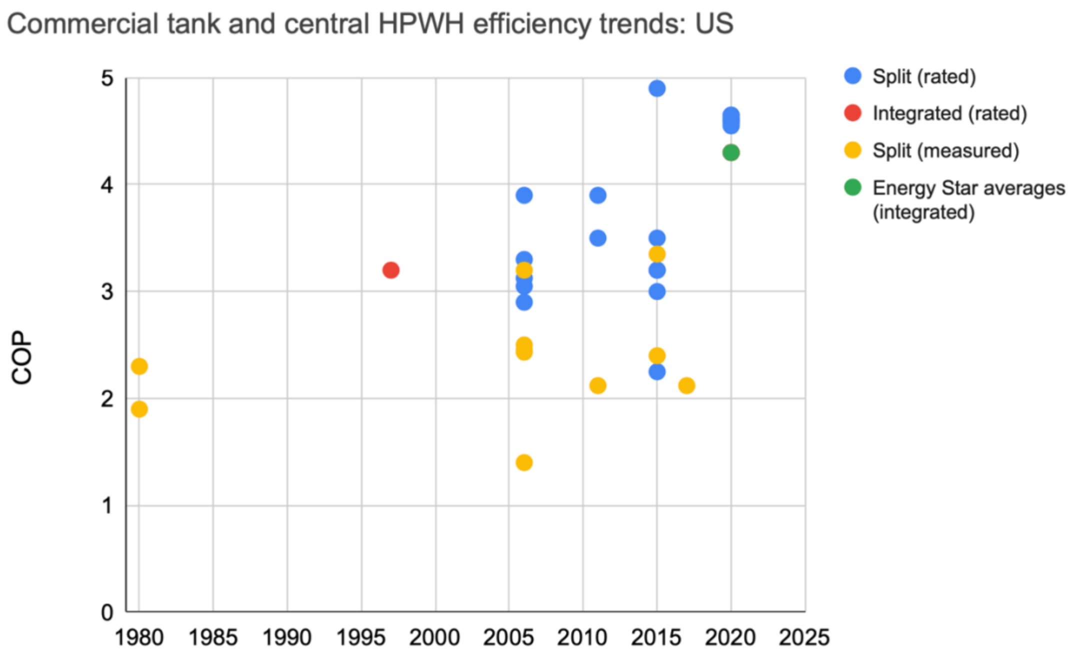

Figure 20. *COPs are for the water heater in isolation of the entire system (tanks, if separate, distribution, etc.). Note: x-axis value is year of published measurement, not necessarily year of HPWH manufacture. Sources: Zogg (2008), FEMP (1997), Heller and Oram (2015), Hoeschel and Weitzel (2017), Sachs (2002), Radcliff et al., (2007), Bowers et al., (2011), EPRI (2015), ENERGY STAR website.*

BILL SAVINGS AND COSTS OF COMMERCIAL HPWHS

Compared to residential customers, commercial customers tend to face less favorable energy price ratios for switching to heat pump water heaters (paying comparatively less for fossil fuels compared to electricity rates). Based on the energy prices commercial customers pay today (for electricity and fuels), the average break-even COP for HPWHs is 3.0. Figure 21 shows the distribution of break-even COP on a cost basis by energy source, which is the most important factor for determining savings. For HPWHs with COP of 3--which is attainable with modern equipment and is well below the average of ENERGY STAR lab-based test performance (approximately 4.2)--about half of current natural gas water heating customers would experience savings, and 75% of district heat customers.

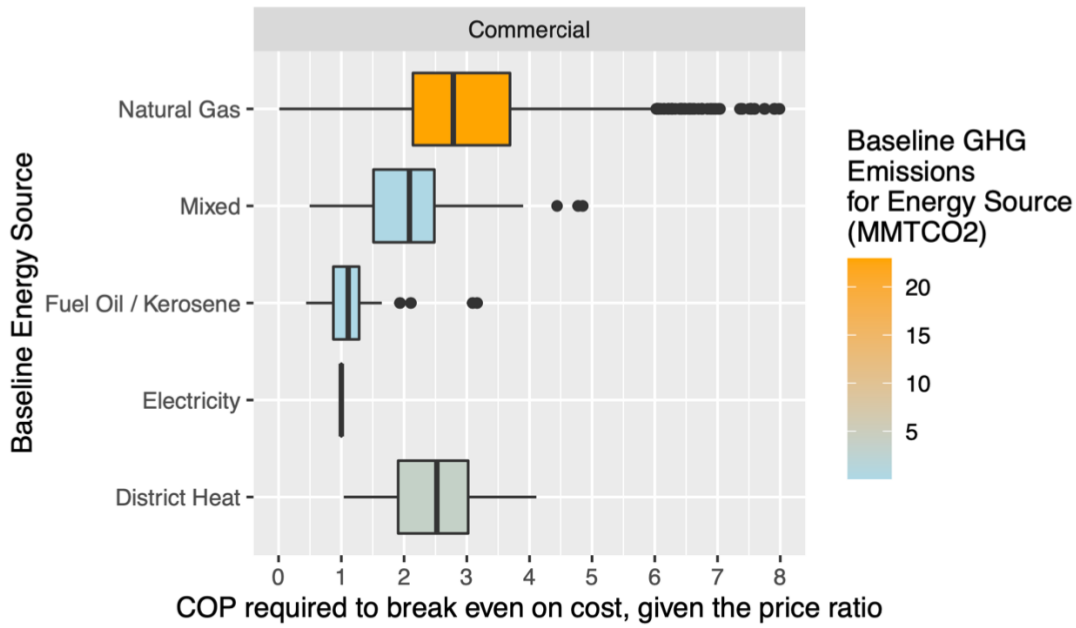

Figure 21. *Break-even COP on an ongoing-cost basis for commercial customers by baseline energy source. Detailed summary data for this figure are shown in Table A19.*

There is a much wider range of customer sizes, application specifics, site infrastructure, and other differences in the commercial (and industrial) sectors compared to the relative homogeneity of residential customers. A key factor for most commercial customers is the need for favorable project economics to support deciding to switch from fuels to heat pumps. Figure 22 presents the implied break-even project costs for a heat pump with a COP of 3.5 (in "unit cost" terms of $/kBtu/hour thermal output, since commercial projects occur across a range of scales). Table 8, following the figure, summarizes the midpoint estimates for each grouping.

In order to be cash-positive after 10 years, our simplified analysis indicates the incremental project cost for choosing a heat pump versus one-for-one replacement of a conventional natural gas system needs to be no more than $30/kBtu/hour for the median customer (and is approximately the same between small and large customer groups).

District heating customers, representing the next largest energy using group within the commercial sector, have relatively higher breakeven project costs (a median of $50/kBtu/h for small sites and $70/kBtu/h for large sites). The other groups--electric resistance, fuel oil / kerosene, and mixed fuels--all have higher cost targets, reflecting the relatively low performance and high cost of the systems compared to heat pump water heating.

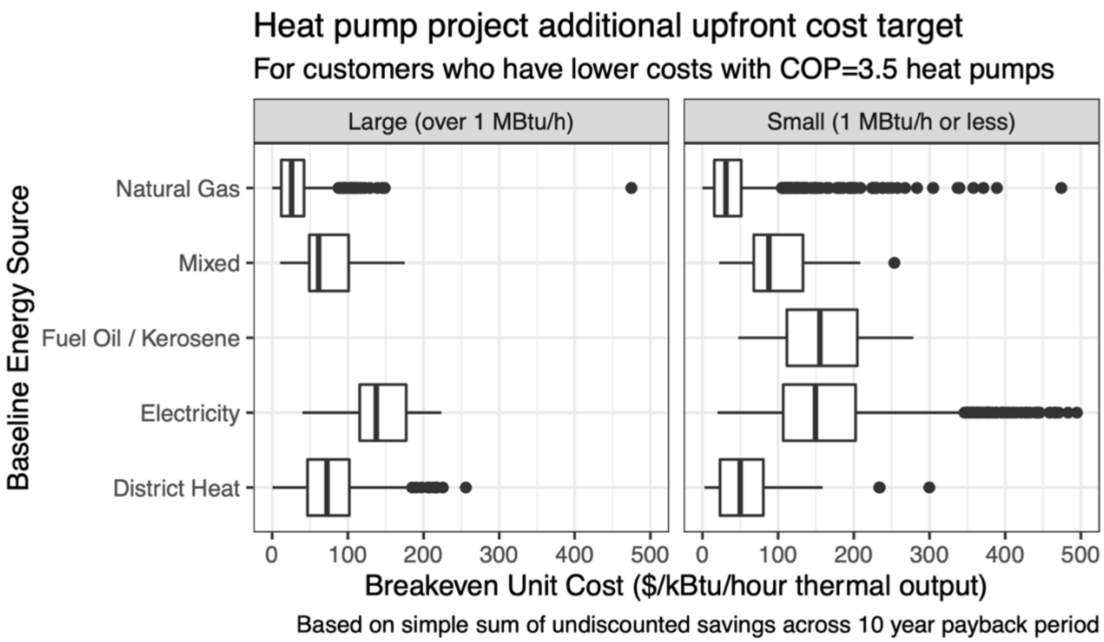

Figure 22. *Target incremental upfront project cost (compared to alternative cost) to achieve a 10-year payback period or better on a heat pump project, with undiscounted "simple" cash flow analysis of the expected bill savings and without accounting for possible gains from flexibility. The plots are grouped by the estimated capacity of the thermal equipment: Large (over 1 million Btu/hour) vs. Small (under that level). Key summary statistics for this figure are presented in Table 8.*

Table 8*. Summary statistics from Figure 22, showing the mean and median breakeven project cost for each group.*

Baseline Energy Source	**Site Scale**	**Mean breakeven cost ($/kBtu/h)**	**Median breakeven cost ($/kBtu/h)**
District Heat	Large (over 1 MBtu/h)	$ 81	$ 72
Electricity	Large (over 1 MBtu/h)	$ 140	$ 137
Mixed	Large (over 1 MBtu/h)	$ 74	$ 61
Natural Gas	Large (over 1 MBtu/h)	$ 31	$ 26
District Heat	Small (1 MBtu/h or less)	$ 64	$ 50
Electricity	Small (1 MBtu/h or less)	$ 168	$ 150
Fuel Oil / Kerosene	Small (1 MBtu/h or less)	$ 159	$ 155
Mixed	Small (1 MBtu/h or less)	$ 103	$ 88
Natural Gas	Small (1 MBtu/h or less)	$ 66	$ 31

Total project costs (equipment and installation) of commercial heat pumps are not well documented. Our synthesis of the literature on unitary (vs split) heat pumps (summarized in the Appendix) suggests total project costs of ~$80/kBtu/hour without challenging installation requirements. The costs of conventional unitary commercial water heaters depend on whether they are gas ($35/kBtu/h) or electric ($65/kBtu/h). Thus the incremental cost for a unitary HPWH replacing a gas unit is ~$45/kBtu/h (i.e., $80/kBtu/h minus $35/kBtu/h).

Given these cost estimates, the economics are tight for replacement of natural gas water heating systems (assuming no incentive for demand flexibility), by far the largest source of emissions in the commercial water heating sector (23 MMT CO_2e/year). The expected incremental total project cost for a heat pump is ~$45/kBtu/h compared to a replacement with another gas unit. This is above the median break-even project cost target of $30/kBtu/h shown in Figure 22.

It is important to note that this is not a definitive analysis, and is based on a single scenario for COP (3.5) without considering the nuances of sub-sector applications or additional benefits and savings available from flexible operation. For example, water heaters installed where there is a need for cooling (e.g., in a commercial kitchen) or in locations with significant waste heat (boiler rooms, laundry) could have much higher performance and better outcomes. There could be spillover gains in the commercial market from cost reductions in HPWHs from residential adoption and scale-up as well. Finally, flexible operation of HPWHs in response to future prices and programs could help advance more commercial systems past the break-even point in competition with gas. With advances in performance to a COP of 4.0 (which is near the current ENERGY STAR average lab test results), and with 20% of the load flexible, the median breakeven cost indeed approaches $45 for small sites. Furthermore, the cost of commercial HPWH could come down with technology learning as more systems are deployed, suggesting a pathway to more widespread cost effectiveness.

For other applications the economics are more favorable today. Our work suggests the expected additional cost for a heat pump to replace a failing electric water heater is $15/kBtu/h, which is very favorable for most customers (over 95% would have a project payback faster than 10 years). The calculus is similar for current users of fuel oil or kerosene.

District heating replacements are often large, custom-engineered “bespoke” systems, often serving a large building or campus. As Table 7 demonstrated, the average spending on hot water for sites with district heating is about 50x that of sites with natural gas storage water heaters. For large sites, the target project cost is $70/kBtu/h, which is approximately in line with the best all-in industrial-scale project costs reported in 2020, by Arpagaus (2020). The range of costs for large heat pumps is from $70 - 300/kBtu/h (see Appendix). These results suggest many, but not most, customers could have project payback periods of 10 years or sooner. Given the relatively similar use-cases for district heating systems (domestic water and hydronic heating), there may be opportunities to standardize and reduce the costs of these systems so that even more customers would save.

FLEXIBLE WATER HEATING TO INTEGRATE WITH RENEWABLE ENERGY

Similar to our approach in the residential sector, we also assessed the potential increase in bill savings and fraction of commercial customers who experience savings with flexible operation, in response to future real-time prices or demand response programs. Figure 23 shows the results of this analysis across scenarios that include: three retail electricity price ratios (1:1 (flat / no time-of-use changes), 2:1, and 3:1); COP between 1 and 5; and between 0-30% of the daily load flexible and available to shift from high to low-price times.

The overall results are similar to the residential sector: the COP is the most important factor for project outcomes, with few sites benefiting with COP less than 2, and COP in the 3-4 range most favorable in terms of cost savings. Flexibility is also an important factor, however, particularly with higher price ratios approaching 3:1. In that case, there are approximately double the expected savings for customers who are replacing a gas water heater with a heat pump ($1000 vs. $500/year). This increases the fraction of customers who experience lower bills from 75% to 95%. For district heating customers, there are also significant savings on the order of a 15-40% increase in bill savings from incorporating flexible operation. Given the relatively tight economics for commercial water heating, these gains from flexible operation could be important for overcoming financial hurdles to adoption.

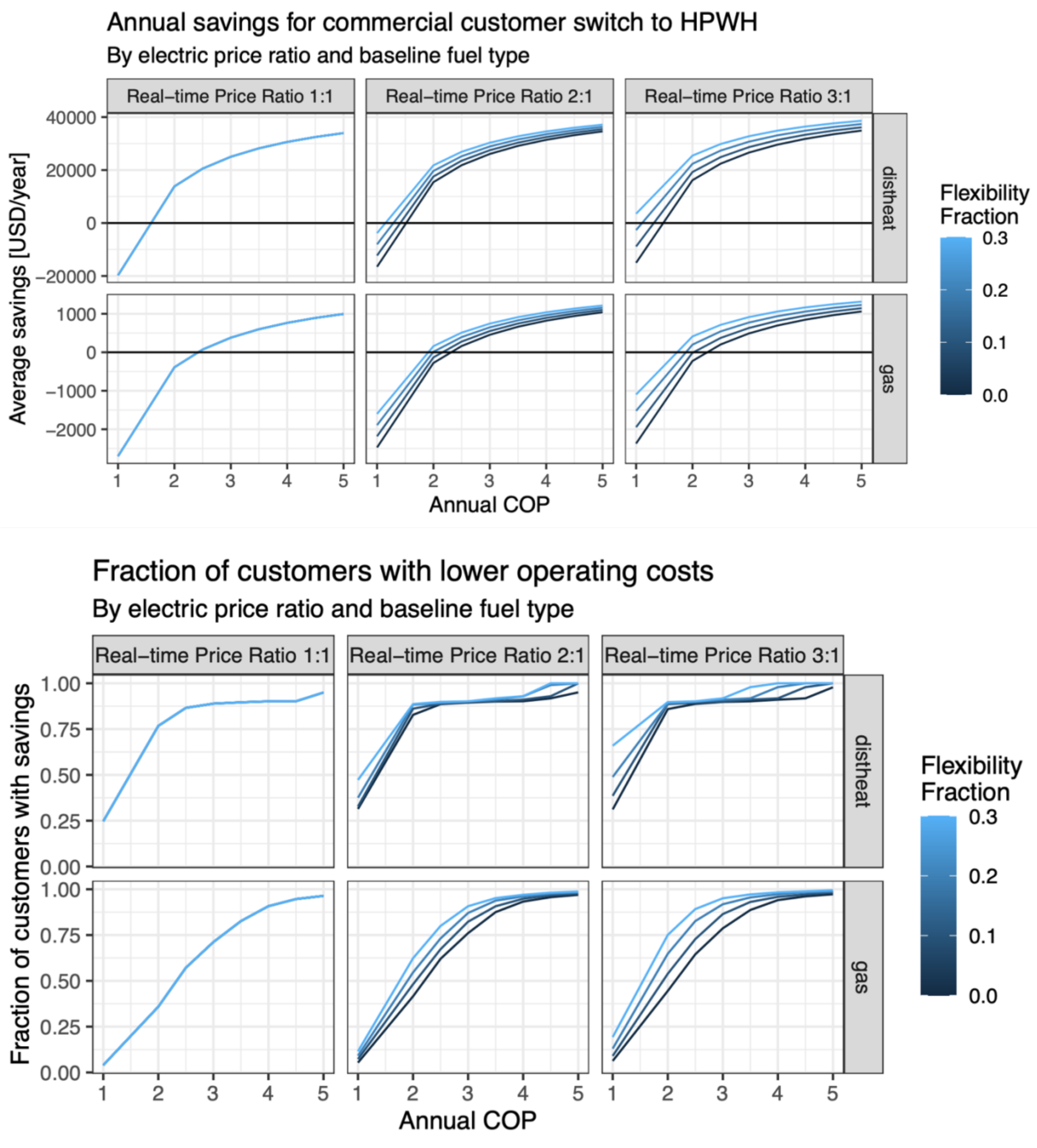

Figure 23. *Average commercial customer outcomes for a range of scenarios for HPWH performance (COP), retail "real-time" electricity price ratios, and the fraction of load that can be shifted from high-price to low-price times. The two rows in the plots correspond to different "baseline" technology in use: district heating and natural gas water heaters. Note that the scales in the top plot are different between these two groups since district heating customers use much more energy per site.* ***Top:*** *average annual savings in operating costs for HPWH compared to status quo.* ***Bottom:*** *fraction of customers with savings.*

Residential and commercial specialty applications

Across the sectors we studied, there are a range of special applications of heat pumps that merit their own focus. Two of these are briefly summarized below to illustrate the importance of nuanced and detailed understanding to advance the heat pump market: swimming pool heaters and district heating hot water systems. Application areas like these could be the focus of targeted R&D to ensure decarbonization advances beyond typical domestic hot water applications.

SWIMMING POOL HEATERS

Pools exist in association with single-family homes, multifamily buildings, schools, colleges, lodging, and private and public recreation centers. Thanks to low water temperature elevation requirements compared to domestic hot water[32], rated COPs range from 3 to 7,[33] but the lack of a test standard forces reliance on incommensurate manufacturer reported values. Currently available products serve the needs of residential as well as larger commercial pools. There are unfortunately no ENERGY STAR ratings for these products. Concerns about space availability, cool spots, and noise for in-home applications would be largely irrelevant in pool applications.

There are 8.3 million pools in single-family homes (plus an unknown number in multifamily buildings), of which ~2.5 million are heated. Cursory reference is made to 300,000 public/community pools[34] but no primary sources could be found. We estimate about 80,000 pools at lodging properties.

While pools operate at much lower temperatures than water heaters, their volume means that a typical residential pool can store as much heat as 10s to 100s of typical residential HPWHs, depending on the volume and temperature. Once pools are up to temperature, the typical energy use in a residential pool is about the same as a HPWH if a cover is used (and about five times as much if one is not used)[35]. Heat pumps in pool heating applications are thus ideal candidates for demand-response applications, as the pools cool off slowly and can thus be heated when rate and grid-conditions are most advantageous. These systems are far less costly than solar-thermal pool-heating systems, and function year round. A FEMP report notes the value of HPWHs for indoor pools and spas, where there are significant dehumidification needs (FEMP 1997). Armstrong et al., (2019) identifies four models of HP pool heaters,

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[32] The efficiency of heat pumps is higher when the temperature difference between the "hot" (condenser) and "cold" (evaporator) sides of the system are closer together. This is related to a concept known as "Carnot's theorem," which is documented online and in engineering textbooks, and defines the maximum COP limit, $COP_{max} = T_{hot} / (T_{hot} - T_{cold})$.
[33] See https://www.energy.gov/energysaver/heat-pump-swimming-pool-heaters
[34] See https://www.liveabout.com/facts-about-pools-spas-swimming-safety-2737127
[35] https://www.energy.gov/energysaver/gas-swimming-pool-heaters

with heat output ranging from 90 to 140 kBTU-h. There are at least two dozen HPWHs in the market today applicable for pools.[36]

The earliest documented HPWHs for pools date back to the early 1940s (in Switzerland; Zogg 2008). According to Calm (1987), the swimming pool heat pump water heating market was “well established” in Europe as early as 1985. DOE offers consumers a web page seemingly endorsing their use.[37] A decade ago, Brookhaven National Laboratory conducted field tests of two commercial heat pump heaters (and other heater types) (McDonald 2009). Measured results for two units were 4.5 and 5.0. At that time, the low capacities of heat pump pool heaters (~100kBTU/h) were seen as a limitation for larger pools, but today’s units come in a wide range of capacities.

Hotels and recreation centers are probably the main location of pools (and spas/jacuzzis) in the non-residential sector, and thus a promising goal for deployment programs. DOE surveys[38] identify 91,000 hotels/motels/inns nationally and 100,000 "recreation" buildings, many of which have pools. Hotels have drain-water and sewer hookup nodes as potential heat sinks, not to mention the hot, humid air in indoor pool areas. About 42% of hotels surveyed had indoor pools and 45% outdoor pools (AHLA 2019), with a highly compatible dehumidification load for the former group. A third of these hotels have spas/jacuzzis as well. While residential spas are mostly integrated (and thus hard to adapt to HPs), most of the commercial ones are site-built and would likely have a separate mechanical cabinet facilitating integration.

DISTRICT HEATING

District heating (centrally produced hot water or steam that is piped to a potentially large number of individual buildings), serves customers in every sector (residential, commercial, industrial). Its benefits include reduced capital cost for individual homes or buildings, reduction of associated maintenance costs, and the saving of space in buildings otherwise occupied by on-site mechanical systems. District heating thermal distribution losses are estimated at only 2.5% today, and are projected to decline to 1.5% with improved energy management (DOE/EIA 2018).

As of 2012, about 48,000 non-residential buildings in the U.S. (5.5 billion square feet) were served by district heating systems, with considerable geographical diversity (DOE/EIA 2018).[39] Current growth is concentrated in hot water systems (expected to increase six-fold by 2050), while steam-based systems are projected to stay at present-day levels (DOE/EIA 2018). District heat is an excellent fit for HPWHs (and efficiencies are far higher when producing hot water versus steam), with many precedents outside the U.S. stretching back decades.[40]

[36] See https://www.lesliespool.com/heat-pumps.htm?utm_medium=organic&utm_source=blog&utm_campaign=heater_vs_heatpump
[37] See https://www.energy.gov/energysaver/heat-pump-swimming-pool-heaters
[38] https://www.eia.gov/consumption/commercial/data/2012/bc/cfm/pba1.php.
[39] See https://www.eia.gov/consumption/commercial/data/2012/bc/cfm/b38.php
[40] Note that there are examples in some countries of consumers moving from district heating to individual HPWH (Roestenberg 2020 and Hirvonen and Kleefens 2020).

In the U.S., district heating systems existed as of 2012 in every state. Remarkably, out of a total of about 650 systems assessed in 2018,16% were fueled by coal and only 1% by electricity, with the vast remainder served by natural gas (DOE/EIA 2018).

Heat pumps have been used for district heating in Europe for many decades, with plants approaching 100 MW thermal output. There are early precedents of the use of heat pumps in district heating in the United States, even as far north as Alaska.[41] In 2011, Ball State University converted from a coal-fired district heating boiler to a large heat pump, and steam-to-hot-water transitions are beginning to occur (DOE/EIA 2018). NYSERDA is presently launching a program to promote heat pumps for district heating in New York, which they refer to as a "community heat pump system".[42] While common in Europe, localities in the U.S. are only beginning to expand their sewer services (a good source of waste heat for heat pumps) to include district heat provision, as is occurring in King County, WA[43] and Denver, CO.[44] Many district heating systems are equipped with storage (which can be done in tanks, aquifers, or boreholes), which would enhance flexibility in response to grid needs. In one example, over 15,000 m^3 of storage is integrated into the city of Saint Paul's district heating system (Guelpa and Vittorio 2019).

Industrial heat

The industrial sector offers by far the most diverse applications and configurations of hot water heating, and the opportunities are correspondingly varied and complex, as well as the largest per-site savings opportunities. Segmenting the U.S. industry for heat pump applications is very challenging. Between and within market segments are a range of temperature needs (Fox et al., 2011). Large boilers and process heat equipment comprise the single largest source of greenhouse gas emissions in the industrial sector (Steinberg et al., 2017).

Our analysis of the industrial sector is based primarily on a dataset produced by McMillan (2019), which combines the venerable Manufacturing Energy Consumption Survey (MECS) with EPA greenhouse gas reporting and other supporting datasets to estimate county-level demand for heat in the industrial sector at various temperatures. A great deal of the heat demand in the industrial sector (about 6.5 quadrillion Btu, or, "Quads") requires very high temperatures, above 150°C, which is out of the reach of current heat pumps. However, as we describe in more detail below, emerging heat pump technology in the industrial sector is able to reach up to 150°C. Conversely, we do not assess the likely significant potential for using heat pumps to provide the preheating for higher-temperature systems.

In these low-to-moderate temperature applications, there are 5 Quads of heat demand annually. The overall picture is illustrated in Figure 24. It shows the cumulative distribution of heat for each of the

[41] See http://www.r744.com/articles/9003/alaska_district_heating_project_with_co2_heat_pumps_underway Large projects exist at Stanford University and U.C. Merced.

[42]https://www.nyserda.ny.gov/Researchers%20and%20Policymakers/Clean%20Heating%20and%20Cooling/Clean%20Thermal%20District%20Systems

[43] See https://www.kingcounty.gov/services/environment/wastewater/resource-recovery/sewer-heat-recovery.aspx

[44] See https://www.cpr.org/2021/05/11/sewer-heat-could-be-hidden-ally-against-climate-change-heres-how-denver-is-pulling-it-to-the-surface/

three end use categories estimated in the data source we use: boilers for hot water and steam, the "heat" portion of combined heat and power (CHP), and process heating. Approximately 70% of all the heat delivered by boilers or CHP systems falls below 150°C, while only 9% of process heat is below this level.

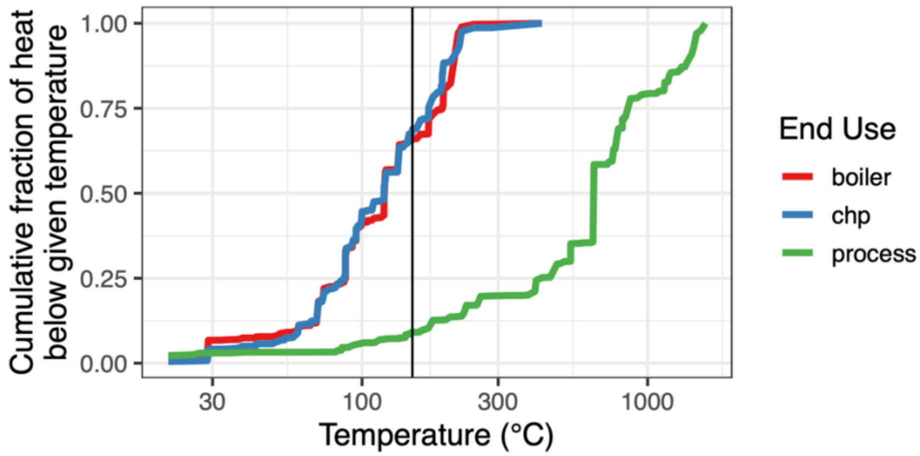

Figure 24. *Cumulative fraction of industrial heat used by delivery temperature.*

Since the focus of this report is heat pumps, we do not address very high temperature heat, above 150°C. Other researchers have identified a range of decarbonized and electric technology for these applications, however, including electric resistance heaters, arc furnaces, hydrogen, microwave, sustainable biomass combustion, and nuclear power (e.g., see Friedmann et al. (2019), McMillan et al. (2021)). Depending on the application, heat pumps may be able to provide pre-heating for these uses, but we do not attempt to estimate the scale of this opportunity.

Our report also excludes current-day electrified heating in the industrial sector, which is already primed for decarbonization as the emissions from input electricity fall. The total electric heating use across all industrial sectors and temperatures currently adds up to approximately 300 TBtu annually (about 2% of the total heat in the sector, based on MECS Table 5.4) (EIA 2021c). These already-electrified applications may or may not be possible to convert to more efficient heat pumps depending on the details on site.

How much of the fuel-based heat below 150°C is replaceable with heat pumps? The wide diversity and customized nature of the applications in the industrial sector mean that some will be addressable and others will not. In some cases, industrial heat is provided through burning fuels that are intrinsically linked with the processes or byproducts on site, and would not make sense to replace. Boilers that burn purchased fossil fuels to make hot water and steam are more obvious candidates for replacement. Sites using the heat from combined heat and power systems, which use waste heat from onsite electrical generation to provide hot water and steam, may or may not be candidates in the near term. As the overall economy is decarbonized, however, the electrical power needs of these facilities are likely to be increasingly powered by renewable and low-carbon energy. This will leave a need for providing useful heat through other means, like heat pumps. In our analysis of the scale of the opportunity for CHP, we assume 45% of the fuel burned is ultimately useful heat (with the other portion for electricity generation and waste heat) (USDOE 2016). Industrial process heat includes a highly diverse set of applications, some of which will be addressable with heat pumps and others requiring other technology. Our analysis below traces the overall total scale of heat in this achievable temperature range, understanding that some, but not all, will ultimately be possible to decarbonize with heat pumps. Table 9 below summarizes the heat demand in the industrial sector up to 150°C.

Table 9. *Summary of industrial heat demand by end-use, for applications up to 150°C. Based on dataset from MacMillan et al. (2019), with additional supporting information from EIA (2021c). Heat demand is based on assumptions for the fraction of fuel that ultimately is converted and useful as heat; we assume 80% efficiency for boilers and process heat, and 45% for CHP.*

Industrial Heat End-use Type	# of sites with end use type	Average annual heat demand per site (MMBtu/year)	Average annual spending per site ($/year)	Total spending across all sites ($/year)
CHP	370,000	2,500	$36,000	$13 billion
Boiler	330,000	6,000	$50,000	$17 billion
Process	200,000	1,700	$13,000	$2.6 billion

INDUSTRIAL EMISSIONS SUMMARY

Within the industrial sector, the emissions associated with heat below 150°C totals 345 million metric tons of CO_2e (MMT CO_2e) per year, with a breakdown of the fuels used in each end-use type shown in Figure 25. Boilers and CHP represent the largest emitting end-uses, with 180 and 140 MMT CO_2e respectively.

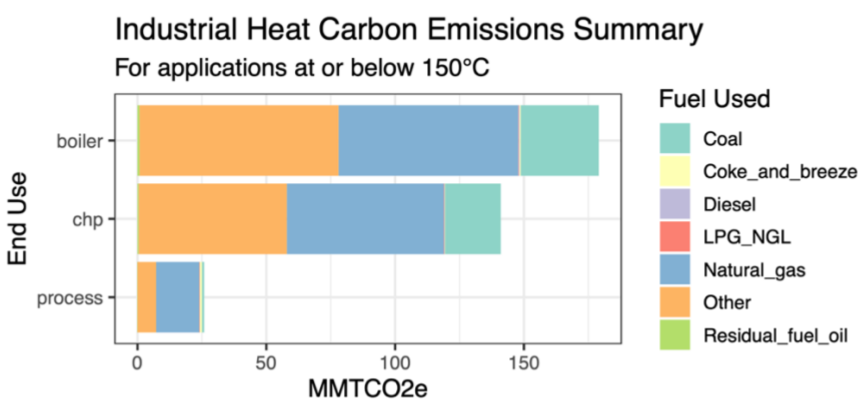

Figure 25. *Carbon emissions associated with fuels combustion for industrial heat by end use type. Based on data from MacMillan et al. (2019), with additional supporting information from EIA (2021c) and stationary emissions factors for the fuels used. This does not include current electric heating in the industrial sector.*

The fuels used in the industrial sector include additional options that are not commonly used in residential or commercial applications. Some are due to high temperature needs. Coal, coke, and breeze are all associated primarily with high temperature processes (e.g., steel manufacturing). A large category represented in the data is "Other" fuel, the identity of which depends on the specifics of the industrial site. Many of these "other" fuels would be difficult to replace with heat pumps because their generation and use are integral to the process at hand. At paper manufacturing sites, "black liquor" (the tar that is extracted from wood in the milling process) is commonly burned as a fuel in combined heat and power systems that provide electricity and heat for those facilities. At petroleum processing facilities, a range of fossil fuel residues, oils, and fractions may be available for heating distillation columns and powering onsite combined heat and power systems. While most of these unique applications are not ready targets for heat pumps, many applications involve more conventional fossil fuels (natural gas, diesel, low-temperature applications of coal). Substitution of heat pumps may be easier for these conventional fossil fuel combustion applications, which result in 200 MMT CO_2e per year across the industrial applications we included in the analysis.

In the industrial sector, application engineering and careful integration with processes are vital for successful replacement of conventional combustion with heat pumps. Figure 26 summarizes the total emissions associated with heat below 150°C across industrial sub-sector groups. Chemicals, paper, food, and petroleum are the largest groups. Even the smaller industrial groups in the inset box of the figure, however, are similar in scale to some of the largest commercial sub-sectors we identified in previous sections.

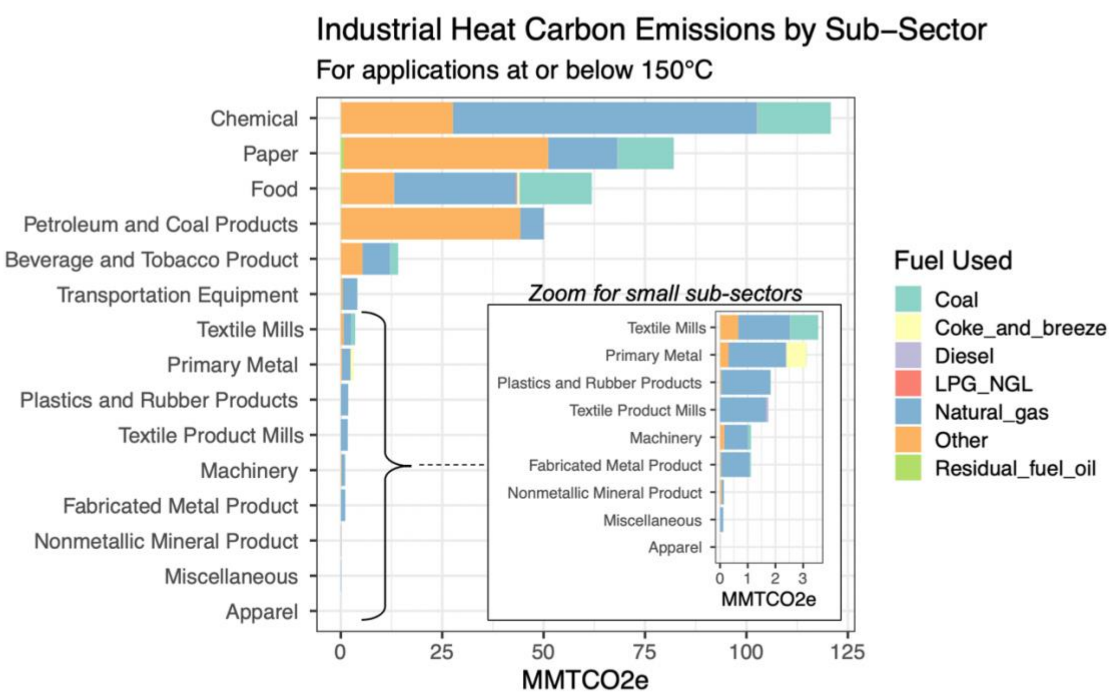

Figure 26. *Carbon emissions associated with fuels combustion for industrial heat by end use type. Based on data from MacMillan et al. (2019), with additional supporting information from EIA (2021c) and stationary emissions factors for the fuels used. Detailed data from this figure is in Table A24.*

INDUSTRIAL HEAT PUMP APPLICATIONS

While conventional buildings-optimized heat pumps do not provide temperatures at levels required for many industrial processes, industry has been introducing **high-temperature heat pumps** (HTHPs), which are significantly expanding the realm of possible applications (Tveit et al., 2020).

Such heat pumps have been used for water and hydronic space-heating since at least the early 1940s, as exemplified by a district heating plant (see next section) with a 4MW (heating capacity) system constructed in Zurich, Switzerland in 1942 (Zogg 2008). Gehring (1996) describes early uses in U.S. dairies and steel fabrication,[45] and uses in Japan (up to 120°C) were noted a decade ago (Tono 2011). Required temperatures are largely higher than those sought in the buildings sector. The targeted heat source is waste-heat streams, which are often in the 30-70°C range. These valuable waste-heat streams manifest in cooling liquid in chillers, waste water, warm compressed air, cooling towers, transformers, or exhaust air (Arpagus et al., 2018a). Research on HTHPs was considerable in the late 1970s and early 1980s, then dropping off for two decades, followed by significant research in the past 10 years. Japan had developed a 400kW HTHP as early as 1985 (Arpagaus 2018b). The U.S. appears to trail behind most other industrialized countries in R&D as well as application, and we have not identified any targeted policies or incentives to help the market develop.

Each industrial application and the techno-economic conditions surrounding it are unique. There has been a decades-long effort to electrify industrial processes, which presumably helps set the stage for innovation. The reward is that each site represents enormous amounts of energy and load compared to typical sites in the buildings sector. Importantly for demand-response, large storage tanks (heated now by pre-existing boilers) are often used in conjunction with these systems.

Arpagaus (2018b) notes that a “great application potential for HTHPs has been identified in the food, paper, and chemical industries, in particular in drying processes, as well as in pasteurizing, sterilizing, evaporation, and distillation.” In arriving at this conclusion, Arpagaus (2018b) segments various industries according to process heat needs. Many are largely served with heat below the 150°C (300°F) currently met with most advanced commercially available systems: food and tobacco ~65%, paper ~90%, chemicals ~50%, machinery ~95%, wood product products ~95%, textiles ~90%, and remaining segments ~85%. This suggests enormous potential for HTHPs even with existing technology.

Large numbers of diverse real-world applications of HTHPs have been achieved by industry. Dairy applications offer an intuitive case study of the role for HPWHs in lower-temperature industrial applications (Tate 2018). NRECA identifies the relevant processes as chilling milk, heating water (to 179°F), and warming drinking water for the cows in winter, with COPs up to 6 to 8. Hot water is also used for flushing alleys. In one case study, water heating and milk cooking were responsible for about 30% of a mid-sized dairy’s total baseline energy use.

[45] DEC marketed them in Europe in 1974 and in the U.S. in 1976 (Gehring 1986).

In our background research we identified a total number of case-studies (actual implementation as well as feasibility studies) describing 44 examples in 18 countries (Figure 27).[46] Arpagaus and Bertsch (2020) document 25 examples within Switzerland alone, representing an aggregate heat delivery of 25 MW. Watanabe et al., (2014) describe seven case-studies in Japan, the earliest of which was written around 2007. Note that we have been unable to find real-world case-study implementation in the United States, but examples likely exist. In the case studies, the applications are variable; many are in the food processing industry where there are often simultaneous heating and cooling needs: Dairies, chocolate making, meat processing, breweries, and others. There are also examples of lumber drying, brickmaking, paint drying, and more. The COP achieved in the case studies are often impressively high (4-7 and up to 10), particularly since many involve simultaneous heating and cooling.

Remarkable advances have occurred in large-scale installations and feasibility studies in Europe, Asia, and Australia, in many cases achieving payback times between three and seven years (Watanabe et al., 2014; EHPA 2018; Leak 2020). While acknowledged as potential contributors to sustainable electrification in the U.S. (Jadun et al., 2017), their full scope of application is not generally recognized in decarbonization assessments and pathway studies.

[46] Australia, Austria, Belgium, Denmark, Finland, Germany, Hungary, Italy, Japan, Netherlands, New Zealand, Slovenia, Switzerland, and the U.S.. Sales of high-temperature heat pumps are also occurring in Portugal, Slovakia, and Spain (EHPA 2019).

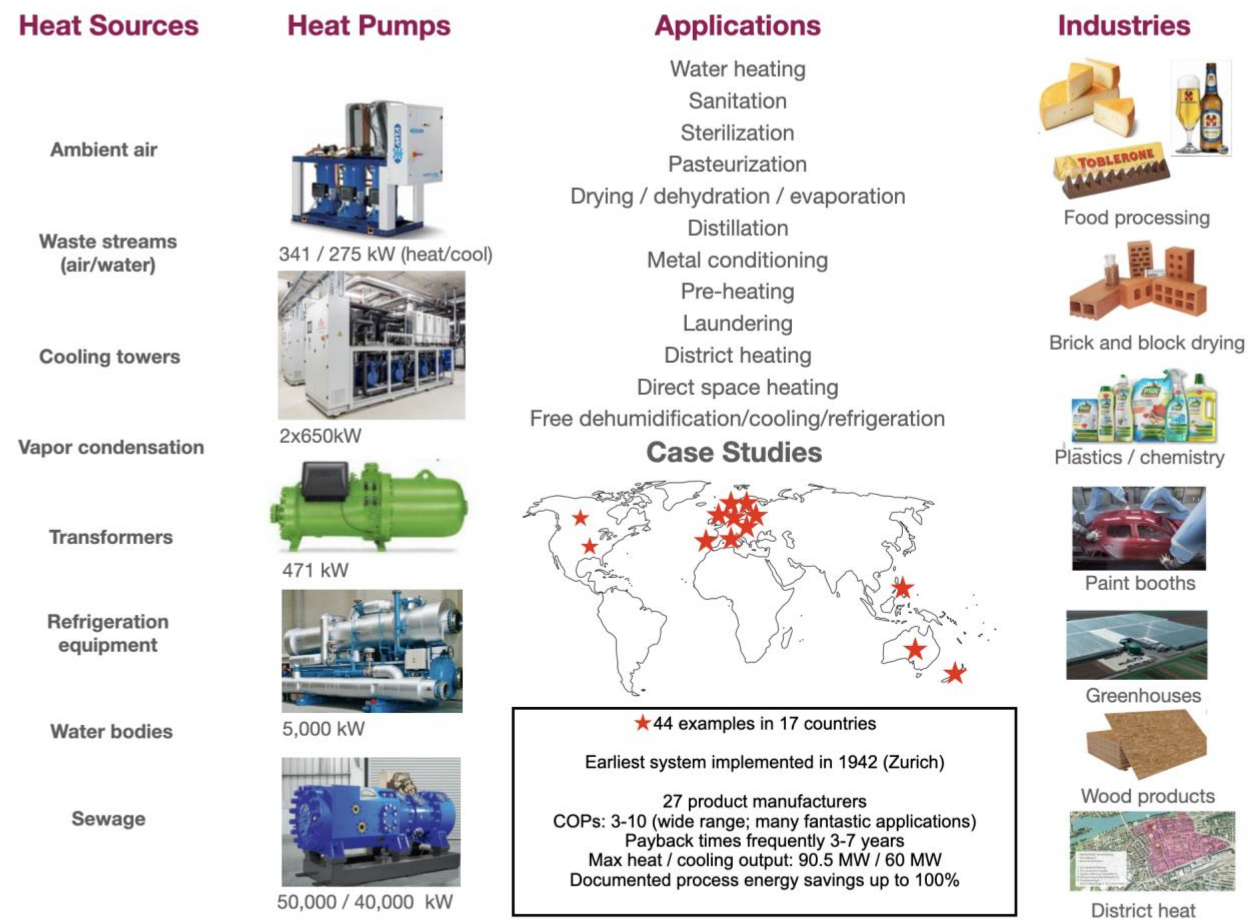

Figure 27. *Examples of high temperature heat pump installations in industry. Sources: Assembled by the authors based on case studies from EHPA (2018), Watanabe et al., (2014), Leak (2020), and Zogg (2008).*

BILL SAVINGS AND COSTS FOR HEAT PUMPS

Based on electricity to fuel price ratios alone, the industrial sector has generally favorable operating cost economics for switching to heat pumps. The average COP required for a heat pump to break even on cost is between 1-2 depending on the sub-sector and fuel used (Figure 28). However, the myriad specific applications and costs of engineering and development for heat pumps makes generalizations difficult. The application areas and case studies described above illustrate the importance of detailed work; the payoffs in carbon savings are immense, and economic benefits from switching to heat pumps are apparent in the operating cost economics as well. **In order to achieve these cost and carbon savings, it will take industrial deployment R&D work to develop pilots and demonstrations of the options.**

Industry associations are understandably sensitive to "one-size-fits-all" approaches to energy savings, and, by extension demand response as well (CIBO 2003). While it is generally more cost effective to install efficient systems from the start than it is to modify (retrofit) them after the fact, some retrofit projects have been documented to achieve payback times between 2 and 4 years (Emerson 2011; Jutsen et al., 2017). Many industrial sector energy managers have expressed a tolerance for payback periods on the level of these successful case studies (Table A26). Only 13% of customers expressed a need for payback faster than 2 years overall in the MECS survey.

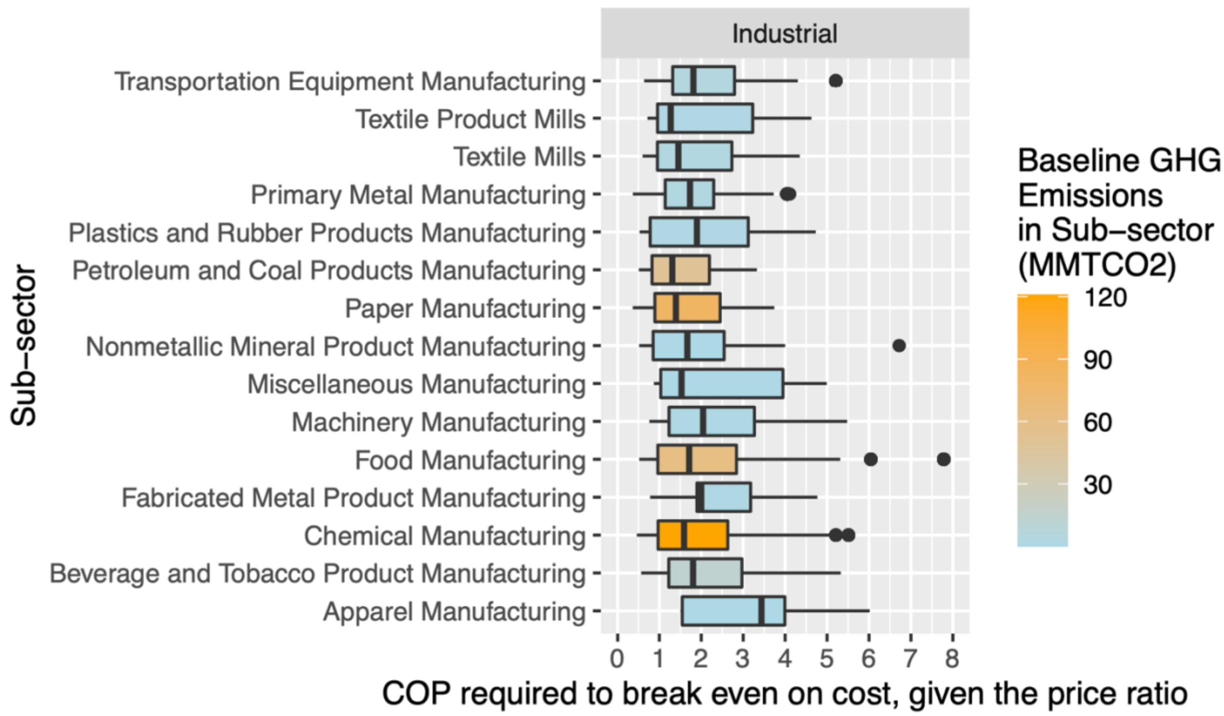

Figure 28. *Heat pump performance (COP) required to break even on operating costs (excluding incentives for demand-flexibility) for industrial sub-sectors. Based on data from MacMillan et al. (2019), with additional supporting information from EIA (2021c) and stationary emissions factors for the fuels used. Detailed summary data are shown in Table A20.*

Market transformation opportunities

The cost saving and emissions cutting opportunities we identified will not be captured without market transformation effort. This section describes a set of actions that could be taken to accelerate a transition to low-carbon hot water and industrial heat, with a focus on federal policy.

RECOGNIZING BARRIERS TO MASS DEPLOYMENT

There are unquestionable advantages to HPWHs, even beyond energy cost savings. For the homebuilder (and new home buyer) there are simpler infrastructure connections. For the ultimate home occupant, added benefits include reduced fire risks and indoor air quality problems associated with combustion appliances, and (in some cases) added value from the supplemental dehumidifying effect that the units have due to condensation on their cold coils. Manufacturers also note that maintenance costs are lower than for conventional fuel-fired water heaters. However, it is clear that these attributes have not enabled the birth of a vibrant market in the U.S.. Since their modest introduction to the market in the 1950s and more concerted efforts in the 1980s, HPWH uptake has proceeded in fits and starts and today only 1% of new residential water heater sales are HPWHs. Early government reports (Dunning et al., 1978) exhibit clear recognition of the multiple technical and market barriers.

Many of the challenges that dogged early generations of HPWH deployment efforts remain, although to lesser degrees in some cases (Table 10).[47] Limited program evaluations shed some light on market inertia. For example, while more than a third of customers interviewed by Efficiency Vermont were aware of HPWHs, only 1% owned them (NMR Group 2019). Evaluations of the NEEA program find that 93% of participants would recommend HPWHs to others (Cadeo Group 2018). On the other hand, six of eleven installers trained during the program report unwanted cooling as likely to result in customer complaints or service requests shortly after installation. For this same group, four in eleven reported unwanted cooling and noise as reasons for such callbacks, and only half of these installers are likely to recommend HPWHs to their customers (Nevius et al., 2019). Butzbaugh et al. (2017) and TRC (2016) provide good reviews of these dynamics, and generic responses, and are compelled to offer the sad commentary that “HPWH technology is in the early stages of the adoption curve.” Yet, in the Northeast, Efficiency Maine found about 80% of customers “Very Satisfied” and only 6% dissatisfied to some degree (WHEC et al., 2019). According to Butzbaugh et al. (2016), “consumers who fall in this range of the adoption curve are innovators and early adopters who tend to have above average financial resources and education levels.”

In hindsight, the arguably premature commercialization of residential HPWHs (Barbour et al., 1996; Ashdown, et al., 2004; TAIX and Environmaster 2004; Shapiro and S. Puttagunta 2017) that took place in the early 1980s--marked by reliability and quality-control problems--can be seen as resulting in a degree of “market spoiling”, wherein the problems were passed among consumers (and tradespeople) by word of mouth. In another example, a poorly researched program by Connecticut Light & Power deployed several hundred thousand add-on HPWHs that experienced enormous reliability problems before the program was abandoned (Talbot 2012). Northeast Utilities also abandoned an add-on HPWH program after similar problems (Sachs et al., 2012). Yet, warnings about the potential for such problems--particularly the need for ensuring reliability and training of tradespeople--were issued by DOE as early as 1978 (Dunning et al., 1978). Lack of subsequent market research only compounded the problem (Ashdown et al., 2004). Much can still be done to optimize performance (Hudon *et al.,* 2012). Today’s abundance of “HPWH Myths and Facts” brochures[48] is indicative of how embedded negative consumer sentiments have become.

[47] E.g., AD Little (1992) reports recovery rates of only 10 to 24 gallons per hour in 1992. Today, they range from 46 to 130 g/h (per ENERGY STAR product list).

[48] E.g., https://www.contractormag.com/management/best-practices/article/20882745/5-common-myths-and-tips-when-selling-heat-pump-water-heaters

Table 10. *Barriers to the market uptake of traditional HPWHs.*

Inertia	● Consumer tendency to prefer "like-for-like" replacements ● Many (probably most) consumers are unaware that the technology exists ● The vast majority of residential installations are "panic purchases" where no time is available for research. Estimates range from 65% to 85-90% for homes (Parker 2011; Butzbaugh et al., 2017) and at least 85% for commercial installations.[49]
Unclear value proposition	● Equipment and installation costs remain higher than incumbent technologies ● Inability to estimate return on investment (retailers/installers usually also unprepared to do so) ● Split incentives where buyers are not users (e.g., builders, landlords)
Applicability, installation complexities, operations	● Adequacy of hot water flow (especially for units with smaller tanks) ● Thermal conditions (ambient temperatures, overcooling garages, stealing useful heat from conditioned space in winter, etc.) ● Unavailability of 220V circuit and receptacle near unit ● Warranty conflicts if add-on units installed on different manufacturer's tank ● Multiple trades may be needed for installation ● Measured performance has shown to decline significantly when put in small spaces (Shapiro and Puttagunta 2016) ● Units are larger than standard water heaters and may not always fit in the available space ● Because of their air-supply needs, units require significant surrounding space, although some units allow for ducting; care must be taken re: home depressurization ● Need for a condensate drain or pump ● Noise ● Maintenance: Evaporator filter cleaning and replacement ● Prior conversions to tankless water heaters often involve new HW location in house and conversion of WH closets to other uses deemed valuable by consumers
Experience / perception of inferior quality or service levels	● Early units were reported to experience extensive reliability problems, although some reports at the time (Calm 1984) asserted high reliability. Evaluation of the NEEA program found that one-in-six installers receive "frequent" callbacks on HPWH installations (Nevius, Powell, and Abraham 2019) ● In some cases recovery may be more sluggish than that of standard water heaters ● Shorter equipment life (particularly in comparison with tankless water heaters) (TRC 2016)
Trades and market conditions are biased in favor of the status quo	● Most contractors lack incentive/motivation/familiarity with the technology or see it as excessively complex or "experimental", and plumbers (a common supplier) are arguably less focused on and literate about energy efficiency than other trades ● Local service providers may be reluctant or insufficiently skilled to install or perform maintenance. Some have pointed to lack of expertise as contributing to the market collapse in the 1980s (Butzbaugh et al., 2017; Nevius, Powell, and Abraham 2019). ● Absence of local inventory and long lead times due to supply chain inertia (CEE 2016; Nevius, Powell, and Abraham 2019). This typically requires that a "special order" process be initiated ● Distributor constraints and limitations on installer brand/product options ● Bias of some energy codes against electricity (TRC 2016) ● Lack of building department experience (TRC 2016)

[49] See https://www.regulations.gov/document?D=EERE-2014-BT-STD-0042-0042

The differences between barriers in residential and commercial settings have not been systematically examined, but those shown in Table 10 largely apply to both, particularly concerns about reliability (Radcliff et al., 2007). The "landlord-tenant" problem would be even more common in the commercial sector, while issues such as noise could be expected to be less frequent. Some of the problems will be far less common in commercial settings with dedicated mechanical spaces, such as the potential for increasing space-heating costs (Sachs 2002).

Arpagaus (2018b) and the European Heat Pump Association (EHPA 2018) summarize the barriers to fuller deployment of HTHPs in the industrial sector as follows, which are largely overlapping with those facing conventional HPWHs in the buildings sector:

- Lower-cost fossil-fuel systems, typically pre-existing with long remaining service life
- Fast payback time expectations
- Risk aversion: skepticism about new technologies
- Low awareness of options among users and implementing trades (plumbing and electrical contractors)
- Rarity of pilot and demonstration systems
- Poor understanding of how to integrate HTHPs into industrial processes
- Rarity of refrigerants in the high temperature range with low global warming potential

Looking forward, with the potential for widespread use of grid-enabled HPWHs, a new set of barriers must be reckoned with, even once grid-flexibility programs are established. These include consumer confusion about the value proposition, concern about loss of control of their appliances, concern about privacy and security, concern about unavailability of hot water during a grid-disruption event (BPA 2018).

A look at the market for water-heating equipment on the one hand provides a strong existence proof that heat-pump water heaters are viable, save energy, and will be purchased by consumers. On the other hand, uptake is limited and there are numerous barriers identified. Meanwhile, there has been a decades-long effort to electrify industrial processes, which helps set the stage for innovation in a time when decarbonization rather than growing load irrespective of generation choices is the goal.

INITIATIVES FOR NEAR-TERM IMPACT

Targeted national campaigns

By targeting particularly promising market segments, Federal policymakers have new opportunities to build on past successes with high-profile voluntary energy and climate programs. Following are nine possible campaigns, with some degree of intersecting applications in terms of building types, technologies, and decision makers. While many of the targeted end-use locations are not under direct federal control, significant incentives and facilitation can be championed by the federal sector in the form of tax incentives, direct incentives to intermediaries (designers, installers, ESCOs, utilities, etc.), technical assistance, and facilitation. Federal incentives to states and municipalities to address publicly owned and managed facilities could take other forms. Existing ENERGY STAR relationships, particularly with national-accounts companies could be leveraged during participant recruitment. For the initiatives below we estimate several metrics to provide a sense of scale for the direct impact. These include the addressable scale of greenhouse gas mitigation, the annual total customer bill savings, and the implied grid flexibility resource in terms of megawatt-hours shifted per day, which can also be compared to a battery system with similar capabilities.[50] In addition to these direct impacts, there would be important technology learning and market transformation impacts to large-scale initiatives that supported scaling up heat pump technology.

- **Targeted residential HPWH upgrades** could achieve early large numbers of deployments, while developing strategies for harder-to-reach market segments. Influencers of large groups of publicly and privately owned housing units would be emphasized, including multifamily building owners, mobile home manufacturers and park owners, public housing authorities, low-income-housing landlords, and military housing managers. Moreover, the success of pilot projects in the Pacific Northwest suggests that consumer-installed grid-enabling controllers could cost-effectively convert existing water heaters (BPA 2018). If this initiative led to an additional 1% of housing stock upgrading to flexible HPWH each year for a five-year period (a total of about 6 million households), this initiative could cut annual GHG emissions by 4 million metric tons of CO_2e and help customers save a total $900 million per year. The total flexibility resource would be 4 gigawatt-hours, which could replace the need for batteries that have a capital cost of $1.7 billion.
- **Targeted residential new construction incentives** have been most successful in existing regional campaigns. One segment that has been missed is *manufactured housing* (mobile and manufactured homes), which represent 7% of the owner-occupied housing stock and about 95,000 shipments each year[51] (more than the entire HPWH market). Since hot water heaters are factory-installed, a program tailored for this industry (perhaps employing tax incentives) could have material impact. The beneficiaries would be in the lower-income segment of the population, and water heating here represents a far larger fraction (24%) of total energy use than in site-built housing (12%). Production builders are another natural constituency to work with in this regard. Combined space- and water-heating solutions may be a particularly good fit here. If all of the mobile homes produced for the next 5 years ship with flexible HPWH, this initiative could cut annual GHG emissions by 500 thousand metric tons of CO_2e and help customers save $140 million per year. The total flexibility resource would be 400 megawatt-hours, which could replace the need for batteries that have a capital cost of $160 million.
- **Programs tailored for low-income/subsidized housing and disadvantaged communities** could introduce HPWHs and other clean energy electrification upgrades into millions of low-income homes currently receiving rent and/or utility cost subsidies. These programs' budgets could be significantly increased along with a mandate to support electrification. HHS's current $3.3 billion/year Low-Income Heating Energy Program (LIHEAP)[52], DOE's $200 million/year

[50] We assume a COP of 3.0 and that 25% of the load is flexible based on our analysis and synthesis above. We assume the cost of alternative load shifting and balancing on the grid is a stationary lithium ion battery with a $400/kWh capital cost (Mongird et al. 2020).
[51] See https://www.census.gov/data/tables/time-series/econ/mhs/shipments.html
[52] See https://liheapch.acf.hhs.gov/Funding/funding.htm

Weatherization Assistance Program, HUD's $650 million/year Indian Housing Block Grant Program, and HUD's $6.4 billion/year utility allowance subsidies programs[53] could all have budgets boosted to deliver HPWHs (along with amplifying their impact more broadly), with one-time capital payments for installation resulting in partial permanent reductions in energy subsidy requirements. The benefits from reduced energy bills could not only benefit customers but also expand access to programs like LIHEAP. 35 million households are currently eligible for LIHEAP, but only 20% receive assistance due to federal budget constraints.[54] Another mechanism would be to use existing rent subsidy mechanisms for low-income landlords to finance HPWH installations. In addition, HUD's public housing program constructs, maintains, and operates approximately 1.3 million housing units and could readily modify policies to implement HPWHs. These programs would provide an equitable alternative for lower-income households not always able to make use of programs such as tax credits.

- **The four Federal Power Marketing Administrations and Tennessee Valley Authority** could be compelled to do more to promote residential and commercial HPWHs among their wholesale purchasers' customers (including rural co-ops and municipal utilities). Focused campaigns could deploy best-in-class utility programs based on lessons-learned from the last 20 years to reach 20% of their customers in 5 years, which would represent 2% of all customers[55]. Successfully reaching these customers with flexible HPWH could cut annual GHG emissions by 2.2 million metric tons of CO_2e and help customers save $410 million per year. The total flexibility resource would be 2.4 gigawatt-hours, which could replace the need for batteries that have a capital cost of $1 billion.
- **Hotels and other lodging facilities** are the commercial segment with the most intensive use of hot water: 15% of their total energy consumption. By virtue of this, and of the related applications--pools, laundries, restaurants, and hot tap water in the rooms--they are an optimal application of HPWHs. They have available multiple "streams" of waste-heat that can serve heat pumps and often require active cooling (e.g., indoor pools, kitchens, etc.). This sector may represent hot water use equivalent to 6 million homes, but with about 100,000 locations and far fewer decisionmakers. A targeted initiative to deploy flexible heat pump systems that reached 20% of the lodging facilities in the country could cut annual GHG emissions by 450 thousand metric tons of CO_2e and help customers save $70 million per year. The total flexibility resource would be 800 megawatt-hours, which could replace the need for batteries that have a capital cost of $300 million.
- **Swimming pools** are a vast repository of warm water, which can be heated extraordinarily efficiently with HPWHs while offering significant demand flexibility. There are ~2.5 million heated residential pools, 300,000 community pools, and 79,000 pools at lodging properties. Opportunities for synergisms are significant, e.g., where cooling and dehumidification support are usefully provided as HPWH byproducts. Residential pools use about the same total energy as water heating at sites where they are present, but given the significant thermal mass of water could in principle be nearly 100% flexible in timing to optimize renewable energy integration. An initiative to change out

[53] See https://www.hud.gov/program_offices/economic_development/eegb/utilities
[54] See https://www.eei.org/issuesandpolicy/Pages/liheap.aspx
[55] The four PMA's total generation is ~7% of the national total (https://www.eia.gov/todayinenergy/detail.php?id=11651) and TVA's total generation is ~4% of the national total (https://www.tva.com/about-tva/tva-at-a-glance). Thus 11% of the total customers are served, and 20% of this is ~2%.

20% of the residential pool heaters with flexible heat pumps that only run during favorable times on the grid could cut annual GHG emissions by 550 thousand metric tons of CO_2e and help customers save $70 million per year. The total flexibility resource would be 700 megawatt-hours, which could replace the need for batteries that have a capital cost of $300 million.

- **Laundromats** are considered highly desirable settings for HPWHs, given that they have constant waste-heat streams occurring simultaneously with water demand, and normally also high dehumidification and space cooling needs (both of which can be met with the HPWH). There are an estimated 30,000 coin laundries in the U.S., and up to 100,000 laundry facilities in the lodging and hospitality sectors. While an initiative to reach these desirable customers would have significant impact, our analysis does not have sufficient disaggregated detail to estimate the total.
- **District heating** systems today are located in every state, and serve up to 50,000 non-residential buildings (5.5 billion square feet, produced by only 660 large systems). (USDOE/EIA 2018). A remarkable 16% of the energy input (156 TBTU/y) is provided by coal (and could perhaps be targeted first) and only 1% with electricity. Half of the heat is delivered to publicly-owned buildings. About 30 million square feet of district-heated floor space are added to networks each year, representing a rising opportunity (DOE/EIA 2018). In some areas, district heating networks could be expanded opportunistically (in conjunction with conversion to heat pumps with centralized storage). In total, the heating for district heat adds up to over 700 TBTU/year[56], which is equivalent to 40% of the energy used for residential water heating, and nearly double that of commercial water heating. An initiative to reach this sector with heat pumps could have a significant impact.
- **Industrial demonstrations** targeting highly compatible manufacturing contexts could help pave the way for broader adoption of high-temperature heat pumps, while more fully engaging U.S. heat pump manufacturers in this global market. Five full-scale U.S. demonstrations of commercially available technologies in different segments providing heat plus co-benefit services (dehumidification, cooling, space-heating) should be carefully designed and evaluated, and the results widely publicized. Ideal candidates for early pilots are food processing, dairies, and facilities using heat for drying lumber, paint, and similar processes. Based on the results, broader campaigns could be scaled up. The industrial heat sector is a vast and important target for decarbonization, not only in the U.S. but globally as well.

Federal leadership by example

Government buildings consume about one-quarter of all hot water and one half of the district-heating energy in non-residential buildings. The share of housing (subsidized, military, prisons) is not known. The well-established Federal Energy Management Program (FEMP), as well as agency-based energy management offices, energy-oriented procurement protocols, and other initiatives provide the vehicles for deployment. FEMP also issues internal standards for its own equipment purchases, and these could be fortified to emphasize heat pumps.

[56] https://www.eia.gov/analysis/studies/buildings/districtservices/

Many of the campaign concepts noted above would naturally include a cohort of federally-owned buildings. Specific opportunity areas include: Veterans Affairs and other government hospitals; public and other assisted housing; military housing and other hot-water uses on bases (laundry, food service, pools, etc.); prisons; laboratories; supercomputing centers; and other sites with available heat sources and higher-temperature, industrial-type water/heat/cooling/dehumidification uses; and central plants or district heating systems serving various types of facilities.

Federal engagement should include partnering with state and local governments to incorporate schools, colleges, and universities. The federal sector may also be able to use its buying power to leverage larger projects, which could have multiplier effects that benefit the private sector. An example of this may be adding space to existing district heating grids and/or helping finance the establishment of new grids to serve a mix of public and private buildings.

ENERGY STAR program enhancements: residential and commercial

Public and private energy users alike routinely refer to ENERGY STAR for purchasing guidance. The program incorporated residential integrated HPWHs more than a decade ago, and a recent update to version 4.0 made several important improvements. These recent changes included:

- Raising the minimum performance threshold to a UEF of 3.3.
- Including criteria for optional grid-connected functionality.
- Including more heat-pump water-heating product categories, e.g.: split systems, add-on units, pool heaters, and 120-volt options.

There are a number of potential ways to continue to improve the program in the future:

- Focus further on consumer amenity and quality as a criteria for inclusion, including extending existing warranty requirements and introducing noise criteria to allay consumers' perceived barriers to adoption.
- Consider requiring grid-connected functionality or other flexibility as these features become mature.
- Cease endorsing fossil-fuel-fired water heaters (there are 1,300 non-electric water heaters with ENERGY STAR certification).
- Increased focus by ENERGY STAR on large-scale (commercial and industrial) heat pumps through its benchmarking, design guidelines, and voluntary partnership campaigns.
- Increase emphasis on HPWHs in the non-prescriptive non-residential ENERGY STAR Buildings program.
- Consider developing an "ENERGY STAR Most Efficient" program for HPWH to drive innovation towards high performance products.

Tax incentives

Tax incentives (aka credits) are particularly important for market segments where mandatory standards can't be applied, particularly non-residential applications where each system is somewhat bespoke or inseparable from the broader system within which it is embedded. They can also help mitigate the risk of reversion to fuel-based water heating in the face of high HPWH costs. Tax incentives for residential HPWHs were once set at 30% (Franco et al., 2010), and were reduced (arguably prematurely) to $300 (perhaps 10-20% of the installed cost). Uptake was very low: only 2-4% of taxpayers took advantage of any residential energy tax incentive in recent years, and participation and fund distribution was highly skewed towards higher-income households (Crandall-Hollick and Sherlock 2018). To have impact, these should be restored at much higher incentive levels and be much more widely advertised than has been the case in the past. However, it should be kept in mind that lower-income households may not be able to make productive use of consumer tax incentives (with strategies developed to address this).

Seasoned program administrators indicate the need to have deep incentives in place in the absence of minimum efficiency standards. Existing incentive levels for the residential sector, averaging about $400 per heat pump water heater, are insufficient to achieve market transformation.

Deeper incentives for residential and small commercial customers should be scaled to cover the full incremental project cost in order to move the needle on accelerating HPWH. We recommend the following amounts be considered:

- Incentives that result in $1,000 - $1,500 retail savings per unit for HPWH equipment, depending on size, applied at the manufacturer ("upstream") or distributor ("midstream") levels. The actual incentive amount may be lower since supply chain markup adds to the retail impact of lower wholesale prices.
- $1,000 - $2,000 in additional installation support applied as a midstream incentive to installers or downstream refundable tax incentive (or other similar mechanisms) with a streamlined and simple process. This support could be targeted for the many customers who require costly electrical panel and/or building circuit upgrades to power HPWHs.

Historically, utilities have been the primary source of incentives and have achieved very low market penetration in the household sector (with very little attention to commercial and industrial customers). While participation rates are increasing, overall penetration rates--the ratio of HPWH units rebated each year to number of customers--are very low according to the latest national review (from 0 to 0.15% in most cases, with the best at 0.4%) (Rosenberg 2016). We recommend that utility efforts be augmented with federally directed campaigns. Innovative ways of "merging" these two incentive streams should be explored, including focus on particularly promising opportunities such as in the hospitality and food-products industries. Opportunities not deemed attractive to utilities (e.g., pools) could also be emphasized. Some efforts could be carried out in cooperation with states and cities, e.g., in decarbonizing district heating systems or coupling heat pumps to municipal waste infrastructure.

Another role for tax incentives could be to induce the manufacture of HPWHs (millions per year, versus a few tens of thousands today) in the U.S. vs. overseas. Irrespective of where the existing assembly lines are (mostly overseas), far more new ones will need to be built to meet the demand envisioned in our scenarios.

Few if any tax incentives currently exist for non-residential applications of HPWHs. Investment tax credits, accelerated depreciation, and other favorable tax treatments could be implemented to provide clear incentives. Since projects in these sectors are often bespoke, it may be more efficient to design "performance" rather than the "prescriptive" incentives. This could involve creating a program where they are tax-credited on a $/kW saved/stored or $/tonne of carbon basis--with credit given for ancillary savings like cooling, if those measures are pursued as well. Such projects are large enough that engineering documentation could be justified. This would also induce sites to seek the deepest impact possible. For larger commercial and industrial applications, tax incentives could induce co-location of existing sinks and sources of heat, along with indirect incentives such as those routinely used by states and localities to attract industries to their areas (permitting and planning streamlining, local tax relief, tax-increment financing, establishment relevant criteria for economic redevelopment zones, etc.). Refundable investment tax credits may yield a more robust response than do conventional credits.

Irrespective of the exact incentive mechanisms chosen to making grid-enabled HPWHs competitive with conventional electric resistance water heaters as well as fossil-fuel-fired technologies (condensing or tankless water heaters), our analysis suggests that incentives need to approach the full incremental cost of upgrading to HPWHs (equipment plus labor). Incentives should be tailored to reflect relative costs of incumbent technologies (gas vs. electric). Similarly, consideration should be given to ensuring that incentives do not inadvertently steer consumers towards lower-performing products (including units with tanks that are too small to deliver intended performance, cost reductions, and/or grid flexibility benefits), which could create counterproductive market-spoiling effects. In this vein, incentives should be nuanced so as to recognize material cost differences between integrated and split systems (the latter of which may be necessary for contexts such as mobile homes or apartments where it is more challenging to install HPWHs indoors) or ducting (for contexts where ancillary cooling would be unwanted).

INITIATIVES FOR LONGER-TERM IMPACT

Mandatory equipment standards

Minimum efficiency standards for water heaters should be updated to reflect the new realities of the opportunity for heat pumps to replace inefficient and polluting equipment.

Mandatory standards for residential HPWHs were considered and deemed cost-effective as early as 1994 (59 FR 10464, March 4, 1994), but failed to be included in the final rulemaking (66 FR 4474, January 17, 2001) due to concerns about industry ability to manufacture and install the systems.

The current paradigm for water heater standards, does not seek to optimize energy use or emissions across fuels. Thus, electric water heaters have different standards than fuel-based water heaters. The 2015 standards requiring HPWHs were limited to units with tank capacities at or above 55 gallons, a minority share of the market (Ryan et al., 2010). Only about 12% of households have existing tanks that would need to convert to HPWH if replaced with an identical size.

Standards should be broadened to cover the full range of unitary water heaters (not only tanks above 55 gallons) and evaluated for technologies currently not covered, including: split systems, add-on units, pool heaters, and central systems for commercial buildings. **A radical adjustment to the status quo should be seriously considered as well: fuel-neutral GHG-performance-based standards.**

Another element standards should consider is the interaction between HPWH and the grid. Forthcoming standards in Washington are calling for grid-enabled HPWHs (using standard CTA-2045) in 2021, and for all electric water heaters to be grid-enabled in 2022. Oregon will adopt these standards in 2022 as well. In 2020 the California Energy Commission initiated a rulemaking process under Title 20 for demand-responsive appliances (including water heaters).[57] DOE should consider harmonizing with these further-progressed efforts.

Perspective should be retained that known barriers to market uptake must be taken seriously, and not assumed to be universally overcome by mandatory standards. Building codes not oriented towards decarbonization also present obstacles. Furthermore, the trades have devised multiple ways of circumventing existing HPWH equipment standards (Nevius et al., 2019), reducing compliance by half or more. This tendency is compounded by the high cost of panel upgrades, required in many cases, although this may be overcome by plug-in 120V units that are arriving on the market in 2021 from several leading HPWH manufacturers.[58] Meanwhile, sales of fuel-fired tankless water heaters and efficient gas storage water heaters have increased since the introduction of HPWH standards in 2015. (Tankless units are deemed the most profitable type of water heater by installers in the NEEA program (Nevius, et al, 2019)). Importantly, the economic dynamics of grid-enabled water heaters are not captured in the current standards analysis methodology, which uses only flat electric rates rather than more realistic time-of-day/season rates. This prohibits any meaningful assessment of this technology.

Given the realities of the market and experience with adoption thus far there is reason for concern that tightened standards may drive consumers even more strongly from HPWHs to tankless and condensing gas units, suggesting that incentives may be combined with standards at least for a transition period.

As always, stakeholder impacts must be evaluated. U.S. manufacturers of residential water heaters are for the first time in HPWH history ideally positioned to enlarge and dominate the HPWH market in the U.S., as all major U.S.-based manufacturers of domestic hot water heaters also offer heat pumps. These companies make 95% of the units available in today's market, and so are poised to dominate this new market and offset sales from fuel-based and electric-resistance units. With the exception of Westinghouse, all manufacturers of grid-enabled resistance water heaters also produce HPWHs. Few offshore manufacturers offer HPWHs in the U.S. market today, although this could change rapidly if the market is perceived to be poised to grow. U.S. manufacturers should be prepared for this eventuality. The average efficiency of HPWHs sold in Europe in 2019 was lower than that of those sold in the U.S. (EHPA 2020).

A key consumer impact of concern is dissatisfaction with mandated products. Unfortunately, equipment standards are poorly positioned to mitigate these risks, because, by statute, standards are based on a single energy consumption or efficiency metric rather than on product quality. Thus, the standards are silent on factors such as noise level or reliability, as well as "applications" issues such as how the

[57] See https://www.energy.ca.gov/proceedings/energy-commission-proceedings/flexible-demand-appliances
[58] GE plans to launch a product in early 2021, and A.O. Smith and Rheem are developing units as well.

equipment located in a building may have adverse impacts on thermal comfort or humidity levels . ENERGY STAR and other certification programs like the Northwest Energy Efficiency Alliance's Advanced Water Heating Specification should continue to be looked to as vehicles for fostering product quality assurance.

Builders, developers, trades, and service providers can all benefit from the higher-value products (higher markups). In evaluations of the Pacific Northwest HPWH programs, many installers stated that HPWHs were the most profitable type of water heater to install (Nevius et al., 2019). Consumers will benefit if the relative fuel prices and incentives for flexible load embodied in tariffs and payment agreements (combined with any government or utility incentives) are sufficient. Gas-only utilities stand to lose sales unless they diversify; many dual-fuel utilities already promote electrification.

Building codes for integrated savings

Local building codes can amplify or impede uptake of new technologies, even if their use is regulated nationally. While building codes are not set federally, federal policymakers should work with local code officials to mitigate barriers and maximize synergies. Code-related obstacles to deployment of HPWHs are the preclusion of electricity (explicitly or implicitly) by green building ordinances' disallowance of tank-sharing in multifamily buildings (Farnsworth et al., 2019). Some building codes do not allow side venting of combustion appliances (at least for commercial applications), and others apply time-dependent valuation methods that discriminate in favor of gas (TRC 2016).

On the positive side, and equally importantly, building codes influence system design and system integration and thus capture opportunities (and, potentially, demand flexibility) that cannot be simply mandated into isolated products. Moreover, HPWH systems can be productively integrated into HVAC and dehumidification systems, as well as "process" loads in some commercial buildings (e.g., refrigeration systems and waste heat recovery food stores, food service, and hotels). Improved building codes can capture these benefits, while enlarging the market for and uptake of heat-pump water heating.

Local and state codes and standards are catching up to the potential for HPWHs as well; California's Title 24 building codes are now neutral between gas tankless water heaters and HPWHs and will favor HPWHs starting in 2022. Federal policymakers could support local and state officials to harmonize and deploy codes like those that are in process in California and Washington, among others. The upcoming California 2022 code update is poised to move much of the new construction market to HPWHs starting in 2023, with 80,000 units expected per year. This would roughly double national sales of HPWHs. There are numerous local "reach" codes in cities and counties as well that go beyond statewide or national minimum codes, and could be models for replication with federal support.

Other regulatory strategies in this arena include the following:

- To help advance local codes, the federal government can put into place a mandatory "internal" buildings standard for federally-owned buildings to demonstrate and take advantage of these opportunities, while encouraging their adoption by state codes for privately-owned buildings.

- Code officials may consider "retrofit-ready" additions to building codes, e.g. assuring that adequate power, drains, etc., are provided in new construction such that the cost of installing a HPWH in the future is minimized, as already included in the California 2022 code update. Building codes can also offer compliance credits to conventional or grid-enabled HPWHs, as California's has recently done for residential buildings (Joint Appendix 13 (JA13) of Title 24).
- High-temperature HPWHs used in industry are typically uniquely designed and thus not amenable to traditional standards. However, these may be approachable via stationary-source air emissions standards rather than energy efficiency standards.

Low global warming impact refrigerants

Adopting heat pumps can significantly reduce direct combustion of fossil fuel, cutting greenhouse gas, but many common refrigerants also lead to global warming if and when they leak from the systems. The global warming potential (GWP) of refrigerants varies widely. Some cause essentially negligible warming (e.g., ammonia and CO_2-based systems with a GWP of 0-1) while others have GWP that are significantly higher (e.g., R-134a with a GWP of 1430, and other common refrigerants with GWP ranging from 500-2000+)[59]. There are emerging refrigerants with lower GWP (near 5) and favorable qualities for heat pumps as well (Kleefkens 2019).

It is of course important to place the GWP of potential refrigerant leaks in context with the savings from reduced fossil fuel use. Radhavan et al. (2017) analyzed the tradeoffs between leaks in refrigerants and reduced combustion and found that the overall climate impact of refrigerant leaks with conventional refrigerants (i.e., those with a GWP of ~1400) are expected to be on the order of 10% of the avoided emissions from fossil fuel that result from heat pump adoption. While not insignificant, the balance is still in favor of heat pump adoption even with conventional refrigerants.

Federal support for R&D to develop and support scale-up of heat pumps using low-GWP refrigerants could be an important long-run strategy to improve the climate performance of the heating system. These advances would apply in other markets and sectors as well beyond water heating.

Supporting U.S. manufacturing

As the market for HPWH and other heat pump systems grows, there will be an opportunity to grow domestic manufacturing capacity in the highly concentrated U.S. residential water-heater industry. As of 2015, three companies were responsible for almost all U.S. water heater sales.[60] These companies--and offshore manufacturers--have had a protracted roller-coaster ride in attempting to establish a sustainable presence in the U.S. market for HPWH.

Two residential HPWH manufacturers entered the market briefly in the 1950s. No activity is documented for three decades at which time different manufacturers appeared. Activity rapidly rose to 17 manufacturers and products by 1984, falling again to 2 to 5 manufacturers/products for three more decades. This latest, fourth wave of activity is unfolding as with a rise to 11 manufacturers offering an

[59] E.g, see data at https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants

[60] Per CEE (2015): AO Smith 41%, Rheem/Ruud 34%, and Bradford White 20%.

impressive array of 207 Energy-Star-qualified products (per Energy Star's aggregation method). Unlike earlier episodes, all leading manufacturers of conventional water heaters are participating (A.O. Smith, Rheem, and Bradford White -- representing 96% of the market for conventional water heaters). Given this profile, the HPWH market is arguably at its most robust and vibrant point of its history in the U.S. market.

That said, some major manufacturers (Electrolux,[61] GE,[62] and Westinghouse[63]) have in recent years discontinued a total of ten HPWHs previously offered (Schoenbauer 2015) in the U.S., and Rheem and State exited in the early years, although re-entered at some later point (AD Little 1992).

Looking more broadly at today's entire water-heating manufacturing landscape (all product types), today about 55 brands of residential water heaters are offered in the U.S. market, made by 31 manufacturers (US DOE 2020).[64] Of the 9 U.S. companies making any sort of water heater (33 brands), 4 make HPWHs (17 brands). Of the 5 US companies that don't make HPWHs, 3 produce only tankless water heaters (Bradley, Heatworks, and Niagra Industries). Westinghouse makes electric- and fuel-fired storage, and gas-fired tankless water heaters and Bock makes strictly oil-fired storage tanks. In sum, few significant U.S. manufacturers are absent from the HPWH market.

There are two ways federal action could support growth in the capacity of these U.S. manufacturing firms: first is through providing substantial and sustained support for growing the market for HPWH. Given a strong presence in the market these firms are poised to capitalize. The second pathway for support could be targeted tax incentives and other industrial support for supporting domestic manufacturing scale-up, both for HPWH as described above and also for larger commercial and industrial equipment.

Industrial policy innovation and the role of R&D

The combined impact of public-private collaboration over the 70-year development of the U.S. HPWH market has been quite muted. There have been many false starts and a roller-coaster of companies entering and leaving the market, with corresponding erratic fluctuation of HPWH sales. Overall market penetration has been negligible. There are many lessons to be learned from comparing our experience to that of other countries (Mills 2021).

Japan's experience is instructive. Although the country began developing HPWHs nearly five decades later than in the U.S., they leapfrogged over prevailing technology to a CO_2 refrigerant which has far lower global warming potential and higher COP while also significantly expanding application to cold climates. They then surpassed the U.S. in sales in the first launch year, with residential product saturation in the residential sector as of 2019 that is nearly 30-times that of the U.S. This was achieved through a carefully planned combination of R&D support, incentives, and regulatory measures. Japan also manufacturers CO_2 HPWHs for commercial buildings and industrial applications. Japan's successful approach was to develop core technology with public support and then deploy it to all manufacturers on

[61] See https://www.electroluxappliances.com/Search-Results/?q=heat%20pump%20water%20heaters
[62] See https://www.geappliances.com/search.php?search_query=hybrid%20water%20heater
[63] See http://westinghousewaterheating.com/electric-heat-pump-water-heater.html
[64] The manufacturer and domicile of 4 brands could not be identified. All of these companies make exclusively tankless units.

the market, rather than picking winners. This of course fostered competition, and maximized market exposure of the new products.

The European Commission's Horizon program has funded a program targeting industrial-scale heat pump applications in specific sectors where drying (e.g., brickmaking and food products) is a key driver of process heating energy demand.[65] Moreover, all major manufacturers of these systems appear to be based in Europe and Asia, yet their largest potential market is probably the U.S.. Smart industrial policy could help to grow this market and garner the energy and flexible demand benefits, while nurturing an industry of U.S. HTHP manufacturers which appears to be languishing.

The case of Australia offers a particularly stark counterpoint of what can happen when government engagement is incomplete or too short-lived. The introduction of substantial government incentives caused HPWH sales to rise 10-fold within less than two years, but sales plunged to near their pre-program level when incentives were abruptly and prematurely removed. Many manufacturers rapidly entered--and then exited--the market. The degree of destructiveness this caused to policymakers' credibility as well as to HPWH manufacturers' and retailers' commitment to that market has not been estimated, but can be imagined.

In contrast to the aforementioned positive outcome of federal R&D in collaboration with industry in Japan, the U.S. Government has conducted R&D on HPWH since the late 1970s, with unclear results. A serious look should be taken at why public-private collaboration has not borne significantly greater fruit. It also does not help matters that the U.S. Department of Energy claims to have "invented" the heat pump water heater (DOE 2014). In fact, the technology was initially developed by industry, and was introduced commercially more than 20 year prior to DOE's early research projects and 50 years before the commercialization of the unit (with General Electric) that DOE seems to lay claim to.

The HPWH technology is largely "ready", and procrastination-via-research should be avoided. In support of this caution, as of a couple of years ago, the California Energy Commission placed HPWHs very low on the ranked list of technologies requiring publicly funded research (Gupta and Smith 2019). A different kind of research is needed however to accelerate the market: application oriented, systems integration research designed to develop and disseminate best practices to bring deployment costs down.

Of greater concern, roadmaps continue to call for public funds to be invested in improving fossil-fuel water heating systems (Brueske 2019; Gupta and Smith 2019). This is arguably counterproductive and sends mixed messages to industry and consumers.

In terms of commercialization efforts in the United States, it is evident that HPWHs were brought to market prematurely (Mills 2021). While these were decisions made by manufacturers, the government played an active role in encouraging and incentivizing repeated cycles of ill-fated introductions.

Looking forward, HPWHs and larger commercial and industrial heat pumps are likely to be a key competitive frontier. However, there only appear to be two minor U.S. manufacturers focusing on larger HPWH and industrial-scale systems are rare, while overseas companies already manufacture diverse

[65] See DryFiciency program website http://dry-f.eu/

lines of high-output heat pumps. Proactive industrial policy can help U.S. manufacturers catch up and be prepared to have a place in the market.

Conclusion

Efficient and flexible heat pumps meet the moment by creating jobs in an important 21st century sector, lowering customers' energy bills, cutting carbon emissions, and easing integration of renewable energy.

The United States could play a leading role in developing and deploying low-carbon heating technology, creating thousands of jobs. There is a need for low-carbon heat and hot water around the world, and the U.S. could be a leader in this important and growing technology sector.

Each dollar invested in market transformation will eventually lead to a dollar in the pockets of households and the budgets of businesses who benefit from lower energy costs[66]. This clean energy annuity effect can ease the burden of energy poverty for lower income households and provide a long-term, durable, and persistent stimulus effect.

Carbon emissions from fossil fuel have pushed our planet to the brink of a climate emergency. Replacing the millions of direct combustion appliances and equipment we use for heat is a necessary step for stabilizing greenhouse gas.

Finally, the grid is already faced with more frequent times of renewable electricity surplus that will only accelerate as more clean energy generation is added. Flexible heat pump systems can make productive use of this valuable renewable energy, helping balance the grid and cutting the cost of the overall clean energy transition.

Taking advantage of this opportunity will require sustained and significant effort from federal policymakers. After decades of stagnation in heat pump deployment, new approaches like those outlined in this report are needed to transform the market and accelerate a transition towards low-carbon hot water and industrial heat.

[66] Based on the midpoint of our recommended combined equipment and installation incentive, $1,500.

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Appendix 1: Data Analysis Methods

NATIONAL ELECTRIC POWER SYSTEM

The general approach for estimating the value of flexibility is described in the main report. Below are tables and figures with some details on the scenarios we assessed.

To estimate future loads, we conduct an analysis based on actual operations data from 2019 (EIA 2020). The report is based on an "even build" scenario with 50% of new renewables from solar and 50% from wind. When variable renewable generation is over 80% of the total demand we assume that renewables will be marginal and subject to curtailment. The hours when this occurs are labeled as low price times and other hours as high price times. Finally, each customer's average electricity price ($/kWh) is adjusted so that the ratio of high:low prices is equal to some factor (e.g., 2:1 or 3:1) but the average price per kilowatt-hour over the course of the day (for a "flat load") stays the same.

Table A1: *Scenarios considered for electricity system.*

Scenario Name	**New Generation Mix**
Baseline	None -- based on 2019 data
Mostly Solar	75% solar, 25% wind
Even Build	50% solar, 50% wind
Mostly Wind	25% solar, 75% wind

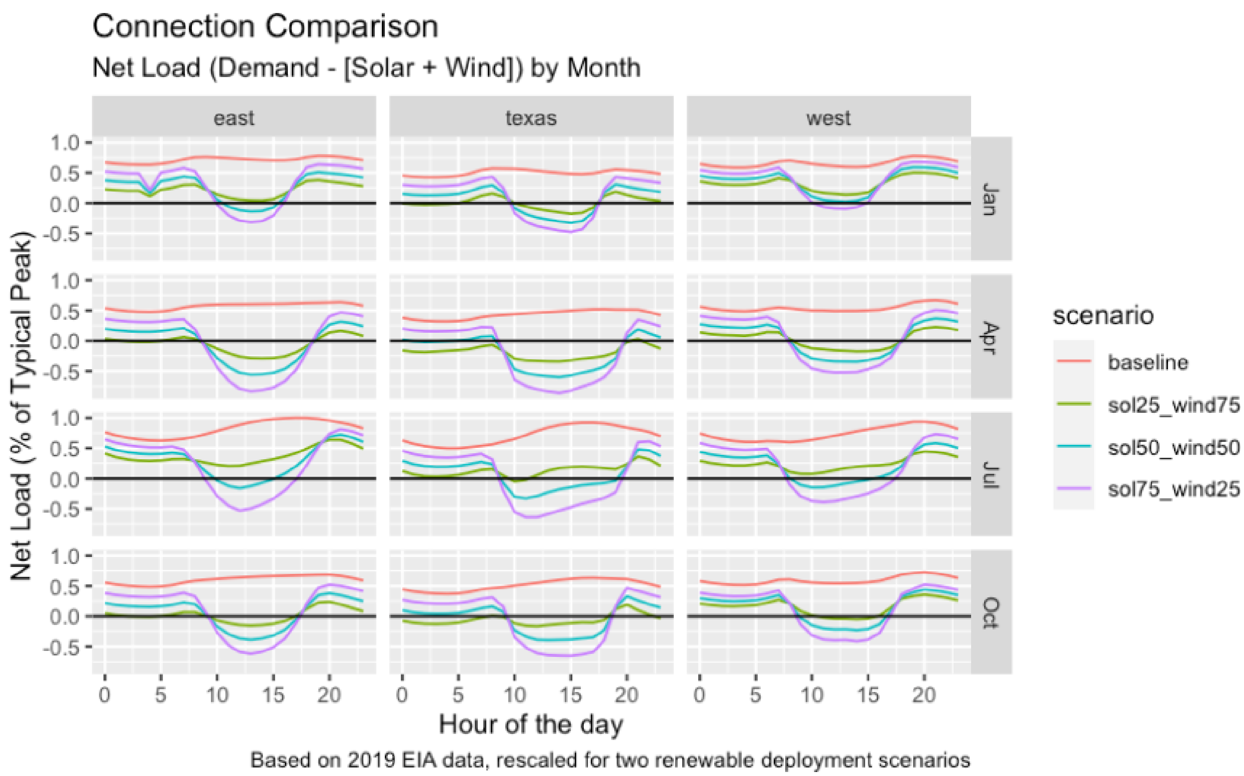

Figure A1: *Estimated future net electricity demand for the east, west, and Texas interconnection.*

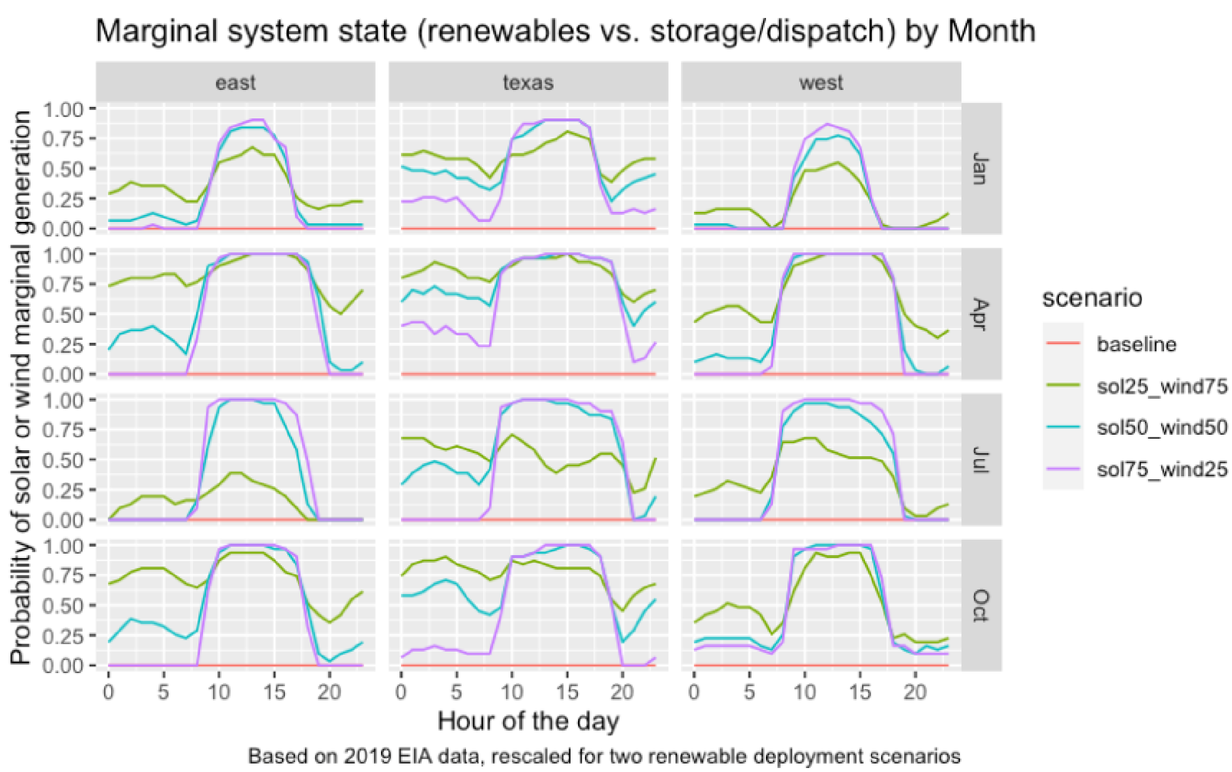

Figure A2: *Estimated future probability of marginal renewable generation in surplus for the east, west, and Texas interconnection.*

RESIDENTIAL HPWH COSTS

The capital cost of water heaters consists of two major components: the equipment cost and the installation cost. All water heaters have some seasonal variations in energy use, as hot water use changes with mains water temperature, but some technologies, including HPWHs, are more sensitive to seasonal changes. HPWHs typically have higher initial cost than conventional storage water heaters. However, they have lower operating costs, which can offset the high initial and installation costs. Table xx displays the common specifications and cost estimates for residential building water heaters. The estimates are obtained from the *Buildings Sector Appliance and Equipment Costs and Efficiency* reports. The reports are produced by Navigant Consulting, Inc. prepared for the U.S. Energy Information Administration.

Table A2. Estimated typical installation costs (Residential)

Metric	Natural Gas	Electric Resistance	Integrated / Hybrid Heat Pump
Typical Capacity (gallons)	40	50	50
Uniform Energy Factor (UEF)	0.81	0.95	3.55
Average Equipment Life (years)	13	13	13
Retail Equipment Cost (2017$)*	1,850	700	1,200
	2,100	900	2,300
Total Installed Cost (2017$)*	2,450	1,000	1,600
	3,700	1,450	3,350
Annual Maintenance Cost (2017$)	-	-	20

* Installed cost reflects differences in installation cost between typical and high-efficiency products. Typical efficiency products are non-condensing, whereas the high-efficiency products are condensing and require different installation. Furthermore, higher UEFs can be achieved by additional insulation, which also increases the size of the unit and the associated installation cost (EIA, 2018).

Table A3. HPWH split system (Sanden CO_2)--much higher COP up to 4-5

Electrical		Plumbing		Freeze protection		Equipment cost	Taxes and permit	Total
material	labor	material	labor	material	labor			
$124	$361	$522	$912	$115	$184	$4,084	$137	**$6,440**

COMMERCIAL WATER HEATERS COSTS

The capital cost of commercial water heaters consists of three major components: the equipment cost, the installation cost, and, a third cost component which differs from residential water heaters, the maintenance cost (***Table A4***.). There are no integrated commercial-specific HPWHs (CHPWHs) on the market (i.e., heat pump module and storage tank combined in one unit); all units are add-on units which are typically designed to be used with a storage tank(s). However, in principle, residential-scale HPWH may be appropriately sized for many small commercial applications.

Table A4. *Estimated Typical Installation costs of commercial natural gas and electric water heaters*

Metric	Natural Gas	Electric Resistance
Typical Capacity (gal)	100	119
Typical Input Capacity (kBtu/h) & (kW)	199	18
Thermal Efficiency (%)	99	98
Average Life (yrs)	10	12
Retail Equipment Cost (2017$)**	4,050	2,700
	4,950	3,200
Total Installed Cost (2017$)**	5,550	3,800
	6,600	3,950
Annual Maintenance Cost (2017$)	270	50

**The range of retail equipment and installed costs represents the range from replacement market to new construction market.

Table A5. *Estimated Typical costs of central commercial HPWHs*

Parameter	HPWH Value
Flow rate (gal/min)	34
Typical Input Capacity (kW)	50
Coefficient of Performance (COP)	3.9
Average Life (yrs)	15
Retail Equipment Cost (2017$)**	47,100
Total Installed Cost (2017$)**	50,950
Annual Maintenance Cost (2017$)	100

Table A6. Cost synthesis for replacing storage commercial water heaters

Fuel	$ / kBtuh (heat)
Natural Gas	35
Electric Resistance	65
Heat Pump	80

INDUSTRIAL HEAT PUMP COSTS

Our synthesis of a literature review of total system capital investment of heat pump technology in the industrial sector is shown in Figure A3. We derived the following specific cost equation across a range of sources.

$$\frac{\$}{kW_{th}} = 1{,}658(kW_{th})^{-0.174}$$

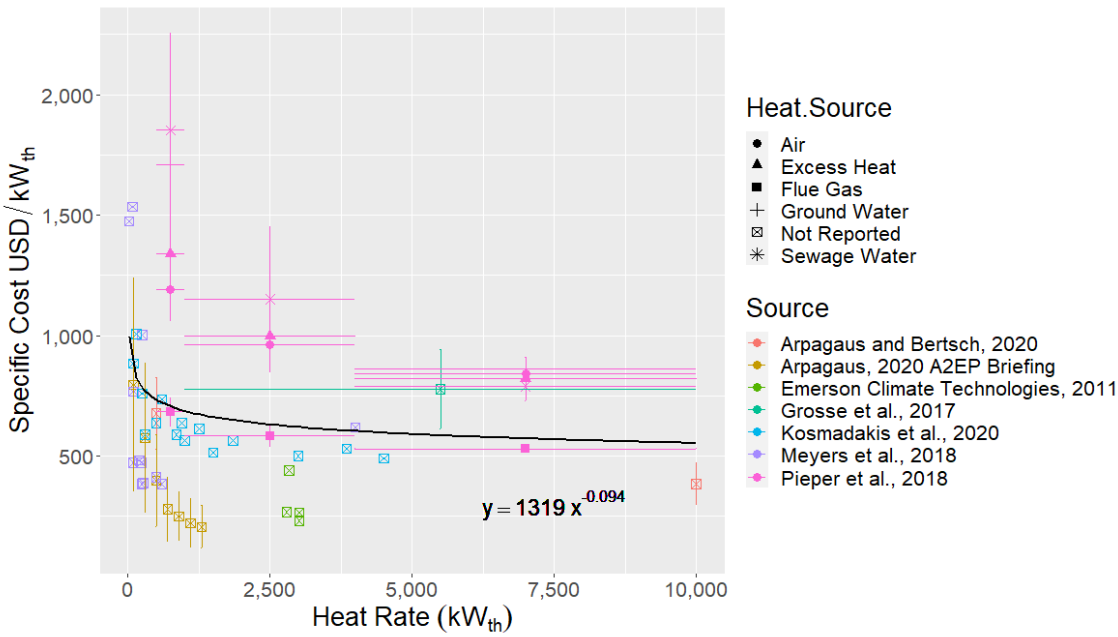

Figure A3. *Synthesis of large commercial and industrial heat pump installation costs.*

Ultimately our analysis in the large commercial sector used the three most recent (2020 dated) sources in Figure A3, based on an assessment of their relative value for estimating current prices for industrial heat pump projects. These are shown in Figure A4 with the equation used to estimate the unit cost of custom heat pumps.

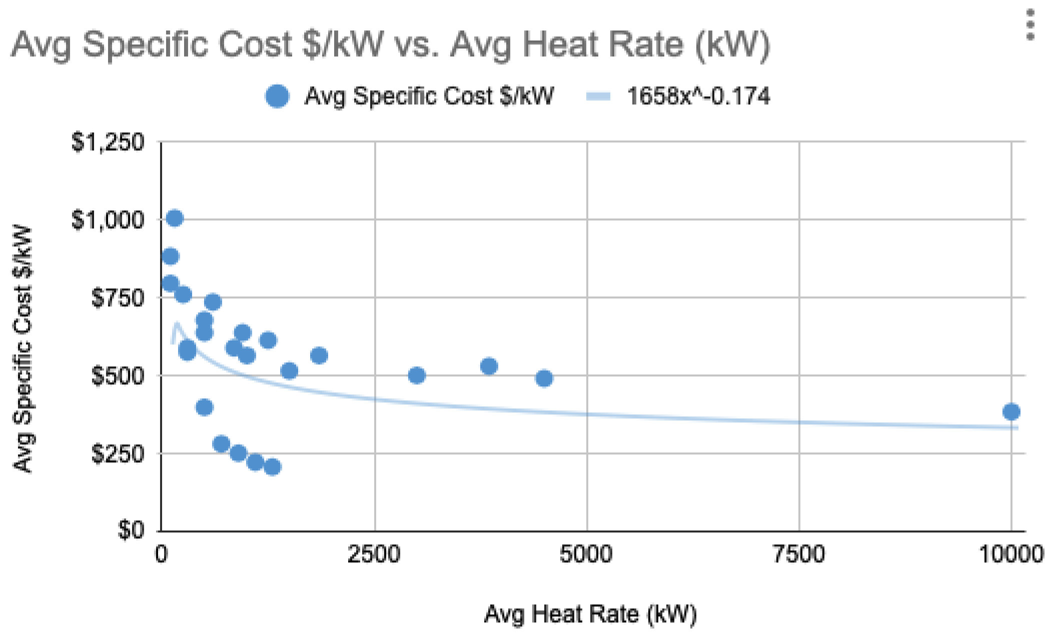

Figure A4. *Synthesis of recent large heat pump unit cost data*

We identified two sources of "cost breakdown" fractions for industrial heat pumps (Tables A7 and A8). These may be valuable for future work in applied R&D to reduce costs. Grosse et al., 2017 offer insight into fixed O&M costs of electric driven heat pumps in the 1 - 10 MW range as well. They project $3,200 to $3,500 per MW_{th}-yr over the next decade. This is expected to drop as the technology matures. These O&M figures and cost breakdown were not included in our analysis but are included here as an informational item.

Table A7. *Percentage breakdown of total system cost by heat source: ground water (GW), waste heat (WH), flue gas (FG), air, and sewage water (SW). From Grosse et al., 2017*

Cost Source	GW	WH	FG
Equipment	47	49	48
BOP	31	16	20
Electrical and I&C	6	13	20
Civil and Structural	10	13	4
Development	3	4	5
Interconnection	3	5	3

Table A8. *Percentage breakdown in total costs by heat source (groundwater (GW), waste heat (WH), flue gas (FG), air, and sewer water (SW). From Pieper et al., 2018.*

Cost Source	GW	WH	FG	Air	SW
Heat Pump	54	48	45	40	38
Heat Source	13	16	12	15	35
Construction	9	18	15	13	12
Electricity	16	16	28	19	7
Consulting	9	2	0	13	8

DATA SOURCES

The data sources we use to support our analysis are listed in table A9. In each sector, the data represent the best available source we could identify for estimating the scale of the opportunity and understanding the diversity of expected economic and technical outcomes across the United States. We focused on national-scale surveys and datasets that provided uniform coverage rather than attempting to stitch together disparate local and regional surveys that may have more granular but divergent approaches.

Table A9. *Summary of data sources used to support the analysis*

Sector	Data Scope	Source
Residential	Hot water demand and incumbent technology characteristics for representative households, with demographic information and other supporting information on energy consumption and expenditures.	Residential Energy Consumption Survey (RECS) microdata from 2015 survey. (EIA 2021a)
Residential	Estimated load shapes for hot water demand by climate zone	Modeling data from a HPWH Load Shifting Study (Carew et al 2018), provided by (Deforge 2020).
Commercial	Hot water demand and incumbent technology characteristics for representative businesses and other commercial building premises, with demographic information and other supporting information on energy consumption and expenditures.	Commercial Building Energy Consumption Survey (CBECS) microdata from 2012 survey. (EIA 2021b)
Commercial	Estimated load shapes for hot water demand by building type	Commercial "Reference Building" load shapes. (Wilson 2014)
Industrial	Estimated demand for heat by industry type, temperature range, and fuel used, at the County level. Estimated load shapes for heat demand.	Manufacturing Thermal Energy Use in 2014 dataset from National Renewable Energy Laboratory analysis. (McMillan 2019)
Industrial	Fuel cost by industry type, by region.	Manufacturing Energy Consumption Survey (MECS) summary data from 2014 survey. (EIA 2021c)
All	Greenhouse gas intensity for stationary fossil fuel combustion in heating appliances and applications.	Environmental Protection Agency stationary emissions data. (EPA 2018)
All	Greenhouse gas intensity for electricity consumption with current-day grid mix.	Environmental Protection Agency "Emissions and Generation Resource Integrated Database" (eGRID) 2018 data. (EPA 2020)
All	Electricity grid generation data by region	Hourly Electric Grid Monitor datasets. (EIA 2020)

Appendix 2: Summary data and tables

This appendix includes a number of summary data tables that support the main report and are the basis for many of the figures.

***Table A10**. Summary of current greenhouse gas emissions from conventional heat sources for hot water and low-temperature industrial heat (circa 2010-2020) that are in the scope of analysis for this report.*

Sector	**Application**	**MMT CO_2e / year**	**Data Source**
Residential	**Water Heating**	140	*Analysis of RECS*
Commercial	**Water Heating**	30	*Analysis of CBECS*
Industrial	Hot water and steam below 150°C provided by **boilers**	180	*Analysis of NREL Industrial Heat Toolbox Data*
Industrial	Hot water and steam below 150°C provided by **CHP**	140	*Analysis of NREL Industrial Heat Toolbox Data*
Industrial	**Process** heating below 150°C	30	*Analysis of NREL Industrial Heat Toolbox Data*
TOTAL	***All in scope for report***	**520**	*Synthesis*

***Table A11**. Summary of current greenhouse gas emissions from conventional heat sources for space heating and high-temperature industrial heat (circa 2010-2020). These are not in the scope of analysis for this report.*

Sector	**Application**	**MMT CO_2e / year**	**Data Source**
Residential	**Space Heat**	220	*Billimoria et al. (2018)*
Commercial	**Space Heat**	170	*Billimoria et al. (2018)*
Industrial	**Space Heat**	20	*Analysis of MECS Survey (EIA 2021c)*
Industrial	Hot water and steam *above* 150°C provided by **boilers**	110	*Analysis of NREL Industrial Heat Toolbox Data*
Industrial	Hot water and steam *above* 150°C provided by **CHP**	70	*Analysis of NREL Industrial Heat Toolbox Data*
Industrial	**Process** heating *above* 150°C	300	*Analysis of NREL Industrial Heat Toolbox Data*
TOTAL	***Not in scope for report***	**890**	*Synthesis*

Table A12. *Estimated primary energy consumed for hot water and industrial sector heat in applications that are technically possible to replace with heat pumps. "Point-of-use" is also known as "demand" or "instantaneous" water heating. Data source: authors' synthesis of CBECS, RECS, and MECS data (see Appendix 1).*

Segment	***TBTU per year***	**% of TOTAL**	**% of sector**	**Elec:Fuel Price Ratio**	**COP to Break even**
All sectors and segments (7.8 EJ, primary energy)	7,656	100%	n/a	n/a	n/a
Single-family	2,082	27%	71%	3.01	2.408
multifamily	618	8%	21%	3.35	2.68
Mobile home	239	3%	8%	2.7	2.16
Centralized / Storage	335	4%	40%	4.2	3.36
Point of use	43	1%	5%	4.2	3.36
System mix	129	2%	15%	4.2	3.36
District heating	341	4%	40%	4.2	3.36
Industrial Conventional Boilers	2,533	33%	65%	2.7	2.16
Industrial CHP (useful heat portion)	918	12%	24%	2.84	2.272
Industrial Process Heat	417	5%	11%	3.16	2.528

Table A13*. Summary statistics for breakeven COP based on operating costs. Supporting Figure 8.*

Sector	Baseline Fuel	5th %	25th %	median	mean	75th %	95th %	Number of Sites
Residential	Natural Gas	1.49	2.31	2.84	3.17	3.55	5.17	56,304,361
Residential	Other	0.94	1.24	1.71	1.89	2.20	3.51	7,324,009
Commercial	Natural Gas	1.35	2.14	2.79	3.08	3.71	5.19	1,734,013
Commercial	Other	0.72	1.04	1.37	2.47	2.18	3.29	1,381,151
Industrial	Natural Gas	2.36	3.07	3.28	2.64	3.71	5.33	268,776
Industrial	Other	0.69	0.97	1.44	1.93	1.99	3.16	627,757

Table A14. *Summary statistics for breakeven COP based on carbon intensity. Supporting Figure 8.*

Sector	Baseline Fuel	5th %	25th %	median	mean	75th %	95th %	Number of sites
Residential	Natural Gas	0.95	1.24	1.54	1.46	1.95	1.95	56,304,361
Residential	Other	0.67	0.67	1.06	1.05	1.32	1.67	7,069,807
Commercial	Natural Gas	0.98	1.28	1.59	1.46	1.73	2.01	1,734,013
Commercial	Other	0.69	1.12	1.42	1.93	1.94	2.90	119,163
Industrial	Natural Gas	0.40	0.92	1.50	1.72	1.97	3.44	268,776
Industrial	Other	0.28	0.64	0.99	0.95	1.41	2.40	627,757

Table A15*. Residential sector emissions from water heating (million metric tons of CO2e per year). Data sources: EIA 2021a, EPA 2018, EPA 2020). See Figure 9 for data view.*

Sub Sector	**Electricity**	**Natural Gas**	**Other**	**Total**
Mobile home	9	0.9	0.6	10.5
Single-family detached house	45.6	38.5	6.5	90.6
Single-family attached house	3.5	3.4	0.1	7
Apartment in a building with 2 to 4 units	4.4	4.8	0.6	9.8
Apartment in a building with 5 or more units	11.7	6.5	1.4	19.6

Table A16*. Residential sector greenhouse gas emissions per household (kilograms of CO2e per household per year). Data sources: EIA 2021a, EPA 2018, EPA 2020). See Figure TTQN for data view.*

Region	Baseline Energy Source	5th %	25th %	median	mean	75th %	95th %	Number of Sites
Midwest	Electricity	407	972	1,540	1,786	2,286	3,999	9,406,971
Midwest	Natural Gas	461	577	891	989	1,255	1,828	16,001,711
Midwest	Other	553	847	1,064	1,205	1,599	2,100	963,053
Northeast	Electricity	144	460	794	843	1,141	1,815	6,802,145
Northeast	Natural Gas	460	595	946	1,063	1,391	2,055	10,598,254
Northeast	Other	474	772	1,259	1,390	1,736	2,863	3,606,139
South	Electricity	473	803	1,218	1,395	1,858	3,051	30,106,882
South	Natural Gas	328	563	795	879	1,170	1,715	12,909,205
South	Other	296	617	883	1,119	1,405	2,152	1,425,887
West	Electricity	260	626	1,042	1,162	1,532	2,682	8,263,881
West	Natural Gas	330	574	843	938	1,182	1,980	16,795,191
West	Other	-	603	1,017	1,071	1,392	2,287	1,328,931

Table A17. *Shipments of residential water heaters over time (number per year in U.S.) See Figure A17 for data view. Sources: Gas and Electric storage: AHRI (2020); 2004-2007. Instantaneous gas water heaters: (EERE 2006) and ENERGY STAR Unit Shipment and Market Penetration Report (2010-2019); HPWH data also from ENERGY STAR (2010-2019).*

Year	Gas Storage	Electric Storage	Gas tankless	Heat Pump water heaters
2000	4,907,007	4,257,433	missing	missing
2001	4,931,267	4,333,170	missing	missing
2002	4,987,976	4,390,495	missing	missing
2003	5,124,265	4,429,880	missing	missing
2004	5,053,775	4,572,932	85,000	missing
2005	4,801,188	4,518,598	156,000	missing
2006	4,654,436	4,791,640	242,000	missing
2007	4,384,428	4,470,232	322,000	missing
2008	4,000,493	4,189,451	missing	2000
2009	3,760,657	3,751,994	missing	missing
2010	3,918,150	3,736,597	384,000	59000
2011	3,953,113	3,738,882	337,000	23000
2012	3,959,444	3,733,988	339,000	34000
2013	4,282,104	4,008,478	397,000	43000
2014	4,471,903	4,277,329	416,000	46000
2015	4,374,199	4,027,067	297,000	55000
2016	4,208,984	3,937,936	304,000	52000
2017	4,359,297	4,127,302	387,000	72000
2018	4,521,373	4,229,912	444,000	65000
2019	4,377,001	4,201,274	491,000	84000

Table A18. *Summary data for distribution of savings for residential customers replacing baseline water heating technology with a HPWH with a COP of 3.0. Data view available in Figure 14.*

Region	Baseline Energy Source	5th %	25th %	median	mean	75th %	95th %	Number of Sites
Midwest	Electricity	-623	-348	-239	-282	-156	-85	9406971
Midwest	Natural Gas	-136	-65	-31	-38	-5	26	16001711
Midwest	Other	-378	-240	-166	-182	-109	-27	963053
Northeast	Electricity	-765	-456	-330	-349	-195	-74	6802145
Northeast	Natural Gas	-175	-89	-49	-45	-2	67	10598254
Northeast	Other	-508	-285	-171	-201	-90	-15	3606139
South	Electricity	-607	-369	-247	-280	-162	-99	30106882
South	Natural Gas	-248	-148	-92	-108	-60	-26	12909205
South	Other	-601	-372	-235	-280	-157	-77	1425887
West	Electricity	-636	-348	-228	-282	-146	-78	8263881
West	Natural Gas	-179	-102	-67	-77	-41	-8	16795191
West	Other	-519	-362	-261	-263	-140	-21	1328931

Table A19. *Break-even COP on an ongoing-cost basis for commercial customers by baseline energy source. This data is shown in figure 21.*

Baseline Energy Source	5th %	25th %	median	mean	75th %	95th %	Number of Sites
District Heat	1.4	1.9	2.5	3.2	3.0	3.7	23854
Electricity	1.0	1.0	1.0	1.0	1.0	1.0	2441974
Fuel Oil / Kerosene	0.6	0.9	1.1	3.5	1.3	1.9	69187
Mixed	1.0	1.5	2.1	1.9	2.5	3.6	1288110
Natural Gas	1.4	2.1	2.8	3.0	3.7	5.2	1734013

***Table A20**. Heat pump performance (COP) required to break even on operating costs (excluding incentives for demand-flexibility) for industrial sub-sectors. Based on data from MacMillan et al. (2019), with additional supporting information from EIA (2021c) and stationary emissions factors for the fuels used. A view of this data is shown in Figure 28.*

Sub Sector	**5th %**	**25th %**	**median**	**mean**	**75th %**	**95th %**	**Number of Sites**
Apparel Manufacturing	1.5	1.5	3.4	3.5	4.0	6.0	13222
Beverage and Tobacco Product Manufacturing	0.7	1.2	2.0	3.0	3.7	5.3	85927
Chemical Manufacturing	0.5	1.0	1.6	1.8	2.6	4.0	51927
Fabricated Metal Product Manufacturing	1.0	1.9	2.0	2.4	3.2	3.8	314358
Food Manufacturing	0.7	1.0	1.7	1.9	2.8	3.9	88992
Machinery Manufacturing	0.8	1.2	2.0	2.4	3.3	5.5	167412
Miscellaneous Manufacturing	0.9	1.0	1.5	2.3	3.9	5.0	64446
Nonmetallic Mineral Product Manufacturing	0.6	0.9	1.7	1.7	2.5	3.2	2720
Paper Manufacturing	0.5	0.9	1.4	1.8	2.5	3.5	4851
Petroleum and Coal Products Manufacturing	0.5	0.8	1.3	1.6	2.2	3.3	5487
Plastics and Rubber Products Manufacturing	0.6	0.8	1.9	1.8	3.1	3.3	41921
Primary Metal Manufacturing	0.4	1.1	1.7	1.9	2.3	3.7	4345
Textile Mills	0.6	1.0	1.5	1.8	2.7	3.3	27489
Textile Product Mills	0.7	1.0	1.3	2.0	3.2	4.6	18638
Transportation Equipment Manufacturing	0.7	1.3	1.8	2.1	2.8	3.6	4798

***Table A21**. CO2e emissions per year from water heating by commercial building subsectors. Data from CBECS survey (EIA 2021b) with emissions intensity from EPA (EPA 2018, EPA 2020). Data visualization is in figure A21.*

Sub Sector	District Heat	Electricity	Fuel Oil / Kerosene	Mixed	Natural Gas
Refrigerated warehouse	-	1,621	-	-	15,782
Other	-	8,245	128	70	24,713
Enclosed mall	25,019	138,433	-	27,327	41,805
Vacant	494	479	69	-	43,005
Laboratory	13,567	1,580	-	-	62,430
Food sales	-	12,506	20	-	157,362
Outpatient health care	23,810	14,221	39	353	194,239
Retail other than mall	10,876	57,974	72	910	220,975
Public assembly	49,861	28,813	3,355	4,663	308,800
Nonrefrigerated warehouse	-	70,234	41	1,181	524,638
Religious worship	-	36,402	486	583	534,547
Public order and safety	251,471	108,578	121	-	875,439
Service	3,488	39,890	45	-	1,135,932
Office	249,144	203,652	433	7,704	1,575,674
Nursing	5,142	74,378	3,607	-	1,965,485
Food service	16,526	318,922	269	28,053	2,150,137
Education	664,465	326,709	9,614	9,393	2,910,920
Strip shopping mall	-	344,273	-	125,447	3,049,660
Inpatient health care	1,113,821	80,795	6,538	83,181	3,053,321
Lodging	1,168,587	194,335	28,597	605	4,088,062

Table A22. *CO2e emissions per year from water heating per commercial building, divided in four national regions. Data from CBECS survey (EIA 2021b) with emissions intensity from EPA (EPA 2018, EPA 2020). Data visualization in Figure 18.*

Region	Baseline Energy Source	5th %	25th %	median	mean	75th %	95th %	Number of Sites
Midwest	District Heat	2813	28395	148819	171064	734200	1954532	5042
Midwest	Electricity	6	42	215	866	2238	28137	483442
Midwest	Fuel Oil / Kerosene	30	110	771	531	1479	1672	4474
Midwest	Mixed	0	0	0	379	0	14323	255248
Midwest	Natural Gas	57	648	6278	8601	34480	493737	489274
Northeast	District Heat	4345	42327	126696	138085	664005	1984821	7478
Northeast	Electricity	5	42	248	497	1403	13766	279352
Northeast	Fuel Oil / Kerosene	5	29	287	440	2225	41202	60900
Northeast	Mixed	0	0	0	233	0	21400	172240
Northeast	Natural Gas	124	1308	11605	15072	64805	889331	285513
South	District Heat	1493	23131	146900	144499	675322	3112003	7253
South	Electricity	8	59	267	1008	2229	18266	1167398
South	Fuel Oil / Kerosene	405	1997	2406	8524	12390	27164	2740
South	Mixed	0	0	0	217	0	7051	553587
South	Natural Gas	116	1960	11948	16213	85790	1313165	515825
West	District Heat	3122	37890	107052	160040	498800	2754214	4081
West	Electricity	8	53	205	640	1218	11415	511782
West	Fuel Oil / Kerosene	402	1884	3737	863	31881	54397	1073
West	Mixed	0	0	0	106	0	556	307035
West	Natural Gas	106	1159	7851	13663	49222	647934	443402

Table A23. *Trends in sales of commercial storage water heaters, by fuel. Sources: Heater Shipments: 1994-1999 from U.S. DOE 2010, and 2000-2019 from AHRI (2020). Unfired storage tanks and boilers used for water heating are not included here.*

Year	Gas-fired storage	Electric storage	Total
1994	91,027	22,288	113,315
1995	96,913	23,905	120,818
1996	127,978	26,954	154,932
1997	96,501	30,339	126,840
1998	94,577	35,586	130,163
1999	100,701	39,845	140,546
2000	99,317	44,162	143,479
2001	93,969	46,508	140,477
2002	96,582	45,636	142,218
2003	90,292	48,137	138,429
2004	96,481	57,944	154,425
2005	82,521	56,178	138,699
2006	84,653	63,170	147,823
2007	90,345	67,985	158,330
2008	88,265	68,686	156,951
2009	75,487	55,625	131,112
2010	78,614	58,349	136,963
2011	84,705	60,257	144,962
2012	80,490	67,265	147,755
2013	88,539	69,160	157,699
2014	94,247	73,458	167,705
2015	98,095	88,251	186,346
2016	97,026	127,344	224,370
2017	93,677	152,330	246,007
2018	94,473	138,882	233,355
2019	88,548	150,667	239,215

Table A24. *Carbon emissions associated with fuels combustion for industrial heat by end use type. Based on data from MacMillan et al. (2019), with additional supporting information from EIA (2021c) and stationary emissions factors for the fuels used. Data visualization in Figure 26.*

Sub Sector	Coal	Coke and breeze	Diesel	LPG NGL	Natural gas	Other	Residual fuel oil
Apparel	-	-	-	0.002	0.007	-	-
Miscellaneous	-	-	0.004	0.002	0.115	-	-
Nonmetallic Mineral Product	0.001	-	0.003	0.000	0.081	0.056	-
Fabricated Metal Product	0.046	-	0.000	0.001	1.037	0.032	-
Machinery	0.106	-	0.002	0.002	0.860	0.148	-
Textile Product Mills	-	-	0.072	0.003	1.670	-	-
Plastics and Rubber Products	0.008	-	0.005	0.001	1.783	0.033	0.002
Primary Metal	0.011	0.729	0.006	0.004	2.078	0.305	0.001
Textile Mills	1.008	-	0.006	0.005	1.872	0.645	0.011
Transportation Equipment	0.086	0.004	0.005	0.009	3.559	0.435	0.036
Beverage and Tobacco Product	1.998	-	0.034	0.006	6.771	5.341	0.007
Petroleum and Coal Products	0.025	-	0.039	0.064	5.736	44.209	0.046
Food	17.850	0.502	0.297	0.129	29.939	12.830	0.338
Paper	13.771	0.000	0.123	0.007	17.081	50.349	0.759
Chemical	18.063	-	0.065	0.056	74.973	27.577	0.054

Table A25. *Estimated average emissions from electricity generation by state. Data are from eGRID online tool (EPA 2021).*

Region	CO2 total output emission rate (lb/MWh) by state 2019
United States Average	884.23
WYOMING	2053.963
WEST VIRGINIA	1929.876
KENTUCKY	1767.68
INDIANA	1623.637
UTAH	1590.641
MISSOURI	1586.815
HAWAII	1550.538
PUERTO RICO	1537.308
NORTH DAKOTA	1436.445
COLORADO	1322.745
NEW MEXICO	1319.372
NEBRASKA	1255.483
MONTANA	1253.318
OHIO	1235.41
WISCONSIN	1225.376
ARKANSAS	1121.449
MICHIGAN	1006.839
ALASKA	969.657
TEXAS	909.538
KANSAS	887.175
GEORGIA	876.208
MINNESOTA	874.768
FLORIDA	873.661
ARIZONA	869.18
IOWA	855.493
RHODE ISLAND	851.411
MISSISSIPPI	835.152
LOUISIANA	823.639
DISTRICT OF COLUMBIA	796.57
ALABAMA	781.905
NORTH CAROLINA	775.01
MASSACHUSETTS	773.102
PENNSYLVANIA	754.916
NEVADA	737.453
MARYLAND	734.631
OKLAHOMA	731.952
ILLINOIS	720.994
DELAWARE	709.974
TENNESSEE	700.313
VIRGINIA	633.189
NEW JERSEY	543.142
SOUTH CAROLINA	535.124
SOUTH DAKOTA	489.05
CONNECTICUT	474.377
OREGON	396.591
CALIFORNIA	385.591
NEW YORK	376.722
WASHINGTON	297.247
NEW HAMPSHIRE	251.051
IDAHO	210.845
MAINE	205.232
VERMONT	40.858

Table A26. *Summary of maximum allowable simple payback period for investments in the industrial sector. This table is a summary of self-reported survey responses, based one publicly available results of the 2014 Manufacturing Energy Consumption Survey (EIA 2021c)*

Subsector	Num. of Sites	Less than 1 year	1 to 2 years	2 to 3 years	3 to 4 years	Greater than 4 years	No Such Require -ment	Don't Know
Food	13,690	4%	12%	15%	11%	4%	26%	27%
Beverage and Tobacco Products	2,443	-	5%	9%	12%	-	40%	28%
Textile Mills	1,355	-	18%	23%	8%	-	32%	11%
Textile Product Mills	4,277	-	-	4%	-	-	61%	21%
Apparel	3,874	-	-	-	0%	-	51%	35%
Leather and Allied Products	466	-	9%	11%	7%	0%	54%	11%
Wood Products	8,398	3%	11%	13%	4%	3%	32%	34%
Paper	3,220	-	11%	20%	10%	13%	21%	22%
Printing and Related Support	14,005	3%	8%	13%	5%	4%	34%	33%
Petroleum and Coal Products	1,918	2%	16%	14%	9%	12%	17%	29%
Chemicals	8,530	3%	17%	17%	10%	4%	23%	27%
Plastics and Rubber Products	8,217	8%	20%	18%	6%	-	19%	28%
Nonmetallic Mineral Products	12,184	1%	8%	13%	10%	3%	37%	29%
Primary Metals	3,138	2%	20%	16%	7%	4%	25%	25%
Fabricated Metal Products	36,439	-	5%	13%	4%	5%	43%	28%
Machinery	15,307	3%	10%	12%	8%	6%	32%	28%
Computer and Electronic Products	6,831	-	13%	13%	4%	-	32%	32%
Electrical Equip., Appliances, and Components	3,298	-	16%	11%	-	-	27%	32%
Transportation Equipment	6,603	8%	17%	17%	2%	-	26%	29%
Furniture and Related Products	7,913	3%	6%	8%	-	-	43%	34%
Miscellaneous	13,001	-	8%	8%	3%	4%	46%	30%
Total	175,107	3%	10%	13%	6%	4%	35%	29%