You're Getting Warmer

A Comparison of Gas Furnaces and Heat Pumps in Midwest Homes

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List of Acronyms

ACEEE – American Council for an Energy Efficient Economy
ASHP – Air Source Heat Pump
ccASHP – Cold Climate Air Source Heat Pump
COP – Coefficient of Performance
CO_2 – Carbon Dioxide
CZ – Climate Zone
eGRID – Emissions and Generation Resource Integrated Database
GHG – Greenhouse Gas
HSPF – Heating Season Performance Factor
HR – Heat Rate
kWh – Kilowatt-hour
MMBtu – Million British Thermal Units
MN CEE – Minnesota Center for Energy and Environment
MSA – Metropolitan Statistical Area
MWh – Megawatt-hour
NREL – National Renewable Energy Laboratory
NYSERDA – New York State Energy Research and Development Authority
ORNL – Oak Ridge National Laboratory
ResStock – Residential Database and Analysis Tool

Contents

Executive Summary

Is it more beneficial to replace an existing gas furnace in a home with a new gas furnace or an electric air source heat pump (ASHP)?[1] Based on analysis comparing those replacement options in five cities in the Midwest, the answer is – *it depends.*

To answer the question, we analyzed how various levels of efficiency for gas-fired furnaces and electric ASHPs compare in terms of source efficiency, lifecycle costs and carbon dioxide (CO_2) emissions. The Midwest states are diverse - there is a broad range of climate zones (CZ), from Zone 4 to 7, different mixes of electric generation sources depending on state and utility service territory, differences in state energy policies and other factors. We selected five study locations to represent the diversity of the region and provide a broad perspective for the assessment:

- St. Louis, MO (CZ 4)
- Chicago, IL (CZ 5)
- Grand Rapids, MI (CZ 5)
- Madison, WI (CZ 6)
- Minneapolis, MN (CZ 6)

In addition to including high-efficiency furnaces and ASHP models in the analysis, this study also included cold climate ASHPs (ccASHP) for comparison.

Our results show that based on specific design temperatures, utility heat rates, energy and equipment costs, and emissions data, none of the five locations demonstrate favorability towards transitioning to an ASHP, in terms of all three criteria considered. For example, our analysis demonstrates that in locations, such as Chicago, Madison, and Minneapolis it is not more source efficient or more cost-effective to replace a heating unit with an ASHP instead of a high efficiency furnace, but an ASHP would dramatically reduce lifetime CO_2 emissions given the electric generation mix in the area. Conversely, in St. Louis, an area with a more moderate climate, the analysis shows that while ASHPs are only slightly less cost effective than a high efficiency furnace, a transition to ASHPs would use more source energy and would dramatically increase life-time CO_2 emissions associated with heating. Table 1 shows which criteria favor replacing an existing heating system with an ASHP instead of a high efficiency furnace for the five cities in the analysis.

Table 1: Benefits of replacing heating system[2] with an ASHP instead of a high efficiency furnace. (Key: ✓ASHP is more favorable than the furnace for that criteria)

City	Source Efficiency	Life-Cycle Costs	Lifetime CO_2 Emissions
St. Louis	—	—	—
Chicago	—	—	✓
Grand Rapids	—	—	—
Madison	—	—	✓
Minneapolis	—	—	✓

[1] As discussed later in the paper, the analysis assumes the AC unit is also replaced at the same time as the heating unit.

Our results demonstrate that for most locations in the Midwest, the full replacement of an existing gas furnace with a high efficiency gas furnace[3] is more favorable than a ccASHP in terms of efficiency, economics and CO_2 emissions, at least in the near term.

This is not, however, a static issue. Repeating this analysis periodically would be useful to account for technological improvements in ASHPs, reduction in equipment costs, energy price fluctuations and an evolving electric grid.

[3] For this analysis a 97 AFUE furnace was used to represent a high efficiency furnace.

Introduction

In the age of "strategic electrification,"[4] the use of ASHPs has become increasingly attractive for multiple reasons, including:

- Reduced HVAC installation and operation costs from streamlining the heating and cooling system with an all-in-one system
- Improved building efficiency in cold climates through continued advancements in cold climate heating technology
- Lower carbon emissions that can help meet jurisdictional climate goals

However, the efficacy and potential for immediate deployment of ASHPs is highly dependent on location and technology. Conventional ASHPs operate most effectively in warmer climate zones where they can avoid significant performance degradation and the need for backup heating systems when they are deployed in cold climates. However, cold-climate inverter technology for ccASHPs continues to evolve, improving performance and overall system efficiency in cold climates. These improvements mean that ccASHPs could soon become a viable replacement option for space conditioning in cold climates.

In this study, we performed a comparative analysis of gas fired furnaces and electric ASHPs to determine when and where in the Midwest it may be more beneficial to replace an existing gas furnace with an electric ASHP instead of a new gas furnace. We compared various efficiency levels of forced air gas furnaces and ducted, electric ASHPs using specific inputs from five different locations in the Midwest:

- St. Louis, MO
- Chicago, IL
- Grand Rapids, MI
- Madison, WI
- Minneapolis, MN

These cities represent some of the diversity of the Midwest. They provide a mix of climates, ranging from CZ4 in St. Louis to CZ6 in Madison and Minneapolis. The state energy policies and energy efficiency requirements vary from state to state, as well as the aspirational goals for clean energy that have been expressed by various states, municipalities and utilities. The different cities also have varying mixes of electricity generation sources, with different amounts of fossil-fueled, nuclear and renewable energy generators on the grid.

Using these differences to inform our analytical model, we determined for each location when it would more beneficial to fully replace a gas furnace with an ASHP instead of a new furnace. Three potential considerations were assessed to make this determination:

1) Source energy efficiency[5]
2) Lifecycle costs
3) CO_2 emissions

[4] Strategic Electrification: "powering end uses with electricity instead of fossil fuels in a way that increases energy efficiency and reduces pollution, while lowering costs to customers and society, as part of an integrated approach to deep decarbonization." (NEEP, 2017)

[5] Site energy: the amount of heat and electricity consumed by a building (site) as reflected in a customer's utility bills. Source energy: the total amount of raw fuel that is required to operate the building (from the energy source), incorporating all transmission, delivery, and production losses. (Energy Star, 2018)

Those three factors were calculated for furnaces, ASHPs and ccASHPs at various levels of equipment efficiency.[6]

Cold Climate ASHP Technology

For the Upper Midwest (CZ 6 – 7), where temperatures consistently dip well below 0° F, backup heating is currently needed with ducted ccASHP technology.[7]

Current ccASHP technology includes an inverter-driven compressor and updated refrigerant, allowing a single compressor system to better serve cold climates. Like a dual compressor system, "the inverter-driven compressor allows the compressor speed to modulate and increase capacity during periods of colder outdoor air temperatures" (MN CEE 2018). Manufacturers claim that current ccASHPs can effectively operate below 0 °F, but more research needs to be conducted on these systems to verify this claim under field conditions.

A recent study by Minnesota Center for Energy and Environment (MN CEE) assessed the efficacy of ducted ASHPs in the field and determined that when installing an inverter-driven ccASHP that is currently available in the marketplace, the ASHP could realistically take on only 80% of the heating load without needing resistance heating or a backup system in Minnesota. That study analyzed two all-electric ccASHP with an electric booster (electric resistance) as well as four hybrid systems which is a combination of a ccASHP and backup gas or propane furnace in various locations in Minnesota. As demonstrated in the study, as the temperature dropped, starting at around 45° F, the backup heating system took on more of the heating load. At 0-5° F, the backup heating system took on the full load (MN CEE 2018).

Non-ccASHPs require even more back-up heating capacity. The MN CEE study indicated that for non-ccASHPs, installers typically set the transition point at which backup heating takes the full heating load between 25° F and 35° F to maintain indoor comfort and ensure the ASHP is not operating at a significantly reduced level of efficiency. This means that the ASHP is only taking 30% to 60% of the total heating load, depending on location in Minnesota (MN CEE 2018).

Although hybrid systems are becoming more popular, for this study, we analyzed all electric split system ASHPs to account for the full replacement of a heating system with either a furnace or ASHP. We assumed for this study that all ASHPs would rely on electric resistance heating when backup heating is required and de-rated the level of ASHP efficiency accordingly.

Study Methodology

We built on a methodology developed by the American Council for an Energy Efficient Economy (ACEEE) in their paper, Comparative Energy Use of Residential Gas Furnaces and Electric Heat Pumps (ACEEE 2016) to conduct our comparative analysis of heating systems. We replicated and adjusted the ACEEE model to include local data for the cities studied, rather

[6] Equipment efficiency levels considered in the analysis include: 82-84 (baseline depends on location) and 97 AFUE furnaces. For ASHPs an 8.5, 9.5 and CC 10.5 HSPFASHP were included in the analysis.

[7] Previous models of ccASHPs have demonstrated the ability to operate at temperatures as low as -15° F, such as the Acadia Hallowell All Climate HP split system unit (Stevens 2013). This is a dual compressor two-stage split system with an economizer which is capable of operating in several modes, helping it to provide heat at extremely low temperatures. Between 2006 and 2011 there were several monitoring field tests of this system which achieved season COP of 2.08 to 3.22 in a variety of cold climates. However, the manufacturer of this system went out of business due to mechanical problems of installed systems (Stevens 2013). So, although the technology exists for a split system ducted ccASHP to operate at extremely low temperatures with little backup heating, this type of system is not currently being manufactured, though there is ongoing R&D.

than average statewide data wherever possible. Specifically, we used the ACEEE methodology when comparing source efficiency and the total lifecycle cost of each piece of equipment in each city. The model was then modified to include more granular data, such as local building design data, average furnace efficiency, utility customer energy costs, relative equipment costs, average utility heat rate for electric generation of the utility serving each city, and findings from the MN CEE and other ccASHP field studies. The modified model also considers the lifetime CO_2 emissions from furnaces and ASHPs based on average emissions from the electric utility serving each city. By modifying the ACEEE model, we were able to examine specific cities and assess important distinctions within our region, including three distinct climate zones, a broad mix of electricity generation sources and the common use of condensing furnaces.

Source Efficiency Comparison

The source efficiency analysis compared the gas used at a furnace level with the fuel used at the power plant level to power an electric ASHP. We compared two different types of furnaces and three different ASHPs in each of the five selected cities in the Midwest. The efficiencies of gas furnaces assessed were 82-84[8] (baseline efficiencies) and 97 AFUE; the ASHP efficiencies were 8.5 HSPF,9.5 HSPF and a 10.5 HSPF ccASHP.[9]

For this analysis, we used statewide gas heating consumption data from the US Energy Information Administration (EIA) 2009 Residential Energy Consumption Survey (RECS) as a baseline for the source efficiency comparison (EIA 2013).[10] City-level average heating consumption data is not available from a public database, so average statewide consumption data was used as a reasonable proxy. Assuming 82-84 AFUE as the installed average furnace efficiency in the five cities, we determined that a 97 AFUE furnace would use proportionally less energy than the baseline for each city. To determine the amount of fuel burned at the power plant level for an 8.5 HSPF, 9.5 HSPF heat pumps and a 10.5 HSPF ccASHP, we assumed that each ASHP will need to meet the same load that was met by the baseline gas system.

To accurately assess the electricity required, the ASHP rated operational efficiency was de-rated based on the winter design temperature for each location according to a model developed by the Florida Solar Energy Center (FSEC) (Fairey 2004). The FSEC model quantifies the impact to the operational HSPF by assessing an efficiency derating when an ASHP is operating less effectively at low temperatures and when electric resistance heating is in use.

Once the annual site kWh required to take on the full heating load was determined, we calculated the amount of fuel consumed by the power plant (source energy) to support an 8.5 and 9.5 HSPF ASHP. A key factor that influences the amount of source energy required is the heat rate (level of efficiency) of the electric generation plant. The lower the heat rate, the more efficient the power plant, and the less source energy required to support an ASHP. We

[8] Given the significant penetration of condensing furnaces in the Midwest, we did not assume an 80 AFUE (federal minimum) as the baseline level of efficiency for gas furnaces. We calculated the average baseline efficiency by state using NRELs ResStock existing home database. The assumed baseline furnace efficiency is between 82-84, depending on the state.

[9] Efficiencies for the ASHPs were derived for the following reasons. The 8.5 HSPF represents the minimum rating required by energy start for a split system ASHP. The 9.5 HSPF represents the level of efficiency halfway between the minimum ES rating and the highest rated non-cold climate system on the energy star website. The 10.5 HSPF for the ccASHP represents the average heating efficiency of ccASHPs listed in the NEEP cold climate heat pump specification listing.

[10] Although 2015 RECS data recently became available, this dataset does not include state level average gas heating data which was necessary for this comparison. Because of the structure of the RECS data, the estimated heating gas use for Minnesota also includes Iowa and the Dakotas. 2009 RECS data combined these states given their smaller population size and similar climate zones. Minnesota represents over 50% of the population of these four states combined.

calculated the source energy required to support the various ASHPs based on heat rates from 4,000 to 14,000 Btu/kWh and determined the point where ASHPs become more source efficient than furnaces, for each level of equipment efficiency. To factor in the relative efficiency improvement for a ccASHP, it was assumed that the ccASHP operates 22% more efficiently[11] than an ASHP rated at 10.5 HSPF, given that it can operate more effectively at very low temperatures and uses less resistance heating (DOE 2013, MN CEE 2018).[12] We then overlaid the 2016 weighted average heat rate of the utility serving each city to determine the level of improvement needed for an ASHP to be more source efficient than a furnace (EIA 2017).[13]

This comparison of energy use between furnace and ASHP types is the foundation for the economic and emission comparison which we discuss in the next section.[14]

Note about EIA Electricity Generation Heat Rate

EIA continues to evolve their method for analyzing the heat rate of non-combustible renewable energy generation as discussed in the guidance document to the EIA's Annual Energy Review, *Appendix F, Alternatives for Estimating Energy Consumption*. There are currently three different methods EIA has considered to calculate the heat rate of non-combustible renewable generation: *fossil fuel equivalent*, *captured energy* and *incident energy approach* (EIA 2011). With the *fossil fuel equivalent* approach, EIA applies a fossil-fuel equivalent conversion factor to renewable generation. The *captured energy* approach assumes renewable generation has a heat rate of 3,412 Btu/kWh or the Btu equivalent to 1 kWh of electricity. This approach has been vetted through the International Energy Agency (IEA) and is currently applied internationally. The last approach, the *incident approach* estimates the conversion efficiencies of renewable generation and estimates the heat rate from that level of efficiency (EIA 2011). Presently, EIA determines the heat rate of renewables through a hybrid approach that combines the fossil-fuel and captured energy approaches, which would attribute a heat rate between 9200 – 9700 Btu/kWh for non-combustible renewables.

For this analysis we attributed a heat rate of 3412 Btu/kWh, consistent with the Captured Energy Approach and IEA methodology, for non-combustible renewables.[15] A breakdown of average heat rates by city over the last 10 years are included in Appendix I.

Life-Cycle Cost Comparison

The second part of this analysis compared the various heating systems on a life-cycle cost basis to understand the potential economic impact to the customer. To determine life-cycle costs, the average purchase and installation costs were combined with the energy costs (based on the

[11] The 22% improvement was derived from two in-field studies conducted by the US DOE and MN CEE which determined the Coefficient of Performance (COP) for the heating season in several existing homes that installed a standalone ducted ccASHP capable of taking on the full heating load.

[12] One study, conducted by US DOE analyzed the operational efficiency of the Acadia Hallowell All Climate HP split system unit over two heating seasons in New Haven, Ct. DOE found the average heating COP to be a 2.8. The other study conducted by MN CEE analyzed two Mitsubishi Hyper Heat Systems with an electric booster in two different locations in Minnesota over a heating season. The average COP for the two systems was 1.8 and 1.9 respectively. To determine the percent improvement between an ASHP and a ccASHP for this analysis, we determined the COP based on Fairey's equation for the three locations of these field studies and determined the relative improvement for the field tested ccASHPs.

[13] We derived the electric heat rate for each city by calculating the average utility heat rate, weighted by kWh generated, for all electric generators, using data from the 2016 Form EIA-923 Electric Generation database.

[14] A technical overview of how this was calculated, and the various assumptions used can be found in Appendix I.

[15] This assumption is also consistent with what ACEEE used in their paper comparing heat pumps and furnace source efficiency.

average annual energy use in the source efficiency comparison) to operate each system over an 18-year lifetime (ASHRAE 2018).[16] The average equipment installation costs were derived from the National Renewable Energy Laboratory (NREL) National Residential Measures database for all equipment other than the ccASHP (NREL 2018).[17] For ccASHP average costs, we used the database developed by the New York State Energy Research and Development Authority (NYSERDA) which compares ccASHP costs to various other heating sources in the Northeast. As a conservative assumption, the low per-ton estimate was used to determine an average cost for the ccASHP units given increased costs in the Northeast (NYSERDA 2017).

To differentiate equipment costs between cities, prices were adjusted using cost factors available through the RSMeans construction cost data service. All equipment costs were based on an 80,000 Btu furnace, and 36,000 Btu ASHP and air conditioner.[18] The average size for the ASHPs in this analysis was based on the average size of the ducted ASHPs referenced in the MN CEE report to support the heating load.

Table 2: Average Equipment Purchase and Install Cost Per City

Equipment Cost Weighted by City Multiplier								
City	**Cost Multiplier**	**85% AFUE**	**97% AFUE**	**8.5 HSPF HP**	**9.5 HSPF HP**	**10.5 HSPF ccASHP**	**SEER 13 AC**	**SEER 14 AC**
National Average	100%	$ 2,900	$ 4,000	$ 6,780	$ 7,780	$ 9,405	$ 4,312	$ 4,512
St. Louis	111%	$ 3,193	$ 4,420	$ 7,492	$ 8,597	$ 10,393	$ 4,765	$ 4,986
Chicago	124%	$ 3,592	$ 4,972	$ 8,428	$ 9,671	$ 11,690	$ 5,360	$ 5,608
Grand Rapids	94%	$ 2,728	$ 3,776	$ 6,400	$ 7,344	$ 8,878	$ 4,071	$ 4,259
Madison	107%	$ 3,081	$ 4,264	$ 7,227	$ 8,293	$ 10,026	$ 4,597	$ 4,810
Minneapolis	113%	$ 3,277	$ 4,536	$ 7,689	$ 8,823	$ 10,665	$ 4,890	$ 5,117

To project total life-cycle costs, an 18-year life of the equipment was assumed, and a 5% annual discount rate applied to the total cost, consistent with the ACEEE model (ACEEE 2016).[19] Current energy costs for the gas and electric utilities serving each city were used as the baseline, and those costs then extrapolated to 2036 based on the 2018 EIA Annual Energy Outlook (EIA 2018).

[16] For simplicity, we assumed an ASHP has the same life expectancy as a furnace. ASHRAE and NREL databases assume a 15-year lifespan for these systems, but as they become more mainstream, it is anticipated that the average longevity of these systems will improve. If we did assume a 15-year lifespan, the economics would be even more favorable for gas fired furnaces.

[17] Although we would have preferred to use local cost estimates for the equipment purchase and install costs, this data was not publicly available, so we used a national database to determine the average cost. To maintain a more equal comparison to the NYSERDA cost values we used for a ccASHP, we assumed the highest cost estimates in the NREL database given the increased costs in New York and the Northeast. We then assessed a cost factor derived from RS Means for each city to assess the relative difference in equipment costs.

[18] The ducted ASHPs in the MN CEE research were sized to serve the heating load at 3 ton and 4 tons. Given that 4 of the 6 locations have a warmer climate than Minnesota, we assumed the average heating load to be 3 tons. The 80,000 BTU furnace and 36,000 BTU AC was selected because these are the approximate average installed sizes based on recent residential code compliance field studies in Michigan, Missouri and Kentucky.

[19] According to ACEEE, 5% represents the typical utility weighted average cost of utility capital over the last decade.

EIA's 2018 Annual Energy Outlook projects that in the Midwest electricity costs will rise by 8.5% and gas costs by 18.7% by 2036.[20]

Standard energy rates were used in this analysis and special rates such as time of use rates were not considered.[21] Surprisingly, fixed and variable energy costs varied widely between locations. Although fixed costs are not necessarily only associated with heating or cooling costs in a home, we factored in both costs to get a complete picture of total costs by energy type.[22] The summer and winter energy costs for 2018 are displayed in Table 3, below.

Table 3: Summer and Winter Energy Costs (2018[23])

City	Electric			Gas		
	Variable Rate ($/kWh)		Fixed ($/month)	Variable Rate ($/Therm)		Fixed ($/month)
	Summer	Winter		Summer	Winter	
St. Louis	$0.13	$0.09	$9.00	$0.77	$0.77	$15.00
Chicago	$0.07	$0.08	$12.93	$0.52	$0.51	$32.40
Grand Rapids	$0.15	$0.15	$7.00	$0.57	$0.58	$11.75
Madison	$0.14	$0.13	$19.00	$0.46	$0.50	$21.89
Minneapolis	$0.11	$0.06	$10.00	$0.62	$0.62	$9.50

Given that this analysis is focused on full replacement, we analyzed the total lifecycle cost differences for a system when the AC unit is replaced at the time of the heating system replacement given the unique ability for an ASHP to serve both heating and cooling demand. To account for this benefit, the cost of an AC unit was discounted from the ASHP equipment cost in the analysis.[24]

Carbon Dioxide Emissions Comparison

The lifetime emissions for each piece of equipment in each state was based on the energy use calculated in the source efficiency comparison. City-specific electricity generation emissions rates were derived from the US EPA 2016 Emissions and Generation Resource Integrated Database (eGRID) (EPA 2018) and used to determine emissions from ASHP operations. The eGRID data provided plant-specific emissions rates which enabled us to determine the current emissions rate for each city. [25] However, the eGRID dataset we used did not include historical trends. To determine a historical trend in emissions, we used the EIA state emissions database to determine the level of CO_2 emissions reductions from power production over the last 10 years by

[20] The estimated increase in electricity and gas costs was multiplied by the current local energy costs to determine 2036 energy costs by city. This EIA multiplication rate was based on the EIA reference case scenario for the West and East North Central regions.
[21] If electric heating rates were offered by the electric utility, those rates were used instead of the traditional rate.
[22] A detailed methodology used for determining life-cycle energy costs can be found in Appendix II.
[23] Sources for energy cost estimates are listed in Appendix II.
[24] A technical overview of how this was calculated, and the various assumptions used can be found in Appendix II.
[25] Similar to the heat rate analysis, using the eGRID 2016 database, we calculated the weighted average CO_2 emissions rate to represent each city-based generator plants within the total portfolio of the utility serving each city. Given that electricity comes from numerous surrounding powerplants, we did not feel we could drill down further than the utility level without omitting generators serving each city.

state.[26] We used a standard CO_2 emissions rate of 117 lb/MMBtu when accounting for natural gas emissions (EIA 2017).[27]

Electricity generation in most states has become less carbon intensive over the last 10 years, though there is a large range in the rate of change (EIA 2018). Of the states we considered in this analysis, Minnesota reduced carbon emissions by the most over a ten-year period, with a 2.8% annual reduction, whereas Missouri only reduced emissions by 0.6% annually.

Table 4: State CO_2 Emission Rates from Electricity Generation (2007-2016)

State	2007 Emissions (lbs/MWh)	2016 Emissions (lbs/MWh)	% annual reduction
Illinois	1152	848	2.6%
Michigan	1461	1151	2.1%
Minnesota	1526	1096	2.8%
Missouri	1865	1756	0.6%
Wisconsin	1699	1385	1.8%

For this study, the observed annual rate of change was used as a proxy for what could happen to local CO_2 emissions from electricity generation in the future.[28] Interestingly, the annual rate of reduction for all states except Missouri is similar to the required annual rate of CO_2 reduction needed to meet the goals set by the utilities serving the cities in this analysis (Balaskavitz, 2018).

Results

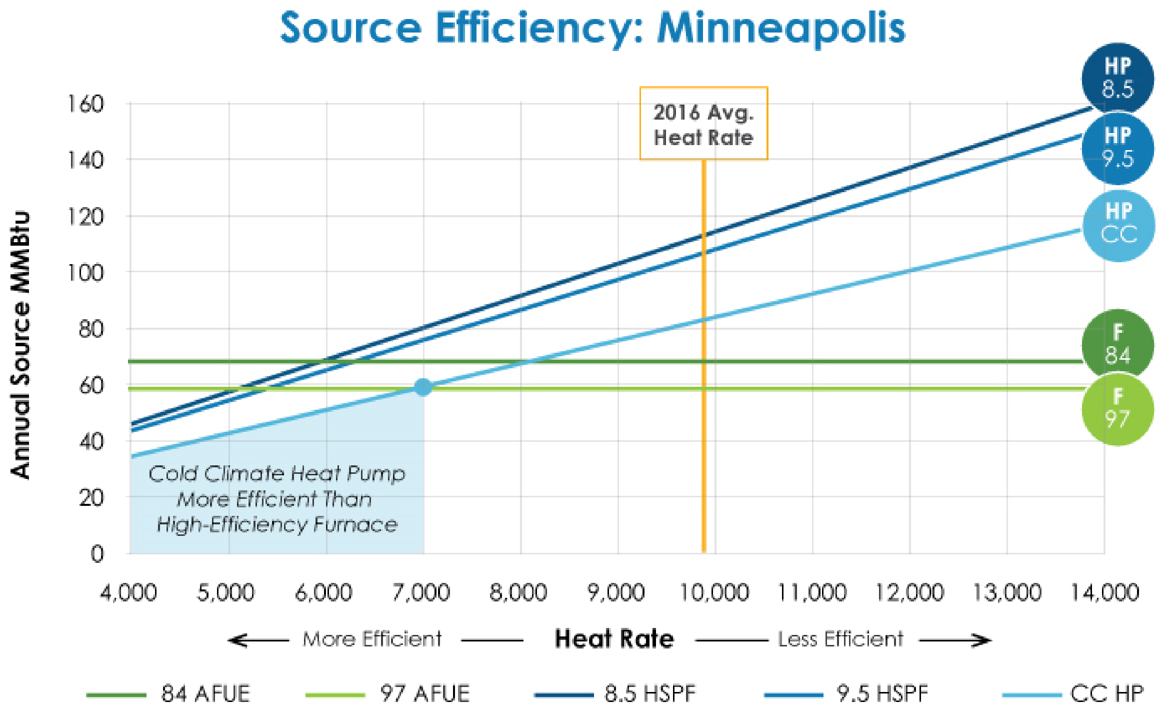
Source Efficiency

The source efficiency analysis shows the point at which an ASHP is more efficient than a gas furnace based on the efficiency of the electric generation source used to power the heat pump. The model shows the inflection point where the power plant heat rate must be so an ASHP is more source efficient than a gas furnace. Additionally, using the generation-weighted average heat rate of each city, the analysis demonstrates the level of improvement needed in generation efficiency for each city to reach that inflection point.

Figure 1 shows the results for Minneapolis. The green lines represent the estimated annual energy use from an 84 (baseline) and a 97 AFUE furnace; the sloped blue lines represent the relative source energy used by an 8.5 HSPF, 9.5 HSPF and 10.5 HSPF ccASHP at the various heat rates; and the orange vertical line represents the average 2016 heat rate in Minneapolis.

[26] We used this as a proxy for potential future emissions reduction, but understand further emissions reductions is not guaranteed and could require costly updates to the grid.
[27] The emissions rate does not factor in transmission losses. Transmission losses were incorporated into the source efficiency comparison.
[28] The EIA Annual Energy Outlook projects a significant increase in renewable and natural gas energy production and a decrease in coal and nuclear projected out to 2050, so some of the increased cost in generation is reflected in the projected energy costs in the life-cycle cost analysis (EIA 2018).

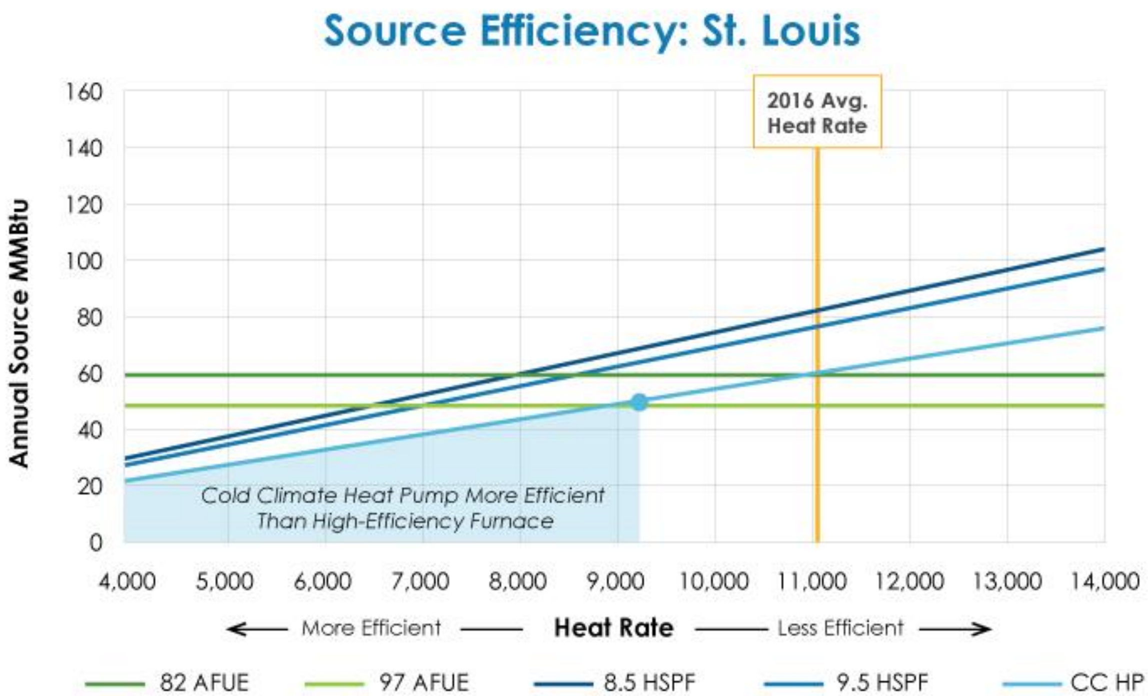
Figure 1: Minneapolis Comparison of Furnace and ASHP Source MMBtu Energy Consumed



Given the winter climate in Minneapolis, the level of efficiency of each ASHP is degraded. Therefore, substantial improvement in generation efficiency or ASHP technology would be required for ASHPs to be more source efficient. Figure 1 shows that, at current generation heat rates, even the baseline existing furnace in the state (84 AFUE) is currently more source-efficient than all levels of ASHP efficiency in the analysis. In fact, the average heat rate needs to improve (i.e. decrease in value) by 45% for a high efficiency (9.5 HSPF) ASHP to be more efficient than a high efficiency (97 AFUE) furnace. When accounting for the improvements in efficiency of a ccASHP, the heat rate needs to improve by 29% for a ccASHP to be more efficient than a 97 AFUE furnace.

On the other hand, in a city with a more moderate climate, such as St. Louis, the operational equipment efficiency of each ASHP is increased, but the heat rate is also much higher than all other cities. As a result, there is a more favorable comparison between ASHPs and furnaces, but a 97 AFUE furnace still generates less source energy. As displayed in Figure 2, a ccASHP is on par in terms of source efficiency with a baseline furnace (82 AFUE) but is less efficient than a 97 AFUE furnace. In order for a ccASHP to be more efficient than a 97 AFUE furnace, the utility heat rate would need to improve by 16%. The continued improvement in ASHP technology and/or a reduction in generation heat rate would only further the favorability for ASHPs in this climate and ccASHP could become more source efficient than a high efficiency furnace.

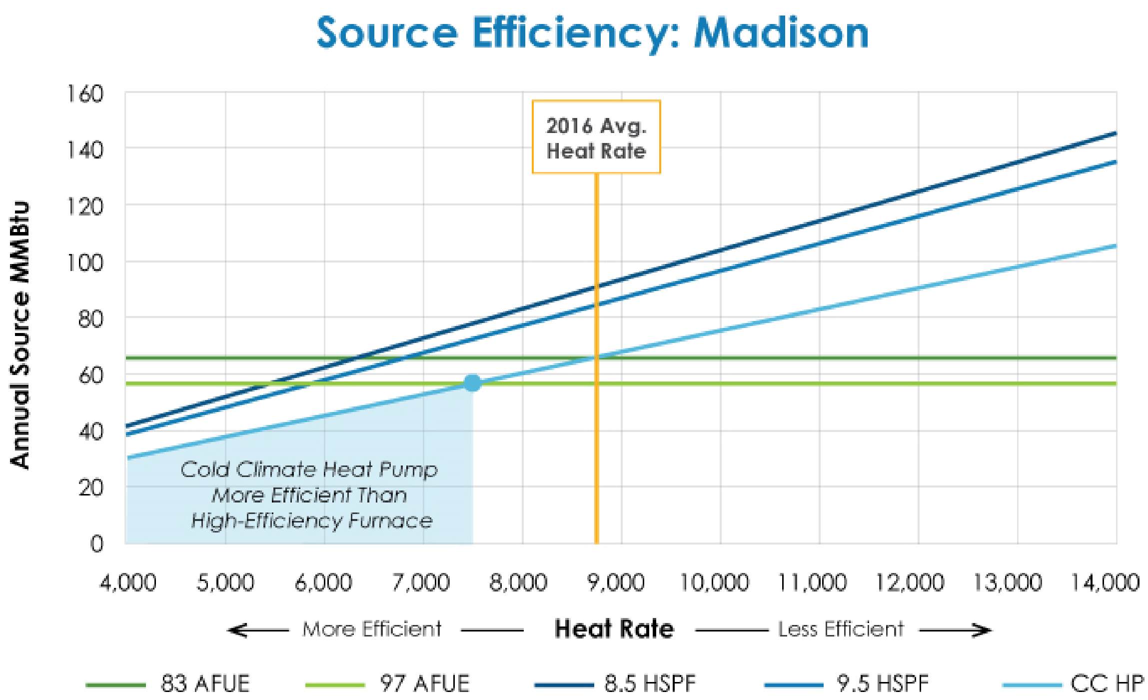
Figure 2: St. Louis Comparison of Furnace and ASHP Source MMBtu Energy Consumed



As electricity generation moves to higher efficiency gas turbines and non-combustible renewable energy generation, ASHPs become more favorable from a source efficiency perspective. Madison is a prime example of this. According to EIA-923 electricity generation data, the 2016 heat rate in Madison is 8753 BTU/kWh, the lowest rate out of the cities in this analysis (EIA 2017). One key reason for this is that the generation mix has continued to shift from coal to natural gas and wind production.

As a result of the low heat rate, Madison displays a similar, but slightly more favorable relationship between the source efficiency of ASHPs and furnaces as St. Louis, despite having a climate that significantly reduces the efficiency of an ASHP. As shown in Figure 3, a ccASHP has the same level of source efficiency as the baseline furnace but is less efficient than a high efficiency furnace. In order for a ccASHP to become more efficient than a high efficiency furnace, the heat rate needs to improve by 14%.

Figure 3: Madison Comparison of Furnace and ASHP MMBtu Energy Consumed



Life-Cycle Economics

The life-cycle analysis shows the cost over time of the various heating technologies. Figure 4 shows the life-cycle cost comparison of various furnace efficiencies (baseline and 97 AFUE) to that of an 8.5 HSPF, 9.5 HSPF and ccASHP for the five selected cities, when a cooling system is replaced at the same time as the heating system. Given the variation in energy costs and system performance, St. Louis is the only city where the lifetime costs of operating an ASHP is on the cusp in terms of life-cycle costs, albeit, still slightly worse than that of a furnace. As previously discussed, there is degradation in system performance as the ASHP operates in colder temperatures. This, coupled with the significantly higher initial cost of an ASHP system, means that it becomes less cost-effective to use an ASHP instead of a furnace replacement. The premium cost to install and operate an ASHP over the lifetime is anywhere from $2,000–11,000, depending on the level of efficiency, in cities other than St. Louis.

However, if we exclude the purchase and installation cost of equipment and only consider the fuel costs, the life-cycle costs change dramatically in some cities. For instance, in St. Louis, ccASHP's now become the most cost-effective heating source, and the cost disparity between ASHPs and furnaces in Chicago and Minneapolis is reduced. This demonstrates that if the cost difference between gas and electric costs are relatively minor, as is the case in these three cities, ASHPs become much more viable from an operational cost standpoint. This also demonstrates that as ASHP equipment costs are reduced, the lifecycle economics of ASHPs for the cities on the margin will become more favorable.

Figure 4: Comparison of Lifecyle Cost of Furnace and Heat Pump Technologies in Midwest Cities when Replacing Both Furnace and Central Air Conditioning

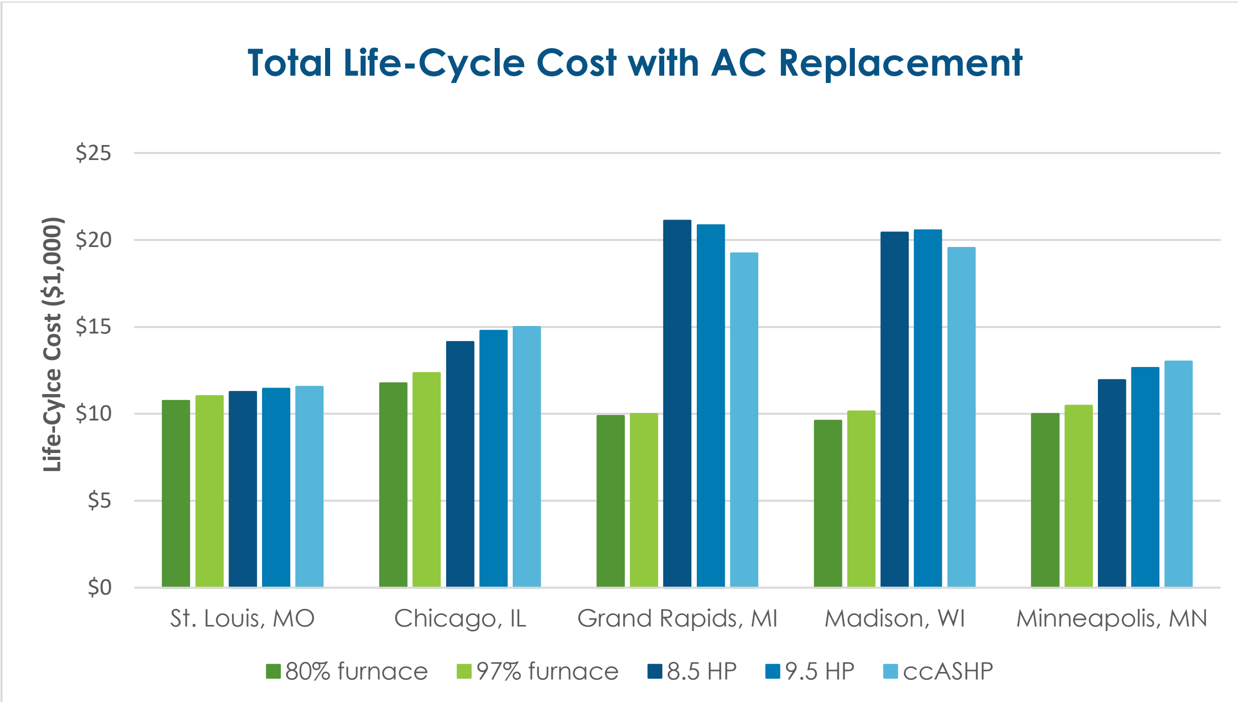
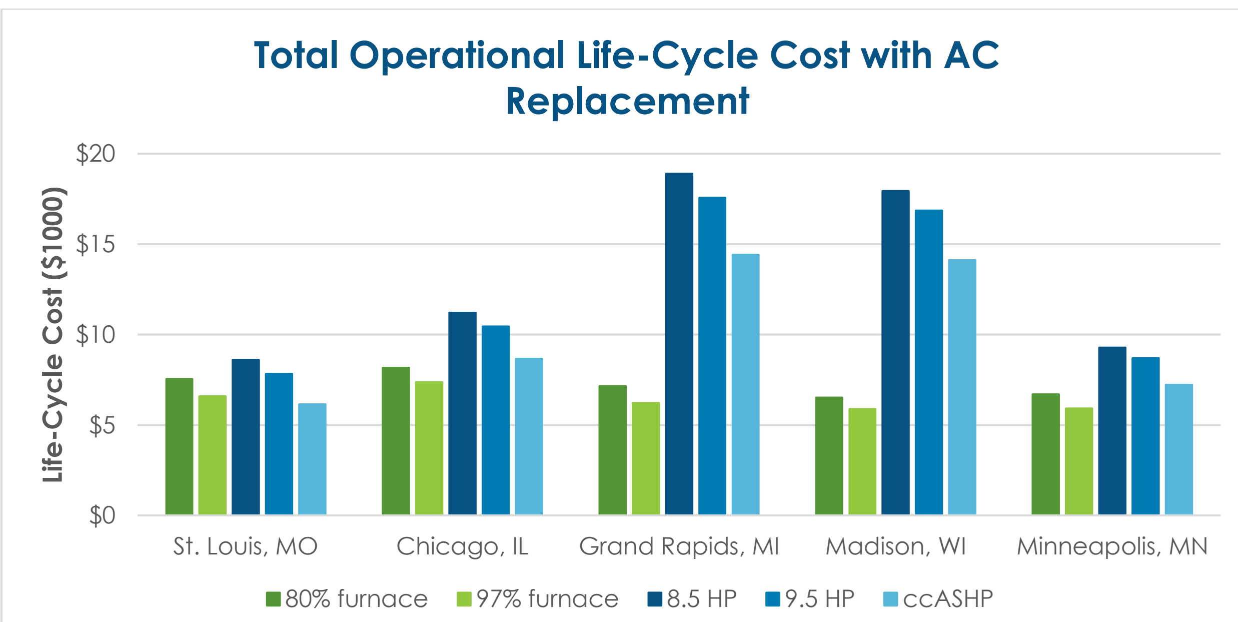


Figure 5: Comparison of Lifecyle Operational Cost of Furnaces and Heat Pumps in Midwest Cities



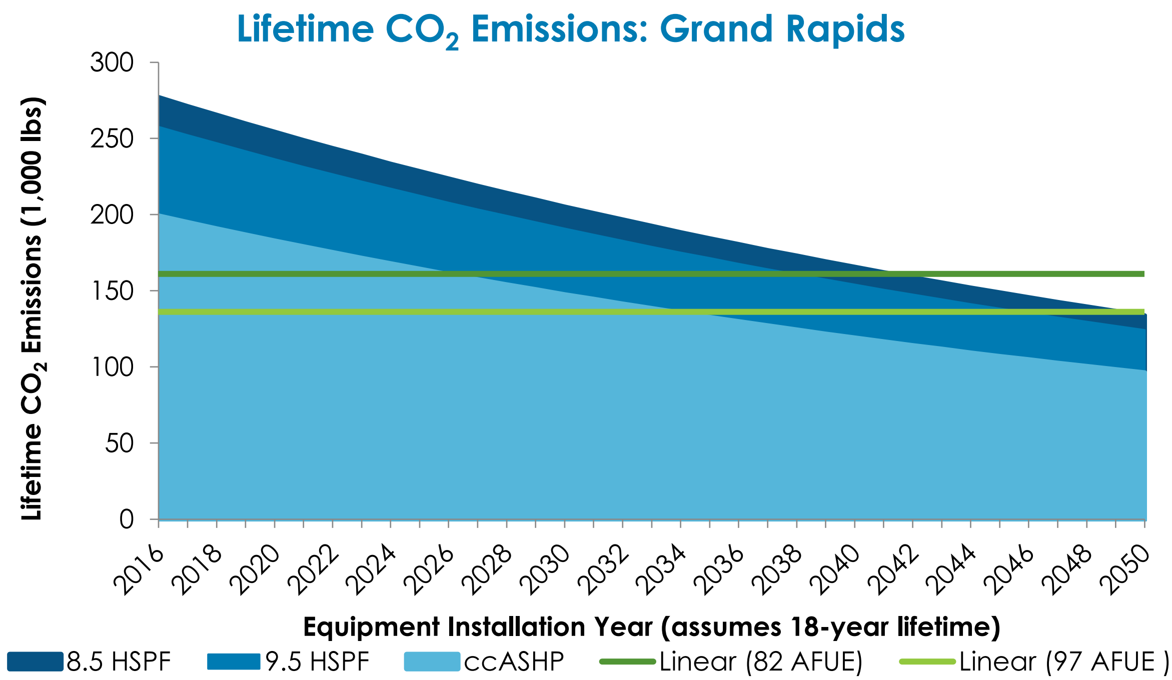
CO_2 Emissions

Grand Rapids and Madison were the two cities that showed the greatest difference in lifetime carbon dioxide emissions in the study.

Below are the lifetime emissions graphs of each city which display the total lifetime emissions of a baseline (82-83 AFUE) and 97 AFUE furnace, as well as an 8.5 HSPF, 9.5 HSPF and ccASHP. Similar to the source efficiency comparison graph, the horizontal lines represent the constant lifetime emissions from the natural gas furnaces, while the vertical lines represent the lifetime emissions from ASHPs that are brought online from 2016 to 2050.

As shown in Figure 6, Grand Rapids, which still relies heavily on coal for much of its generation, shows that currently all ASHPs will produce more lifetime emissions than gas furnaces. However, over the last 10 years, utilities in Michigan have reduced their CO_2 emissions from generation by 2.1% annually. Additionally, the utility serving Grand Rapids has set a goal of reducing carbon emissions by 80% from 2005 levels by 2040.[29] With this commitment, it is reasonable to assume the reduction from the last 10 years will continue. If emissions reduction continues at the same pace, ccASHP will be less carbon intensive than a high efficiency furnace by 2035.

Figure 6: Grand Rapids, MI Lifetime CO_2 Emissions from Heating Equipment

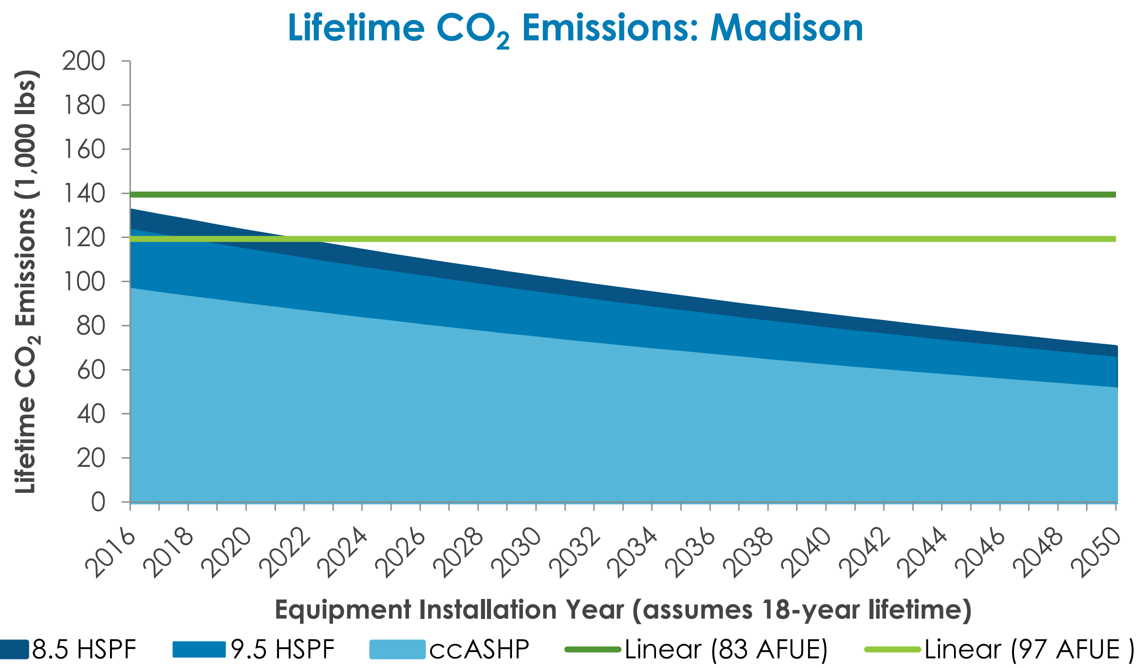


The results are very different for the Madison emissions analysis. 2016 emissions rates in Madison, shown in Figure 7, are the lowest of the cities studied, with a rate of 822 lb/Mwh. A key reason their emissions rate is so low is because they burn very little coal and continue to expand generation from renewables and natural gas plants. Given the low emissions rate in Madison, all ASHPs will emit lower lifetime CO_2 emissions than either the baseline (82 AFUE) or 97 AFUE furnace by 2024. Wisconsin has also seen a significant reduction in CO_2 emissions over the last decade, with an annual reduction rate of 1.8%.

In comparison to the previous two cities, given Missouri's slow pace in reducing CO_2 emissions from electric generation, all ASHPs will have higher lifetime emissions than the baseline (82 AFUE) and 97 AFUE furnace from now until past 2050, unless significant investment in renewables and/or gas power plants is made in the state.

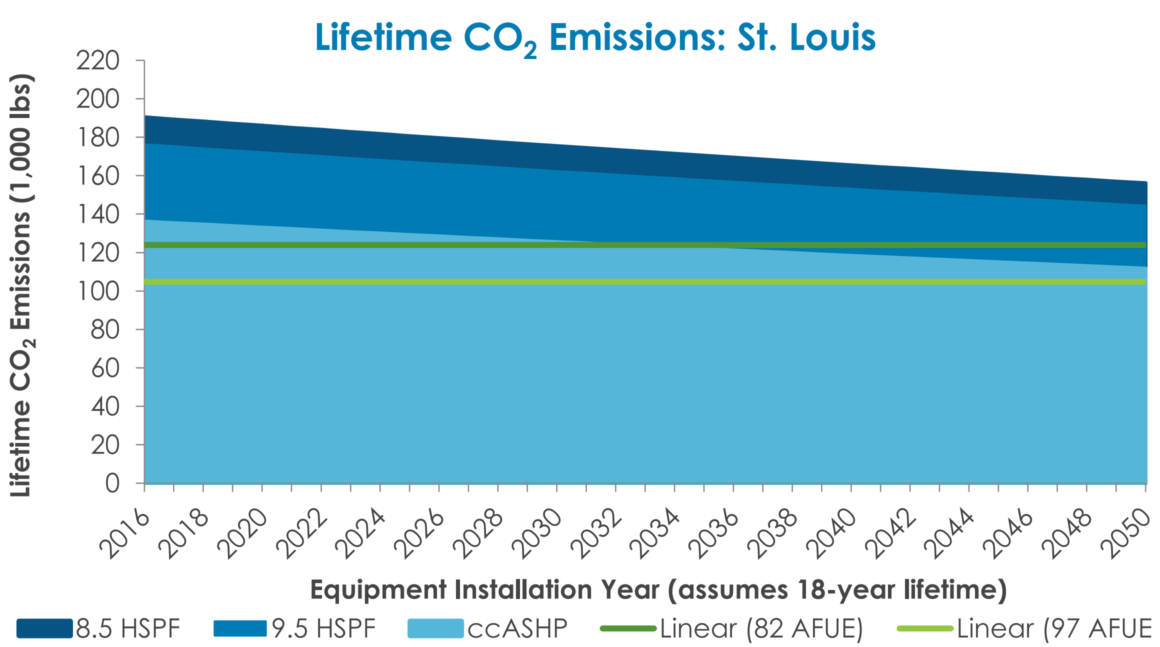
[29] https://old.consumersenergy.com/News.aspx?id=8831&year=2018

Figure 7: Madison, WI Lifetime CO_2 Emissions from Heating Equipment



The utility serving St. Louis has made a commitment to reduce 2005 emissions levels by 80% by 2050 so efforts made by the utility to reduce CO2 emissions could drastically change the projection of this graph.[30] As shown in this analysis, although ASHPs are on the cusp of being more beneficial from an economic standpoint, based on current generation, presently, they are not more efficient nor will help reduce CO_2 emissions from heating. [31]

Figure 8: St. Louis, MO Lifetime CO_2 Emissions from Heating Equipment



[30] https://themissouritimes.com/44352/ameren-sets-goal-cut-carbon-emissions-80-percent/
[31] A breakdown of this analysis, as well as results from the four other locations can be found in Appendix III.

Discussion & Conclusions

The merits of implementing new heating technologies depend on many different factors. Converting to an ASHP for heating and cooling needs is economical and is typically more source efficient than installing a replacement furnace and AC unit in warmer climates. Therefore, ASHPs should be encouraged as a replacement unit for existing homes in those areas (ACEEE 2016). However, as highlighted in this analysis, Midwestern states have a wide variety of climates, electric generation mixes, energy costs and installed equipment efficiencies. In the Midwest, all locations analyzed yielded some benefits from a transition to ASHPs. Nevertheless, there are negative outcomes in all locations as well – making the decision to go from a furnace to an ASHP a complicated choice.

Even in the case of St. Louis, the warmest climate in this analysis, we conclude that heat pumps are on the cusp in terms of lifecycle cost favorability but are less efficient in terms of source efficiency and would result in a significant increase in CO_2 emissions from heating when compared to a furnace. However, places like Chicago, Madison and Minneapolis could benefit in terms of CO_2 emissions reduction from electrifying heating, but it would not be as source efficient and homeowners would incur more costs when compared to a high-efficiency gas furnace. As with any decision impacting building techniques or policies, careful consideration should be given to these three key factors when determining the location-specific, long-term merits of installing each type of equipment.

It is important to note that this analysis should be viewed as a snapshot in time. The research is a representation of the current landscape with respect to electric ASHPs and gas furnaces, though the ASHP market is evolving quickly for both gas and electric end uses. This paper did not analyze electric vs gas ASHPs which is an important step when assessing the future efficiency of heating. Additionally, there are limitations in this analysis in terms of available data, and more granular data for things such as equipment costs, average energy used for heating, efficacy of ccASHPs in the field and other inputs could alter the results and recommendations for cities that are on the margin. As the heating system market continues to evolve and utilities, manufacturers and laboratories conduct more research, improved data will become available, and a similar analysis should be repeated to update the understanding of current and future impacts of electrifying heating in existing homes the Midwest.

Previous Research on ASHPs

Although this study only analyzed the potential benefits when replacing an existing gas furnace with an electric ASHP in the Midwest, electric ASHPs have demonstrated consistent benefits in other comparisons. Specifically, electric ASHPs can be more cost-effective than a gas furnace to install in new homes. Two recent studies by the Rocky Mountain Institute (RMI) and the Southwest Energy Efficiency Project (SWEEP) came to this conclusion. The RMI study, which looked at four locations throughout the U.S. (including Chicago) found that ducted ASHPs were more economical to install than gas furnaces for the homeowner (Billmoria 2018). The SWEEP study determined that ductless ASHPs reduce lifecycle costs, energy use and CO_2 emissions when compared to a gas furnace in five different locations in the Southwest (Kolwey 2018). It is important to note that these studies also analyzed the economics of fully replacing a gas furnace with an electric ASHP and came to a similar conclusion as our report – that it is generally not cost-effective to make this transition in existing homes in colder climates.

Aside from natural gas-specific comparisons, electric ASHPs can also be more cost-effective when compared to other, more expensive heating fuels. Studies by ACEEE examined the replacement of other heating fuels such as electric resistance, propane and fuel oil with an electric ASHP. These were national studies, but for parts of the Upper Midwest ACEEE found significant energy and economic savings when converting an electric furnace or electric resistance heating to an ASHP (Nadel 2016). However, when doing a similar study and comparing the full replacement of propane or fuel oil furnaces and boilers to electric ASHPs, savings were not typically present for the Upper Midwest given the low price of propane and oil in those locations (Nadel 2018).

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Appendix I

Details for Source Efficiency Analysis

Location	St. Louis, MO (CZ 4)	Chicago, IL (CZ 5)	Grand Rapids, MI (CZ 5)	Madison, WI (CZ 6)	Minneapolis, MN (CZ 6)
Furnace					
Avg. annual MMBtu for natural gas furnace	57.7	72.5	75.0	64.9	67.3
Add gas system distribution losses	58.9	74.0	76.5	66.2	68.6
Estimated MMBtu for 97% AFUE furnace	48.8	61.3	63.4	55.5	58.3
Add gas system distribution losses	49.8	62.5	64.7	56.6	59.4
Heat Pump					
99% winter design temp. (° F) (ASHRAE 2017 fundamentals)	12.7	4.4	7.3	-1.2	-5.8
HSPF adjustment factor for HSPF 8.5 unit (Fairey 2004)	0.21	0.30	0.27	0.35	0.39
Adjusted HSPF for nominal 8.5 unit	6.69	5.93	6.18	5.49	5.18
Annual Heating Load	47.31	59.45	61.50	53.87	56.53
kWh per year with HSPF 8.5 unit	7067	10025	9948	9810	10922
Add electric system distribution losses	7492	10626	10545	10399	11577
MMBtu power plant (or source) energy consumed as a function of heat rate					
4,000	30	43	42	42	46
5,000	37	53	53	52	58
6,000	45	64	63	62	69
7,000	52	74	74	73	81
8,000	60	85	84	83	93
9,000	67	96	95	94	104
10,000	75	106	105	104	116
11,000	82	117	116	114	127
12,000	90	128	127	125	139
13,000	97	138	137	135	151
14,000	105	149	148	146	162

Furnace

- Fuel Use: The average annual MMBtu for a natural gas furnace in each location (based on 2009 RECS natural gas heating by state) was used in the analysis
- Baseline Furnace: St. Louis, Chicago and Grand Rapids: 82 AFUE; Madison 83 AFUE; Minneapolis 84 AFUE (RESstock database; average AFUE for each state).
- Distribution loss: 2% for gas and 6% for electric distribution.
- 97 AFUE Efficiency Fuel Use: Average annual MMBtu x (baseline AFUE/97)

Heat Pump

- Design Temperature: 99% winter design temperature by location (ASHRAE 2017 book of fundamentals).
- HSPF Adjustment Factor: Determined percentage of efficiency reduction using Phillip Fairey analysis. Multiplied that percentage by ASHP design HSPF rating.
- Annual Heating Load: 82-84 AFUE multiplied by average annual MMBtu gas use
- kWh Per Year = (((Annual Heating Load*1,000,000))/Adjusted HSPF)/1,000.
- MMBtu source energy consumed as a function of heat rate = (kWh per year w/ distribution loss*Heat Rate)/1,000,000

Average Weighted Heated Rate

Avg. Weighted Heat Rate by City (Utility): 2010-2016							
City	2010	2011	2012	2013	2014	2015	2016
St. Louis	10,308	10,357	10,300	10,277	10,390	10,213	10,300
Chicago	10,488	10,572	10,672	10,539	10,623	10,580	10,477
Grand Rapids	10,139	10,435	10,517	10,459	10,408	10,498	10,696
Madison	10,800	10,724	10,694	10,507	10,632	10,689	10,329
Minneapolis	10,548	10,615	10,825	10,813	10,714	10,614	10,232

Source: EIA-923

Cold Climate Source Efficiency Analysis

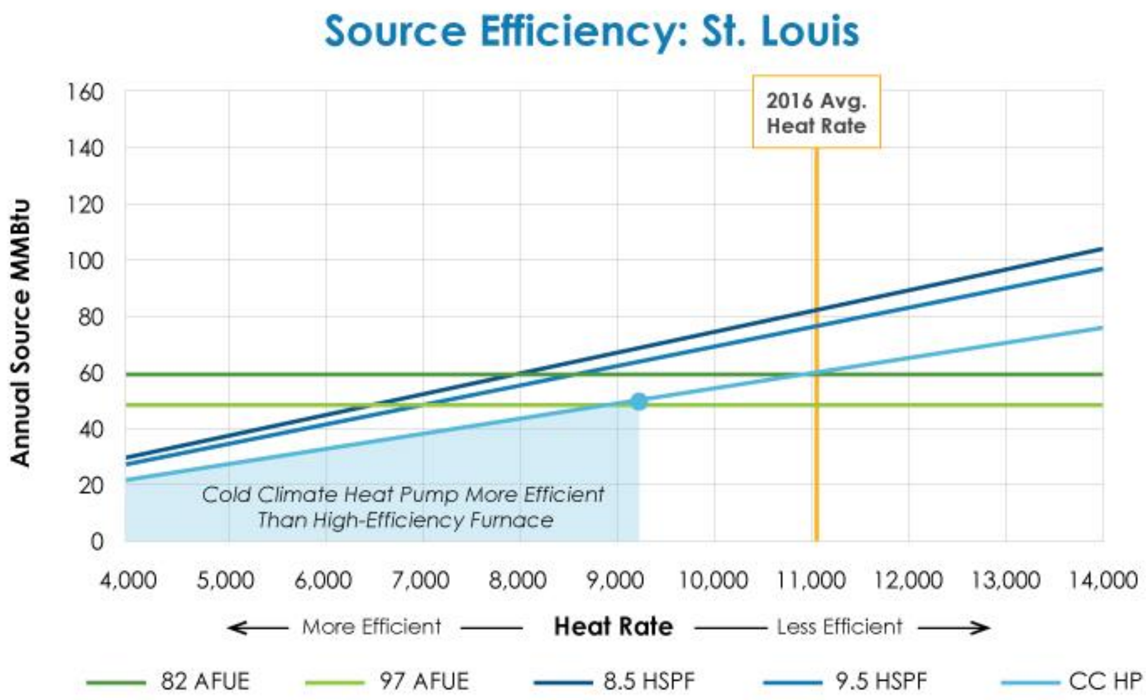
CC Heat Pump					
Adjusted HSPF (22% better than a 10.5 HSPF ASHP)	9.37	8.22	8.60	7.55	7.08
Annual Heating Load	47.31	59.45	61.50	53.87	56.53
kWh per year with a ccASHP	5050	7236	7155	7131	7985
Add electric system distribution losses	5353	7670	7584	7559	8465
MMBtu power plant (or source) energy consumed as a function of heat rate					
4,000	21.4	30.7	30.3	30.2	33.9
5,000	26.8	38.3	37.9	37.8	42.3
6,000	32.1	46.0	45.5	45.4	50.8
7,000	37.5	53.7	53.1	52.9	59.3
8,000	42.8	61.4	60.7	60.5	67.7
9,000	48.2	69.0	68.3	68.0	76.2
10,000	53.5	76.7	75.8	75.6	84.6
11,000	58.9	84.4	83.4	83.1	93.1
12,000	64.2	92.0	91.0	90.7	101.6
13,000	69.6	99.7	98.6	98.3	110.0
14,000	74.9	107.4	106.2	105.8	118.5

Cold Climate Heat Pump

- Adjusted HSPF: Assumed a ccASHP to be 22% more efficient than a 10.5 HSPF ASHP based on field studies conducted by US DOE and MN CEE previously referenced in the paper. Equation: Adjusted 10.5 HSPF * 22%

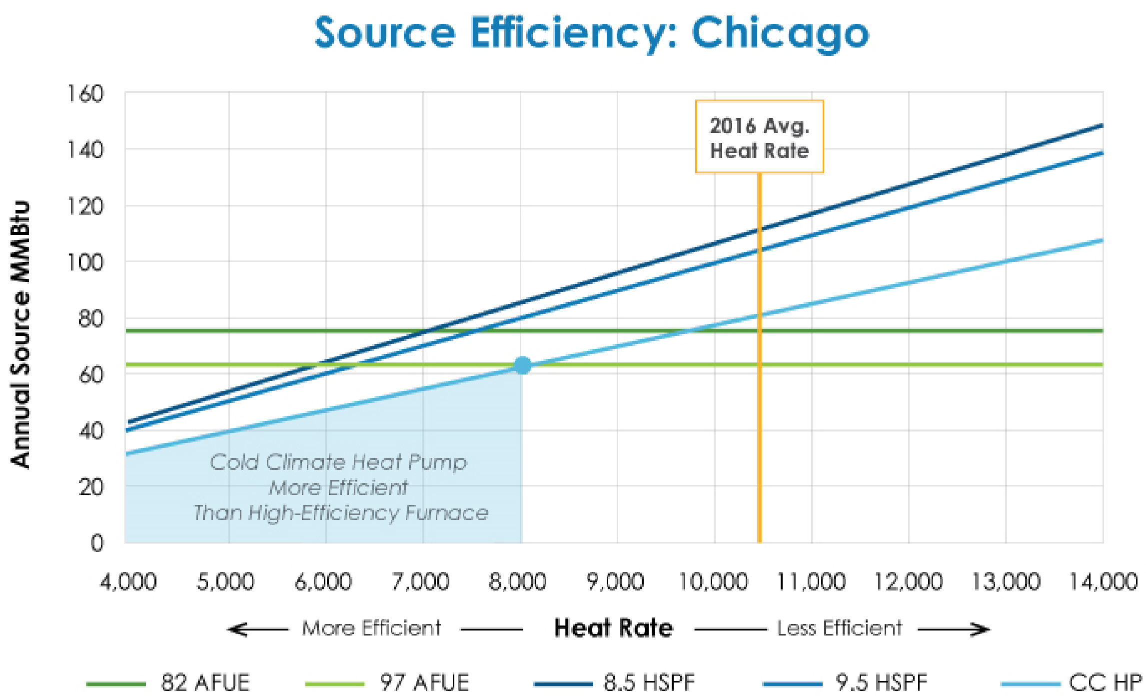
Source Efficiency Comparison – Full Results

St. Louis, MO (CZ 4)



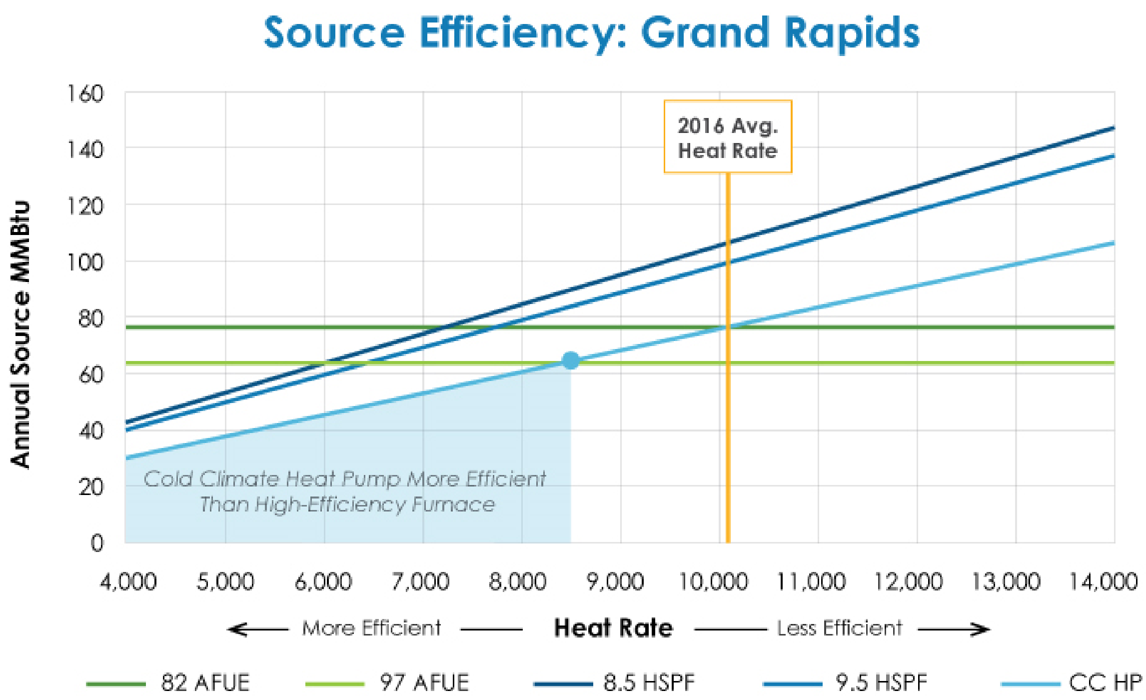
Comparison	Heat Rate Inflection Point	Improvement Needed
ccASHP to 82 AFUE:	10994	1%
ccASHP to 97 AFUE:	9294	16%

Chicago, IL (CZ 5)



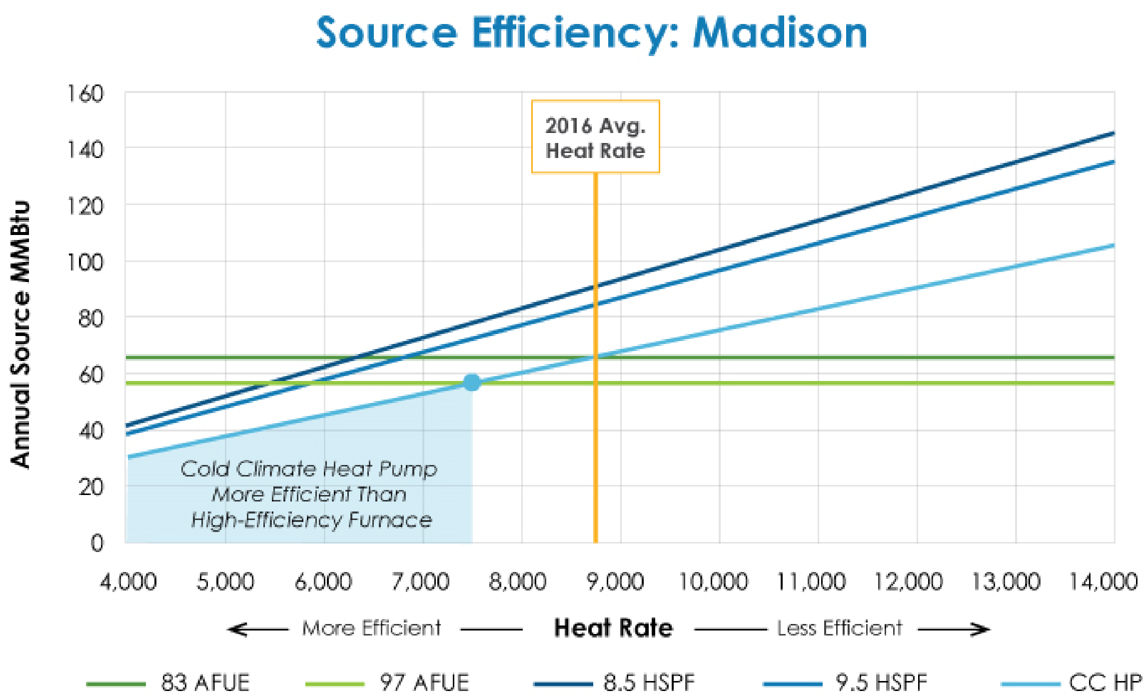
Comparison	Heat Rate Inflection Point	Improvement Needed
ccASHP to 82 AFUE:	9642	8%
ccASHP to 97 AFUE:	8151	22%

Grand Rapids, MI (CZ5)



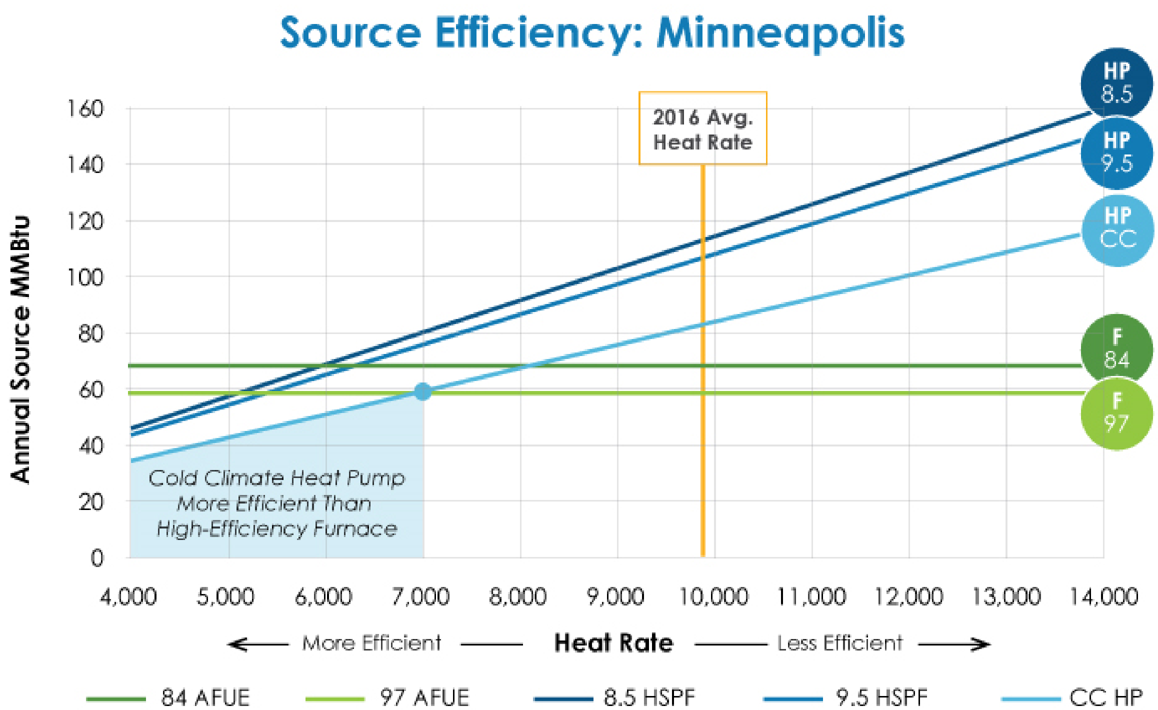
Comparison	Heat Rate Inflection Point	Improvement Needed
ccASHP to 82 AFUE:	10087	0%
ccASHP to 97 AFUE:	8527	16%

Madison, WI (CZ 6)



Comparison	Heat Rate Inflection Point	Improvement Needed
ccASHP to 83 AFUE:	8758	0%
ccASHP to 97 AFUE:	7494	14%

Minneapolis, MN (CZ 6)



Comparison	Heat Rate Inflection Point	Improvement Needed
ccASHP to 84 AFUE:	8110	18%
ccASHP to 97 AFUE:	7023	29%

Appendix II

Details for Life-Cycle Cost Analysis

Average Weighted Equipment Costs

Equipment Cost Weighted by City Multiplier								
City	Cost Multiplier	85% AFUE	97% AFUE	8.5 HSPF HP	9.5 HSPF HP	10.5 HSPF ccASHP	SEER 13 AC	SEER 14 AC
National Average	100%	$ 2,900	$ 4,000	$ 6,780	$ 7,780	$ 9,405	$ 4,312	$ 4,512
St. Louis	111%	$ 3,193	$ 4,420	$ 7,492	$ 8,597	$ 10,393	$ 4,765	$ 4,986
Chicago	124%	$ 3,592	$ 4,972	$ 8,428	$ 9,671	$ 11,690	$ 5,360	$ 5,608
Grand Rapids	94%	$ 2,728	$ 3,776	$ 6,400	$ 7,344	$ 8,878	$ 4,071	$ 4,259
Madison	107%	$ 3,081	$ 4,264	$ 7,227	$ 8,293	$ 10,026	$ 4,597	$ 4,810
Minneapolis	113%	$ 3,277	$ 4,536	$ 7,689	$ 8,823	$ 10,665	$ 4,890	$ 5,117

- National average purchase and install costs were derived from the NREL National Residential Efficiency Measures Database for all equipment other than ccASHPs. ccASHP costs were derived from the NYSERDA report referenced in the paper. High end costs were used for all equipment other than ccASHPs and low-end costs were used from the NYSERDA report for ccASHPs. Costs were assessed based on an 80,000 btu/hr furnace and a 36,000 btu/hr ASHP and AC unit.
- We assessed relative differences in costs by city by applying a cost multiplier from the RSMeans construction and cost service database for 2018 Q3.

Utility Summer and Winter 2018 Energy Costs

City	Electric			Gas		
	Variable Rate ($/kWh)		Fixed ($/month)	Variable Rate ($/therm)		Fixed ($/month)
	Summer	Winter		Summer	Winter	
St. Louis[32]	$0.13	$0.09	$9.00	$0.77	$0.77	$15.00
Chicago[33]	$0.07	$0.08	$12.93	$0.52	$0.51	$32.40
Grand Rapids[34]	$0.15	$0.15	$7.00	$0.57	$0.58	$11.75
Madison[35]	$0.14	$0.13	$19.00	$0.46	$0.50	$21.89
Minneapolis[36]	$0.11	$0.06	$10.00	$0.62	$0.62	$9.50

- The electricity and gas costs for each city are based on the current summer and winter fixed and variable energy costs for the utility serving each city. If a special electric rate for electric heating was available, it was included.

Location	St. Louis, MO	Chicago, IL	Grand Rapids, MI	Madison, WI	Minneapolis, MN
Local Utility Costs					
Gas Rate – Winter	$7.67	$5.10	$5.81	$4.96	$6.22
Gas Rate – Summer	$7.67	$5.16	$5.71	$4.60	$6.22
Electric Rate – Winter	$0.09	$0.08	$0.15	$0.13	$0.06
Electric Rate - Summer	$0.13	$0.07	$0.15	$0.14	$0.11
2036 gas rate – Winter	$9.10	$6.05	$6.90	$5.89	$7.39
2036 gas rate - Summer	$8.33	$5.61	$6.20	$4.99	$6.76
2036 electric rate- Winter	$0.10	$0.09	$0.16	$0.14	$0.07
2036 electric rate - Summer	$0.14	$0.08	$0.16	$0.15	$0.11
Annual heating cost (2036 energy prices)					
Baseline furnace	$645	$698	$612	$558	$573
97% furnace	$564	$630	$532	$502	$506
8.5 HP	$700	$909	$1,514	$1,450	$757
9.5 HP	$662	$865	$1,431	$1,382	$723
CC HP	$585	$765	$1,250	$1,221	$639
Purchase cost including installation					
Baseline furnace	$3,193	$3,592	$2,728	$3,081	$3,277

32 Electric and Gas: https://www.ameren.com/missouri/residential/rates/
33 Electric: https://www.comed.com/MyAccount/MyBillUsage/Pages/CurrentRatesTariffs.aspx Gas: https://accel.peoplesgasdelivery.com/home/gas_rates.aspx
34 Electric: https://www.consumersenergy.com/residential/rates/electric-rates-and-programs/electric-charges-explained Gas: https://www.consumersenergy.com/residential/rates/gas-rates/gas-charges-explained
35 Electric: https://www.mge.com/customer-service/home/elec-rates-res/ Gas: https://www.mge.com/customer-service/home/gas-rates-res/archive/index.htm?d=2018-06
36 Electric: https://www.xcelenergy.com/staticfiles/xe/Regulatory/Regulatory%20PDFs/rates/MN/MNResRateCard.pdf Gas: https://www.centerpointenergy.com/en-us/Documents/RatesandTariffs/Minnesota/Residential-Sales-Service.pdf

97% furnace	$4,420	$4,972	$3,776	$4,264	$4,536
8.5 HP	$7,492	$8,428	$6,400	$7,227	$7,689
9.5 HP	$8,597	$9,671	$7,344	$8,293	$8,823
ccASHP	$10,393	$11,690	$8,878	$10,026	$10,665
SEER 13 central AC	$4,765	$5,360	$4,071	$4,597	$4,890
SEER 14 central AC	$4,986	$5,608	$4,259	$4,810	$5,117
LCC - Install + Operation (18-year life, 5% real discount rate)					
Baseline furnace	$10,736	$11,753	$9,878	$9,598	$9,977
97% furnace	$11,013	$12,340	$9,990	$10,136	$10,456
8.5 HP	$16,245	$19,740	$25,367	$25,221	$17,054
9.5 HP	$16,780	$20,300	$25,043	$25,242	$17,667
10.5 HP	$16,557	$20,026	$24,256	$24,666	$17,505
ccASHP	$17,227	$20,629	$23,493	$24,298	$18,134
Additional LCC savings for cooling					
HSPF 9.5/SEER 17	$364	$173	$124	$96	$146
HSPF 10.5/SEER 21	$687	$280	$200	$156	$237
LCC - Install + Operation (18-year life, 5% real discount rate) -if heat pump replaces central AC unit					
8.5 HP	$11,259	$14,132	$21,107	$20,412	$11,938
9.5 HP	$11,430	$14,767	$20,849	$20,549	$12,631
ccASHP	$11,554	$14,990	$19,222	$19,545	$13,008

- The predicted gas rate in 2036 was derived by multiplying the electric and gas rate for each city by estimated increase in energy costs from EIA at 1.187 and 1.085 for gas and electricity, respectively.
- The estimated 2036 gas and electricity rate was multiplied by the energy use estimate for all equipment types listed in the source efficiency section in appendix I to determine annual heating costs.
- Life-cycle costs were assumed by adding the purchase and install cost to the cost of operating a unit for an 18-year lifetime. This analysis included a 5% discount rate to account for the time-value of money.
- We then determined the additional energy savings from improved cooling efficiency associated with installing a high efficiency heat pump, when compared to an AC unit that meets the federal minimum standard. Based on the NREL database ASHPs with an HSPF of 9.5 had a 17 SEER and a 10 HSPF had a 21 SEER unit.
- This analysis considered the economic savings if a homeowner replaced their AC unit at the same time as the furnace. In this case we subtracted the cost of a new AC unit from the ASHP cost as well as the additional savings associated with improved cooling efficiency.

Appendix III

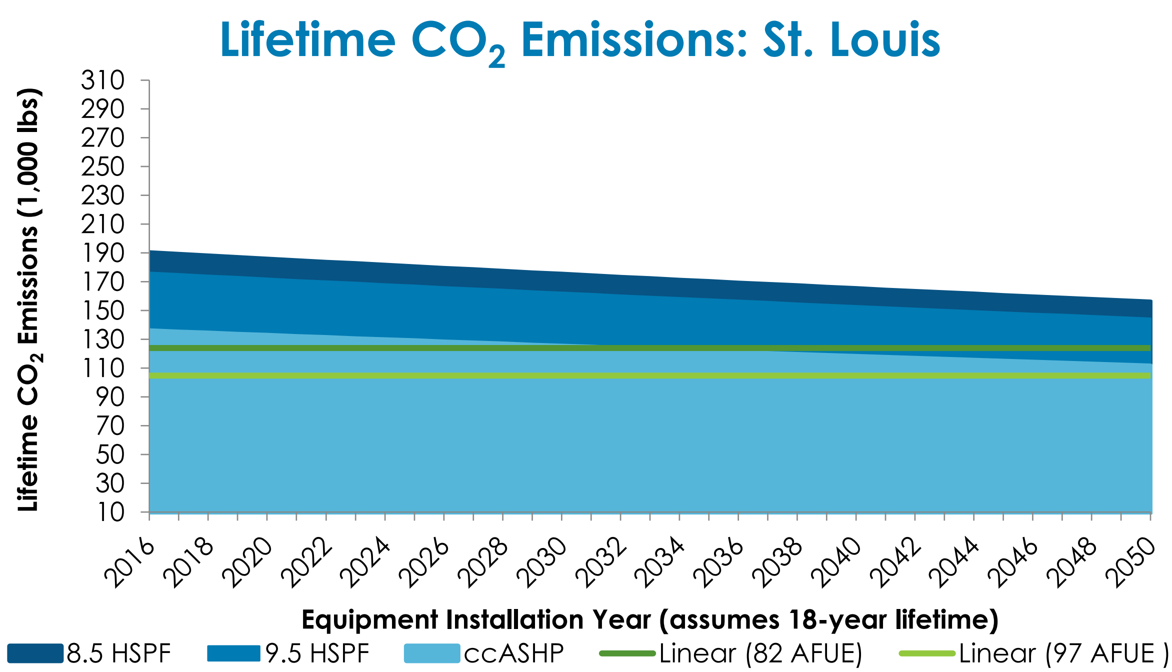
Detailed Description of Lifetime Emissions Analysis

- Gas emissions: The annual energy use from the source efficiency analysis, was multiplied by the gas CO_2 emissions rate (117 lbs/MMBtu) and projected out over an 18-year lifetime.
- Electric Emissions: To determine lifetime electric emissions the delta between 2007 and 2016 state emissions rate was determined and an average annual improvement calculated. This was then multiplied the 2016 emissions rate for each city MSA to project reduced emissions through 2050.
- The 2016 emissions rate was multiplied by the annual electricity use for each of the seven equipment types analyzed and projected out over an assumed 18-year useful life of the equipment.

Lifetime Emissions Results by City

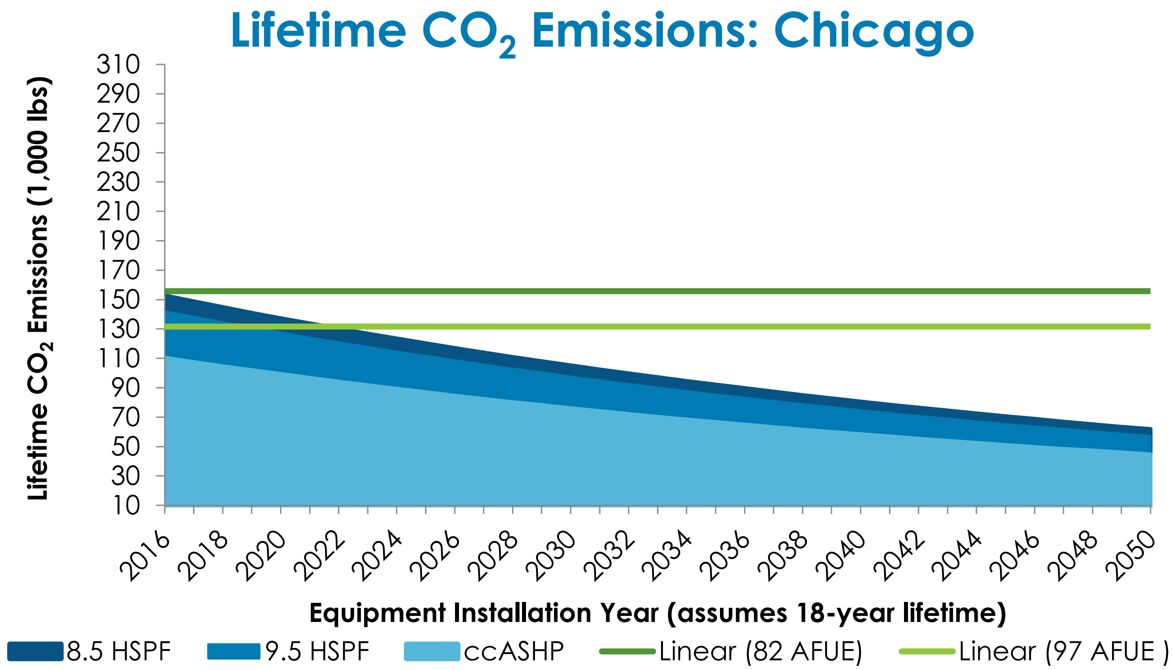
Below are five graphs comparing lifetime heating emissions for gas and ASHP heating types based on the 2016 CO_2 emissions rate in each city MSA. The percent reduction for each graph was determined by the average annual CO_2 emissions reduction per state over the last decade. The horizontal lines represent lifetime emissions from the baseline and 97AFUE gas furnace and the descending bars represent lifetime emissions from an 8.5 and 9.5 HSPF and a ccASHP.

Missouri: 10-year annual reduction – 0.6%



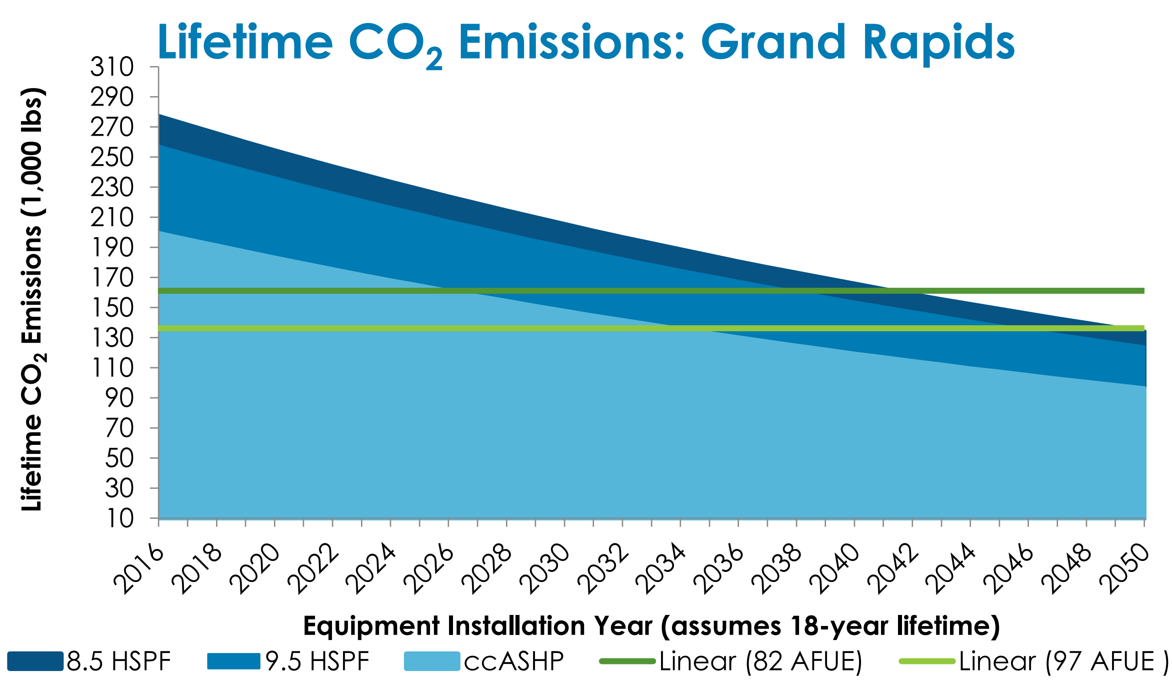
Comparison	HR Inflection Point (Year)
9.5 HSPF to 97 AFUE	Past 2050
ccASHP to 97 AFUE	Past 2050

Illinois: 10-year annual reduction - 2.6%



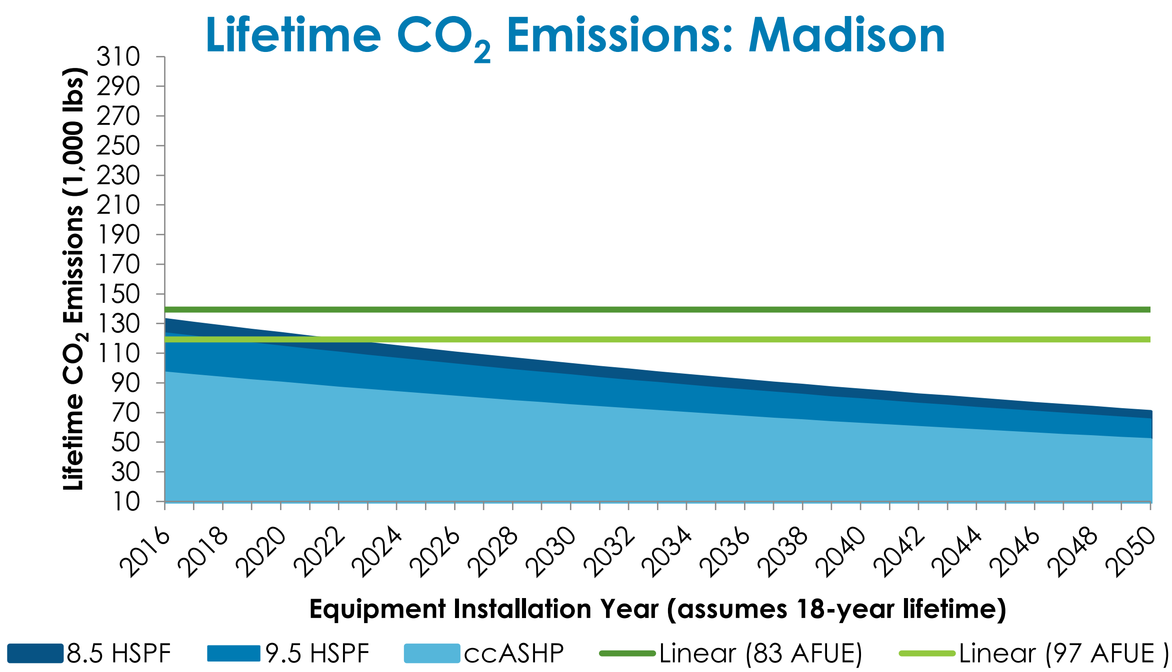
Comparison	HR Inflection Point (Year)
9.5 HSPF to 97 AFUE	2019
ccASHP to 97 AFUE	Pre 2016

Michigan: 10-year annual reduction – 2.1%



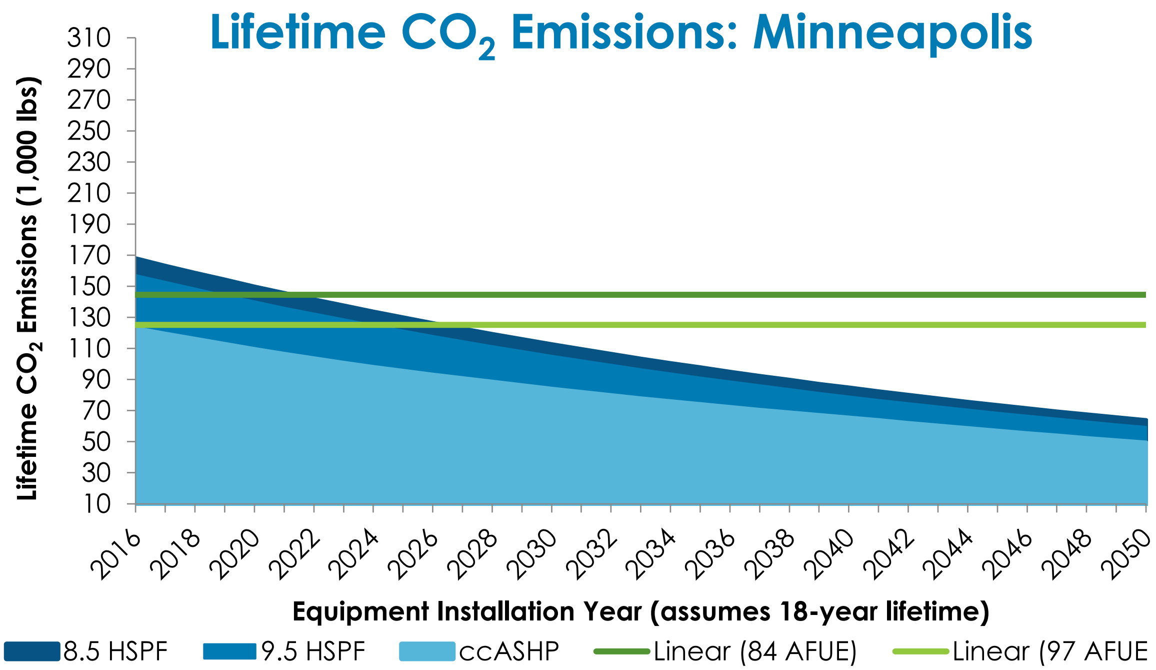
Comparison	HR Inflection Point (Year)
9.5 HSPF to 97 AFUE	2047
ccASHP to 97 AFUE	2030

Wisconsin: 10-year annual reduction – 1.8%



Comparison	HR Inflection Point (Year)
9.5 HSPF to 97 AFUE	2017
ccASHP to 97 AFUE	Pre 2016

Minnesota: 10-year annual reduction – 2.8%



Comparison	HR Inflection Point (Year)
9.5 HSPF to 97 AFUE	2025
ccASHP to 97 AFUE	2016