International High Performance Buildings Conference

School of Mechanical Engineering

2021

Pathways to Decarbonization of Residential Heating

Alex Fridlyand
Gas Technology Institute

Paul Glanville
Gas Technology Institute

Michael Garrabrant
Stone Mountain Technologies, Inc., mgarrabrant@stonemtntechnologies.com

Fridlyand, Alex; Glanville, Paul; and Garrabrant, Michael, "Pathways to Decarbonization of Residential Heating" (2021). *International High Performance Buildings Conference.* Paper 354.
https://docs.lib.purdue.edu/ihpbc/354

Pathways to Decarbonization of Residential Heating: Potential for Thermally-Driven Heat Pumps

Aleksandr FRIDLYAND[1]*, Paul GLANVILLE[1], Michael GARRABRANT[2]

[1]Gas Technology Institute
Des Plaines, IL 60018
(847) 768-0500; afridlyand@gti.energy

[2]Stone Mountain Technologies Inc.
Johnson City, TN 37604

* Corresponding Author

ABSTRACT

Space and water heating are the largest consumers of energy in residential buildings, up to 85% in cold climates. In addition to conservation measures, improving the building thermal envelope and optimizing the heat and hot water distribution, improving the performance of the heating technology is critical to provide a pathway to significantly reduce carbon emissions, with a focus on existing buildings. Conventional fuel-fired heating systems that use existing infrastructure have approached their thermodynamic limit over the past 15-20 years. While the performance of electrically-driven heat pumps, that would use electricity produced at the margin in a fuel-switching scenario, have improved, their performance in cold climates is highly dependent on regional and seasonal characteristics of the supplied electricity and the capacity of the heat pump and the grid itself to support this peak winter demand. The Gas Absorption Heat Pump (GAHP) is a thermally driven technology that can serve as the next step in fuel-fired heating with Coefficient of Performance (COP) value of 1.4 at design conditions with sufficient capacity to meet peak heating loads. The GAHP would serve as a drop-in replacement for furnaces, boilers and other conventional technologies, significantly reduce emissions, require no updates to existing infrastructure, and provide optionality as delivered decarbonized fuels become more widely available. This study looked at several locations in North America and compared potential emission and economic savings versus several baseline technologies, including furnaces, boilers, electric heat pumps, and various water heating options. The results show that the GAHP provided the lowest operating cost and highest emissions reduction (CO2e). Based on the results, the use and pursuit of GAHPs as a pathway to decarbonization is necessary to meet climate goals.

1. INTRODUCTION

Representing a combined 4.3 quads per year, the natural gas and propane consumed by U.S. homes is a significant energy expenditure and, as a result, source of greenhouse gas (GHG) emissions. The majority of this expenditure is used to provide heat and provide hot water, 3.7 TCF of natural gas and 3.4 billion gallons of propane to single-family and multifamily buildings, which predominantly use these delivered fuels for space and water heating during the heating season (EIA RECS, 2015), with >45% of the natural gas being used just between December and February (EIA, 2019). The challenge, as policymakers, builders, utilities, and end-users seek to reduce the greenhouse gas (GHG) impact of our homes, is that the installed base of space and water heating equipment is low-efficiency. For fuel-fired water heating, majority of which are storage-type (>90%), only 5% of the storage water heaters are 0.67 Uniform Energy Factor (UEF) or greater, qualifying for EnergyStar with the rest near or at the minimum allowable efficiency (Ryan, 2016). For central warm-air furnaces, which are in 85% of homes heated with natural gas or propane, less than half have a rated efficiency of 90% or greater, as an Annual Fuel Utilization Efficiency (AFUE) (DOE SNOPR, 2016). Further penetration of higher-efficiency conventional heating equipment, generally understood to have UEF > 0.90 and AFUE > 90%, is hampered by persistently low natural gas prices, the challenges with cost-effectiveness of infrastructure upgrades in retrofits (e.g. replacing appliance venting), and the absence of strong regulatory drivers to limit GHG emissions (e.g. carbon pricing), among other trends. Thus, the potential remains to mitigate the GHG impact of how we heat our homes, a particular challenge in existing and cold climate buildings.

To address this challenge, in this paper the authors examined the potential of a non-incremental solution for high-efficiency heating in residences, the gas absorption heat pump (GAHP). Applied as a combined space and water heating solution, the GAHP has a potential for a 40% reduction in fuel use for both loads and proportional reduction in emissions, while providing equal or better thermal comfort cost-effectively, compared to baseline equipment. This potential was explored via a techno-economic analysis, using open-source building energy simulation (BES) tools that are calibrated to experimental and field-derived GAHP datasets. This study looked at several locations in North America and compared potential emission and economic savings versus several baseline technologies, including furnaces, boilers, electric heat pumps, and various water heating options.

2. DESCRIBING THE GAS ABSORPTION HEAT PUMP

In prior efforts (Glanville, 2019 and Garrabrant, 2020), the authors have described the development and early demonstration of a pre-commercial gas-fired absorption heat pump (GAHP) for residential and light commercial applications (see Figure 1), based on the single-effect ammonia-water vapor absorption cycle in a heating-only mode. The GAHP is designed with a focus on easily manufactured components, at a projected equipment price of approximately $5,000, 30-50% that of GAHPs currently available on an approximately equal sizing basis. The absorption cycle is driven by a variable, 16 kW burner required to drive the refrigerant vapor from its absorbed state in the desorber (or "generator"). The unitary air-to-brine GAHP is installed outdoors and connected to indoor loads via a hydronic loop, with a nominal output of 23 kW, 4:1 system modulation, and operation without backup or supplemental heating.

Figure 1: Pre-commercial GAHPs operating at WI demonstration sites

During initial proof-of-concept development, a team including an absorption technology development company, a research and development (R&D) institute, and industry partners demonstrated several early generation prototypes in a laboratory environment. With a design described in prior reporting (Garrabrant, 2016), this GAHP was based on a simplified single-effect absorption cycle design, with a "thermal compressor" intended for mass manufacture. This "thermal compressor", comprised of an absorber, desorber, solution pump, solution heat exchanger, and rectifier, is integrated with the remainder of the heat pump components, including the condenser, expansion valve, evaporator, and refrigerant heat exchanger. A direct-fired combustion system drives the cycle, from which approximately 40% of the GAHP heat output to the hydronic loop is drawn from the evaporator load. The remaining 60% of heat output is heat recovery from (a) the hot weak solution and its heat of sorption within the absorber and (b) the warm flue gases exiting the direct-fired desorber at ~149°C via a flue-to-hydronic condensing heat exchanger (CHX). The operating efficiency, as a Coefficient of Performance on a gas-input basis (COP_{Gas}) ranges from 1.40-1.90, depending on ambient and loop temperatures and modulation stage, with "condensing" level combustion efficiency by virtue of the CHX. These GAHPs demonstrated a nominal COP_{Gas} value of 1.65 at 8ºC ambient and 38ºC return and an extreme cold condition performance of 1.2 at -25ºC with a return of 35ºC, via 3rd party testing and on a higher heating value basis, with a more complete performance map shown in Figure 2 below. Peak power demand of early prototypes was up to 600 W, driving the solution pump, evaporator fan, combustion blower, and system controls. Subsequent generations of GAHPs were characterized, both in a) further laboratory testing, including testing to the ANSI Z21.40.4 standard methodology, resulting in an AFUE of 139% for U.S. Climate Region IV, and certification to the Ultra-Low NO_x emission standard of < 14 ng/J output, and b) the installation of eight GAHPs in residential field sites, in TN, IL, WI, and ON, demonstrating more than 10,000 operating hours, up to 53% fuel savings for space/water heating versus a measured baseline, and operation at down to -34ºC outdoor conditions. Additionally, improvements in effective cycling, managing simultaneous space and water heating demands, end-user comfort, and power consumption were demonstrated, with several sites continuing to operate at the time of writing.

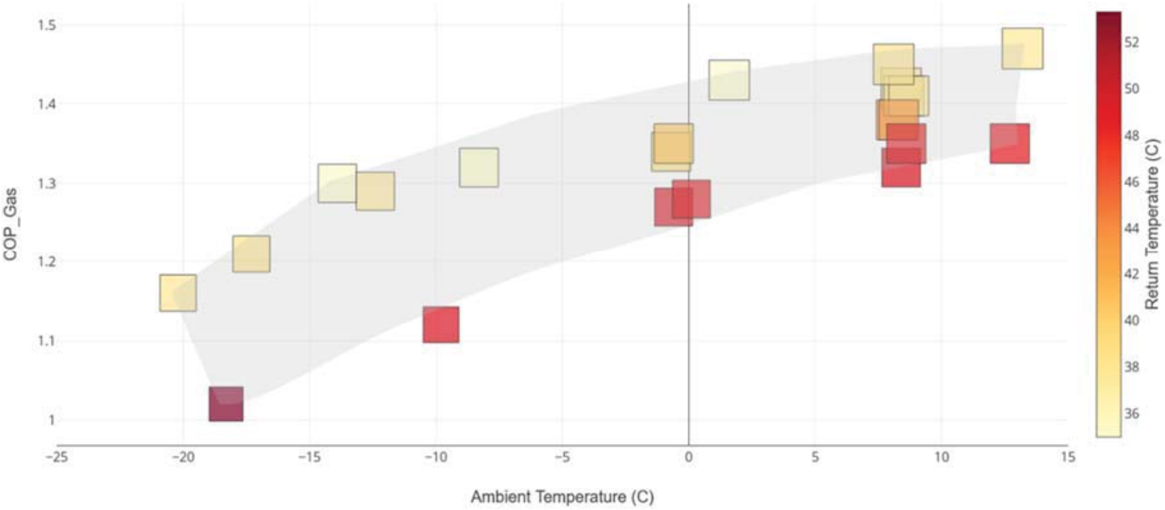

Figure 2: Steady-state efficiency of pre-commercial GAHP in 3rd party laboratory testing

3. MODELING METHODOLOGY

The objective of this analysis was to estimate the energy and cost savings potential of the GAHP combined space and water heating system ("combi" system) in cold climate retrofit applications. The analysis was performed using a combination of open-source BES tools maintained by the U.S. Department of Energy, specifically BEopt and EnergyPlus, and a custom GAHP combi model that uses a performance map based aforementioned laboratory and field-derived datasets. BEopt was used to develop prototypical residential building models and as a source of performance data of electrically-driven heat pumps, to be used for comparison. Three different home sizes were simulated, in nine different locations, and six different HVAC scenarios. Table 1 summarizes the high-level building characteristics used in the analysis, where each home was assumed to be two-story, with four bedrooms, three bathrooms, and a two-car attached garage. The building models were built to approximately International Energy Conservation Code (IECC) 2006 building code. Per the table, three building sizes are considered, though not in all locations/climate zones, reflecting expected nominal capacities of the GAHP at commercialization of (e.g., 35, 29, 23, 18 and 12 kW). Concerning the assumptions regarding the building construction, default assumptions within BEopt from the Building America House Simulation Protocols were used (Wilson, 2014) were applied, where not prescribed in the IECC 2006 codes. Typical home construction varies significantly by vintage, location, and extent to which energy efficiency retrofits have been performed, making it difficult to state definitively what is a "typical" retrofit scenario in each location. The IECC 2006 code was therefore chosen as the common reference point between the newest construction and older construction homes. Further details on the building construction are provided in detailed reporting (Garrabrant, 2020).

Table 1: Locations and buildings used in simulation

Building Location	Climate Zone	Building 1 Size (Large)	Building 2 Size (Mid)	Building 3 Size (Small)	Foundation
Fargo, ND	7-dry	278 m^2	223 m^2	N/A	Unfinished Basement
Rochester, NY	6-moist				Unfinished Basement
Minneapolis, MN	6-moist			167 m^2	Unfinished Basement
Chicago, IL	5-moist				Unfinished Basement
Philadelphia, PA	5-moist			N/A	Unfinished Basement
Denver, CO	5-dry		N/A		Unfinished Basement
Portland, OR	4-marine				Slab
Louisville, KY	4-moist				Unfinished Basement
San Francisco, CA	3-marine				Slab

3.1 Modeling of HVAC and Water Heating Equipment

The table below summarizes the HVAC scenarios considered in the analysis. All HVAC system models were taken directly from BEopt with minor modifications and the baseline storage water heater (0.62 EF) model is a custom option added to BEopt to reflect the current federal minimum. The variable speed heat pump option was modified to size the equipment based on the maximum load (as opposed to cooling load only by default), to better reflect how a "cold-climate" heat pump would be sized. The furnace models were modified to include part-load efficiency curves, including equation 1, for condensing furnace, equation 2, for non-condensing furnace, with the part-load ratio (PLR) defined as in equation 3. These modifications were made to better account for cycling efficiency losses of typical furnaces. These curves were added directly to the EnergyPlus models generated by BEopt and simulated separately.

$$Normalized\ Efficiency = 0.9 + 0.1 * PLR \tag{1}$$

$$Normalized\ Efficiency = 0.8 + 0.2 * PLR \tag{2}$$

$$PLR = load/capacity \tag{3}$$

Table 2: Equipment Scenarios

Equipment Case	Space Heating Details	HVAC Equipment Sizing	Water Heating Details
Baseline / Gas	80% AFUE Furnace	Auto-sized for peak heating load	0.62 EF, 180 L Storage
Better / Gas	95% AFUE Furnace	Auto-sized for peak heating load	0.62 EF, 180 L Storage
Best / Gas	95% AFUE Furnace	Auto-sized for peak heating load	0.96 EF, 58 kW Tankless
GAHP Combi	13 kW output minimum	Auto-sized for peak heating load	246 L IST
Baseline / Electric	7.7 HSPF Heat Pump	Auto-sized for peak cooling load	0.92 EF, 225 L Storage
Best / Electric	10.0 HSPF Variable Speed Heat Pump	Auto-sized for peak heating load	0.92 EF, 225 L Storage

The equipment cases represented were meant to represent "likely" retrofit scenarios to be encountered. For this reason, electric heat pump water heaters were not considered given their low market penetration and the unlikely scenario that both the central HP and the electric water heater would be swapped out for much more expensive options. Similarly, the "Best / Gas" scenario is also unlikely given the long payback periods of tankless water heaters in retrofit scenarios (Fridlyand, 2019). However, it was left for comparison given its comparable performance to tankless water heater-based combis, which could be more cost effective in retrofit scenarios (Fridlyand, 2021).

3.1 Modeling of the GAHP Combi System

The GAHP combi was simulated by modifying the "Best Gas" scenario BEopt model. The indoor furnace was replaced with a hot water heating coil to represent the hydronic air handler. The storage water heater was replaced with a stratified 9-node storage tank model, indirectly heated by the GAHP, and with heat loss characteristics similar to the tanks used in the field (~44 W in standby). The GAHP itself was modeled as a user-defined plant component and a custom Energy Runtime Language (ERL) script within the EnergyPlus input file. The "Best Gas" scenario was chosen as the basis to accurately capture the reduced infiltration of closed combustion heating systems. The duct heat-loss model as implemented in BEopt was preserved, overall space heating demand was not impacted.

The GAHP plant model acted as a simple heating device responding to demand from the space and water heating branches. The maximum heating capacity and the efficiency of the GAHP was determined using six unique performance curves, following a similar approach used in EnergyPlus for electric heat pumps (US DOE, 2018). The overall heating capacity of the GAHP was determined from the rated heating capacity and a function (CAPFT) of outdoor dry bulb temperature ($Tamb$) and hydronic return temperature ($Tret$), as shown in equations 4 and 5, with coefficients defined in Table 3. Knowing the maximum heating capacity of the GAHP for a given condition, the PLR was determined according to equation 6.

$$GAHP\ Heating\ Capacity = Rated\ Heating\ Capacity * CAPFT \tag{4}$$

$$CAPFT = \ a1 * Tamb + b1 * Tamb^2 + c1 * Tret + d1 * Tret^2 + e1 * Tret * Tamb + f1 \tag{5}$$

$$Part\ Load\ Ratio\ (PLR) = \frac{load}{capacity}\ for\ 0.2 \leq PLR \leq 1 \tag{6}$$

Table 3: Equation 5 and 8 Coefficients

	a	**b**	**c**	**d**	**e**	**f**
Eq. 5	0.00428	-8.6E-05	0.004093	-0.00014	2.26E-06	1.011452
Eq. 8	-0.00318	6.6E-05	0.011763	-6.1E-05	-4.8E-05	0.382999

The minimum modulation level of the GAHP is 25%, with a minimum cycle time of 45 minutes, resulting in a minimum PLR of ~0.2. If the requested load was below the minimum PLR, the GAHP would not activate. At other conditions, the GAHP would meet the heating load and consume gas according to the following equations, where, $EIRFT$ is the energy input ratio function of outdoor dry bulb and hydronic return water temperatures, with coefficients defined in Table 3. In equation 9, $EIRFPLR$ is the energy input ratio function of the part load ratio. To account for the defrost performance penalty (up to 4% near -2.8°C), an additional energy input ratio function of outdoor dry bulb temperature was used defined in equation 10. Between the minimum modulation rate at $PLRmin = 0.25$ and the minimum cycle time at $PLR = 0.2$, the GAHP is expected to cycle to meet load. An additional cycling penalty function was defined to account for increased energy use in this range, defined in equation 11. In one example, Figure 3 compares the predicted versus measured efficiency as a function of outdoor dry bulb temperature and part load ratio.

$$Gas\ Use = \frac{Load * EIRFT * EIRFPLR * EIRDEFROST}{CRF} \tag{7}$$

$$EIRFT = \ a2 * Tamb + b2 * Tamb^2 + c2 * Tret + d2 * Tret^2 + e2 * Tret * Tamb + f2 \tag{8}$$

$$EIRFPLR = \ 0.0864 * PLR^2 \ - \ 0.0681 * PLR \ + \ 0.9814\ for\ 0.25 \leq PLR \leq 1 \tag{9}$$

$$EIRDEFROST = \ -0.0011 * Tamb^2 \ - \ 0.006 * Tamb \ + \ 1.0317\ for - 8.89°C \leq Tamb \leq 3.333 \tag{10}$$

$$CRF = 0.4167 * CR + 0.5833; \quad CR = \frac{PLR}{PLRmin}\ for\ 0.2 \leq PLR \leq 0.25 \tag{11}$$

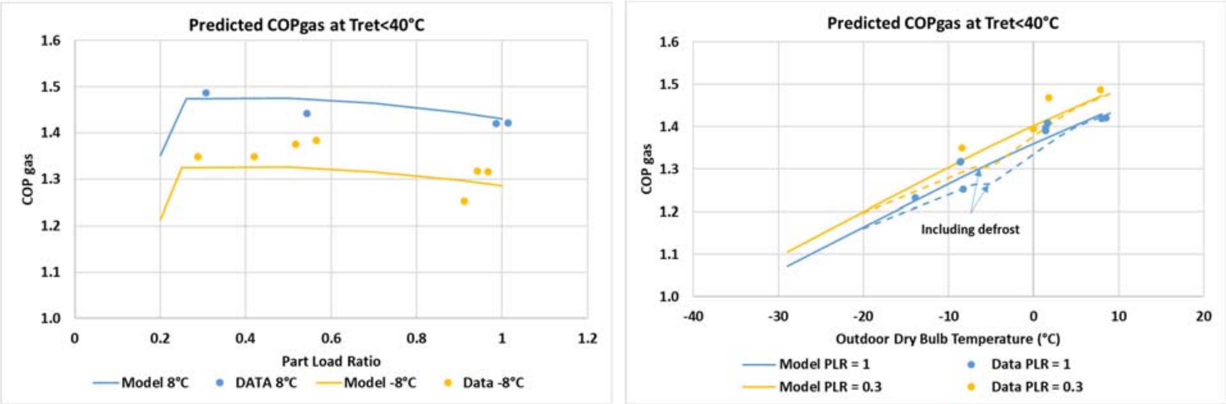

Figure 3: Predicted COP_{Gas} as function of PLR (Left) and ambient temperature (Right) for T_{Return} = 37°C

The electricity use of the GAHP was modeled using a simple approach, defining the consumption of the outdoor unit as 2.7% of the heat delivered and the pump energy as 1% of the heat delivered, both consistent with field measurements. The supply temperature setpoint for the GAHP followed an outdoor air temperature reset for space heating, summarized in Table 4. The supply water temperature setpoint was fixed at 54.4°C for hot water recovery, to meet the mid-tank setpoint target of 51.7°C. The balance of the EnergyPlus model, e.g., tank and water heating coil heat transfer effectiveness, was tuned to achieve a typical return water temperature of ~40.5°C, as observed at the field demonstration sites. For each location and building type, the rated heating capacity of the GAHP was auto-sized to better match the other HVAC scenarios which were all auto-sized by BEopt and to ensure that the GAHP could meet the peak heating load over the course of the year. This capacity was determined by dividing the maximum observed hourly heating load by the output of the *CAPFT* function at the corresponding outdoor dry bulb temperature and an assumed return water temperature of 37°C. The minimum rated capacity of the GAHP was fixed at 13.2 kW to ensure that there was enough capacity to meet the DHW demand. Economic and environmental assumptions are shown in Table 5 (SEEAT, 2019).

Table 4: Outdoor air temperature reset strategy

Ambient Dry Bulb Temperature, °C	**Supply Water Temperature, °C**
12.7 or above	43.33
12.7 to -20.6	Linear curve fit based on end points
-20.6 or below	51.67

Table 5: Economic and environmental assumptions by region, based on EIA and US EPA Data (SEEAT, 2019)

Location	**Gas Winter Price ($/Therm)**	**Annual Average Electricity Price ($/kWh)**	**Electric Grid CO2e* (kg/MWh)**	**Gas CO2e Emissions (kg/MWh)**
Chicago	$ 0.76	$ 0.125	972	230
Denver	$ 0.69	$ 0.121	912	
Fargo	$ 0.67	$ 0.102	959	
Louisville	$ 0.98	$ 0.105	908	
Minneapolis	$ 0.77	$ 0.127	959	
Philadelphia	$ 0.98	$ 0.139	770	
Portland	$ 1.10	$ 0.107	818	
Rochester	$ 1.05	$ 0.176	599	
San Francisco	$ 1.14	$ 0.174	562	
***Non-baseload (marginal) power plants**				

4. RESULTS AND DISCUSSION

An important feature of modeling exercises of this nature is the assumed sizing of the equipment, as over-sized equipment can suffer poor performance at part-load and otherwise due to short-cycling and conversely, while uncommon, under-sized equipment can excessively rely on lower efficiency auxiliary/backup heating (when applicable). Figure 4 highlights for Building 1, the modeled peak heating demand versus the calculated GAHP capacity. In Figure 5, annual performance predicted for the GAHP Combi in each location for Building 1 is shown, defined on a fuel-only basis (COP_{Gas}) and total fuel and electricity input basis (COP_{Total}). The results are comparable to field observations and align with expected performance in cold climates. Figure 6 plots the variation of the annual COP_{gas} by location and building size. The hot water use for each building stays the same and the primary difference between the buildings is the size and therefore the overall heating load. Figure 7 compares operating cost savings.

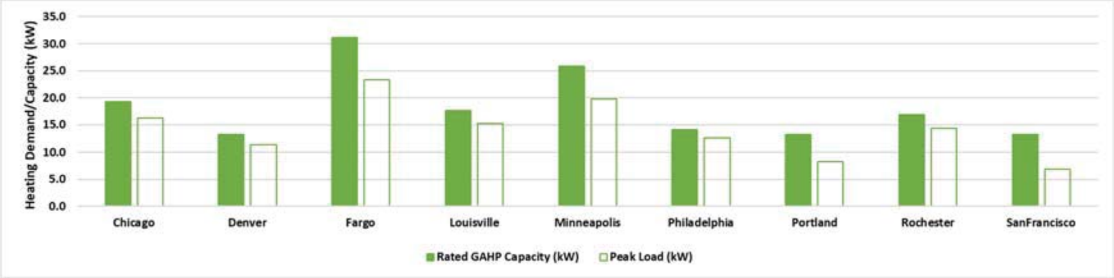

Figure 4: Building 1 peak heating demand and resultant GAHP sizing

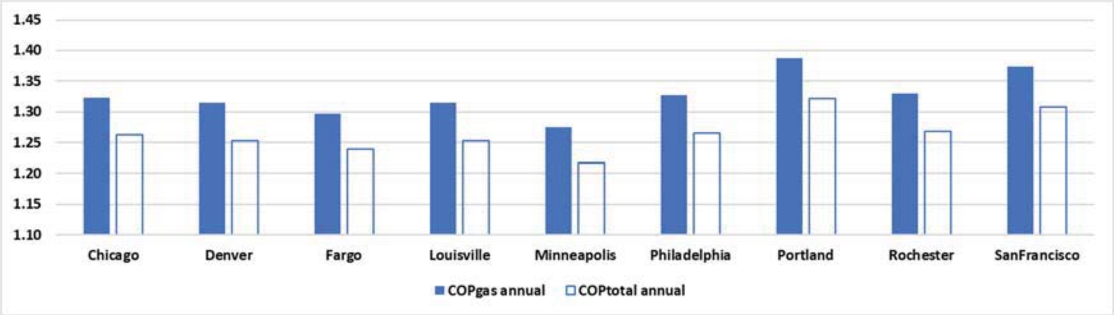

Figure 5: Building 1 annual GAHP COP_{Gas} and COP_{total}

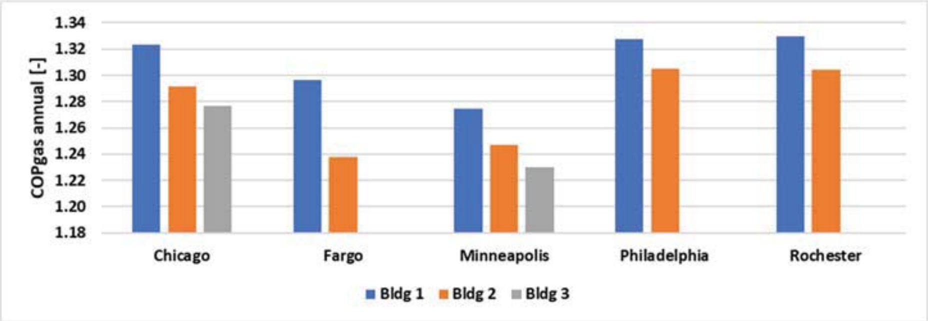

Figure 6: Comparing annual GAHP COP_{Gas} across region and building size

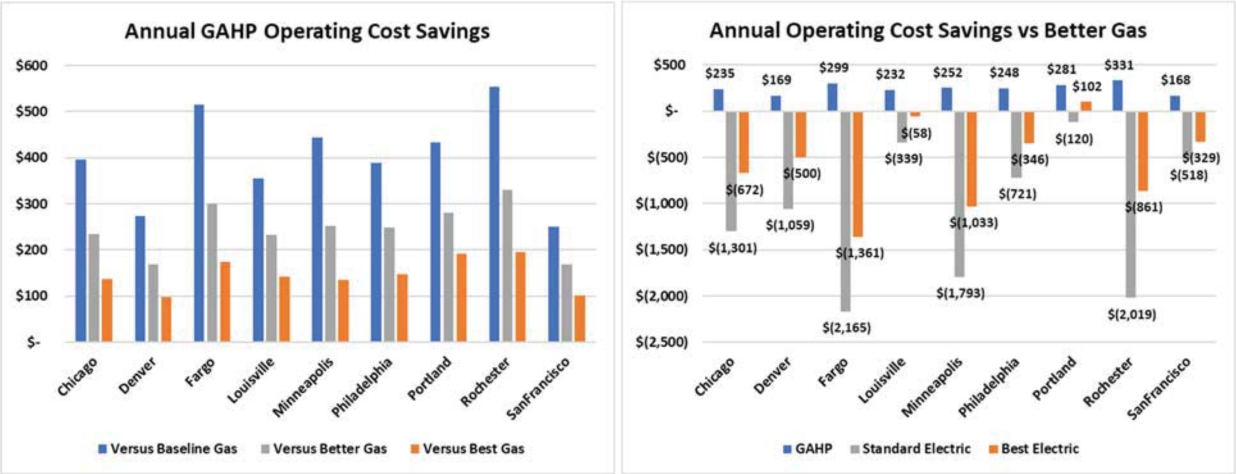

Figure 7: Comparing annual HVAC operating cost savings for gas options (L) and electric vs GAHP options (R)

The projected GAHP energy and cost savings are the highest compared to the baseline gas case which uses both non-condensing space and water heating technologies. The savings are the lowest when compared to the "Best Gas" scenario, condensing furnace and tankless water heating. However, due to the tough economics for tankless water heaters, e.g., 20+ year payback periods, this is not a likely retrofit scenario to occur (Fridlyand, 2019). With increasing prevalence of condensing furnaces and low penetration of high-efficiency water heating gas technologies, the "Better Gas" scenario is the more likely retrofit scenario to be encountered in the near future, against which a GAHP combi system delivers improved performance.

Figure 8 highlights the CO_2e emission savings, for Building 1, for the GAHP combi system versus all other equipment scenarios, highlighting the attractive emission savings in all regions. Similarly, the GAHP combi system provides operating cost and energy consumption savings in all cases as well. It is important to highlight that the marginal electricity grid emission were considered here. Per U.S. Environmental Protection Agency (EPA), renewable efficiency measures typically do not impact baseload power generation. The increased or decreased demand for electricity in buildings is managed on the margin (US EPA, 2020), which for the foreseeable future will still be dominated by fuel-fired power plants. Other scenarios including on-site renewable electricity generation, increases in renewable gas use, or changes to the grid generation mix were not considered due to the speculative nature of any future projections and to limit the scope of the analysis.

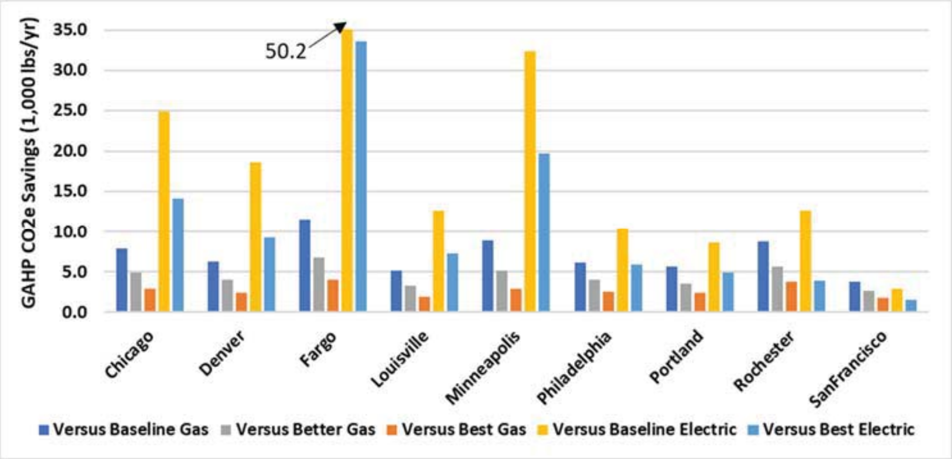

Figure 8: Annual CO_2e savings for GAHP combi versus other equipment scenarios for building 1

When compared to fuel-fired equipment scenarios, the most likely GAHP retrofit scenario, efficiency benefits are coupled with the elimination of negative interactive effects from low-efficiency gas water heaters on HVAC (combustion/dilution air requirements). This impact is significant, however it is somewhat blunted by the GAHP system's increased power demand. For example, when comparing the Chicago-area Building #1 from GAHP system to baseline gas, the annual fuel savings are significant, at 48%, however operating costs and CO_2 reductions are not as significant, $395/year and 35% respectively, due to the incremental power requirements of the GAHP and the hydronic heating system, increasing electricity consumption by 83% or 824.1 kWh/year.

6. CONCLUSIONS

This study built on the results of prior successful laboratory and field evaluations of a single-effect Gas Absorption Heat Pump (GAHP), to estimate the potential for energy and greenhouse gas emissions (GHG) savings in different locations and retrofit scenarios in North America. Using performance data measured as a function of outdoor and return water temperature to the GAHP, a combined space and water heating system was simulated in nine different locations, three different building sizes, and compared to five other gas and electric HVAC scenarios. In all cases considered, the GAHP system offered the greatest GHG emissions savings and the lowest annual operating costs, based on the current average retail energy prices and marginal electric grid GHG emission factors. While the electric grid power generation mix will continue to change, energy prices will vary, and the economics may change, presently, the GAHP combined space and water heating system in cold climates is predicted to be best and most cost-effective option for reducing GHG emissions in residential buildings.

REFERENCES

EnergyStar Program, via the U.S. Dept. of Energy (2010). *Energy Star® Water Heater Market Profile*, report prepared under contract BOA#4200000327.

Fridlyand, A., Liszka, M. (2019). *Lab Testing of Tankless Water Heater Systems*, NEEA Report E19-306, https://neea.org/resources/lab-testing-of-tankless-water-heater-systems

Fridlyand, A., Baez Guada, A., Kingston, T., Glanville, P. (2021). *Modeling Modern, Residential, Combined Space and Water Heating Systems Using EnergyPlus*, ASHRAE Transactions, (in press).

Garrabrant, M. Stout, R. Keinath, C. and Glanville, P. (2016). *Experimental Evaluation of Low-Cost Gas Heat Pump Prototypes for Building Space Heating*, International Refrigeration and Air Conditioning Conference Paper 1573.

Garrabrant, M., and Keinath, C. (2020). *Pre-Commercial Scale-Up of a Gas-Fired Absorption Heat Pump*, Report DOE-SMTI-8219-1 prepared for the U.S. Dept. of Energy under contract DE- EE0008219.

Glanville, P, Fridlyand, A., Keinath, C., and Garrabrant, M. (2019). *Demonstration and Simulation of Gas Heat Pump-Driven Residential Combination Space and Water Heating System Performance*, ASHRAE Transactions; Atlanta Vol. 125, pp. 264-272.

Raustad, R., (2011). *Modeling Variable Refrigerant Flow Heat Pump and Heat Recovery Equipment in EnergyPlus*, FSEC-CR-1960-11.

Ryan, S. (2016). *Making ENERGY STAR® Water Heaters a National Early Replacement Priority*, presentation made at the ACEEE Hot Water Forum, Portland, OR.

Source Energy and Emissions Analysis Tool (SEEAT), (Accessed 2019). http://seeatcalc.gastechnology.org/.

U.S. Census. (2019 ed.), *American Housing Survey*.

U.S. Dept. of Energy (DOE), (2016). *Supplemental Notice of Proposed Rulemaking (SNOPR) 2016. Technical Support Document: Residential Furnaces*, Prepared for the DOE by Navigant Consulting, Inc. and Lawrence Berkeley National Laboratory.

U.S. Dept. of Energy (DOE), (2018). *EnergyPlus Version 8.9 Documentation: Engineering Reference*, https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.9.0/EngineeringReference.pdf

U.S. Energy Information Administration (EIA), (2009-2015). *Residential Energy Consumption Survey (RECS)*. www.eia.gov/consumption/residential/

U.S. Energy Information Administration (EIA), (Accessed 2019). *Natural Gas Monthly Report.*

U.S. Environmental Protection Agency (EPA), (Accessed 2021). *Greenhouse Gases Equivalencies Calculator - Calculations and References*. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Wilson, E., Horowitz, S. (2014). *Building America Housing Simulation Protocols*, NREL/TP-5500-60988.

ACKNOWLEDGEMENT

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) 2017, Award Number DE-0008219."

Additional support was provided by Utilization Technology Development under projects 1.13.F and 1.16.H.