TAF The Atmospheric Fund

Gas Absorption Heat Pumps

TECHNOLOGY ASSESSMENT AND FIELD TEST FINDINGS

ACKNOWLEDGMENTS

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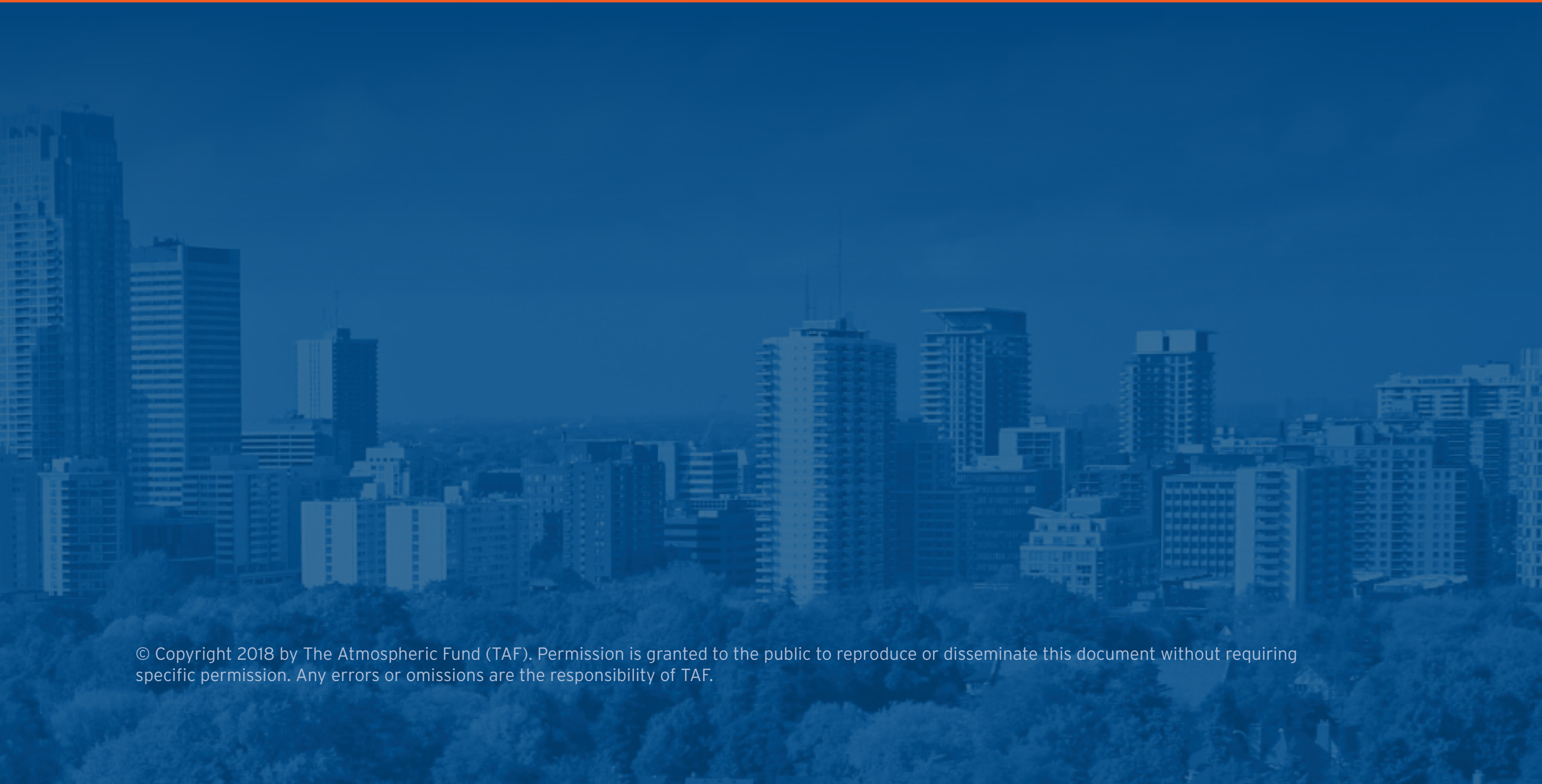
TAF The Atmospheric Fund

About The Atmospheric Fund (TAF)

Founded in 1991 by the City of Toronto, TAF's mission is to invest in urban low-carbon solutions to reduce emissions and air pollution. To date, TAF has invested more than $50 million, helping Toronto save more than $60 million in energy costs and contributing to a city-wide carbon emissions reduction of 24 per cent below 1990 levels.

Visit taf.ca for more information or contact **Keith Burrows**, Energy and IEQ Research Coordinator at **kburrows@taf.ca**.

THE ATMOSPHERIC FUND
75 Elizabeth Street
Toronto, ON M5G 1P4



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Abstract

Natural gas is the primary fuel for space and water heating in both Canada and the United States. Although electrification of heating combined with the decarbonisation of electricity generation is an important climate strategy, natural gas will continue to be used to heat buildings and water systems for the foreseeable future.

For this reason, it is critical that gas is used as efficiently as possible. This paper provides an overview of high-efficiency gas absorption heat pump (GAHP) technology, and presents The Atmospheric Fund's (TAF's) energy and emission findings from a detailed study of two GAHPs installed as part of a domestic hot water system in a multi-unit residential building in Toronto, Ontario. This paper also explores the cost and carbon effectiveness of GAHPs compared to alternative technologies such as electric heat pumps and condensing boilers.

1.14 Coefficient of Performance (COP)

1.16 Gas Utilization Efficiency (GUE)

Performance of the GAHPs met TAF's expectations and was in-line with the manufacturer's performance curves. TAF observed a mean Coefficient of Performance (COP) of 1.14 and Gas Utilization Efficiency (GUE) of 1.16 during cold weather operation, between November 1st 2017 through May 31st 2018.

Introduction

Space and water heating account for the majority of building sector energy use and carbon emissions in Canada. Achieving federal, provincial and municipal carbon reduction targets will require deep reductions in heating energy use and emissions.

The City of Toronto, for example, aims to reduce emissions 65 per cent below 1990 levels by 2030,[1] which will require a dramatic reduction in natural gas emissions from buildings. Conventional gas-fired heating equipment (i.e. boilers, furnaces, and water heaters) are available with rated efficiencies approaching the theoretical maximum efficiency of combustion technology (<100 per cent). While this is a marked improvement over previous generations of equipment, it is insufficient for the deep carbon reductions required to achieve our targets. While electric heat pumps can offer higher efficiencies, in much of Canada the operating costs of electric heat pumps exceed those of gas-fired equipment due to differences in fuel costs. Considering that gas is the primary fuel used for heating and domestic hot water (DHW) systems in Canada,[2] alternative heating technologies that enable buildings to consume natural gas more efficiently are a key priority for improving energy efficiency and reducing carbon emissions.

The Gas Absorption Heat Pump (GAHP) is one such technology. Although not yet widely used in Canada, these heating systems are becoming popular in Europe where they have been primarily used for light commercial and industrial applications. GAHP technology promises efficiencies significantly exceeding 100 per cent, while still using low-cost natural gas as the primary fuel source. This is important in many Canadian markets where the relatively high cost of electricity limits the near-term market potential for conventional electric heat pumps. In such markets, the GAHP technology has the potential to help achieve near-term carbon reduction goals while reducing energy costs. In the longer-term, GAHPs fueled with renewable natural gas could provide a pathway to decarbonizing space and water heating.

To determine if GAHPs are a technology that can provide efficient heating and reduce carbon emissions in a cold climate, The Atmospheric Fund (TAF) installed two units as part of a DHW system in a large multi-unit residential complex. This paper represents TAF's findings, including an assessment of the suitability of the technology for scale-up.

HOW DO GAS ABSORPTION HEAT PUMPS WORK?

GAHPs and electric heat pumps both leverage a refrigeration cycle to draw energy from air, ground or water to provide highly efficient heating and/or cooling to buildings. However, there are three significant differences between these technologies:

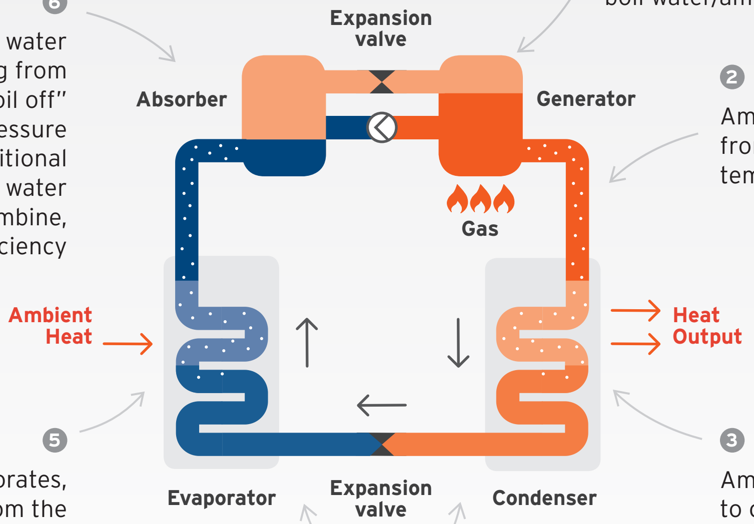
① GAHPs use gas combustion to drive an absorption refrigeration cycle, whereas conventional heat pumps use electricity to drive a vapour compression refrigeration cycle.

② An ammonia-water solution is commonly used as the working fluid in GAHPs instead of the Hydrofluorocarbons (HFCs) used in conventional electric heat pumps.

③ GAHPs are highly efficient, but less so than their electric counterparts.

The process used by a GAHP to generate useable heat is detailed in Figure 1 below.[3]

Figure 1: Ammonia-based GAHP heat generation process



① Gas is combusted to boil water/ammonia mix

② Ammonia vapor separates from solution at high temperature and pressure

③ Ammonia vapor moves to condenser heat exchanger, where external heating system loop is warmed

④ Ammonia condenses as heat is exchanged and moves to evaporator at low temperature and pressure

⑤ As ammonia evaporates, heat is drawn from the surrounding air or water as part of phase change and returns to the absorber heat exchanger

⑥ In parallel, hot water remaining from refrigerant "boil off" moves to low-pressure absorber where additional heat is generated as water and ammonia recombine, adding to system efficiency

PRIMARY USES

To date, GAHPs have primarily been used for commercial water and space heating applications, but are beginning to appear in some European single-family homes. Residential-scale units are expected to be introduced to the North American market in the near future. TAF expects market penetration to increase in regions that have low natural gas prices, high electricity rates and high heating demands (e.g. Ontario and the Northeastern United States). GAHPs are more efficient than condensing boilers and, in markets with low natural gas prices, can provide heat at lower operational costs than electric-based systems.

In domestic hot water (DHW) applications, GAHPs can be coupled with gas boilers to provide systems with efficiencies exceeding 100 per cent. GAHPs can also be used as a stand-alone system to provide DHW, although budget constraints, operational temperature limitations and/or space requirements may favour hybrid systems in applications with high domestic hot water demand.

GAHPs are also used in low-temperature heating applications such as radiant floor heating. Although some GAHPs can supply water at relatively high temperatures (in excess of 65°C), GAHPs operate more efficiently with lower return (and therefore lower supply) temperatures.[a] Multiple units can be combined to provide greater heating capacity. GAHPs can also be used to provide space heating in systems with higher design temperatures during periods of lower heating demand (e.g. during shoulder seasons), when combined with boilers that supply high-grade heat when required.

As an indication of the expanding interest in this technology, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy sponsored a project to design and prototype a low-cost, high-efficiency GAHP space heating system for homes. This project was undertaken with the recognition that gas boilers and furnaces "have been approaching their thermodynamic limit over the past 30 years and improvements for high efficiency units have approached a point of diminishing return."[4] Interest is growing in GAHP technology as these systems can operate at efficiencies that are not physically possible with traditional gas-fired heating systems.

> In Canada, the Federal, Provincial and Territorial governments have jointly identified the development of a market for residential GAHPs as an aspirational goal for 2030 in both space and water heating.[5]

In Canada, the Federal, Provincial and Territorial governments have jointly identified the development of a market for residential GAHPs as an aspirational goal for 2030 in both space and water heating.[5] The Ministers also established a long-term goal of having the efficiencies of all space and water heating equipment available in Canada exceed 100 per cent, effectively moving entirely to heat-pump technologies.

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[a] "supply" in this report indicates heated water sent out from the system (i.e. GAHPs), "return" refers to the cooler water coming back to the system after heat has been extracted.

CLIMATE BENEFITS

The primary climate benefit of GAHPs is that they can reduce the use of fossil fuels for heating and DHW in instances where an electric based system is not a viable option. Since they use less gas to do the same amount of work as conventional gas-fired equipment, their operation results in fewer combustion emissions at the site and fewer fugitive methane emissions from natural gas extraction and transport. When GAHPs are used as an alternative to conventional gas-fired equipment, they can reduce combustion emissions by 20-50 per cent depending on the efficiency of the system being offset.

The use of ammonia as a refrigerant provides a secondary, less significant, climate benefit.[b] Although ammonia is hazardous to human health if directly exposed, it does not deplete the ozone layer and has zero global warming potential (GWP). GAHPs are generally made for outdoor installation and pre-charged with ammonia in a sealed loop by the manufacturer. Contact with the fluid is unnecessary during maintenance or operation, and there is minimal risk of exposure.

Although electric heat pumps with alternative refrigerants (like CO_2) have entered the market, most conventional electric heat pumps use HFCs as a refrigerant. These chemicals do not deplete the ozone layer (as required by the Montreal Protocol), but they do have a significant GWP—thousands of times greater than carbon dioxide. Although refrigerant emissions in the aggregate are a significant issue, refrigerant leakage associated with an individual heat pump (which is minimized with proper disposal at end of life) does not offset the climate benefits of electric heat pumps in a low-carbon grid.

HCF refrigerants will eventually be phased out via the Kigali accord—an amendment to the Montreal Protocol—however, this will not begin until 2019 and will take decades to complete. GAHP systems that use ammonia as a refrigerant do not contribute to this serious climate issue.

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[b] Ammonia and water are commonly used as the working fluids in GAHP systems, but water and lithium bromide may also be used. Like ammonia, lithium bromide has zero GWP.

Case Study Project

TAF and the project partners designed and implemented a GAHP pilot project to assess the viability of this technology that has the potential to significantly reduce natural gas consumption.[c] Not all building managers can or are willing to move to an electric heating solution, and in this situation GAHPs promise the highly efficient use of gas.

TAF sought a site for the GAHPs where the units could be installed as part of a gas-fired DHW system in order to maximize emission reductions. Using the GAHPs in a DHW system allows the air-sourced heat pumps to operate at their maximum efficiency during the summer months and provides an opportunity to test system performance through seasonal variation in temperatures.

The site selected was a social housing complex in Toronto, Ontario consisting of two buildings with a combined 372 apartments for seniors, and a gross floor area of 16,258 m^2. The buildings were constructed in 1972 and both are four-story concrete structures with original brick cladding and single-pane, aluminum-framed windows.

Prior to the project retrofits, two oversized gas boilers located in a basement boiler room provided space heating and DHW for both buildings. The boilers are each rated at 4.4 MMBTU/h and ran at an average efficiency of approximately 54 per cent based on TAF's pre-retrofit monitoring. The boilers heated a 3,200 gallon DHW storage tank (which remains post-retrofit) that is the source of hot water for both buildings.

STUDY MOTIVATIONS

TAF investigated the following questions through this multi-residential GAHP demonstration project:

1. Are air-source GAHPs a viable domestic hot water solution in the Greater Toronto Area climate?
2. Does actual performance measure up to stated performance?
3. How does outdoor temperature affect performance?
4. Is this technology appropriate for future projects in cold climates in North America?

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[c] TAF's partners for this project include Toronto Community Housing, Ecosystem, Enbridge and Union Gas.

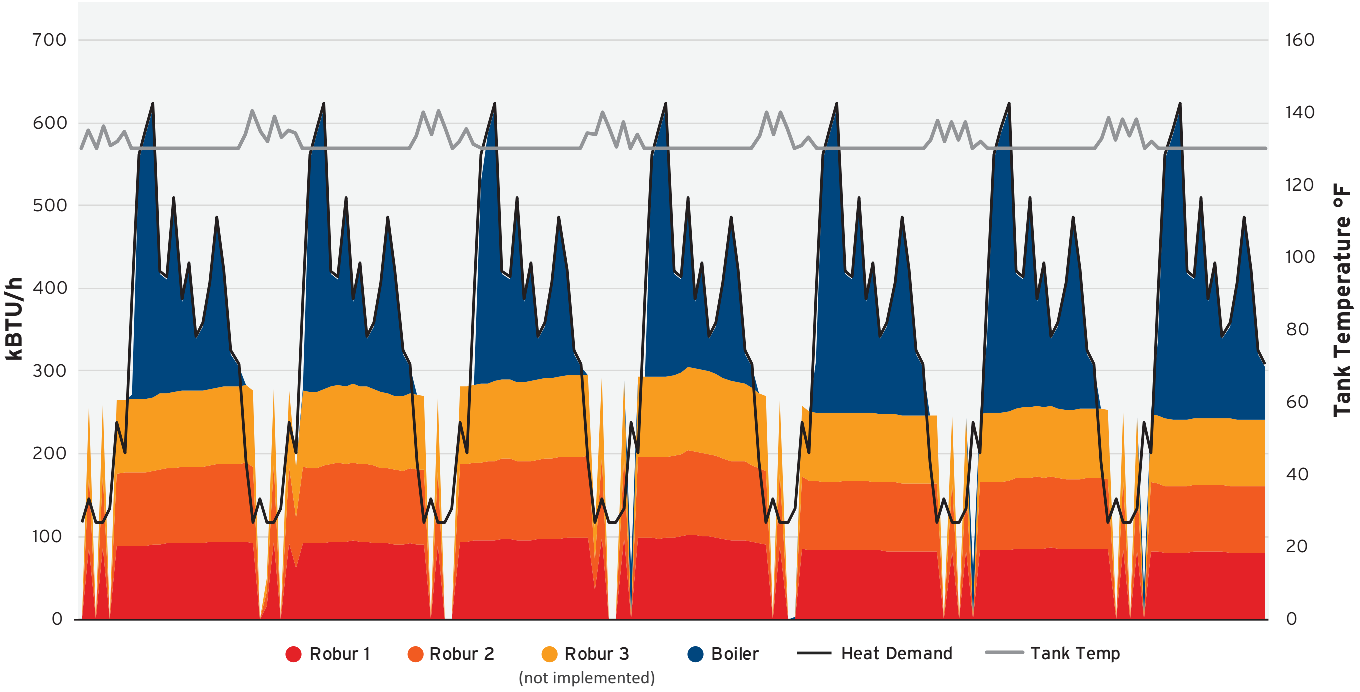
After an evaluation of the few available GAHP systems sold in the Canadian market, the project team selected Robur's model GAHP-A, which is a non-reversible hydronic heat-only system with a heating capacity of 123.5 kBTU/hour and a maximum outlet temperature of 60°C. Ecosystem, TAF's engineering partner on the project, modelled various DHW system scenarios and determined that two Robur units could provide 58 per cent of the site's overall DHW capacity and 100 per cent of its daily non-peak capacity. The heat pumps provide heat to the DHW system via a brazed plate, double walled heat exchanger. Any additional heating required to meet the DHW setpoint of 54°C is provided by a pair of Viessmann 200 CM2-246 condensing boilers, which provide both space heating and supplemental DHW. Modelled efficiency of the combined DHW system is 110 per cent.

110%

modelled DHW system efficiency

Ecosystem also modelled installation of a third GAHP (Figure 2 below), which when combined with the other two units would have covered 78 per cent of the buildings' DHW needs. However, the ideal location for this equipment (closest to mechanical room) had limited space in which to install three units.[d] The project team settled on two units installed just outside the boiler room, which minimized the length of the exterior glycol piping and avoided any noise issues for occupants (maximum sound pressure at five meters is 57 dB, slightly higher than a modern window air conditioner).

Figure 2: GAHP and boiler modelling output for a week in January of 2015. Modelling done for TAF by Ecosystem[6]



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[d] Each unit is 129 cm high, 85 cm wide and 123 cm long. The manufacturer specifies minimum clearances of 46 cm to the side, 91 cm to the front, and 61 cm to the back.

Two installed Robur GAHPs

Although the project team could have designed a system where the GAHP supplied 100 per cent of the site's DHW needs, this would have meant installing the equipment on the roof, which would have increased construction costs. This type of system would also have been overbuilt to handle peak demand hours; in essence running the last unit only a few times a day when hot water demand is highest. Combining the heat pumps with condensing boilers was the most cost effective solution given the GAHPs' maximum heating output and DHW demand at the site.

MONITORING

In order to evaluate the performance of the GAHPs, the project team installed monitoring equipment that captures and stores gas consumption, glycol water flow, and supply/return temperatures in one minute intervals. Performance analysis in this paper is based on the monitoring results from November 2017 to May of 2018.

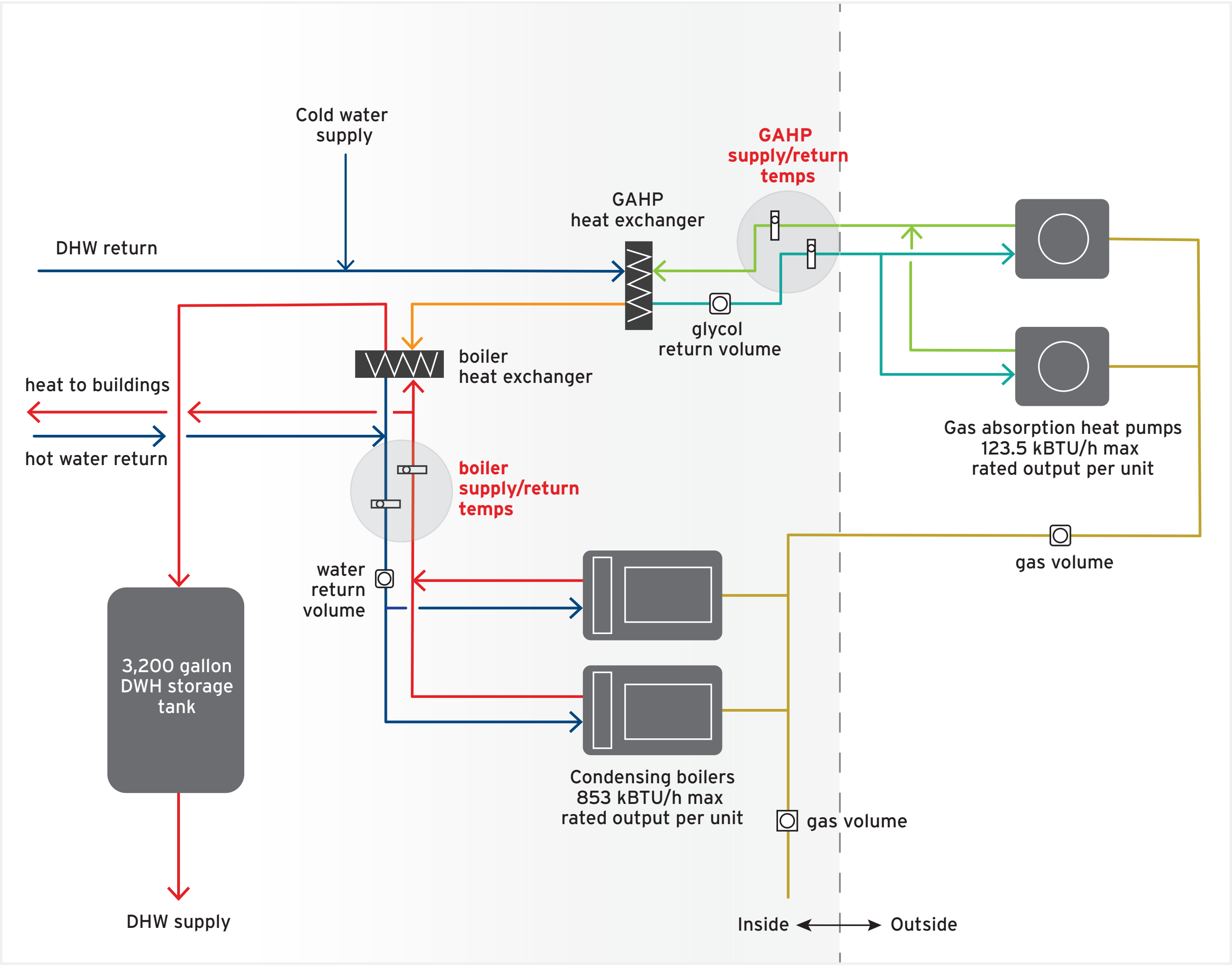
Accuracy and range of installed monitoring equipment can be seen in Table 1. Electricity consumption for the units and corresponding variable frequency drive (VFD) pumps is monitored on 15-minute intervals. This level of monitoring is not necessary or typical for general operation, but was required to ensure accurate tracking of real-time operating performance for this demonstration project.

Table 1: Installed monitoring equipment

Type	Manufacturer and Model	Location	Range		Operational Accuracy	
			Min	Max	At Min Flow	At Max Flow
Gas flow	Sierra, Quadra Therm 780i	installed on gas line dedicated to GAHPs	0	5.4 m^3/h	± 0.5% of reading plus 0.5% of full scale below 50% of full scale flow	± 0.5% of reading above 50% of the full scale flow
Temperature	3 wire 100 Ohm resistance temperature detector (RTD)	supply from GAHP	0	80°C	0.18°C (0.1^2 sensor+ 0.15^2 transmitter)	
		return to GAHP	0	80°C		
Water/ glycol flow	Krohne, Enviromag 2000 + IFC100 with PFA Teflon liner	return to GAHP	0	6.81 m^3/h	± 0.3% of the measured value ± 1 mm/s	

Boiler room monitoring locations can be seen in Figure 3. Although not shown in the figure, the project team also monitors electricity consumption of the GAHPs and all pumps used to move fluids through the DHW and heating systems. Note that electricity consumption outside of what the GAHPs themselves consume is not included in performance numbers reported in this paper.

Figure 3: Boiler room and GAHP monitoring flow



PERFORMANCE AND OPERATION

GAHP performance is commonly quantified via the Gas Utilization Efficiency (GUE), which is a ratio of gas energy input to heat energy output. In this paper, the GUE corresponds to gas-only efficiency, while Coefficient of Performance (COP) indicates a net efficiency value that includes the electricity consumed by the unit to pressurize the ammonia/water solution. (Electric consumption had a small impact on performance, accounting for just 1.4 per cent of total energy consumed by the units during the monitoring period.)

$$\text{GUE} = \frac{\text{USABLE HEAT SUPPLIED}}{\text{NATURAL GAS CONSUMED}}$$

$$\text{COP} = \frac{\text{USABLE HEAT SUPPLIED}}{\text{NATURAL GAS CONSUMED + ELECTRICITY CONSUMED}}$$

The project team encountered some operational issues that negatively affected performance and energy output of the GAHPs. Operational issues and recommendations to avoid them for future projects are as follows:

- **High water return temps** – water returned to the GAHPs was at temperatures near or in excess of their operational limit of 50°C. This was caused by two old 4.4 MMBH backup boilers that were manually started (in error) in late December and remained on at high capacity for over two weeks. This significantly impaired performance of the GAHPs, and TAF excluded this operational data from the analysis. The poor performance from this period highlights the importance of proper sequencing of supplementary equipment in a GAHP-based system.
- **Water flow sequencing** – during periods when there was no demand for hot water or return temperatures neared 50°C, the GAHPs were automatically shut down along with a VFD pump which moved the glycol solution through the heat exchangers and heat pumps. The glycol pump was sequenced to shut down after the GAHPs, but often the units would go into alarm mode for premature stoppage of the glycol flow, shifting the full DHW heating load to the condensing boilers. Instead of a time interval, the engineering team eventually settled on shutting down the glycol pump only after the GAHPs stopped consuming electricity, which corrected the issue.

Outside of these operational issues, the heat pumps performed well. Actual performance met TAF's expectations for cool weather operation, with a mean COP of 1.14 and GUE of 1.16 for the period of November 1st 2017 through May 31st 2018, during normal operation. These performance results are primarily from cold-weather operation, when the GAHPs are expected to perform at their worst.

Grouping performance of the GAHP system by ambient temperature quartiles (Table 2 below) reveals higher average COP/GUE values as outdoor temperatures increase. This is expected behavior, as it becomes easier to pull heat from the ambient air as the air gets warmer. It is important to note that average daily GUE and COP values exceeded 1.0 even in the coldest quartile where temperatures averaged -5.9°C.

1.16 GUE

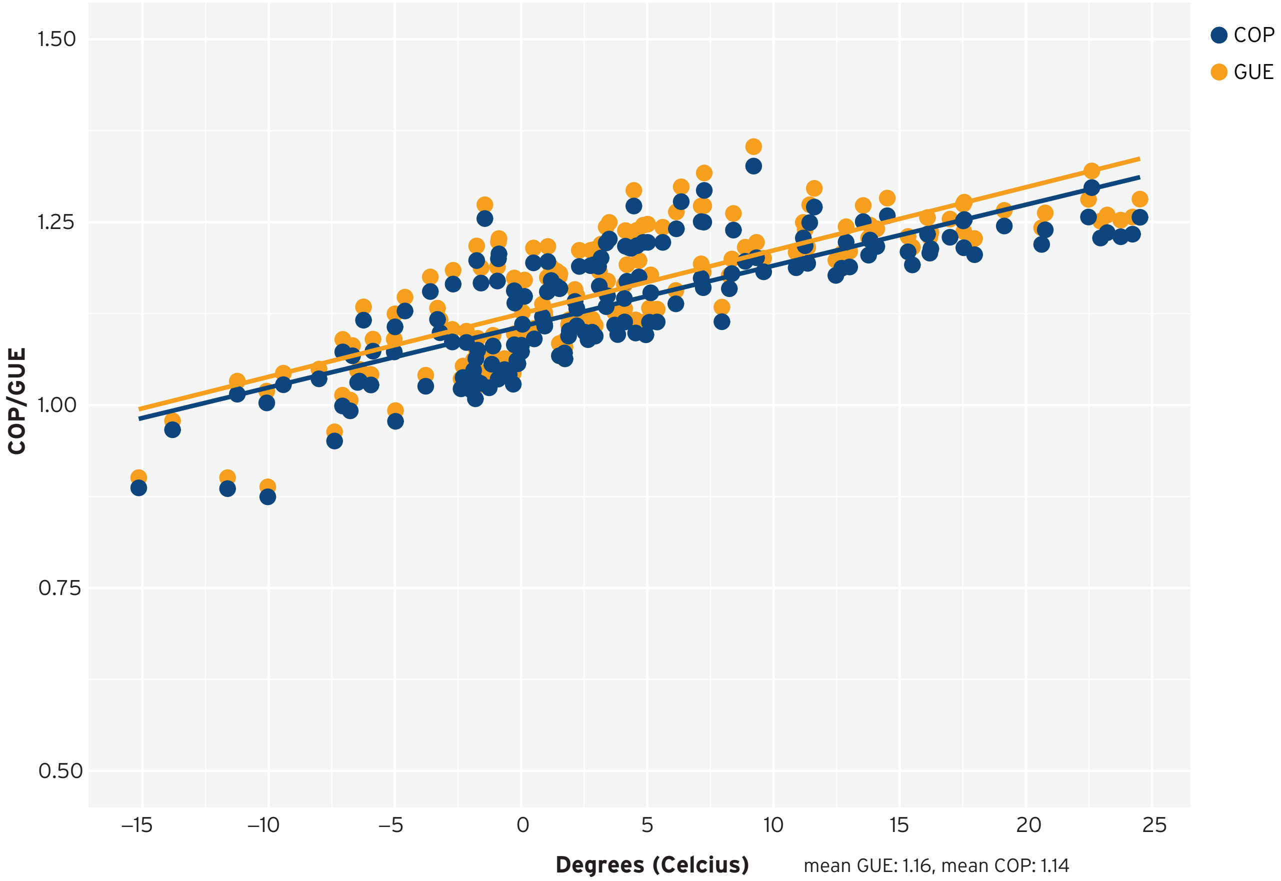
1.14 COP

Table 2: GAHP performance by outdoor temperature quartile

Quartile	Average Outdoor Temp (°C)	GUE	COP	Average Return Temp (°C)	Average Supply Temp (°C)
1	-5.9	1.04	1.02	42.8	45.5
2	0.4	1.13	1.11	43.1	46.3
3	4.7	1.18	1.16	43.1	47.0
4	15.9	1.25	1.23	43.6	47.7

The exterior temperature influence on GAHP performance is seen clearly when daily COP and GUE values are plotted against average outdoor temperatures. As seen in Figure 4, there is a strong and positive correlation between GAHP performance and outdoor temperature over this period, with 60 per cent of the variation in GUE and COP attributable to variation in outdoor temperatures ($r^2 = .602$ for GUE and $r^2 = .598$ for COP). Figure 4 also shows that when outdoor temperatures reach -12°C, GAHP efficiency at the site falls below 1.0. When exterior temperatures fall below -13°C, GAHP efficiency falls to that of a condensing boiler. This is in-line with the manufacturer's performance curve, which indicates a GUE of .94 at ambient temperatures of -13°C and supply temperatures of 45°C (average GAHP supply temperatures during this study were 46.6°C).

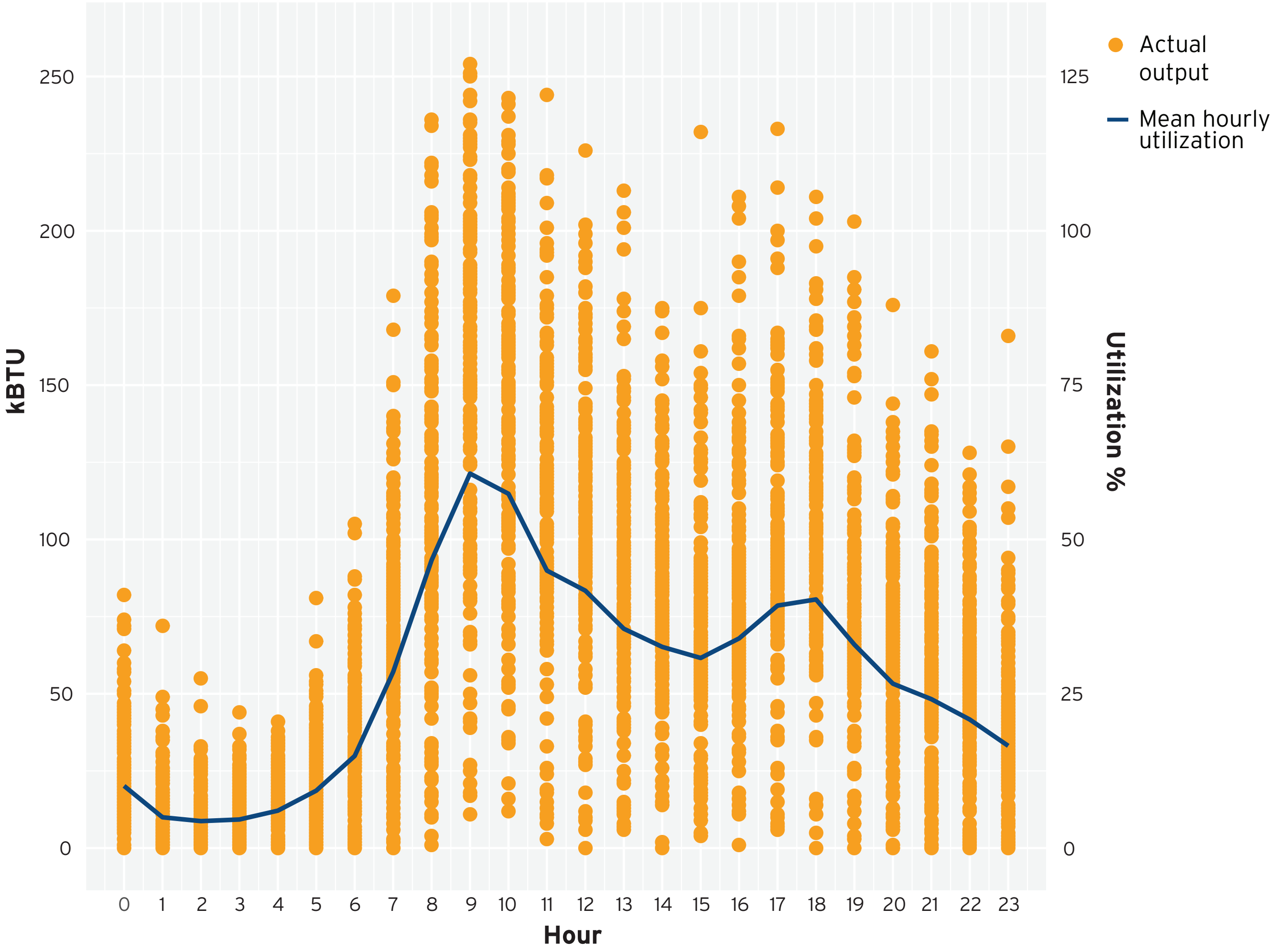
Figure 4: Daily GAHP performance plotted against the average daily exterior temperature



Domestic hot water use at the site – with peaks and valleys in demand – results in fluctuating utilization of the GAHPs over the course of a day, with output peaking between 8-10 a.m. and a secondary peak occurring between 4-6 p.m. Figure 5 below shows actual hourly output for the two GAHP units, along with average hourly capacity utilization, which was estimated using the manufacturer's ambient temperature performance curve. Capacity utilization during the day (7 a.m. through 7 p.m.) averages 40 per cent and peaks at 61 per cent at 9 a.m. While fluctuating utilization can be expected in a DHW implementation, hourly GAHP output is well below pre-installation modelling.

The project team is addressing underutilization by prioritizing the GAHPs when the DHW system requires heat. Instead of calling for heat from the GAHPs and boilers simultaneously, the GAHPs will start first with the boilers firing up if demand cannot be met by the GAHPs alone. The team expects this to increase the GAHP utilization and output outside of the heating season. Increasing utilization during the winter and shoulder seasons presents a more difficult challenge, as the boilers are running and providing heat to the DHW system throughout the day. It is unlikely that heating-season utilization of the GAHPs can be increased significantly without physically reconfiguring the DHW system.

Figure 5: Hourly GAHP system output and capacity utilization (based on manufacturer's performance curve) for both units

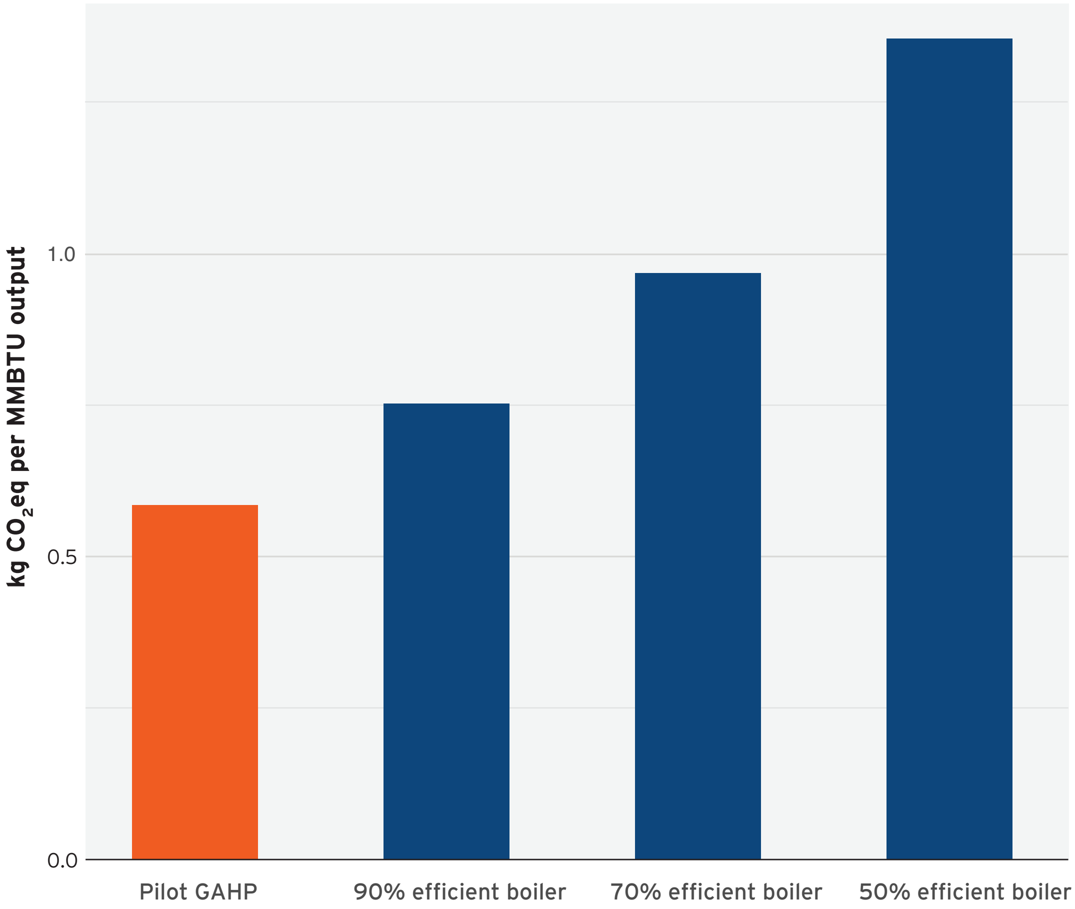


GREENHOUSE GAS EMISSION ANALYSIS

GAHPs can lower carbon emissions when they displace energy consumed by a less-efficient fossil fuel heating system. In the case study DHW system, the heat generated by the GAHPs—with measured efficiencies greater than 100 per cent — displaces heat that would have been generated by condensing boilers operating at approximately 90 per cent efficiency.

TAF estimated emissions savings by measuring the difference between GHG emissions from the operation of the two GAHPs and the emissions that would have resulted from generating the same amount of heat from boilers of varying efficiencies. The less efficient the boiler being displaced is, the greater the opportunity for emissions savings. Figure 6 compares actual emission intensities (including gas combustion and electricity consumption) from the two GAHPs to the estimated gas combustion emissions from boilers of varying efficiencies, which represent the range of boiler operating efficiencies seen by TAF in typical buildings.[7,8]

Figure 6: GAHP and boiler CO_2eq emission intensities



NOTE: Carbon emission intensities of various gas hydronic heating systems based on an emissions factor of 1899 grams of CO2eq per cubic meter of natural gas (this factor is used for all natural gas emissions in this document).

One of the two buildings at the case study site

When compared to a 90 per cent efficient condensing boiler, the GAHPs saved approximately 3.83 tonnes of CO_2eq emissions and 2,048 m^3 of natural gas during the seven-month analysis period. Using a model built from the monitoring data to estimate GAHP performance over an entire year, TAF projects annual savings of 5,390 m^3 of natural gas and 10.1 tonnes of CO_2eq emissions. This is equivalent to the emissions resulting from driving a gas combustion automobile for 39,839 kilometers.[9]

10.1
tonnes CO_2eq

projected emissions saved annually

Grouping operational data into quartiles based on outdoor temperature (Table 3) reveals a clear pattern between temperature, average hourly emissions savings, and GAHP performance.

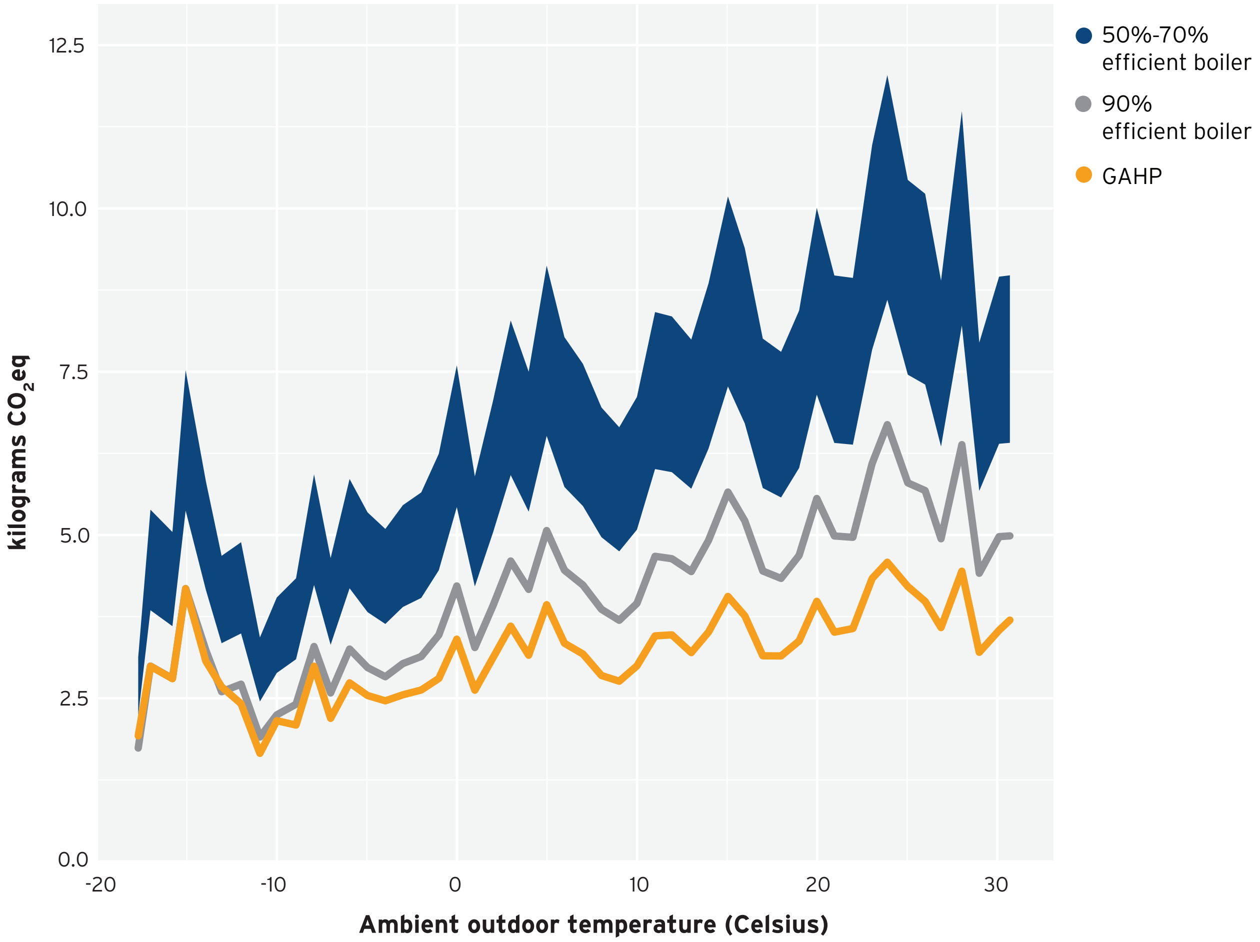
Table 3: GAHP and boiler emissions by outdoor temperature quartile

Quartile	Average Outdoor Temp (°C)	Average hourly emissions savings vs. 90% efficient boiler (grams CO_2eq)	Average hourly emissions savings vs. 70% efficient boiler (grams CO_2eq)	GUI	COP
1	-5.9	376	1,203	1.04	1.04
2	0.4	723	1,775	1.13	1.13
3	4.7	1,041	2,311	1.18	1.18
4	15.9	1,319	2,687	1.25	1.25

Operation of the GAHPs resulted in emission reductions when compared to a typical condensing boiler in all but the coldest of temperatures; when outdoor ambient temperatures were above -13°C, the heat pumps provided an emission benefit. For those cold days when average daily temperatures were below -13°C, a 90 per cent efficient condensing boiler would have released fewer emissions. Heat output and emissions savings increase with warmer outdoor temperatures as the GAHPs operate more efficiently in warm weather. Notably, the GAHPs emitted fewer emissions than older non-condensing boilers would have across the full range of outdoor temperature conditions encountered during the assessment period.

The emissions impact of outdoor temperatures can be seen in Figure 7. It shows average hourly carbon emissions for the case study GAHPs based on outdoor temperature. Also included are the emissions associated with 90 per cent efficient boilers—which represent the current high performance gas-based alternative for DHW heating—and a range of boilers with efficiencies between 50 per cent and 70 per cent, representing the efficiency of most existing systems.

Figure 7: Average hourly boiler and GAHP emissions based on outdoor temperatures



When displacing less efficient gas or oil-based systems, the use of GAHPs can result in GHG emission savings. However, in a region with low-carbon electricity (like Ontario), electric based systems are a superior choice from an emission standpoint; in these regions, the use of electric heat pumps results in fewer carbon emissions than GAHPs.[f] In regions with high-carbon electricity generation, GAHPs can offer significant emissions reductions compared to electric heat pumps; however, this can be expected to change over time as North American grids continue to decarbonize. Figure 8 highlights the impact that location has on emission intensities of electric air-source heat pumps (ASHPs).[g,10] As a side-by-side operational comparison of the GAHPs and equivalent electric

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[f] This is especially true when fugitive methane emissions associated with extraction and transportation of natural gas are accounted for; only direct GHG emissions from natural gas combustion are included in the emissions calculations in this paper.

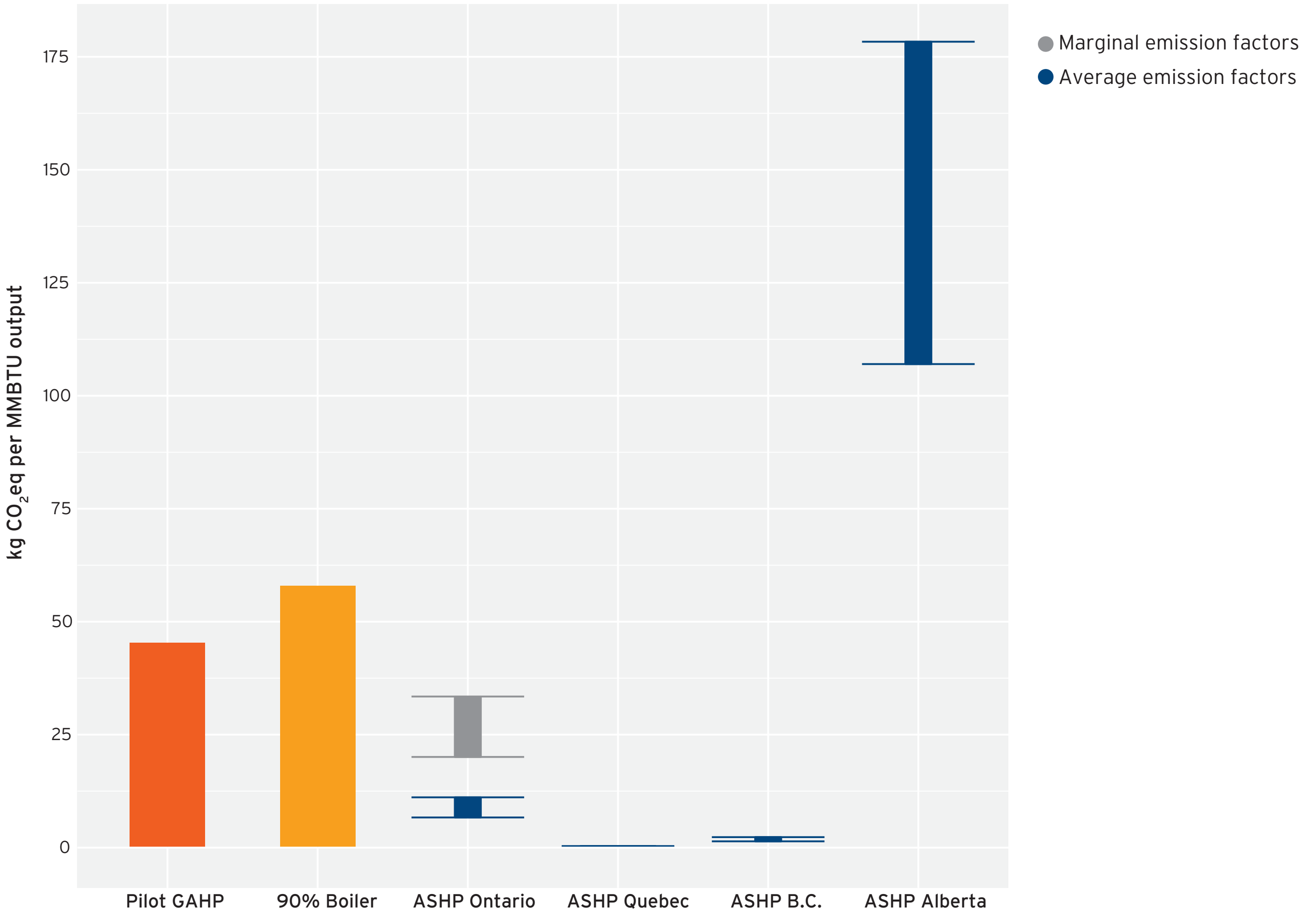
[g] Provincial electric emission factors were obtained from the 2018 National Inventory Report.

ASHPs in a DHW scenario was not possible, ASHP emissions (and operational costs) are presented in ranges, based on theoretical COP values between 1.5 and 2.5, representing likely efficiencies of air to water ASHP systems running in cold climates.

The ASHP COP range of 1.5–2.5 is based on manufacturer specifications for air to water electric heat pumps available in Canada, multiple studies of cold-weather field and laboratory performance of ASHPs, and a case study done by Ecotope on an air to water electric heat pump system in a 194-unit multi-residential development in Washington state.[11] The Ecotope project found COP values (2.7 in the winter and 3.3 in the summer) that exceed our upper threshold of 2.5, but the heat pumps were installed in an underground garage that provides a significant buffer to outdoor temperatures.

Estimates of ASHP emissions and costs for this analysis are theoretical and do not account for the real-world challenges associated with using ASHPs for water heating, such as the space required for installation of multiple units likely needed to meet demand, outdoor temperature operational limitations, and supply/return temperature constraints. These are all factors that need to be considered when evaluating the implementation of an ASHP DHW system in a multi-residential setting.

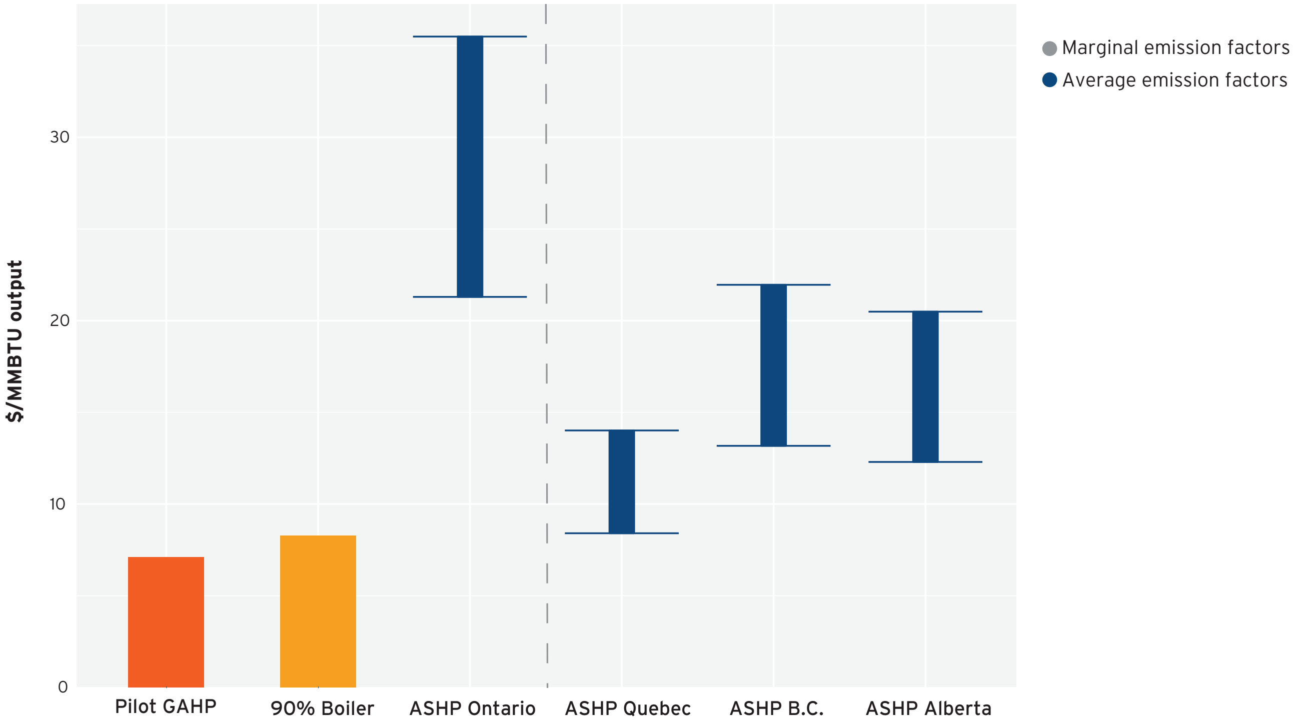
Figure 8: Gas and electric heat pump CO_2eq emission intensities



NOTE: CO_2eq emission intensities for gas and electric systems are shown for different provinces. Note the grey Ontario column uses TAF's marginal electricity factors; this is the one location where marginal emission factors were readily available.[12] GAHP results are based on project operational data; boiler and ASHP emissions are based on theoretical efficiencies (90 per cent for condensing boiler and between 150–250 per cent for the ASHPs).

Comparing operational costs between systems illustrates the importance of exploring GAHP technologies. Demand for gas-based heating systems will likely persist in regions with relatively high electricity costs (compared to natural gas), even in those jurisdictions where the carbon performance of electric heat pumps is superior. Figure 9 highlights operational cost disparities between gas and electric heating systems in different provinces.[h]

Figure 9: Gas and electric heat pump operational cost comparison



NOTE: Operational cost comparison of gas and electric systems in different provinces.[13,14] GAHP results are based on project operational data; boiler and ASHP costs are based on theoretical efficiencies (90 per cent for condensing boiler and a range of 150–250 per cent for the ASHPs).

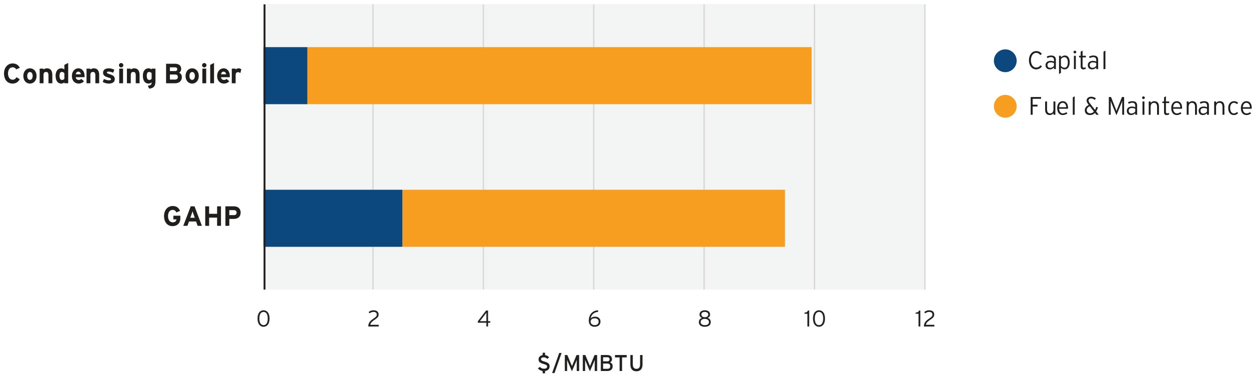
[h] Natural gas cost: $.2708 per m^3 (Ontario Energy Board), Ontario kWh: $.1632 per kWh, Alberta kWh: $.1034, B.C. kWh: $.1108, Quebec kWh: $.0707 (provincial electricity prices per Hydro Quebec).

COST CONSIDERATIONS

Although the case study GAHPs are far more efficient than condensing boilers, they are also currently more expensive (per BTU) in the Canadian market.

In order to provide a clear picture of costs, TAF calculated a levelized cost of service (LCOS) that accounts for capital costs and the present value of future fuel and maintenance costs; it represents the total cost per unit of energy delivered (Figure 10). The levelized cost shows that over the lifetime of the equipment, the boilers installed at the site are slightly more costly per unit of heat provided.[i] Installation costs are excluded from this LCOS analysis, as these can vary widely from site to site. Installation costs can have a significant impact on the LCOS however, and a premium will be paid to install GAHPs while the Canadian market matures. TAF does expect GAHP installation costs to shrink as more manufacturers enter the Canadian market and installers become more familiar with the product.

Figure 10: LCOS comparison (excluding installation costs) between the case study GAHPs and condensing boilers installed at the site



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[i] A seven per cent discount rate was used for this analysis. Assumptions include 20-year equipment lifespans, 60 per cent annual utilization rate for both systems, and a two per cent inflation rate for Ontario energy prices.

Recommendations

GAHP performance during the study period met TAF's expectations and was in line with the manufacturer's documented performance curves. Although capacity utilization has been lower than expected due to challenges in controls integration and sequencing with the primary heating system, the GAHPs themselves have performed well. Future projects should consider the following components:

- **Space and sound:** Air-source GAHPs require outdoor installation and can take up considerable space. Carefully evaluate where they will be installed to minimize loop exposure to cold outdoor air while avoiding acoustic issues for building occupants. Determine if structural modifications are necessary when installing this equipment on the roof.

- **System integration:** In a combined system, GAHPs will add complexity to the larger system they are integrating with. Careful design needs to address different operational temperatures between boilers and GAHPs, sequencing of pumps, and the impact of outdoor temperatures on GAHP output. Spending time to anticipate how changes in one part of the system will affect GAHP performance during the design phase is strongly recommended, as this can help prevent costly operational issues later on. TAF also recommends working closely with the GAHP installer/manufacturer to ensure proper sequencing and controls.

  Based on experience from this project and discussions with the manufacturer, TAF recommends separating the boiler and GAHP heating loops as much as possible in order to maintain low GAHP return temperatures and maximize GAHP utilization and efficiency. The use of a pre-heat tank warmed by the GAHPs, with boilers providing any additional heat necessary to reach DHW setpoint temperatures, should be considered.

- **Optimal operation:** The GAHPs will operate most efficiently with cool return temperatures (in this case below 50°C, but this may vary by manufacturer), and the system should be optimized with this in mind. In addition, cycle length should be maximized, while minimizing the downtime between cycles when heat built up by the units will dissipate (rapidly in cold outdoor temperatures). The project team made multiple changes to the DHW system to improve GAHP performance, and eventually settled on calling for GAHP heat in stages after the DHW storage tank temperature drops below the 54°C setpoint. A designated lead heat pump runs first, with the second unit starting up after 10 minutes if additional heat is needed; the units alternate as the lead each week in order to prevent wear and tear on a single GAHP. This configuration helped lower return temperatures, increased utilization, and led to better overall system performance. TAF recommends planning for and allocating time and resources for optimization once the system is operational.

Key GAHP design and operational considerations are summarized in Figure 11.

Figure 11: GAHP design and operation considerations

MAXIMIZE

- GAHP utilization
- Tuning / optimization resources
- Warm weather operation
- Cycle length

MINIMIZE

- Hydronic loop exposed to outdoor temperatures
- Accoustic impacts on building occupants
- Return temperatures
- Time between cycles

CONCLUSION

GAHP technology offers significant performance improvements when compared to conventional gas-fired heating equipment. Based on this pilot installation, GAHPs can generate significant carbon and operating cost reductions when installed in the appropriate context.

GAHPs are best suited to applications where they displace fossil fuel based systems, and where relative energy costs make electric heat pumps economically unattractive for building operators. Water heating applications are ideal, due to the relatively low supply/return temperatures and the ability to take advantage of much higher efficiencies during warm weather. Low temperature space heating (e.g. in-floor radiant) is another suitable application although performance was not tested in this context. From an economic perspective (due to the relatively high capital cost), GAHP technology is best-suited as a lead system working in tandem with conventional boilers to meet peak loads.

Notwithstanding the performance benefits, there are a number of barriers to scaling up the adoption of GAHP technology. First, although levelized costs for the GAHPs may be slightly lower than condensing boilers, they have higher initial capital costs per unit of energy provided. Second, integrating GAHPs with conventional equipment adds complexity and therefore requires additional design and commissioning effort and expertise. Third, there are relatively few engineers and contractors with experience or even awareness of the technology. Successful scale-up will therefore require: (1) reducing the installed cost of GAHPs (e.g. through economies of scale); (2) development of a network of engineers and contractors familiar with the design, installation, optimization, and maintenance of GAHP technology; and (3), increases in natural gas prices (e.g. through increased carbon prices) to create more market interest in higher-performance gas combustion technology.

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