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Title: Review of Research, Development, and Deployment of Gas Heat Pumps in North America

Abstract

In North America, natural gas is the predominant fuel for providing heat and hot water to residential and commercial buildings. In the U.S., the majority of homes and businesses use natural gas for heating and collectively consume 65 billion therms overall for space heating and hot water, equal to 23% of national natural gas consumption. In Canada, half of homes heat and 65% generate hot water with natural gas and a greater fraction of business, 80%, use natural gas for the same. Additionally, where available, consumer surveys indicate that natural gas is a preferred fuel for thermal comfort over alternatives.

Despite its status as the predominant domestic and commercial fuel for heating and service hot water, direct use of natural gas for thermal comfort in North America is declining and may be undergoing a nascent transformation towards the expanded use of gas heat pumps (GHP). GHPs are at a cost premium over conventional, and even high-efficiency gas-fired heating equipment (e.g. furnaces, boilers.) While in many cases GHP products remain at the pre-commercial stage, they are receiving renewed attention due to potentially significant increases in delivered efficiency and the ability to provide seasonal comfort through some combination of heating, cooling, and hot water outputs. Market trends and pressures driving this interest include: (a) GHP technologies that may offer improved reliability, efficiency, financial payback, and end user comfort, (b) regulatory pressures concerning energy efficiency and both criteria and greenhouse gas (GHG) emissions, and (c) other environmental drivers concerning the primary energy budget of residential/commercial buildings, including pursuit of “Zero Net Energy” buildings.

In this paper, the authors review GHP research, development, and deployment (RD&D) efforts in North America. The review of these efforts, supported by industry and government, includes GHPs based on the following operating cycles: vapor compression cycles, vapor absorption cycles, vapor adsorption cycles, Stirling/Vuilleumier cycles, ejector cycles, and other cycles. In addition to a review of RD&D efforts, the authors identify GHP technology developments, those with sufficient laboratory and field demonstration data, to project economic and emissions benefits.

Introduction and Background

Due to its widespread availability, low operating costs to consumers, and high performance as a fuel, natural gas is a predominant source of delivered energy to buildings in North America. In the U.S., of the 28.5 quads (30.1 EJ) of natural gas consumed in 2016, 27% (7.8 quad, 8.2 EJ) were consumed directly in buildings, the vast majority for heating processes (space heating, water heating, process heating incl. cooking). Considering that 75% of electricity generated in the U.S. is delivered to buildings, 27% of which is generated by natural gas-fired power stations[1], an additional 7.7 quads (8.1 EJ) of natural gas is consumed to deliver electricity to buildings, with 54% of natural gas consumed in buildings through direct use or as electricity [LLNL, 2016]. This fact considered, that approximately half of the energy from natural gas delivered to U.S. buildings is used directly for thermal comfort and the other half converted to electricity prior to delivery, this conversion is critical in considering the final use of this energy.

Using a basic example, if the natural gas is converted to electricity in an efficient simple cycle power plant, 40% of the fuel’s energy is converted to electricity. Transmission and distribution losses are an additional 5% [EIA, 2018], reflecting an efficient electricity grid network in the U.S., thus 38% of the

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[1] Electricity generated in the U.S. is 34.6% coal-fired, 27.4% gas-fired, 22.4% nuclear, 6.6% hydro, 5.6% wind, 1.4% biomass, 0.9% solar, 0.6% oil-fired, and 0.4% geothermal [LLNL, 2016]

natural gas' energy is delivered to the home as electricity. While greater generation efficiencies are possible with combined-cycle gas turbine power stations (up to 60%), this calculation results in a net electricity conversion closer to the overall U.S. grid, with a net generation efficiency of 33.6% [LLNL, 2016]. By contrast, the development, transmission, and delivery of natural gas loses approximately 8% of the fuel's energy value prior to delivery at the home [NIBS, 2015]. Using residential water heating in this example, the EnergyStar ® criteria[2] in the U.S. for electric water heaters is an Energy Factor (EF) of 2.0 or greater, requiring heat pump technology and for gas water heating is a tankless water heater with an EF of 0.90 or greater, requiring "condensing combustion efficiency". In this simple example, the direct use of gas yields 9% greater units of output (hot water) for the same input of natural gas. Alternatively, direct use of natural gas yields 9% fewer greenhouse gas emissions versus the electricity-heat pump example.

The case is similar in Canada, with the majority of building space heating and water heating provided from natural gas, 64% and 72% of all inputs respectively. These fractions, greater than the U.S. due to the colder climate, further displace direct use of electricity in buildings for space and water heating, 18% and 21% respectively. Certainly electric heat pumps (EHPs), with Coefficients of Performance (COP) of 3.0 or greater on a site energy basis (depending on ambient conditions) can also deliver high-efficiency space and water heating, however EHPs are a small fraction of the electric heating markets in Canada with only 10% of the space heating market and 0.5% of the water heating market – alternatively for buildings with electrically-driven heating, 90% of space heating and 99.5% of water heating equipment use inefficient resistance heating (i.e. Joule heating) [EMMC, 2017].

With its wide use as a fuel for heating, providing thermal comfort to the majority of buildings in the U.S. and Canada, the preferred direct use of natural gas in buildings may be undergoing a significant shift on several fronts, prompting further innovation in heating technologies:

- *Efficiency:* In the U.S., active but stalled regulations to increase the minimum allowable efficiency for gas-fired warm air furnaces from a 78% Annual Fuel Utilization Efficiency (AFUE) to 92% for larger furnaces representing the majority of the market. In the U.S., this impacts the majority of homes as furnaces (88%) are much more common than boilers (12%) for gas-fired domestic heating. In Canada, with a colder overall climate and a more aggressive regulatory environment, > 90% AFUE has been required since 2012. Prior to the implementation of these "condensing minimum" requirements, incentives based on EnergyStar or other metrics were successfully driving the market towards these condensing efficiency levels. For example, despite having only a > 78% AFUE requirement in the U.S. since 1992, government and utility incentives towards efficient equipment, approximately half of the installed furnaces in the U.S. are 90% AFUE or greater. Thus, with mature high-efficiency heating equipment saturating the market, regulators are reasonable in raising the allowable minimum efficiencies to advance cost-effective energy efficiency, however this creates a vacuum for products hitting the maximum theoretical combustion efficiency of approximately 98% AFUE. Note that a more comprehensive review of these regulatory changes is provided in by Glanville [Glanville, 2017].
- *Emissions:* In areas of particularly high local air pollution, gas-fired heating products have historically been subject to equipment-specific emissions limitations for oxides of nitrogen (NO_x). In the U.S., this is primarily in California where water heaters, boilers, process heaters, and warm air furnaces have had incrementally decreasing allowable limits for NO_x emission rates ranging from 40 ng NO_x/J to 10 ng NO_x/J. The most recent of these rule changes is the South Coast Air Quality Management District (SCAQMD) decreasing the limit for warm air furnaces from 40 ng NO_x/J to 14 ng NO_x/J, with recent compliant product offerings introduced in 2018 after several years of non-compliance. While these shifting NO_x limitations have a large impact on the gas-fired heating industry, more recent and important are policy concerning greenhouse gas (GHG) limitations. In Canada, the government has committed to reducing overall GHG emissions from 2005 levels by 30% in 2030 and 80% in 2050. While these aggressive targets are not matched by the U.S. federal government, which is infamously withdrawing from the 2015 Paris Climate

[2] EnergyStar is the energy efficiency labeling scheme administered by the U.S. government.

Accord, several states and municipalities have established similar GHG emission limits, including those shown in Table 1. As a result, the GHG emissions associated with gas-fired heating in buildings is under increased scrutiny as a ready target for displacing with electric heat pumps (EHPs) which, in tandem with 'decarbonization' of the electricity grid, is put forward as a climate-friendly heating solution by many organizations.

Table 1: Various State-Level GHG Emission Targets in the U.S.

	2030 Target	2050 Target
California	40% below 1990	80% below 1990
New York	40% below 1990	80% below 1990
Connecticut		80% below 2001
Washington	25% below 1990	50% below 1990
Oregon		75% below 1990
Vermont	50% below 1990	75% below 1990

- *Zero Energy Buildings:* As noted by Glanville [Glanville, 2016], the recent significant reduction in the installed cost of on-site solar photovoltaic (PV) systems has led to the rise of "Zero Energy Buildings" (ZEB) that may shift from niche projects to broad adoption in the near term. In the U.S. California adopted of ZEB goals in 2007, for all new residential and commercial buildings to be ZEB by 2020 and 2030 respectively. This goal drove builders, architects, and engineers to experiment with ZEB designs. This trend is also present in Canada, and following a concrete and common definition of a ZEB is one that, on a source energy basis, has an annual delivered energy consumption less than or equal to renewable energy generated on-site and exported (NIBS, 2015). For the majority of ZEB projects, the method of on-site renewable energy generation is with a large solar PV array, and the buildings are constructed to be well-insulated and to minimize infiltration to minimize HVAC loads, which are met by highly efficient equipment (e.g. air-source heat pumps). This creates a challenge for direct use of natural gas, imported non-renewable energy, which must be wholly offset by exported renewable energy to the grid. Technically this is feasible, and even economically favorable in heating-dominant climates [Glanville, 2016], however this so-called "Mixed-Fuel ZEB" approach can be problematic. With conventional gas-fired equipment in Mixed-Fuel ZEBs, (a) they become less favorable as electric heat pump technology improves, the electricity grid further decarbonizes, and/or PV efficiency improves and (b) it faces the 'net-exporter' problem, in which districts with a significant number of ZEBs will all be exporting excess renewable electricity in the cooling season to offset source energy imports (natural gas) during the heating season, which in turn drives down the source energy credit value of that exported renewable electricity. In short, for ZEB to take advantage of the cost, reliability, and comfort advantages of gas-fired heating equipment, their source energy efficiencies must exceed that electrically-driven options.

In total, these market drivers in the U.S. and Canada where gas-fired heating equipment predominate other technologies, these market need to shift towards higher efficiency options to remain competitive and minimize adverse environmental impacts. The technology to meet these requirements are Gas Heat Pumps (GHP), gas-fired equipment capable to exceeding the traditional limitations of combustion efficiencies by driving heat pump cycles with thermal inputs. This comes as other world economics, often with more aggressive environmental requirements and higher energy costs, have initiated large programs to develop and deploy gas-fired heat pump technologies, namely in Japan and the European Union. In this paper, the authors highlight several recent activities to bring cost-effective GHPs to the U.S. and Canadian markets.

Gas Heat Pump Primer – Cycle Overview

All heat pumps, electrically or gas-driven, deliver heating for thermal comfort partially or wholly by moving ambient energy from the outdoor to an indoor environment, operating against an adverse temperature gradient. A form of a Carnot device, an idealized thermodynamic cycle operating between cold and hot temperature reservoirs, heat pumps use an electromechanical and/or thermal input to drive heat against this gradient, from a cold source to a hot sink. Using this thermodynamic limitation, the maximum operating Coefficient of Performance (COP) is set by the temperature difference between these reservoirs. This ‘Carnot limit’ sets the maximum achievable COP for a heat pump, for example assuming a 5°F pinch at both outdoor and indoor heat exchangers, providing 120°F (49°C) heat to indoors while it is 32°F (0°C) outdoors has a theoretical COP limit of 6.0, while providing the same heating while it is 0°F (-17.8°C) outdoors has a theoretical COP limit of 4.5. These limits are based on the quantity of useful work put into the system, hence the ease of use with electrically-driven motors/compressors on a “site energy basis”, but for thermally-driven processes the conversion from heat to work (e.g. by an engine) must also be applied. Often times, these heat pumps are able to operate ‘reversibly’ and move heat from indoors to the ambient environment as air-conditioning, also over an adverse temperature gradient.

The majority of heat pump cycles are refrigeration cycles, the reverse-Carnot heat engine described previously and more specifically a reversed Rankine cycle. The purpose of a refrigeration cycle is to move heat from a low temperature source to a high temperature sink and this is accomplished via by cycling a refrigerant between this high and low pressure such that the saturation temperature during phase change favors this direction of heat flow from the evaporator to the condenser. It is the job of the compressor, electromechanical or “thermal compressor”, to lift the pressure of the vapor refrigerant exiting the evaporator and it is the job of the expansion valve to drop the pressure of the liquid refrigerant exiting the condenser by roughly the same amount.

The simplest version of a refrigeration cycle is the *vapor compression cycle*, where externally supplied work drives a mechanical compressor to raise the pressure of the vapor refrigerant. In this simple cycle, shown in Figure 1, work is most commonly supplied by electricity, with work generated at a power plant and transmitted through the electricity grid, or directly as shaft work from a prime mover (e.g. internal combustion engine). As shown, in this cycle the major components are as follows: the compressor raises the pressure of the refrigerant(s) with externally-supplied work, at the high-side pressure the vapor refrigerant yields its latent heat through phase change in the condenser exiting as a liquid, the expansion valve is a controlled restriction which manages refrigerant flow as it drops the liquid to the low-side pressure, and finally the liquid refrigerant absorbs heat from the ambient environment in the evaporator exiting as a low-pressure vapor to the compressor.

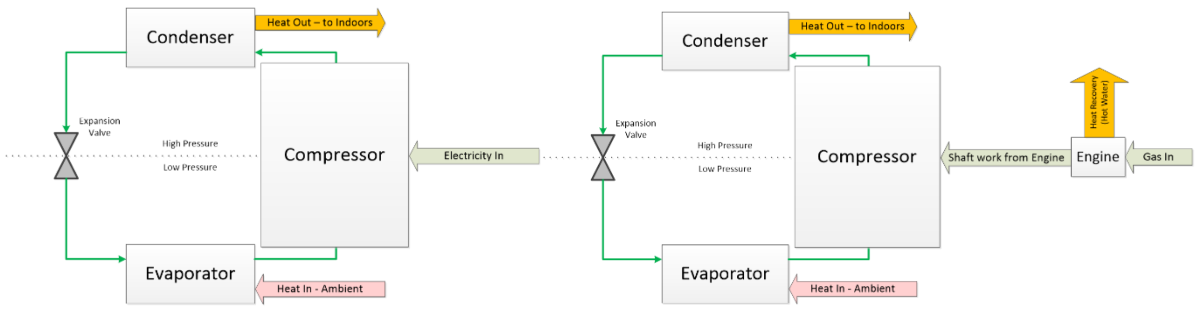

Figure 1: Simplified Diagrams of an Electric-Driven (left) vs. Gas-fired Engine-Driven Vapor Compression Cycle (right) – Heating Mode

Due to its simplicity and, in more recent years, improvement in the reliability and operating efficiency of electromechanical compressors, electrically-driven heat pumps (EHP) using the vapor compression cycle are a very common form of HVAC, used in 99% of all air-conditioning (cooling) equipment and an increasing share of heating equipment [EIA, 2010]. EHPs, deployed in heating applications, sometimes providing seasonal (reversible) operation in a cooling mode and, potentially, humidity control and domestic hot water (DHW) using a desuperheater. While these EHPs are efficient, naturally as illustrated by the prior water heating example their source energy efficiency and GHG emissions impact depend on the generation mix of the electricity grid. Building on the advantages of these vapor compression cycles, the most common form of GHP is the internal combustion (IC) engine-driven GHP. This IC driven GHP (IC-GHP) uses a vapor compression cycle similar to the EHP, but with a variable-speed natural gas engine to drive the compressor, in place of the electric motor. These technologies are shown in the simplified diagram in Figure 1. The IC-GHP can take advantage of similar components as the more common EHPs, recovery of waste heat otherwise wasted at the power plant, and providing peak load management for the broader electricity grid.

As alluded to previously, several other types of GHPs do not use the vapor compression cycle and can be broadly grouped as “thermally-driven” heat pump cycles (alternatively non-vapor compression). As true heat pumps, thermally driven heat pumps use ambient heat as the source of heat to be upgraded, but like gas-engine driven heat pumps, they commonly permit heat recovery to provide additional thermal comfort or DHW. This paper will also describes various thermally driven heat pump systems, which can be separated into three groups:

- **Sorption Heat Pumps:** Sorption heat pumps are characterized by treating the ‘refrigerant’ as a sorbate, which interacts with a sorbent within the cycle to create the desired refrigeration effect. These sorbent heat pumps are further classified along two dimensions, whether the sorbent is liquid (vapor absorption) or solid (vapor adsorption), and whether the cycle is open or closed.
- **Ejector Heat Pumps:** Ejector heat pumps are, in effect, two inter-linked Rankine cycles, where a source of thermal energy at a boiler drives off a vapor refrigerant to a controlled expansion device (turbine for power stations, ejectors in this case), which in turn raises the pressure of a refrigerant towards a condenser. This “top” Rankine cycle drives the refrigerant compression while the “bottom” Rankine cycle represents the refrigeration cycle. The two cycles meet at the expansion/compression (ejector) and share one or multiple condensers.
- **External Combustion Engine Heat Pumps:** Where vapor compression cycles can utilize directly applied mechanical work for refrigerant compression, as IC-GHPs show, several different thermodynamic cycles can be thermally-driven. Most prominently, these include Stirling engine cycles and the heat pump-focused Vuilleumier cycle. As heat pumps, these cycles either have all work output applied to the heat pump process (Stirling) or do not have any work output and are purely heat pumps (Vuilleumier). Technically, the Rankine cycle as applied in the aforementioned ejector heat pump topic could be classified here (the “top” cycle could be viewed as a “steam engine”), however the authors are treating ejector heat pumps separately due to their unique nature.

Note that there are other types of “heat-pump” like cycles, including thermo-acoustic, magneto-caloric, thermo-elastic, and other exotic cycles. The authors decided not to include these in this study, as these cycles are either (a) not directly applicable as GHPs or (b) at the early “proof-of-concept” stage.

Gas Heat Pump Primer – Advantages in Heating

Similar to how gas-fired equipment are preferred for building space heating, GHPs are generally excellent in the heating mode. This is so much the case that several GHP developments in the U.S./Canada and several products available in the E.U. are *heating only* GHPs optimized for space heating. This is primarily due to the fact that GHPs commonly employ heat recovery. As combustion-driven processes, the portion of input energy that isn’t directly driving the heat pump process (e.g. refrigerant compression) is waste heat. In the context of a thermal power generating station, this waste heat is rejected and unusable, however in a GHP in the heating mode this waste heat is capture through simple heat exchange. In the previously described IC-GHP, a common configuration in commercial buildings is the variable refrigerant flow (VRF) configuration, wherein the engine-driven compressor provides high pressure vapor refrigerant to the building which returns to the GHP via a liquid suction line, not unlike conventional split A/C systems. In this case, heat recovery from cooling the engine jacket and/or hot exhaust gases is possible for hydronic heating and/or DHW, however this is not readily combined with the heat capacity of the vapor refrigerant supply. Packaged IC-GHPs, with an internal water-cooled condenser connected to the waste heat recovery, as an air-to-water/brine GHP is a more straightforward, but less common, illustration of GHP heat recovery.

The advantages of GHP heat recovery are best illustrated through the introduction of sorption heat pumps, specifically liquid sorption heat pumps, using the *vapor absorption* cycle. These cycles distinguish themselves from solid sorption systems (adsorption heat pumps) by using a liquid sorbent, the advantage being that the liquid can be transported through the system. The use of vapor absorption cycles for refrigeration and comfort cooling dates back to the 19th Century, with early contributions to the cycle and its variants from Faraday and Einstein [Herold, 1996], predating widespread electrification and the shift towards vapor compression. As a thermally-driven GHP, absorption heat pumps utilize thermal energy to drive a heat-pump cycle where a refrigerant is cyclically absorbed and desorbed from a secondary fluid, while the refrigerant is still compressed by an electromechanical pump, however it is compressed as a liquid in solution with the absorbent, as lifting the pressure of a liquid versus a vapor requires significantly less energy. Thus, while the job of refrigerant compression is performed by a relatively small, low-power solution pump, the primary input to the process is thermal energy required to drive the refrigerant vapor from its absorbed state in the desorber (or "generator"), taking a low-temperature refrigerant/sorbent mixture and providing a high-temperature, vapor refrigerant.

The two most common absorption heat pump working fluid pairs are ammonia/water (NH_3/H_2O) and water/lithium bromide (H_2O/LiBr), which the first fluid represents the refrigerant and the second as the sorbent. Generally, while the refrigerant requires high purity through the refrigeration cycle (condenser, exp. valve, evaporator), the sorbent does not. As a result, it is most common to cycle "strong" (high refrigerant concentration) and "weak" (low refrigerant concentration) solution between the absorber and desorber, wholly within the "thermal compressor". Figure 2 shows a simplified diagram of a single effect absorption cycle, wherein many components are shared with the vapor compression cycle (Figure 1), however the compressor is replaced by the components within the "thermal compressor", including the sorbent solution.

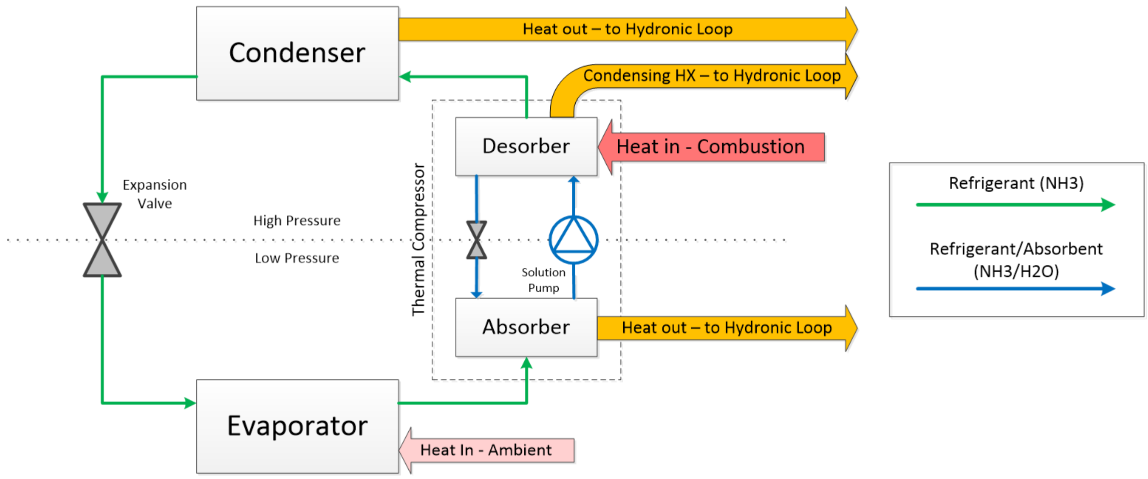

Figure 2: Simplified Diagram of Single-Effect Absorption Cycle

As illustrated in prior U.S. R&D, this simple single effect cycle in the heating mode has several heat inputs and outputs to the process: the heat of combustion input to the desorber with flue gas heat recovery downstream in a condensing heat exchanger (CHX), the transfer of ambient heat from the evaporator to the condenser from the "refrigeration effect", and the recovery of the heat of sorption within the absorber. As recorded in later testing, these heat outputs are proportionally 50% Absorber, 40% Condenser, and 10% CHX [Glanville, 2017]. As shown here, the heat recovery from the exhaust gases and from the hot solution releasing the heat of sorption accounts for 60% of the total heat output. Conversely, only 40% of heat delivered to this hydronic loop is from the ambient environment ("refrigeration effect"), and for this reason GHPs in the heating mode are much less sensitive to cold conditions [Garrabrant, 2016]. This contrasts with EHPs, which often have a lower temperature that the unit switches over to electric-resistance heating, which relegates high-efficiency EHP operation to the milder portions of the winter. For example, two common temperature settings to switch-over are 40°F (4.4°C) and 32°F (0°C). If these settings were used in Chicago, based on climate data, this would eliminate 3,140 and 1,788 hours out of the year respectively, which when excluding June 1st through August 31st represent 48% or 27% of the heating season [TMY, 2005].

Gas Heat Pump Primer – Challenges in Cooling

In the 1990s, a critical milestone was reached in the development of GHPs operating in the cooling mode, the Generator-Absorber Heat Exchanger (GAX) cycle variation of the vapor absorption cycle using the ammonia-water working pair. The GAX was developed by Phillips Engineering and represented a non-incremental breakthrough in gas cooling, increasing the cooling COP from 0.6 to 0.70, which is used in many modern "reversible" gas-fired absorption heat pumps such as those manufactured by Robur [ORNL, 1995 and Punwani, 2005]. The advantage offered by the GAX cycle was to provide a boost to the heating efficiency of the cycle and, to a lesser extent, to its cooling efficiency temperature of the absorber. While attractive in the 1990's, during a period of expanded natural gas usage and relatively lower operating efficiencies for electrically-driven air conditioners (A/C), the use of gas-fired heat pumps for A/C is difficult from source energy and operating cost basis.

As an illustration, the current EnergyStar criteria for residential central A/C is to have greater than a 15 SEER rating with greater than 12 EER performance. Using commonly applied national source energy factors for supplied electricity and natural gas, 3.15 and 1.09 respectively [NIBS, 2015], this corresponds with an operating COP_{Source} of 1.12, noting that the majority of COPs reported in this study and elsewhere are on a "site energy" basis unless otherwise indicated. A gas-fired heat pump using the GAX cycle with a COP_{Site} of 0.70, on a gas input basis only (as is commonly reported), would have a COP_{Source} = 0.64, nearly half that of the EnergyStar air conditioner. To be competitive on a source energy basis[3], this gas-fired heat pump would require a COP_{Site} of 1.22, on a gas input basis, which is only possible with the use of multi-effect cycles. Things are further complicated if the electrical input to the gas-fired heat pump were included with its "COP". For example, a 3.0 ton nominal output gas-fired heat pump consuming 400 W for controls/fans/etc., would need to have an equivalent COP_{Site} of 1.40, on a gas input basis, to be competitive with the 15 SEER A/C unit, <u>which has not been demonstrated cost-effectively for any type of gas-fired heat pump</u>. As time passes, the electricity grid becomes less source-energy intensive as coal-fired power stations are retired in favor of renewable electricity generation, and the A/C technology continues to advance beyond 20 SEER, this challenge is exacerbated. Thus, gas-fired heat pumps generally, based on the absorption cycle and others described in this document, are best applied in mixed and heating-dominated climate regions, not cooling-dominated regions.

Gas Heat Pump Developments in North America

With their differences in scale, level of technical maturity, and application to cold-climate heating, cooling, or both, this section includes a brief history and review of GHP developments in the U.S. and Canada, with a focus on residential applications.

Vapor Compression Heat Pumps

As described previously, the most common manifestation of the IC-GHP is the commercial sized VRF systems. The major IC-GHP manufacturers active in Japan include Aisin Seiki, Yanmar, and Panasonic/Sanyo with 700,000 cumulative sales through 2015 [Osaka Gas, 2018]. A key driver for the development and adoption of the IC-GHP is reduction in peak electric demand and reduced electricity usage. Recently, Aisin and Yanmar adapted their IC-GHP product line to the North American market. Blue Mountain Energy (BME) marketing the Sierra GHP (formerly Intellichoice marketing NextAire) is the distributor of the Aisin IC-GHPs, introduced in 2009. Yanmar's IC-GHP models, distributed under their brand name, were certified for the North America in 2016. Through their local distributor, Aisin offers an 8-ton and 15-ton IC-GHP VRF system which utilizes Daikin VRF fan coils. In conjunction with Oak Ridge National Laboratory (ORNL) and Southwest Gas, IntelliChoice developed an 11-ton rooftop unit (RTU) IC-GHP for commercial HVAC manufactured in the U.S. [Intellichoice Energy, 2018]. Aisin IC-GHPs can also be paired with Technocasa air-to-water units (Yoshi AWS) to adapt the VRF system to hydronic heating and cooling. Intellichoice Energy partnered again with ORNL to develop a residential-sized IC-GHP with 5-tons of cooling and approximately 70,000 Btu/hr of combined space heating and DHW heat recovery [Vineyard, 2016]. Yanmar IC-GHP product line includes 8-ton, 10-ton, 12-ton and 14-ton VRF systems, which are compatible with Daikin VRF fan coils. In addition, Yanmar offers a 3-pipe 14-ton VRF design that can provide simultaneous heating and cooling. These IC-GHPs all use synthetic refrigerants, like other vapor compression EHPs, most commonly R-410A.

For commercial-sized IC-GHPs available in the U.S. and Canada, Figure 3 presents the rated efficiencies for the Yanmar and BME products defined as COP on a gas input basis (HHV), and

[3] Note that source energy is often a good surrogate for both operating cost and greenhouse gas emissions, however a more detailed comparison would be needed for each.

electrical consumptions. Note that heating and cooling performance are at full output and rated at 47°F and 95°F respectively. The residential-sized BME/Intellichoice system represents R&D data and not a finished product. Concerning product cost, in their development with Intellichoice, the U.S. Department of Energy has laid out a cost target of $936/ton for the commercial-sized GHPs [Goetzler, 2014] and for the residential-sized system to reduce costs from $15,000/unit to $9,000/unit [Vineyard, 2016].

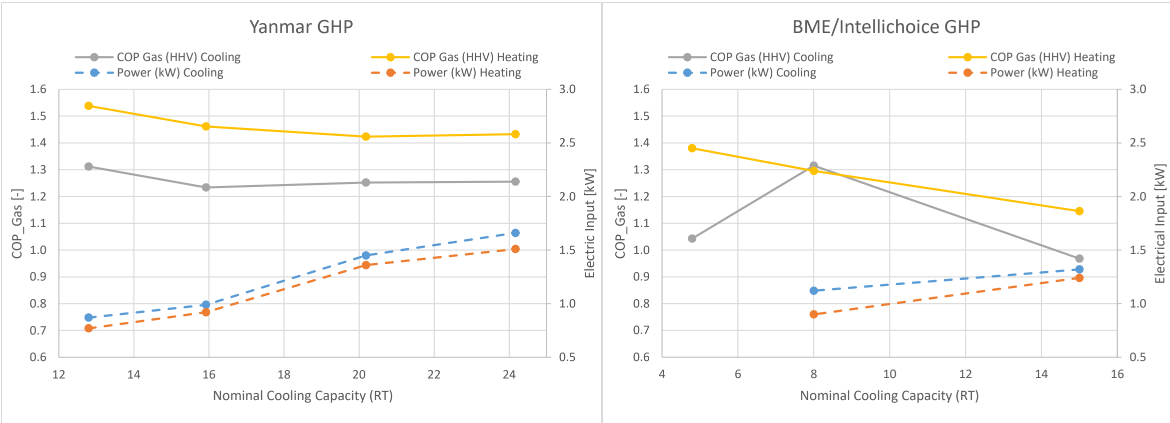

Figure 3: GHP Efficiencies and Power Consumption [Yanmar & BME, 2018]

In cold climates, IC-GHPs can utilize engine heat recovery to supplement heating output in order to maintain both indoor supply temperatures and heating capacity at low ambient temperatures. Some designs utilize engine heat recovery for supplemental water heating to increase energy savings. Recent developments include an IC-GHP design incorporating a generator for self-powered or black-start capability. The HiPOWER+ GHP was developed by Aisin and other manufacturers for the Japanese market after several natural disasters. While not yet available in the U.S., this technology offers a resilient HVAC option that can operate during power outages, while addressing the need for improved energy efficiency.

Sorption Heat Pumps

Sorption heat pumps include GHPs using the *vapor absorption* and *vapor adsorption* cycles, where the sorbent is in the liquid and solid phases respectively. Both versions are under active development in the U.S. and Canada, building on products developed in the E.U. and new developments. Sorption heat pumps benefit by the ability to reach smaller scales, more suitable for domestic applications, where reducing the size of prime-movers for vapor compression GHPs may not be cost-effective, particularly if emissions controls are required. As in the E.U., there is more activity with *vapor absorption*-based GHPs, gas absorption heat pumps (GAbHPs), due to higher performance in the heating mode, and as such the authors will focus on GAbHPs.

For GAbHPs, over comfort cooling/chilling, the ammonia-water working pair is preferably used for refrigeration purposes, whereas a different working pair, lithium bromide-water is used for space cooling applications [63]. For applications that are exclusively or predominantly heating, the NH_3/H_2O working pair is the preferred pair for product development. While other working pairs are possible, Table 2 compares the two major working pairs more extensively.

Table 2: Comparing the Major GAbHP Working Fluid Pairs

	Advantages	Disadvantages
H_2O – LiBr	- Limited concerns regarding toxicity, zero ODP. - Good performance in multi-effect chilling applications	- For outdoor installations in freezing climates, water as refrigerant is problematic. - For heating applications, crystallization risk is high due to solubility limitations, this "GAX-like" cycle is not feasible
NH_3 – H_2O	- Excellent thermodynamic properties, predominant industrial refrigerant and 4-5	- Concerning safety, NH_3 is hazardous in small quantities, subject to stringent regulations [Liebendorfer, 2015]

	x cheaper by weight than common refrigerants. - Zero GWP and ODP - Mixture has natural anti-freeze properties	- NH_3 is incompatible with copper, a common HVAC material, design tradeoffs are necessary. - Strong affinity of pair requires rectification, minor energy penalty to avoid excessive temperature glide

Efforts to commercialize heating-focused GAbHPs, exclusively using the NH_3/H_2O working pair, are summarized as follows:

- *Light Commercial in Europe:* For several decades, the major manufacturer of gas-fired NH_3/H_2O heat pumps for light commercial applications was Robur. Robur has a complete line of products, including water-to-water/brine, air-to-water/brine versions of chillers and reversible heat pumps. Their flagship "GAHP" product has a nominal 40 kW output (136,000 Btu/h) and provides approximately 5 tons of cooling. The *Gas Utilization Efficiency* (GUE), a European seasonal rating of efficiency of up to 164% (heating) and 67% (cooling), noting that these are on a Lower Heating Value (LHV) basis [Robur, 2017]. Robur has provided their products to other manufacturers for packaging and branding, which in the past included Fulton Boilers (North America) and several manufacturers in Europe of boilers and other heating equipment.
- *Residential in Europe:* Beginning in 2011, the European Union funded a significant, €10 million, program to develop and deploy a smaller-scale gas-fired absorption heat pump as a retrofit solution for European homes. The project team, including multiple heating equipment manufacturers, utilities, universities, research organizations, and Robur, developed and deployed what is now sold as the "K18" product: a heating-only air-source gas-fired absorption heat pump with a nominal 18 kW heating output (appx. 61,000 Btu/h). This effort, which produced a significant volume of laboratory and field demonstration research through 2015 [Heat4U, 2018], also spawned several competitors to develop products in this category, including Viessmann [Dawoud, 2011] and, more recently, Bosch [Albers, 2017]. All products using the NH_3/H_2O working pair have similar operating efficiencies to that of the commercial-sized Robur products, claiming 35-45% energy savings over conventional boilers [Heat4U, 2018 and Albers, 2017]. The primary motivation for these gas heat pumps in Europe, beyond the operating cost savings, are the renewable energy credits, as (a) multiple EU nations have requirements for on-site renewable energy, which gas heat pumps qualify for and (b) as the EU efficiency standards are source-energy based, these gas heat pumps have the highest ratings of A++. In addition to these major players, there are several start-ups and minor manufacturers also developing NH_3/H_2O gas heat pumps, including E-Sorp and FireChill.

Figure 4 Photo of Field Demonstration and Product Marketing of Robur "K18" Product [67]

- *Low-Cost Gas Absorption Heat Pumps in North America:* As with the previously noted applications in Europe, there has been recent progress by GTI and its industry partner Stone Mountain Technologies Inc. (SMTI) to design, develop, and demonstration low-cost GAbHP using the NH_3/H_2O working pair in residential and commercial applications. These devices, ranging from a 10 kBtu/h output (appx. 3 kW) residential gas absorption heat pump water heater to a commercial water heating GAHP with 140 kBtu/h output (appx. 41 kW). In general, these efforts seek to focus on low-cost designs, aiming for equipment costs that are 50% or lower than that of similar EU-developed products, by focusing on easily manufactured heat exchangers and vessels, with the following highlights:

- *Residential DHW-Only GAbHP:* SMTI and GTI demonstrated three “alpha” prototypes, using an 80-gallon platform, reaching heating COPs (site/gas basis) of 1.4-1.8 depending on cycle parameters [Garrabrant, 2014]. With further development and early-stage pilots, GTI demonstrated that 2^{nd} and subsequent 3^{rd} generation prototypes could deliver 50% or greater energy savings over the baseline, with a projected Uniform Energy Factor of 1.30 and unit cost of appx. $1,500 [Glanville, 2017]. GTI is currently expanding on these results in a field trial of 4^{th} generation DHW-Only GAbHPs working with additional manufacturing partners.
- *Residential Whole-House Heating & Commercial Water Heating:* Scaling up the same air-source, single effect, NH_3/H_2O direct-fired absorption cycle to 80 kBtu/h output and later 140 kBtu/h output, SMTI has worked with GTI and their manufacturing partners to demonstrate a pre-commercial GAHP capable of a projected 140% AFUE, with operating efficiency at or better than existing GAHPs and cold climate electric heat pumps, shown in Figure 5 [Garrabrant, 2016]. After laboratory evaluation by GTI from -13°F to 50°F ambient conditions, the team monitored GAHP performance supplying heat to a commercial warehouse and both heat and domestic hot water (DHW) to a residence over several years, both using standard hydronic air coils for forced-air heating [Glanville, 2017]. Like the Robur and other EU-based units, this GAHP is similar to a boiler, in that it is an air-to-water/brine heat pump supply heat to a closed hydronic loop, which can independently supply hydronic air coils, indirect tanks for DHW, and other zones (e.g. radiant) as the site requires. The units have demonstrated 4:1 modulation and a peak supply temperature of 160°F, with efforts underway to improve on both and units use a “hot gas bypass” methodology for defrost. Subsequent demonstrations are in various stages of planning for GAHP trials at additional residences and as a commercial water heater in commercial food service and laundry applications. The pre-commercial GAHP unit, with a target price of $5,000 for the 80 kBtu/h version is projected for commercial release in two to three years, with developments underway to add a high-efficiency vapor compression module for efficient chilling for seasonal cooling (two-pipe system).

Figure 5 Photos of DHW-Only GAbHP and GAbHP Combi Systems in Field Trials

Similar to the light-commercial and domestic-sized developments of GAbHPs, there also is activity with gas-fired adsorption heat pumps (GAdHP), using a wide range of sorbent materials, including: carbon, zeolite, silica gels, metal hydrides, and metal organic frameworks (MOF) [Zhong, 2014]. Preferred working fluids are water, ammonia, and hydrogen, which can be used without risk of crystallization or other issues associated with GAbHPs. Typically, GAdHPs are deployed as large waste-fired chillers while domestic-sized chillers struggle with cost-effectiveness due to low efficiencies (like GAbHPs), however it is less common to be used in a heating-focused GAdHPs, with only a few manufacturers offering adsorption-based heat pumps for space and water heating, including Viessmann and Vaillant. More recently, SaltX, a company affiliated with ClimateWell, has sought to develop and commercialize a gas-fired whole-house heating system using ammonia as a working fluid and a proprietary salt matrix [SaltX, 2017]. In general, while GAdHPs have operating efficiencies of 10-15% lower than comparable GAbHPs, they have the potential for market success by virtue of lower first costs, with fewer heat exchangers and using cheaper materials, and with fewer moving parts, less concern for material wear and corrosion, could have better reliability.

Other Thermodynamic Cycles

Beyond IC-GHPs, GAbHPs, and GAdHPs, which represent the majority of commercially-available GHP technologies, there are several other thermodynamic cycles that have technical potential as GHPs. This is not intended to be exhaustive, more detailed reviews of GHP technologies and cycles are available [Bakker, 2010 and Goetzler, 2014]. Note that all of these efforts are pre-commercial and, in most cases, do not represent packaged prototype equipment in an operational environment.

- *External Combustion-Engine (ECE) Heat Pumps:* Using Stirling-type engines and their variants, namely the Vuilleumier-cycle, these ECE-HPs have high potential for operating efficiencies and achieving higher heating/lower chilling temperatures than other GHP cycles, however lack of cost-effective designs and long-term reliability issues have historically been a problem [ADL, 1986, Goetzler, 2014]. While there is a long history of the development of Stirling GHPs, duplex engine designs and other versions with and without solar/waste heat integration, the two primary efforts approaching commercialization are by boostHEAT and Thermolift. The French company boostHEAT is developing an external combustion engine-based “Heat Pump Boiler” for the European boiler market, however limited details regarding performance have been published, the manufacturer’s measured performance is a GUE = 1.83 (LHV basis), which is a 12% improvement over currently available GAbHPs [boostHEAT, 2018]. Using a different variation of the ECE-GHP, intended to operate as a heat pump cycle, Thermolift is working to commercialize a Vuilleumier-cycle based ECE-GHP. Building on prior work by the University of Dortmund [Bakker, 2010] and Sanyo [Toshikazu, 1999], Thermolift is developing a demonstration prototype and expects heating COPs of 1.6–2.2 and cooling COPs of 0.8–1.2 [Schwartz, 2016]. Their technology improves upon earlier mechanically controlled designs by utilizing a magnetic actuation system to precisely control the amplitude and timing of the oscillating displacers.
- *Ejector Heat Pumps:* Like absorption cycles, ejector refrigeration dates back to the 19th century, with more recent efforts to exploit this cycle in air-conditioning [Elbel, 2008] and heat pump applications, with the theoretical potential for cooling COP of 0.80 to 1.20 using a binary-fluid design [Shahamiri, 2012 and Glanville, 2014]. While bench-scale experimentation and companion computational fluid dynamics simulation of binary-fluid ejectors suggest that these promising operating efficiencies are technically feasible, these have not be realized for a circulating system and other analyses suggest the technical COP potential is lower [Buyadgie, 2012]. Current research efforts continue to seek for and optimize to a suitable working fluid pair and developing a compact, cost-effective fractionation/condensation method.

Analysis and Conclusions

While these GHP technologies reviewed all have a potential to improve the efficiency of gas-fired equipment for thermal comfort while reducing GHG and air pollutant emissions, from the perspective of utilities and policymakers their technical potential depends on a number of factors beyond rated steady state and seasonal efficiency metrics. These include the baseline efficiency and quantity of existing equipment, local utility rates, HVAC loads impacted by building types and climate region, and other factors. As a simple analysis to demonstrate potential savings, the authors considered residential space heating in the U.S., the most significant natural gas end use load in buildings. The authors selected the domestic-sized GAbHP based on the SMTI design described previously, with a pre-certification 140% AFUE, with estimated seasonal natural gas and emissions reductions of 43% over low-efficiency furnaces (80% AFUE) and a 34% reduction over condensing furnaces (92% AFUE). This analysis determines the estimated GHG emissions savings, population-averaged annual gas utility cost savings, and the estimated installed cost premium for the GAbHP to meet at least an 10-year simple payback. In this analysis the following assumptions and inputs are used:

- The proportion of the approximately 54 million gas-fired furnaces in U.S. homes is distributed based on state-level shipments of furnaces and fraction of furnaces by state that are non-condensing or condensing [SNOPR/NOPR, 2016].

- The statewide average space heating load, in MMBTU of natural gas consumed [RECS, 2009].
- Annual average statewide residential natural gas prices, using the appliance standard HHV of 1,024 Btu/scf for reference [EIA, 2018].
- For calculating installed cost premiums for simple payback, an annual utility cost escalation rate of 2% is assumed and for calculating the GHG emission rates a factor of 11.7 lbs CO_2e/therm is assumed.

First concerning GHG emissions, Figure 6 shows the estimated annual GHG emissions savings from a 10% market penetration of furnaces by GAbHPs on a per state basis. This neglects GAbHP installations as replacements for non-furnaces and new construction. Interesting trends arise where cold climate states that have a small population and a large proportion of condensing equipment (e.g. NH) show only moderate savings while mild climates with large populations (e.g. CA) show large savings potentials. Midwestern states in cold climates with large populations and low penetration of condensing heating equipment, Illinois, Michigan, and Ohio, show the greatest potential for savings. If GAbHPs were to reach 100% replacement rates for gas-fired furnaces, this would result in 68.2 MMTCO_2e/year avoided, the equivalent to the avoided CO_2 emissions of adding 17,260 wind turbines (a 34% increase in the U.S.) [EPA, 2018 and AWEA, 2018].

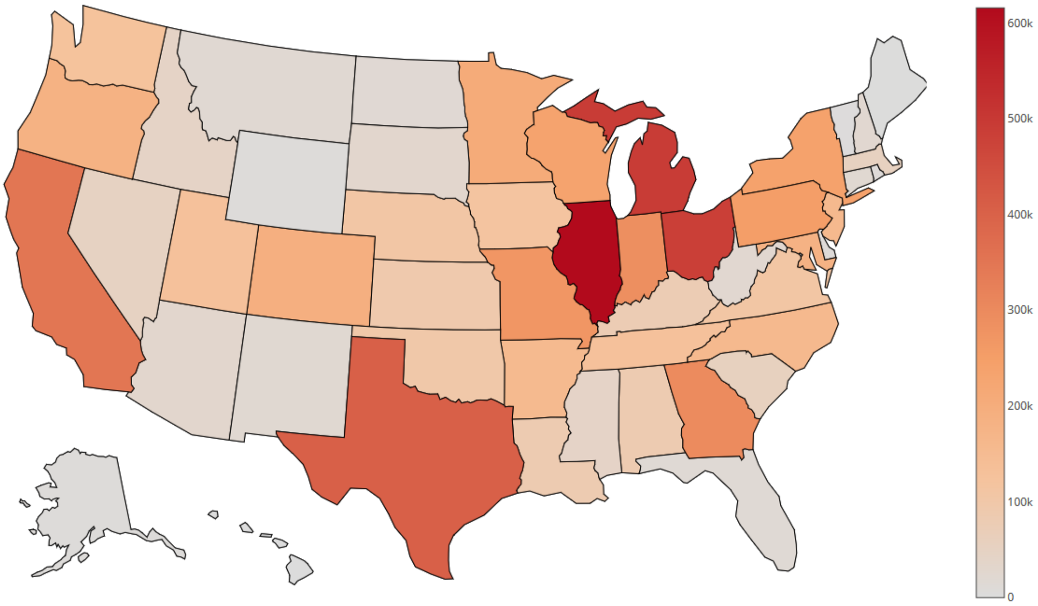

Figure 6: GHG Annual Emissions Savings Potential (Metric Tons CO_2e) for 10% Residential GAbHP Market Penetration of Furnaces by State

Cost-effectiveness matters, naturally, for efficient technologies to succeed in the U.S. and Canada where subsidies for gas-fired equipment do not have the magnitude as in Asia or Europe. The population-weighted estimated annual operating cost savings are shown in Figure 7, which is driven by the local utility costs, proportion of high-efficiency baseline equipment, and the magnitude of the heating loads. Regions in the Northeast with a cold climate and high utility rates have the highest annual savings, while states with a higher proportion of condensing equipment and lower utility costs, such as Colorado and the Dakotas, have lower savings despite the cold climate. There is a general linear trend with utility costs, however the magnitude of the heating season is important as shown by warm weather states Florida and Arizona. Note that this estimate assumes that the GAbHP is operating as a combined space and water heating system and the home consumes DHW consistent with the "High Usage" pattern used in certifying equipment in the U.S.

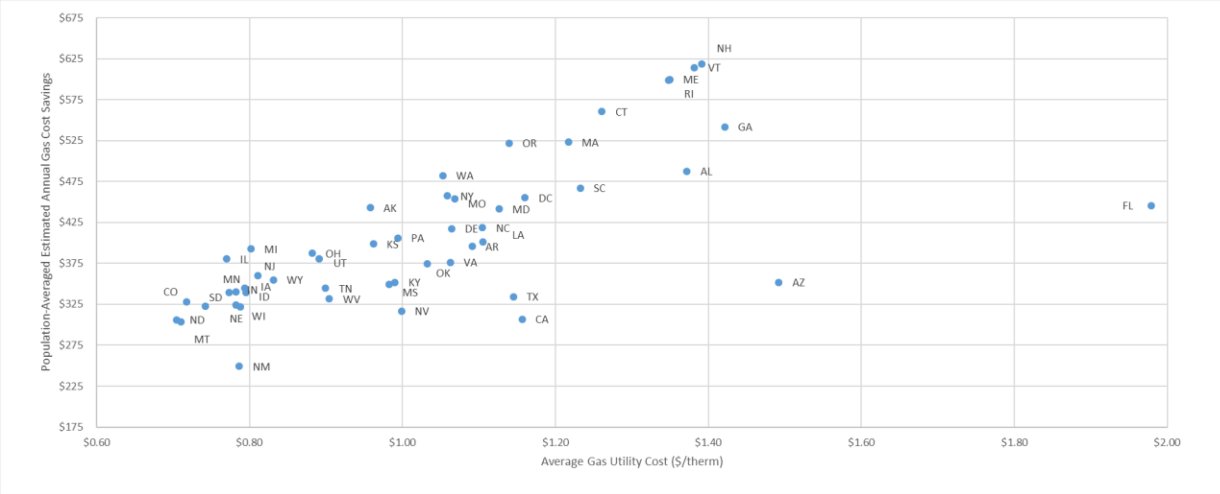

Figure 7: Population-weighted Estimated Annual Operating Cost Savings (Gas-only)

These highly-efficient equipment need to make up for higher up front costs through energy savings over the life of the product. Using the assumptions outlined previously, the allowable installed cost premium for the GAbHP is shown in Figure 8 sorted by average annual space heating gas demand and state. As seen with annual cost savings, cold-climate states in the Northeast and Midwest towards the right-hand side can tolerate higher installed cost premiums to be cost-effective, noting that even condensing furnaces do not always have a 10-year simple payback [Leslie, 2015]. In milder climate states, like California and New Mexico, presumably the GAbHP will be a smaller device, 40 kBtu/hr output versus the 80 kBtu/hr output size from prior field trials, which would have a similar reduction in equipment cost, so the lower allowable installed cost premiums do not preclude GHPs from these states.

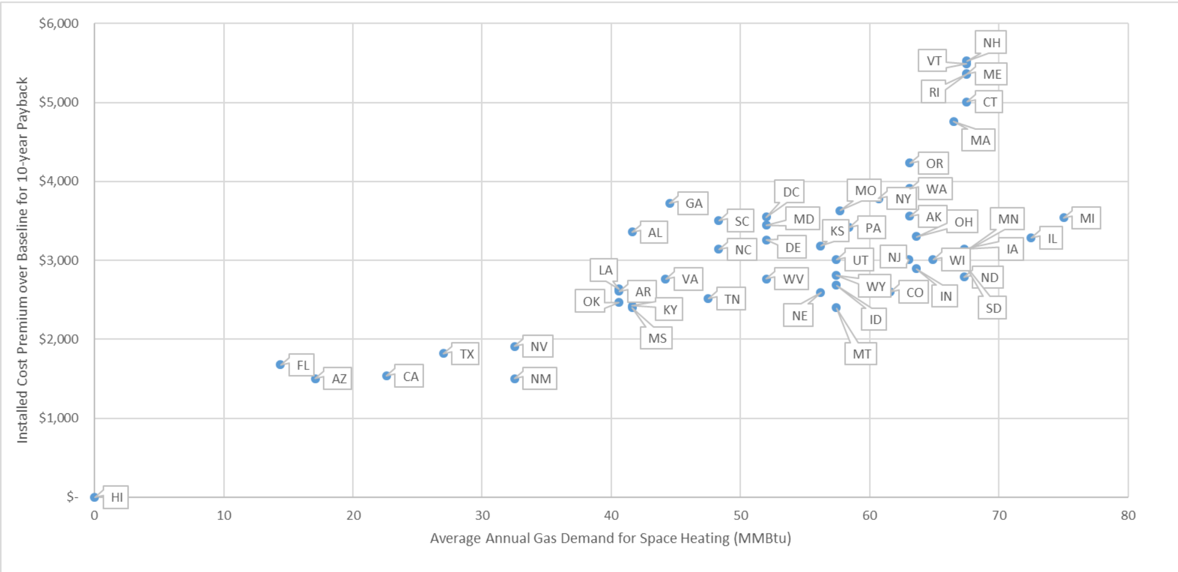

Figure 8: Installed Cost Premium Allowable for a 10-year Simple Payback

In conclusion, the authors provided a broad overview of GHP technologies with a focus on the most mature technologies, using vapor compression and sorption heat pump cycles. In reviewing the development status of key GHP efforts in North America and looking ahead to earlier-stage and emerging GHP technologies, the authors outlined the challenges and opportunities for widespread GHP adoption in North America. At its current crossroads, facing regulatory pressures and market drivers towards further integration of low-carbon technologies, GHPs can be a key solution for the gas industry’s future.

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