The Role of Gas Heat Pumps in Zero Net Energy Buildings

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ABSTRACT

The U.S. Department of Energy and State of California have established aggressive targets for Zero Net Energy (ZNE) Buildings, the latter requiring new residential and commercial construction to be ZNE by 2020 and 2030 respectively. To meet these goals, special attention must be paid to heating equipment, particularly in northern states (with 5,500 or more annual heating degree days), as these equipment often consume the largest proportion of site energy. In the U.S., natural gas remains the dominant heating fuel for buildings, representing 69% of site and 59% of source energy consumed for space heating, and is projected to grow. While cost-effective, gas heating equipment historically have low to moderate efficiencies, with delivered efficiencies at or below 98% (HHV basis). As a result, direct use of natural gas can be overlooked for ZNE buildings. With the cost-competitive gas heat pumps (GHPs) for residential and commercial applications, available or in late-stage development, this could change.

In this paper, we define the opportunity for gas heat pumps in ZNE buildings, focusing on the residential, multifamily, and small commercial sectors. As space and/or water heating equipment with Coefficients of Performance (COP) in excess of 1.4, GHPs can reduce source energy consumption by 33%, thus improving the cost effectiveness of ZNE buildings by reducing the installed cost of on-site renewable equipment. The authors outline case studies in multiple climate zones, using GHP performance data from prior laboratory and field studies.

Introduction

With the recent significant reduction in the installed cost of on-site solar photovoltaic (PV) systems and regulatory drive towards greater energy efficiency requirements, Zero Net Energy (ZNE) buildings may shift from niche projects to broad adoption in the near term. As is often the case, the State of California led this charge with adoption of ZNE goals in 2007, for all new residential and commercial buildings to be ZNE by 2020 and 2030 respectively. This goal drove builders, architects, and engineers to experiment with ZNE building designs. The New Buildings Institute (NBI) and Department of Energy (DOE) databases indicate 38 commercial and 77 residential buildings were independently validated as ZNE buildings, with over a third of ZNE homes winners of the Housing Innovation Award in 2015, sponsored by DOE (NBI, 2015).

The common definition of a ZNE building 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 ZNE buildings, 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). As an example, an existing 3,599 ft^2 ZNE home built in the Portland, OR region was built with highly insulated walls and triple-pane windows, has a 10 kW PV array, a mini-split electric heat pump (EHP) for HVAC and an electric heat pump water heater (EHPWH) for domestic hot water (DHW), with an estimated annual electricity cost of $235 and incremental builder cost of $54,402 over baseline with PV incentives (DOE, 2015). This “all-electric” home represents a more traditional definition of ZNE, wherein the annual site electricity consumption is off-set by exported renewable electricity generated on-site. This older definition of ZNE treated renewable electricity generated on-site differently by equating it with electricity from the grid, neglecting grid losses from generation, transmission, and distribution. The current, common ZNE definition on a source basis addresses this with the conversion factors shown in Table 1.

Table 1. Source/Site Conversions for ZNE Definition (NIBS, 2015)

Energy Flow	**Source Energy/Site Energy Conversion**
Grid Electricity to Building	3.15
Exported Renewable Electricity	3.15
Natural Gas to Building	1.09

With this method of source energy accounting, ZNE buildings may be benefit from direct use of natural gas by addressing some of the challenges they face in broad market adoption, which include: construction expense (including on-site renewable plant) and operating costs. These challenges are magnified in colder climate regions of the U.S., with greater than 5,500 heating degree days per year. Representing 40% of the population (EIA, 2012), the largest energy expenditure for cold-climate ZNE buildings is most often space heating, a load that is highest in the season when solar PV output is at its lowest. Additionally, unitary EHP and EHPWHs often revert to resistance heating during high demand and with cold weather, further increasing heating energy requirements (Larsen, 2013 and Ecotope, 2015). As a result, a ZNE building must (a) minimize HVAC loads through reduced infiltration and improved insulation, (b) require larger on-site renewable plants to offset heating season delivered energy consumption during the balance of the year, or (c) a combination of the two. For these reasons, only 17% of the previously noted ZNE homes are in Cold/Very Cold climate regions (NBI, 2015). As natural gas heating equipment (furnaces, boilers) are common in conventional buildings, installed in 60% of single family homes built in 2014 for example (Dept. of Commerce, 2015), the opportunity for high-efficiency natural gas heating equipment for operating cost and source energy savings is high, as demonstrated by Brand et al. (2015). While high-efficiency gas heating equipment, condensing furnaces, boilers, and tankless water heaters, may have a role in ZNE buildings, the potential of advanced technology with source energy efficiencies greater than 100% is even greater.

Introducing Gas Heat Pumps

Gas heat pump (GHP) technologies have seen limited adoption in the US, Asian and European residential and light commercial markets. Heating and water heating in these markets is dominated by direct gas fired units and electric heat pump/electric resistance units; systems which are limited to coefficients of performance (COP) less than 1.0. Electric heat pumps can achieve higher coefficients of performance but their source energy COP values are only marginally better (1.0-1.2) in most cases and are lower than conventional heating systems in colder climates (ambient temperatures < 32°F)[1]. Note that this study focuses on unitary electric heat pumps for comparison, as the GHP technologies discussed are intended as whole-house

[1] Note that the EnergyStar criterion for unitary heat pumps is a Heating System Performance Factor (HSPF) of 8.5 for split and 8.2 for packaged systems. Using a recently developed methodology, these correspond to a COP at 47°F of 3.92 and 3.86 respectively (Kim, 2013), which on a source-energy basis yield COPs of 1.25 and 1.23.

equipment. A gas heat pump has the potential to offer higher source energy COPs when compared to both conventional gas heating and electric heat pump options.

A gas heat pump is a heat pump that is driven by the onsite combustion of natural gas. The two most common forms are the engine-driven vapor compression heat pump and the thermally driven absorption heat pump. The current study will focus specifically on the gas absorption heat pump (GAHP). An absorption heat pump uses the heat of combustion to separate the refrigerant from the sorbent in the desorber. Low temperature heat is added to the system in the evaporator. Heat is removed from the system in the refrigerant condenser, the absorber (where the refrigerant and sorbent are combined) and the condensing combusted gas heat exchanger. The source energy COP of this system is 1.4, including combustion losses and electricity inputs. Over the past few decades there has been a renewed interest in smaller capacity absorption heat pumps for both heating and cooling applications. Recently there has been significant progress in the development of a residential capacity ammonia-water gas absorption heat pump water heater (GHPWH). Garrabrant et al. (2014) offers a more in-depth review of this technology and the underlying theory.

Glanville et al. (2016) presented field test data of a GHPWH coupled to a water storage tank. The nominal heating capacity of the unit is 2.9 kW at a COP of 1.5 (at 70°F), where testing indicated the ability of the GHPWH to achieve a Uniform Energy Factor (UEF) of 1.3. This study builds on the investigation presented by Garrabrant et al. (2014) which evaluated the steady state performance of three 2.9 kW GHPWH units in a laboratory setting. This performance testing also indicated the potential to achieve and Energy Factor (EF) of 1.3. One of the field evaluation units is shown in Figure 1.

Figure 1. GHP as Water Heater (Left) and Space Heater (Right) Units in Field, in WA and TN

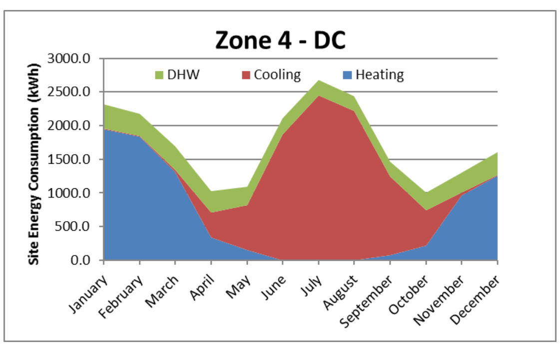
Garrabrant (2015) presented the development and evaluation of a prototype 23.4kW ammonia-water GAHP for residential space and water heating. The prototype maintained high coefficients of performance over the range of ambient conditions, from -13°F to 65°F, and hydronic return temperatures, from 85°F to 125°F. In addition, the ability of the system to modulate while maintaining performance was also demonstrated. This is important because this would allow the system to load match and reduce the number of start-up and shut-down periods experienced. Managing this inefficiency is important to maximizing overall system performance.

As a compelling technology for energy savings, there are several efforts to commercialize GHPs for residential water and space heating applications. Gluesenkamp (2014) presented development work for a residential capacity lithium bromide-water GAHP water heater. An initial prototype was fabricated and tested but performance numbers were not presented. System size is roughly twice that of a conventional water storage tank. This is partly a result of the chosen working fluid pair. Water, the refrigerant in this case, has a large specific volume.

The high source energy coefficients of performance offered by GHP systems makes them ideal candidates for use in ZNE buildings. This is because they will use less source energy than other space and water heating systems, and reduce the amount of onsite renewables needed to offset delivered energy. The use of a GHP will help to reduce the obstacles for residential and commercial property owners to achieve ZNE by reducing the size and cost of off-setting on-site renewables. In addition, the heat pumps utilize energy from the ambient which is a form a renewable energy (as recognized by the EU) and could additionally be factored in to further reduce the amount of on-site renewables required. The following study will investigate the source energy and cost savings of residences using GHP systems, and the reduction in renewable plant size and cost to achieve a ZNE building.

Modeling Methodology

The goal of this study is to estimate the benefit of GHPs in ZNE buildings, providing space and water heating, through reduced annual operating costs and source energy consumption compared to existing heating equipment options. Through a reduction in annual source energy consumption, GHPs may permit a reduction in the renewable plant size by decreasing annual delivered energy consumption (grid electricity/natural gas), reducing installation costs and limiting the footprint of the on-site renewables. Using results from recent laboratory and field demonstrations of GHPs in residential applications (space and water heating), this study focuses on single-family homes (SFH) in Climate Zones 4 to 6. Using *EnergyPlus* prototype residential building models to generate monthly site energy consumption[2], this focus on mild and cold climates covers slightly cooling-dominated and heating dominated homes, as shown in Figure 2.



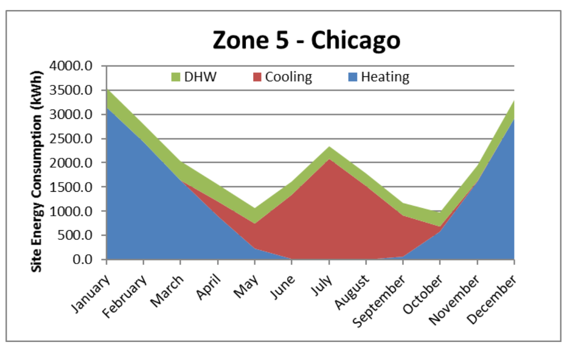


Figure 2. Site Energy Demands for HVAC & DHW at Washington, DC (left) and Chicago (Right) SFHs

The example single family home (SFH) in Washington, DC in Zone 4 has a peak site energy consumption during the cooling season, where in Chicago, IL in Zone 5, the peak site energy consumption is during the heating season, each with 2,400 ft^2 of conditioned space. Applying these loads to a ZNE home will require, in addition to high-efficiency HVAC and DHW equipment, an on-site renewable plant capable of generating sufficient electricity annually to off-site source energy delivered to the home. As a result, colder climate ZNE homes may

[2] Residential Building Models had 2012 IECC slab (Zone 4) or unheated basement (Zone 5/6) construction.

struggle by minimizing source energy inputs during the heating season, when on-site solar PV generation is at a minimum. Overlaid onto these loads, a ZNE home will also have to meet non-HVAC/DHW loads. For the two example homes in Figure 2, Figure 3 shows site electricity consumption, including lighting, appliances, plug loads, and fans. The source energy impact of these loads, in addition to heating, cooling, and DHW, must be offset by exported renewable source energy generated on-site. The A/C load is shown for comparison[3], highlighting the large magnitude of these various electrical loads. By contrast, these baseline example homes with baseline gas heating equipment, a non-condensing furnace and minimum efficiency gas storage water heater, have large seasonal swings in natural gas usage as shown in Figure 4. This is typical, regardless of climate zone, with high consumption during the heating season with steady DHW, drying, and cooking loads.

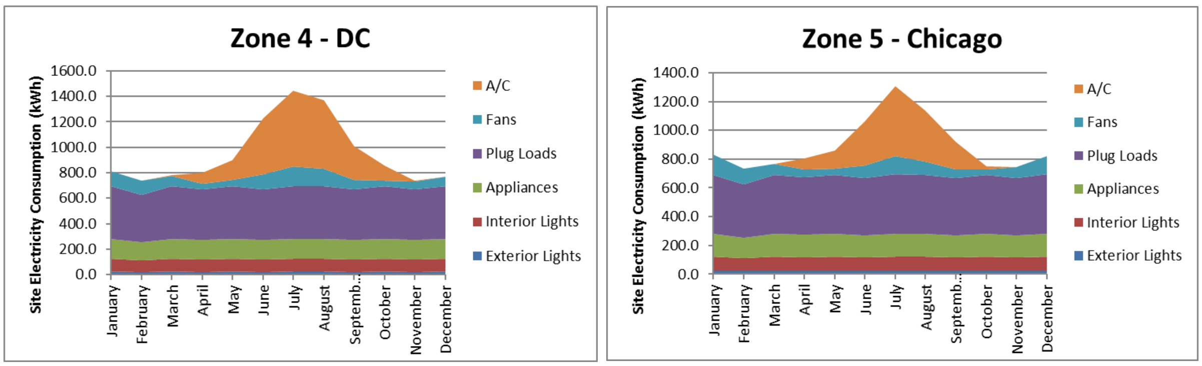


Figure 3. Site Electricity Demands at Washington, DC (left) and Chicago (Right) SFHs

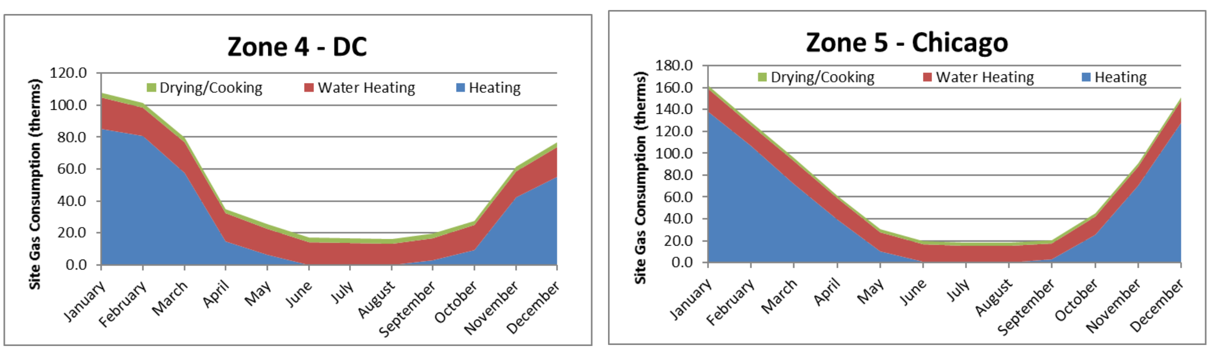


Figure 4. Site Natural Gas Demands at Washington, DC (left) and Chicago (Right) SFHs

Beginning with these baseline SFH building energy models, with locations in DC, Chicago, and Minneapolis, climate zones 4, 5, and 6 respectively, the authors use the following methodology to estimate the size of an on-site renewable plant *just large enough* for a ZNE home, for a suite of HVAC and DHW equipment, estimating installed and operating costs:

- Outlined a range of cooling, heating, and DHW equipment, including baseline, high-efficiency, and GHP options, with assumed energy efficiencies, installed costs, and, for gas equipment, typical electrical power draws. Efficiencies are selected as follows: (a) gas baseline equipment are set at DOE minimum efficiencies for current (GSWH) and soon to be (Furnace – DOE, 2015) regulations, (b) the advanced option for gas tankless water heating

[3] Assumes an A/C unit with a COP of 4.0

(GTWH) is selected as the most common condensing-type rating[4], (c) the baseline electric equipment (EHP and EHPWH) are at the EnergyStar levels, and (d) the A/C system was assumed to be very high performance for ZNE (Anderson, 2008). Systems were assumed to be right-sized for meeting heating/cooling/DHW loads. For reference, the model the peak heating demand of each SFH is 22,970 Btu/hr, 30,469 Btu/hr, and 29,620 Btu/hr for DC, Chicago, and Minneapolis respectively (IECC 2012).

Table 2. Equipment Cases for Study

Case	**Cooling**	**Heating**		**DHW**	
		Equipment	**Gas Eq. Power (% input as elec.)***	**Equipment****	**Gas Eq. Power (kWh/day)***
1		92% AFUE Furn.	1%		
2		8.5 HSPF EHP	N/A		
3		92% AFUE Furn.	1%		
4		8.5 HSPF EHP	N/A		
5		92% AFUE Furn.	1%		
6		8.5 HSPF EHP	N/A		
7			2.5%	0.95 EF GTWH	0.2
8			2.5%	GHPWH***	0.55
9			2.5%	N/A (Combi)	0.75

* Power draw of gas equipment based upon GTI/SMTI laboratory measurements
** GSWH = gas storage water heater, GTWH = gas tankless water heater
*** Study ignores the annual impact of the E/GHPWH on heating/cooling equipment

A matrix of cases was developed, with different equipment selection as shown in Table 2. Note that the EHP/GAHP rated equipment efficiency is based on climate zone 4, the units in zones 5/6 are treated as follows:

- Using EnergyPlus model for each SFH, with an EHP and unheated basement, the *percentage increase* of EHP input consumed by defrost mode and supplemental resistance heating per unit output is determined over the heating season from DC to Chicago (4 to 5) and DC to Minneapolis (4 to 6). For each SFH, the energy input (per unit output) for defrost is a 6.3%, 6.2%, and 4.5% and for supplemental heat is 9.4%, 19.8%, and 31.2% for DC, Chicago, and Minneapolis respectively.
- For EHP cases (2/4/6), heating electricity input is adjusted to account defrost for all sites and for the *relative increase* in electricity used for supplemental heating. For GAHP cases (7-9), with no supplemental heating, only defrost is applied[5].

- Used the *EnergyPlus* prototype residential building models (IECC 2012), with slab (DC) or unheated basement (Chicago, Minneapolis) constructions, estimate monthly non-HVAC/DHW loads (see Figure 3). These were held constant from case to case per SFH.
- Using the same SFH models, the cooling, heating, and DHW loads were extracted (see Figure 2) for each climate zone model. For each equipment case, the monthly gas and electricity consumption were calculated for each end use (e.g. heating).

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[4] The largest fraction, 38% of all "condensing efficiency" GTWHs certified have a 0.95 EF, with none certified at the EnergyStar® level of 0.90 (AHRI, 2016).
[5] Depending on design, GAHP may use less or no additional electricity for defrost mode, as compared to EHPs.

- For each location, the output of a conventional 1 kW solar PV array in each location was estimated using the National Renewable Energy Laboratory *PVWatts®* calculator[6].
- Using estimated total annual electricity and gas demand estimated for each SFH and equipment case, the total source energy inputs to the SFH were calculated. With an iterative solver, the size of the renewable PV plant scaled up from the 1 kW system (Figure 5) is determined to exactly offset required source energy inputs to the SFH.

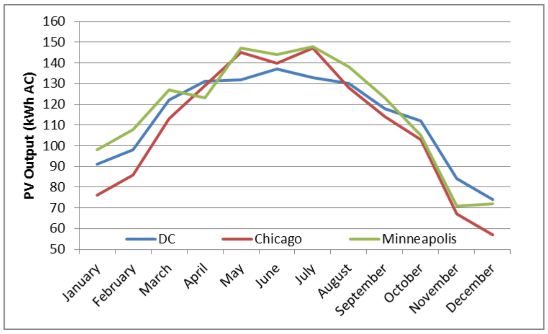

Figure 5. Estimated PV Output (kWh AC) for 1 kW Plant by SFH Location

- For each SFH and equipment case, operating and installed costs were estimated using average utility costs[7] in Table 3 and equipment installation costs in Table 4. PV installation costs assumed a constant $3.38/W installed (NREL, 2016). For annual operating costs, electricity exported to the grid is credited at the residential rate[8]. Installation costs are assumed to be for retrofits, the GHP cases require that the home already has gas service.

Table 3. Utility Prices (EIA, 2015)

Location	Electricity ($/kWh)	Gas ($/therm)
Washington, DC	$0.1334	$1.31
Chicago, IL	$0.1181	$0.83
Minneapolis, MN	$0.1177	$0.92

Table 4. Equipment Installation Costs

Equipment		Equip. Cost	Install Cost	Reference
18 SEER A/C (3 Ton)		$4,000	$450	
Energy Star EHP (3 Ton)		$4,300	$450	
Gas Furnace (40 kBtu/hr)		$1,300	$1,350	
Min. Efficiency GSWH		$450	$600	
Condensing GTWH		$1,200	$877	
EHPWH		$1,100	$450	
GHPWH		$1,800	$600	
	Alone	$2,800	$1,000	
	Combi[9]	$3,600	$1,400	

[6] Assumed as south facing, 96% inverter eff., 14% system losses, and fixed 30° tilt (Chicago, DC) or 35° tilt (Minn.)
[7] Authors did not consider tiered, time-of-use, or other variable utility rate structures, a subject for further analysis.
[8] As net metering rates can be below retail rates, this conservative assumption yields minimum operating costs.
[9] In the "combi" arrangement, equipment costs include pumps, heat exchanger, and indirect hot water storage tank.

Results and Discussion

Using the methodology outlined previously, Figure 6 shows the annual operating costs by site and equipment case without PV offsetting electricity consumption and generating revenue with net metering. Operating costs are greatest for the mild climate in DC, with higher utility rates and greater cooling requirements, with Chicago and Minneapolis costs very similar. For the climate zones 5 and 6, the lower costs of gas heating compared to the EHP in cases 1/2, 3/4, and 5/6 are apparent, with lower operating costs with GAHP/GHPWH cases (7-9).

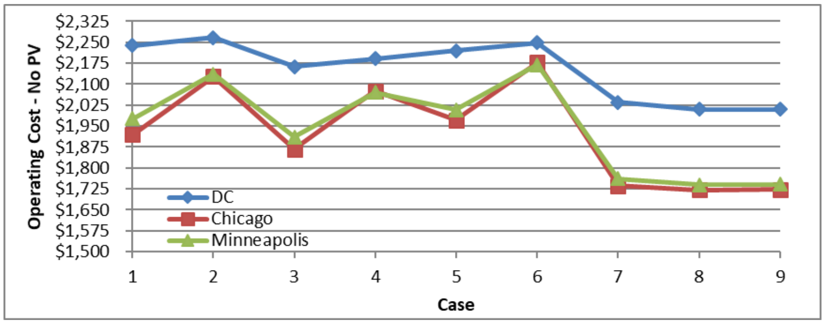

Figure 6. Annual Operating Costs (Gas & Electricity) by Site without On-site PV

Iteratively, the required size of the on-site renewable plant (PV) is estimated for each case based on source energy inputs required (electricity/gas) to be *exactly* ZNE. The size of this PV array is shown in Figure 7 for each case and site. The Chicago site requires the largest array, in large part because the annual PV output is lowest for the Chicago site (Figure 5), and the trend from site to site is very similar. The GAHP/GHPWH cases (7-9) require the smallest PV arrays to be ZNE while the EHP (2/4/6) cases require the largest arrays overall. With a smaller PV array by 1-3 kW, the GAHP/GHPWH can be enabling technologies for ZNE buildings.

As ZNE homes, the annual operating costs become savings with net metering for all cases, as shown in Figure 8. The DC area site is close to breaking even in all cases and for the heating-dominated sites, the impact of low natural gas prices is apparent as the furnace cases (1/3/5) and GHP cases (7-9) have the greatest savings. As the GAHP/GHPWHs consume more electricity than the conventional gas-fired equipment and, more importantly, the smaller PV array needed for ZNE exports less electricity throughout the year, their annual savings are slightly lower when exported electricity is credited at 100% of the retail rate. If exported electricity is credited at 50% of the retail rate, the GAHP/GHPWH cases have the lowest operating costs in cold climates (Chicago/Minneapolis).

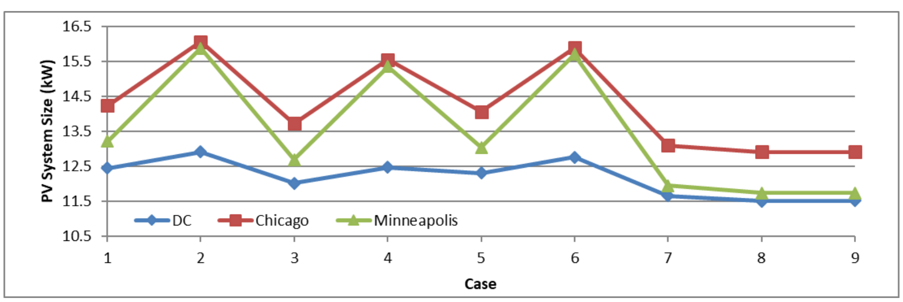

Figure 7. Estimated On-site Renewable Plant (PV) Size for ZNE

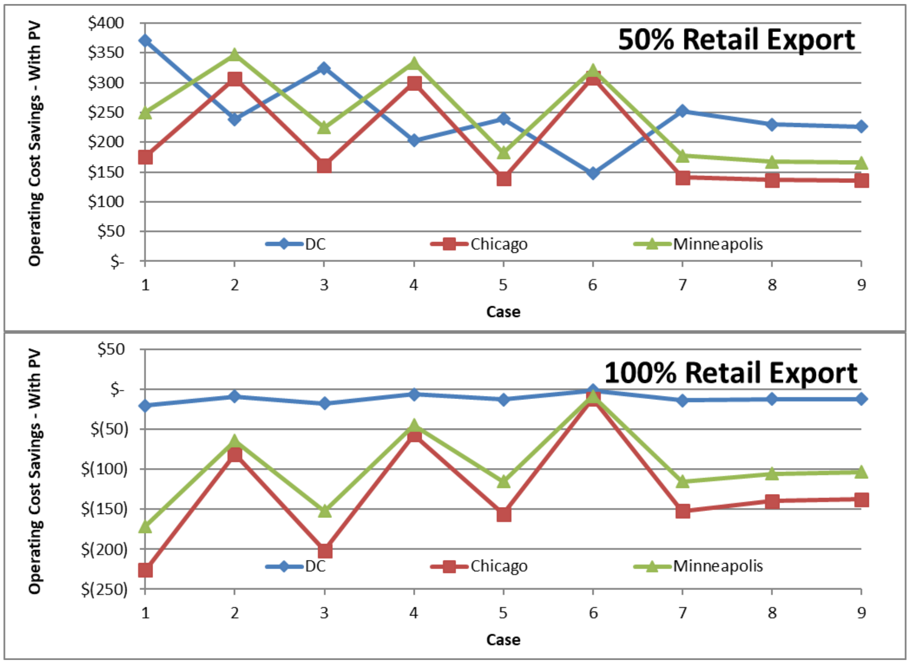

Figure 8. Annual Operating Savings by Site with On-site PV Net Metering at 100% and 50% Retail

With defined PV array sizes for each site and equipment case, the installed equipment costs[10] are shown in Figure 9. Note that HVAC and DHW equipment costs are constant from site to site, variation is PV array size alone. By permitting a smaller array for ZNE homes, the GAHP/GHPWH cases (7-9) reduce PV costs by up to $4,700 (DC) to $14,000 (Minneapolis). For climate zones 5 and 6, where EHP backup heating requires larger PV arrays, the effect on total cost is large. However, the estimated installed costs of GAHP/GHPWH equipment are greater than conventional gas equipment and, unlike EHP cases, require a standalone A/C system, thus maximum savings are reduced to up to $1,900 (DC) to $10,300 (Minneapolis). Despite this, a GAHP/GHPWH-equipped ZNE home can be the most cost-effective option.

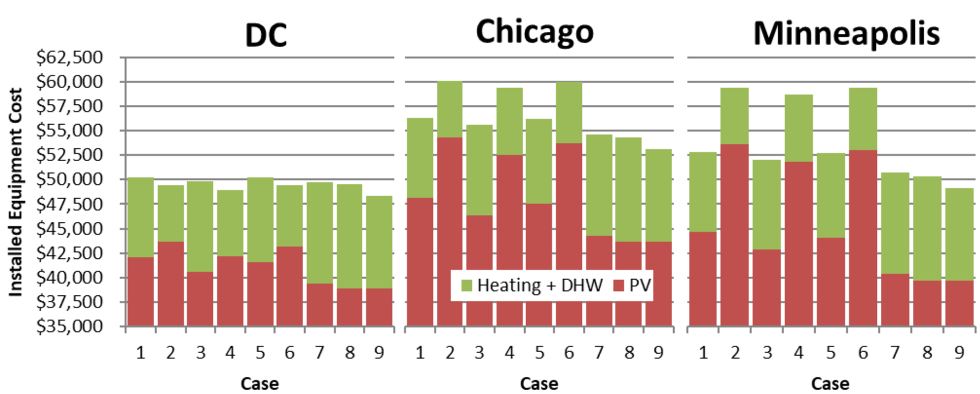

Figure 9. Installed Equipment Cost (Heating, DHW, PV equipment) by Site

[10] Note that for EHP cases (2/4/6) the installed cost of the A/C equipment is omitted as it is already integrated.

Comparing the impact of cooling versus heating-dominated climates on these modeled ZNE homes, Figure 10 shows the monthly net source energy consumption for the DC and Chicago site cases. The curves have similar features, with a pronounced and slightly flattened "double hump" for DC and Chicago respectively, indicating a large source energy output during the heating months, a peak of PV array exported energy in the spring with higher PV output and minimal HVAC loads, a decrease in exported energy with peaking cooling loads in summer, followed by a slight increase in exported energy in the fall with similar effects as in spring. The variation between the cases is small, however the impact of GAHP/GHPWH cases (lightest shading) shows a general flattening (toward zero) of these curves.

Examining the Chicago site in Figure 11, showing source energy inputs as electricity and gas, the source of this flattening effect is apparent. For the three cases shown, the electricity load is constant for all loads except heating and DHW and the small gas load associated with drying and cooking is also constant (see Case 6). For the GAHP/GHPWH case 8, the source energy inputs during the heating and cooling seasons are reduced overall and thus, a smaller PV array is required to offset annual source energy inputs. The Furnace/GSWH case (1) and EHP/EHPWH case (6) have similar source energy input requirements and require similarly sized PV arrays.

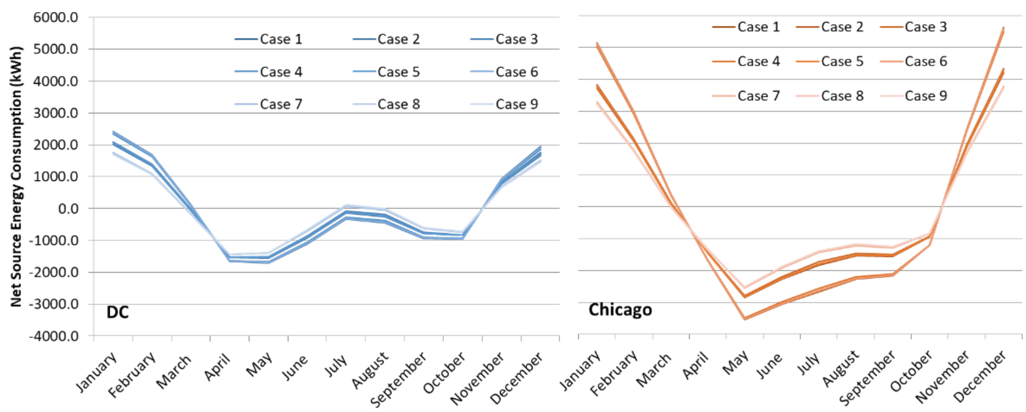

Figure 10. Comparing Monthly Net Source Energy Consumption between DC (Left) and Chicago (Right)

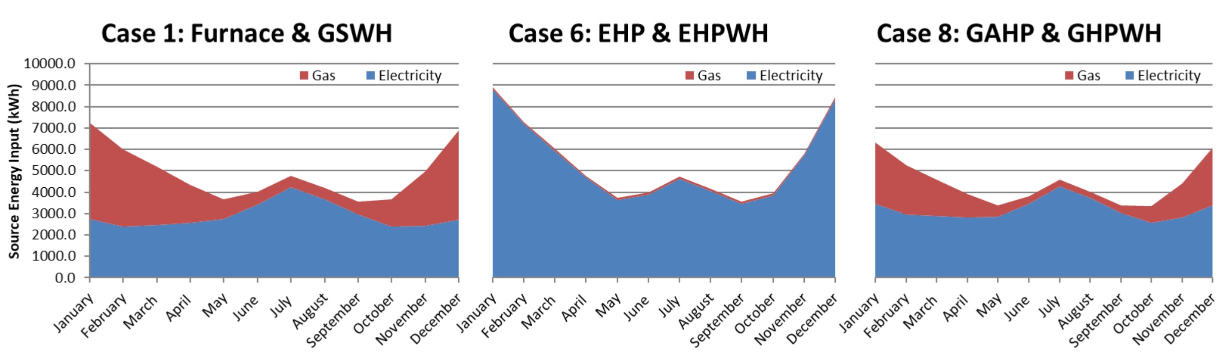

Figure 11. Monthly Source Energy Inputs (Gas & Electricity) for Chicago Site – Selected Cases

Conclusions

The role of gas absorption heat pumps (GAHP) in Zero Net Energy (ZNE) homes was investigated by evaluating the energy requirements for homes in three locations (D.C., Chicago and Minneapolis) which correspond to three climate zones (4, 5, and 6). Nine space and domestic hot water heating system combinations were evaluated for the three houses and locations. The investigation showed that GAHPs could have a significant impact on reducing the amount of source energy used for space and domestic water heating in ZNE homes. This is because GAHPs achieve higher source energy coefficients of performance (COP) when compared to standard gas heating systems and electric heat pumps in cold climates. Reducing the amount of source energy used for space and domestic water heating enables the ZNE homes to have less on-site renewables (PV) to offset source energy use. As a result, the installed cost of the on-site renewable plant (PV) is lowest for the GAHP/GHPWH cases (7 – 9) at all three locations (D.C., Chicago, and Minneapolis). Cost savings are offset by the higher equipment and installation costs of the GAHP/GAHPWH, with total installed equipment savings most prominent in the heating dominated cold climate locations (Chicago and Minneapolis). In the mild climate location (D.C.) the reduction in required on-site renewables is less significant because the heating load is lower while the heating equipment cost is the same. The combi GAHP system (case 9) offers the lowest installed cost for all equipment (PV, heating and DHW).

The limitations of electric heat pumps used for heating in cold climates is shown in the required size of the on-site renewable plants (PV) needed for Chicago and Minneapolis (cases 4, 5 and 6). In the colder climate regions, EHP systems are unable to maintain high heating loads and on colder days and switch over to electric resistance heating which has a source energy COP of 0.317, increasing the amount of source energy used by the home.

The study also highlights the impact of low natural gas prices and the importance of minimizing the electrical load of the GAHPs. With the current natural gas prices, the furnace cases (1, 3 and 5) offer the highest annual cost savings of all combinations considered. The GAHP cases (7, 8 and 9), while operating at significantly higher COPs, offer the second highest cost savings. This due to in large part to the size of the PV array needed to be ZNE; with larger arrays, the exported electricity drives savings slightly lower. Given the installed cost of PV, however, this type of savings is not cost-effective. This is also due to higher electrical load for GAHPs, thus further minimizing the GAHP electrical load will increase savings.

An additional point of interest is that the 'baseline' annual operating cost data shows that the GAHP/GHPWH cases (7-9) offer the lowest operating cost for the homes investigated (in climate zones 4, 5 and 6) without on-site renewables. This shows that GAHPs can play a significant role in reducing source energy use in homes within climate zones 4, 5 and 6. Widespread adoption of this technology would help to reduce the equipment cost and further reduce the GAHP installed equipment cost which was the highest among the cases investigated.

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