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Cost-Optimal Sizing and Operation of a Hybrid Heat Pump System Using Numerical Simulation

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ABSTRACT

Heat pumps have grown in popularity in recent years, and are now used to heat over 12 million U.S. homes (U.S. Energy Information Administration, 2017). While air source heat pumps can provide outstanding performance at high ambient temperatures, their efficiency (strictly their coefficient of performance) and capacity both degrade at low ambient temperatures when heating demand is highest. Some homeowners utilize hybrid (or dual fuel) heating systems, which use a heat pump at high ambient temperatures and a furnace at lower temperatures when the heat pump's capacity is insufficient. These hybrid systems allow the homeowner to avoid the additional capital cost of installing a larger heat pump to meet peak heating demand.

This study discusses heating choices for single family homes that currently use a central air unit for cooling alongside a natural gas or fuel oil furnace for heating. We determine that in most US climate zones, it is prudent to replace an air conditioner at the end of its life with a heat pump sized for the peak cooling load and operate it in tandem with the existing furnace. We also assess the emission implications of such a conversion and determine the electricity prices below which a homeowner will break even over the investment's lifetime.

INTRODUCTION

Of the 80 million U.S. single-family homes that have space-heating equipment, more than half use natural gas or fuel oil warm air furnaces as their primary heating system (U.S. Energy Information Administration, 2017, p. Table HC6.1). Among these homes, 78% are equipped with central air conditioning systems, which are typically installed in the same air path as the furnace and utilize a common blower fan (U.S. Energy Information Administration, 2015). At the time of system replacement (typically every 10-15 years, according to the National Association of Home Builders (National Association of Home Builders, 2007)), an existing air conditioning system can be replaced with a heat pump for a moderate incremental price, allowing for a portion of annual heating demand to be provided by electricity instead of fossil fuels.

There are several advantages to employing a heat pump over a furnace for space heating. Heat pumps use a vapor-compression cycle to move heat from a low-temperature reservoir to a high-temperature reservoir. This allows for a high coefficient of performance (COP) when the desired space temperature is close to ambient temperature. For example, when the ambient temperature is 60°F (~15.5°C) and the desired space temperature is 68°F (~20°C), the COP of an air source heat pump may be around 4.5 (Goodman, 2018). This means that for every unit of electricity consumed by the heat pump, 4.5 units of thermal energy are added to the space being conditioned. In regions with high fractions of renewable electricity on the grid, heat pumps may also result in fewer emissions than traditional fossil fuel heaters.

A drawback to heat pumps is that both their efficiency and capacity degrade as ambient temperatures drop. Air

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source heat pumps are particularly susceptible, as they must extract thermal energy from the ambient air (ground source heat pumps extract energy from the soil, which tends to be warmer than the air during the heating season). To accommodate for the degradation in capacity, most residential heat pumps are equipped with a supplementary electric resistance heater that provides additional heat when the building's heating demands exceed the compressor's capabilities. These resistance heaters can provide additional capacity for low capital cost, but only have a COP of unity.

One concern about operating heat pump-only systems is that a large amount of inflexible electric heating demand can cause upstream problems in the distribution system, even if capacity problems are addressed. Navarro-Espinosa and Mancarella conclude that the highly-correlated, inflexible electric demand required by heat pumps representing as little as 30-40% of a region's space heating requirements can cause overheating of transformers and feeders in the electric distribution system (Navarro-Espinosa and Mancarella, 2014). Heinen et al. found that installing heat pump-only systems or heat pump systems with auxiliary resistance heaters in as few as 25% of buildings could cause substantial jumps in system-wide electricity peaks (Heinen, Burke and O'Malley, 2016).

An alternative to all-electric heating is dual fuel – or hybrid – heating, which combines a heat pump with a backup fossil fuel furnace. These systems typically employ the heat pump when ambient temperatures are above a designated changeover temperature (exploiting the heat pump's high COP) and the furnace at lower ambient temperatures. This type of configuration could make heat pumps much more attractive in cold climates, where they have yet to gain mainstream popularity.[1]

This paper considers the condition of an existing single-family home with a working furnace and a central air conditioner that is due for replacement. The authors consider the cost, energy, and emissions implications of replacing the air conditioner with a heat pump that is operated in tandem with an existing fossil natural gas or fuel oil furnace as a hybrid heating system. Using Building Energy Modeling (BEM), we determine cost-optimal sizing strategies for hybrid heating systems in all 16 IECC U.S. climate regions.

LITERATURE REVIEW

A limited body of work assesses strategies for employing hybrid heat pump systems in residential buildings. As early as the late 1980s, Gustafsson and Karlsson (Gustafsson and Karlsson, 1989) compared the results of a mixed-integer linear programming model to the OPtimal Energy Retrofit Advisory (OPERA) model, which uses a derivative method and assumes continuous cost functions. Both models conclude that a minimum life-cycle cost is achieved by combining a hybrid heat pump system with inexpensive envelope and ventilation retrofits.

Klein et al (Klein, Huchtemann and Müller, 2014) used BEM to run numerous energy models for a building with different parameters for insulation, nominal heat pump capacity, and the size of a hot water buffer tank. Based on these simulations they identified system configurations that minimize primary energy consumption. They found that while heat pump-only systems achieved the greatest primary energy savings over fossil fuel-only systems, similar results could be achieved using hybrid systems with heat pumps sized to less than one-third of the capacity required for a heat pump-only system.

Bagarella et al. (Bagarella, Lazzarin and Noro, 2016) used BEM to perform an energy and economic analysis of hybrid heat pump systems in residential buildings. They found that hybrid configurations with heat pumps sized to cover between 50-70% of the building's peak load had the best economic performance and could provide 50-90% of the building's aggregate space heating demand.

Heinen et al. (Heinen, Burke and O'Malley, 2016) used a linear programming model to analyze how hybrid heat pump systems could be operated to facilitate the integration of renewable energy by shifting demand between gas and electric systems. They found that a least-cost configuration employed a heat pump sized to accommodate 10-17% of a building's peak heating load and provided 47-70% of the aggregate space heating demand.

In a review of a number of these analyses, Bloess et al. (Bloess, Schill and Zerrahn, 2018) concluded that

[1] 71% of residents who use heat pumps as their primary heating system live in the South, and only 13% live in either the Northeast or Midwest [1, Table HC6.7, HC6.8]

"power-to heat technologies can cost-effectively contribute to fossil fuel substitution, renewable integration, and decarbonization," but also found that many of the numerical results were idiosyncratic to specific assumptions. For example, Klein et al. employ single scalar values for the primary energy intensity and per-kWh price of electricity, neglecting spatial and temporal variation in the price and carbon intensity of electricity sold throughout a region (Klein, Huchtemann and Müller, 2014). Bagarella et al. found that their results were highly sensitive to variations in the input parameters; for example, variations in gas prices of 30% could shift fossil fuel-only systems between being the best economic performers and the worst (Bagarella, Lazzarin and Noro, 2016).

Most studies also confine their research to the conditions in a single European country, considering only one or two climate regions (Klein, Huchtemann and Müller, 2014; Bagarella, Lazzarin and Noro, 2016; Heinen, Burke and O'Malley, 2016). These analyses fail to capture how a region's unique weather profile governs both the heat pump's COP and capacity requirements.

This study inverts the problem; instead of making singular assumptions about the price of electricity and the properties of the climate, we attempt to discern how they interact to dictate the performance of hybrid heating systems across the United States.

METHODOLOGY

Building Model and Heating Equipment

The building modeled in this study is a single-family detached house that is two stories tall, has a conditioned floor area of 2400 square-feet, and is controlled by a single-zone thermostat. In order to ensure computational tractability, the slab floors were modeled as adiabatic. We assume that the building is outfitted with an existing warm air furnace and a central air conditioner that is at the end of its useful life. In this configuration, the existing cooling coil is installed in the same duct that returns air to the furnace, and the blower fan installed in the furnace is used for both heating and cooling applications.

Two versions of the model were created with different heating systems. One version employs the furnace for all of its heating needs and a single-speed direct expansion (DX) coil for cooling.[2] The other version keeps the furnace but replaces the air conditioner with a single-speed air conditioner/heat pump, which shares the heating load with the furnace. The all-air configuration used in this study (which is typical of American homes) does not facilitate thermal storage, such as the buffer tank used in (Klein, Huchtemann and Müller, 2014; Bagarella, Lazzarin and Noro, 2016; Heinen, Burke and O'Malley, 2016). This limitation provides an added constraint not seen in most other studies.

The building model used for these analyses is based on the 2006 International Energy Conservation Code (IECC) Residential Prototype Building for single family homes (Department of Energy, 2013).[3] The Pacific Northwest National Laboratory produces a comprehensive set of these models based on local climate constraints across the United States. In order to avoid biasing the model by using different construction standards for different regions, a single building construction based on the Baltimore/Washington D.C. standard was used for all climate zones.

Air source heat pumps are particularly susceptible to degradation in both coefficient of performance, $COP(T)$, and heating capacity, $Cap_R(T)$, with falling temperatures. For these analyses, $COP(T)$ (non-dimensional) and $Cap_R(T)$ (in tons) are determined by Equations 1 and 2, where T is the ambient temperature in Celsius. These are fitted based on the tabulated performance data for a generic DX split-system with a Seasonal Energy Efficiency Ratio (SEER) of 16 and Heating Seasonal Performance Factor (HSPF) of 9.0.[4]

[2] A direct expansion (DX) system directly transfers heat from the air to a refrigerant loop without the aid of an auxiliary working fluid. This contrasts "hydronic" systems, which chill a water and glycol solution that is then used to provide cooling to the spaces being conditioned.
[3] PNNL has also produced Prototype Buildings associated with the 2009 and 2012 IECC standards, but these were found to be too energy efficient to accurately reflect the existing U.S. building stock.
[4] The COP of the heat pump also degrades due to cycling losses. As the part-load fraction (heating energy delivered divided by total heating capacity) decreases to zero, the COP decreases linearly to 85% of the computed value of COP(T). This is consistent with the results found in (Bagarella, Lazzarin and Lamanna, 2013). The heat pump also includes a 200-watt (~680BTUh) crankcase heater and operates in a reverse cycle to defrost the outdoor coils when they collect ice.

$$COP(T_C) = \frac{4}{1.230 - 0.028T_C + 0.001T_C^2} \qquad T_C \in \{-20{,}20\ °\mathrm{C}\}, T_F \in \{-4{,}68\ °\mathrm{F}\} \quad (1)$$

$$Cap_R(T_C) = R\left[0.790 + 0.023T_C + 0.0002T_C^2\right] \qquad T_C \in \{-20{,}20\ °\mathrm{C}\}, T_F \in \{-4{,}68\ °\mathrm{F}\} \quad (2)$$

Our desk research[5] shows that the system costs for an air conditioner and a heat pump can be modelled to vary with system size (tonnage) as shown below:

$$\mathrm{C_{AC}} = \$640 + (\$220/\mathrm{ton}) * \mathrm{R\ tons} \quad (3)$$

$$\mathrm{C_{HP}} = \$820 + (\$340/\mathrm{ton}) * \mathrm{R\ tons} \quad (4)$$

where C_{AC} and C_{HP} refer to the total capital cost of a new air conditioner and heat pump in US dollars, including both the compressor unit and the indoor coil but not the installation cost. R is the rated system capacity in tons. While one ton (12,000 BTUh) generally refers to cooling capacity, here it refers to both cooling and heating capacity.

The furnace used in these analyses has a burner efficiency of 78%, which is the default provided in the prototype model (this is typical of non-condensing units). The fan is a simple on/off constant-volume fan. Fan power is presumed to be small and is therefore neglected in the energy calculations.

Climate Zones and Weather Data

In order to explore the impact that climate has on the operation of hybrid heat pump systems, 16 cities were selected as representatives of the U.S. climate regions (Oliver, 2005). These cities are based largely on those used to create the Department of Energy Commercial Reference Buildings (U.S. Department of Energy, 2018), but with Boise, Idaho substituted for Boulder, Colorado due to availability of weather data.

For each city, a weather file and a design day file were retrieved from the a public weather data repository (National Renewable Energy Laboratory, 2018). The weather files hold "hourly meteorological values that typify conditions at a specific location" for one year (Wilcox and Marion, 2008, p. 1), including ambient temperature, wind speed, and solar conditions. These files are commonly used by engineers and architects to forecast the consumption of a designed building.

Design day files include the maximum temperatures and temperature ranges for various "design" conditions. Based on these parameters, a standard procedure (American Society of Heating Refrigeration and Air Conditioning Engineers, 2013, pp. 310–311) is used to generate a 24-hour temperature profile. For each city, design days representing the 0.4% and 99.6% extremes of observed dry bulb temperature conditions were used to determine the minimum required sizes of a central air conditioner and warm air furnace for the model house.

Bivalence Temperature and Thermostat Operation

A set of preliminary EnergyPlus simulations were run to determine the model building's required heating rate over a range of ambient conditions. Figure 1 shows a scatter plot of the computed heating rate vs. the ambient temperature, including simulation data from all 16 climate regions. Overlaid are the capacity curves for heat pumps of various sizes, ranging from 1.5 tons to 10 tons (5275W - 26377 W). In the absence of solar gains and internal generation, the building realizes a maximum static heat loss for any given ambient temperature, governed by conduction and infiltration. This is delineated by the dashed orange line, which follows the relatively smooth upper bound of the scatter plot (outlier points above the line are correlated with abnormally high wind speeds, which increase infiltration; points below the dashed line have heat loss partially offset by solar gains). The point at which each curve intersects the dashed

[5] Prices were collected from hvacdirect.com

line estimates the heat pump's bivalence temperature, where the stationary output of the heat pump operating at its maximum capacity matches the static heat loss of the house (Klein, Huchtemann and Müller, 2014). A heat pump of a given size can only satisfy the entire house's heating demands if the ambient temperature is above the corresponding bivalence temperature.

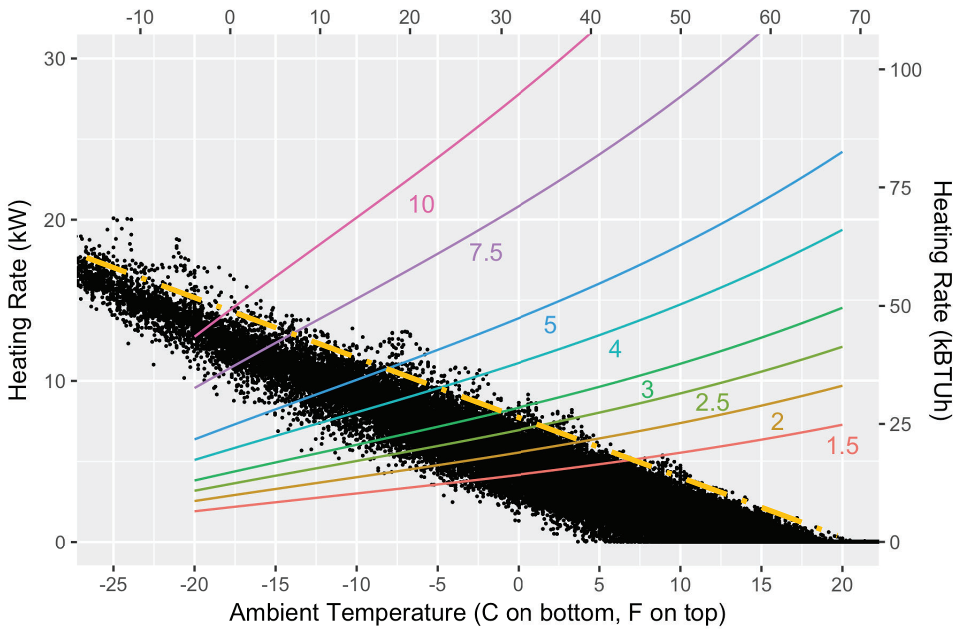

Figure 1. Scatterplot of heating demand vs. ambient temperature for the IECC building model in all 16 climate zones. Colored lines represent capacity curves for heat pumps of various sizes, labelled in tons.

The model includes a simple dual-fuel thermostat that operates the heat pump in tandem with the existing warm air furnace. Above the bivalence temperature, the heat pump provides the building's heating requirement. Below this temperature, the building's full heating load is satisfied by the furnace.

RESULTS AND DISCUSSION

Aggregate emissions from space heating were computed for all simulations. Natural gas is assumed to emit 150 pounds of CO2 per MMBTU of heat delivered (232 g/kWh_{th}) and fuel oil is assumed to emit 207 pounds of CO2 per MMBTU of heat (320 g/kWh_{th}). These values assume stoichiometric combustion of each fuel and account for the 78% furnace efficiency (U.S. Energy Information Administration, 2018). For the remaining analyses, we take the grid emissions to be 1 lb/kWh_e (454 g/kWh_e). This approximates the average emissions of the U.S. grid as of 2016 (the most recent year for which data have been compiled) (Environmental Protection Agency, 2016).

The results show that in all climate regions, the use of a heat pump sized to the building's peak cooling load in tandem with an existing furnace results in a steep reduction in emissions over a system that uses a furnace for its entire heating requirement (labeled "AC" in Figure 2). In all zones except Zone 8 (Northern Alaska), this configuration results in emissions reductions of at least 13% for homes with natural gas furnaces and 19% for homes with oil furnaces. The greatest percent reduction in emissions occurs in zones 1-3, where savings range from 27-39% for natural gas and 40-55% for fuel oil.

The greatest absolute reductions occur in colder zones: homes in regions 4C, 5A, 5B, 6A, and 7 that utilize hybrid heat pump/natural gas systems achieve CO2 reductions in excess of 1 metric ton per year relative to homes that only use a furnace. This translates to a fractional savings between 13-32%. For homes with existing fuel oil-fired furnaces, this figure climbs to at least 1.9 metric tons, and fractional savings of 19-45%.

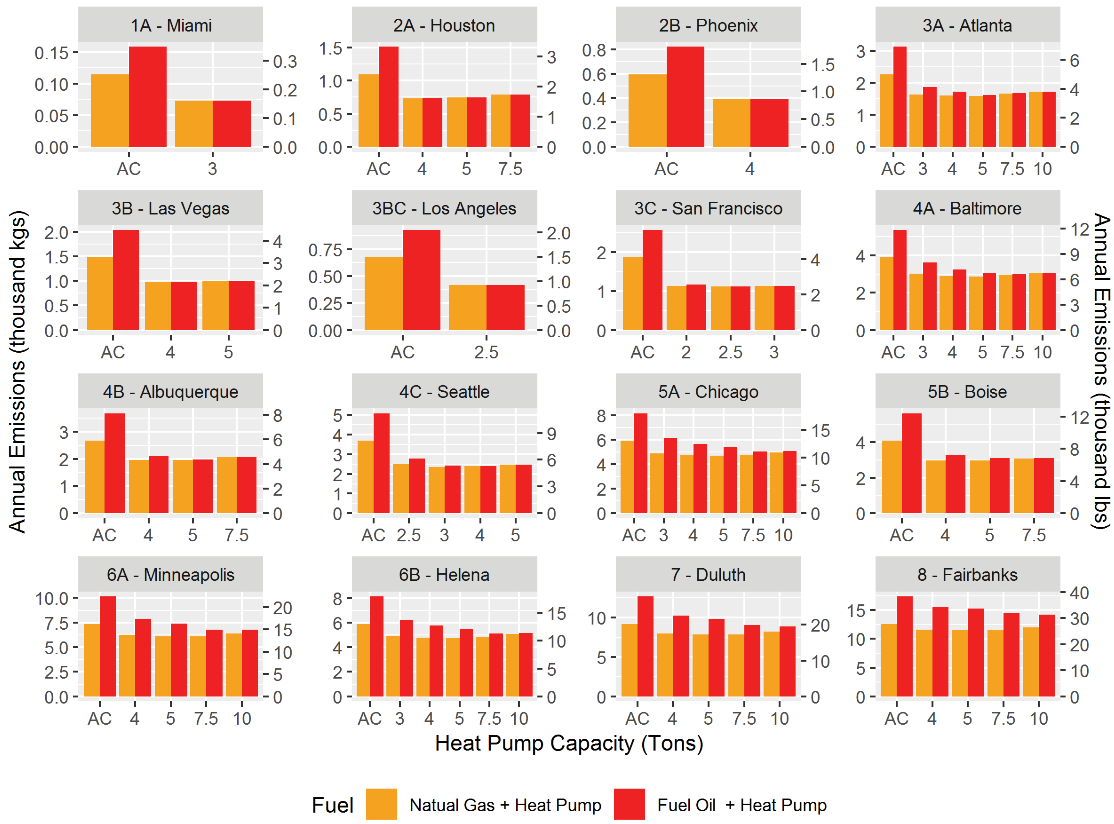

Figure 2. Annual CO2 emissions for hybrid systems in each climate zone. The x-axis describes the rated capacity of the heat pump installed in tons, where only heat pumps that can satisfy the peak cooling demand are considered. The first set of columns in each plot, labeled "AC", represents the "furnace-AC" case, where there is no heat pump and all heating demand is satisfied by the furnace. Heat pumps that are oversized relative to the peak heating load are excluded, as these have similar operation to heat pumps sized to the full heating load but with poorer performance due to degradation in part-load efficiency.

An area of interest is under what conditions a hybrid heating system is more economical than heating with a furnace alone. One can compute a "break-even" price for electricity. That is, if electricity can securely by procured at or below this rate for the life of the project, the hybrid heat pump configuration achieves cost parity with the furnace-AC system.

This break-even price is determined by setting the annualized cost of owning and operating a furnace-AC system equal to the annualized cost of owning and operating a hybrid heat pump system (see Equations 5 and 6). The prices of electricity (per kWh) and gas (per therm) are expressed as p_e and p_g. The annual quantities of electricity (in kWh) and natural gas (in therms) required for heating are expressed as $f_{e,R,z}$ and $f_{g,R,z}$ for the bivalent heating case, where R is the rated capacity of the installed heat pump and z is the climate zone. The annual gas required (in therms) for the furnace-AC case is denoted as $F_{g,z}$. These formulae do not account for cooling energy.

The annualized costs of owning a new air conditioner or heat pump are expressed as $c_{AC,R}$ and $c_{HP,R}$, and are computed based on the capital costs of the new systems, $C_{AC,R}$ and $C_{HP,R}$, using an annuity payment factor of 0.09634, which corresponds to a 5% interest rate over a lifetime of 15 years. A similar computation is performed to compute the break-even price for a home heated by fuel oil, making the appropriate substitutions for units, quantities, and prices.

$$p_g F_{g,z} + c_{AC,R} = p_g f_{g,R,z} + p_e f_{e,R,z} + c_{HP,R} \tag{5}$$

$$p_e = \frac{p_g(F_{g,z} - f_{g,R,z}) + (c_{AC,R} - c_{HP,R})}{f_{e,R,z}} \tag{6}$$

Because the conditions presume that the existing air conditioner is at the end of its useful life and in need of replacement, the installation cost for a new unit would be applied independent of the unit selected. If we assume that these costs do not vary with the type of unit or size selected, they can be neglected from the arithmetic. Maintenance costs are neglected for the same reason.

We assume that natural gas costs $1.00 per therm delivered ($10.00 per MMBTU)(U.S. Energy Information Administration, 2019c) and fuel oil costs $3.00 per gallon ($21.49 per MMBTU)(U.S. Energy Information Administration, 2019b), applying a plus-minus $0.25 sensitivity to the natural gas price and a plus-minus $0.50 sensitivity to the fuel oil price. In all climate regions, it was found that among hybrid heating systems, those configured with a heat pump sized to only meet the cooling requirement (and no larger) had the lowest annualized cost. Compared to furnace-AC systems, the economics of these "minimally-sized" configurations are determined by both climate region and the prices of electricity and fuel.

In homes heated by natural gas, the break-even electricity price for installing a minimally-sized heat pump as a replacement for an existing central air conditioner varies from $0.10-$0.13 per-kWh in colder climates (Zones 4-8, see Figure 3). For homes heated by fuel oil, this price climbs to $0.24-$0.30 per kWh, suggesting that a homeowner would break even on the purchase of a heat pump even if electricity prices were nearly double the 2018 national average of ~$0.13 per-kWh (U.S. Energy Information Administration, 2019a, p. 133). For lower electricity prices (as are found in much of the United States), the hybrid heat pump system would result in appreciable savings: for a home in Zones 3 or 4 with a fuel-oil furnace, adopting a hybrid heating approach would reduce annual expenses by 27-44%.[6]

In warmer climates (1A, 2B), heating demand is low enough that it becomes difficult to recoup the marginal capital cost of purchasing a heat pump instead of an air conditioner through operational savings. In these regions, an independent heat pump system may be a better option, as it allows one to avoid the costs associated with owning and maintaining multiple heating systems. Those analyses are not performed here.

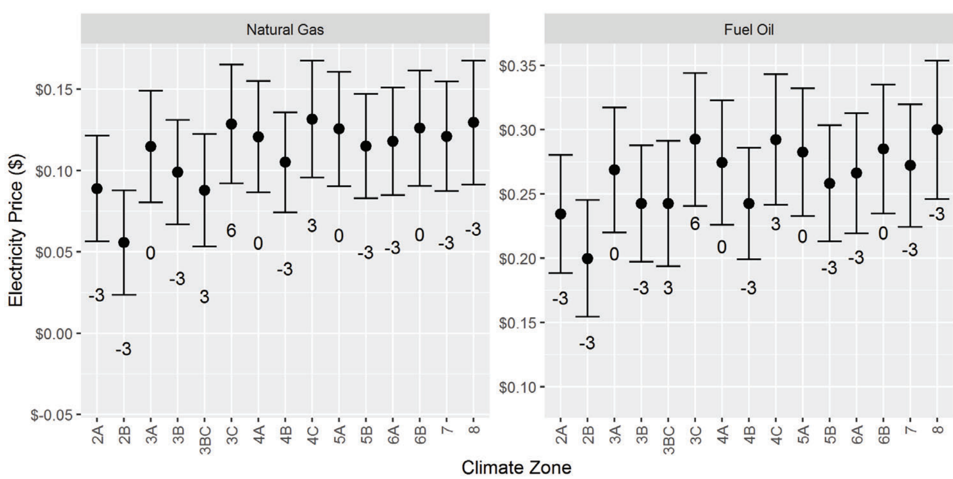

Figure 3. Break-even prices for electricity for a minimally-sized heat pump in each zone. The number below each range-plot indicates the bivalence temperature for each zone. Zone 1A (Miami) is excluded because the low heating demand

[6] This calculation assumes electricity purchased at the national average price $0.1289 per-kWh and fuel oil priced at $3/gallon.

generates deep negative prices. For natural gas, computations are based on a price of \$1.00/therm ± \$0.25 (\$10.00/MMBTU ± \$2.50). For fuel oil, computations are based on a price of \$3.00/gallon ± \$0.50 (\$21.49/MMBTU ± \$3.58).

CONCLUSION

We analyzed the environmental and economic implications of upgrading existing furnace-AC systems in single family homes to hybrid (dual-fuel) heating systems in various climate regions across the United States. We determine such a conversion can cause emissions reductions exceeding 50% in some climate zones, and, depending on fuel prices, may result in sizable cost savings.

While heat pumps have only gained a strong foothold in warmer climates, this study has established that there are sizable benefits to deploying heat pumps in colder climates as part of hybrid systems. The greatest absolute emissions reductions and cost savings are available for homes that currently use fuel oil as their primary fuel source. Beyond that, there are strong opportunities for economical deployment of hybrid heat pump systems in natural-gas heated homes throughout the country's colder climate regions.

ACKNOWLEDGEMENTS

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NOMENCLATURE

$Cap_R(T)$	Operating capacity in tons of heat pump with rated capacity R at temperature T
$COP(T)$	Heat pump coefficient of performance at temperature T
$C_{AC,R}$	Capital cost in US Dollars of air conditioner of capacity R
$C_{HP,R}$	Capital cost in US Dollars of heat pump of capacity R
$c_{AC,R}$	Annualized cost in US Dollars of air conditioner of capacity R
$c_{HP,R}$	Annualized cost in US Dollars of heat pump of capacity R
$f_{e,R,z}$	kWhs of electricity consumed annually for heating by a heat pump of capacity R in zone z
$f_{g,R,z}$	Therms of gas consumed annually by a furnace with a heat pump of capacity R in climate zone z
$F_{g,z}$	Therms of gas consumed annually by a furnace in zone z operating without a heat pump
kWh_e	Kilowatt-hour of electricity
kWh_{th}	Kilowatt -hour of thermal energy
$MMBTU$	Million British Thermal Unit of thermal energy
p_e	Price of electricity per kWh in US Dollars
p_g	Price of natural gas per therm in US Dollars
R	Heat pump or air conditioner system capacity in tons
T	Ambient temperature in Celsius

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DISCUSSION

Farzin Rad, Enbridge Gas, Inc., Toronto, ON, Canada: One of the slides on emissions considers the average energy generation mix across the U.S. This creates a misleading slide as the GHG savings are very sensitive to electrical generation.

Noah Rauschkolb: Using historical region-specific emissions factors provides a false sense of precision. Any large-scale change in electricity use (heat pumps, electric vehicles, etc.) will necessitate an expansion of generation capacity and result in a change to the generation mix. Rather than attempt to model these changes, we use a reasonable heuristic.

Sreenidhi Krishnamoorthy, Engineer/Scientist III, Electric Power Research Institute, Palo Alto, CA: How was the cost analysis performed? Did you calculate life-cycle cost or was it just the fuel cost?

Noah Rauschkolb: The life-cycle cost analysis was done; however, some capital cost was assumed throughout the country.