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EnergyPlus™ Models for Advanced Gas Heating Systems - Phase 2

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Executive Summary

EnergyPlus™ is the US Department of Energy's (DOE) flagship whole building energy simulation engine. It is commonly used by itself or on the backend of other building energy simulation software. It permits the simultaneous simulation of a whole building's energy consumption and its interaction with the surrounding environment. Prior to the start of this project, EnergyPlus had limited ability to simulate advanced condensing furnaces; no models existed for gas heat pumps; and only limited functionality existed for modeling combined space and water heating systems (combis). While the popularity and importance of EnergyPlus have grown dramatically within the energy efficiency community, decision makers considering best HVAC options for a building or in policy development had significantly limited options for comparing state of the art gas appliances to their electric counterparts. It was therefore the objective of this work to address these limitations of EnergyPlus.

In Phase 1, GTI leveraged technology performance data collected as part of other GTI projects to develop simulation capability for condensing furnaces and GAHP combis, which has in turn been used to estimate their energy savings potential. Work in the second phase of this project focused on refining models developed as part of Phase 1 with new experimental data as well as performing an expanded energy and cost savings analysis. Major accomplishments of Phase 2 include:

- A whole new mathematical framework was developed for simulating tankless based combis, anchored by new experimental data for tankless and combis.
- The GAHP combi model was refined with new data for the latest pre-commercial prototypes. The refined model now captures the impact of cold temperatures, cycling penalties, and defrost
- New tools were developed for automating simulations and analyses of the GAHP and tankless combis to permit more expansive analyses to be performed
- Energy savings analyses were performed for tankless and GAHP combis in a variety of locations and usage scenarios. These analyses demonstrated the competitiveness of the GAHP compared to the best electric options in cold climates for the foreseeable future, and that advanced tankless combis can yield savings comparable to condensing furnace – water heater alternatives

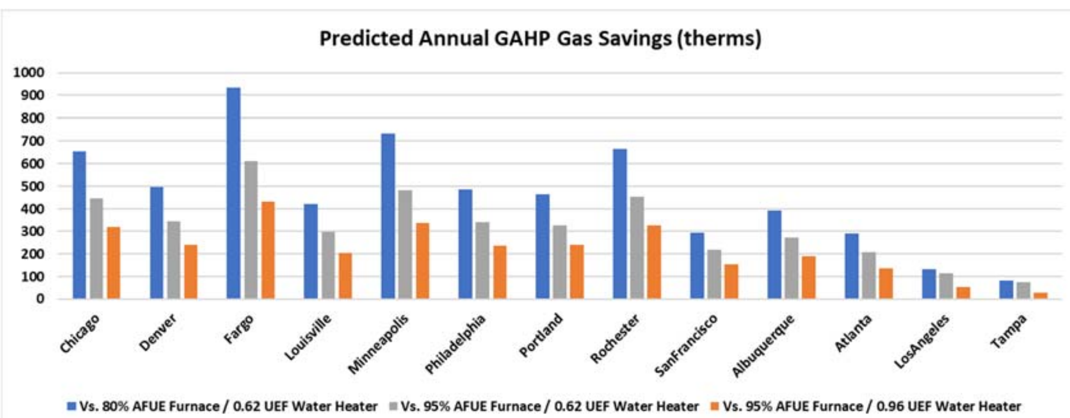

Figure E 1. Predicted GAHP Combi gas savings for a 3000 sq-ft, circa 2006, single-family home

Phase 3 of this project (in proposal stage) will push out the results of Phase 1 and 2 out to the public through direct updates to EnergyPlus and peer reviewed publications. While widespread public dissemination was originally planned for Phase 2, the higher than expected complexity of the tankless combi models and late availability of new GAHP data, has delayed direct updates to EnergyPlus. However, public dissemination through peer reviewed publications and presentations has already begun with three conference presentations delivered in 2019, and more planned for 2020-2021.

1. Introduction

EnergyPlus™ is the US Department of Energy's (DOE) flagship whole building energy simulation engine. It permits the simultaneous simulation of a whole building's energy consumption and its interaction with the surrounding environment. It utilizes detailed local weather data, including solar radiation and ground temperatures, it accounts for all internal loads (e.g., occupancy, water draw, appliance heat loss), and it allows the HVAC system to fully interact with the building. While EnergyPlus is often used directly, it is also commonly used on the backend of other building energy software including BEopt, OpenStudio, DesignBuilder, Autodesk Insight 360, and TRANE 3D Plus.

In development for close to 20 years, it is becoming the primary tool for evaluating the energy consumption of buildings during the design and commissioning as well as for the development of codes and standards. While laboratory and field trials of new technologies provide an excellent snapshot for heating/cooling performance of a particular technology, EnergyPlus permits additional questions to be answered such as: How does the regional difference such as weather, building construction, vintage, state adoption of energy building code affect system efficiency? EnergyPlus permits the extrapolation of limited experimental data to the analysis of how different buildings consume energy throughout the year. In addition, EnergyPlus has extensive support for building code compliance and ratings, e.g., Leadership in Energy and Environmental Design (LEED), with Residential Energy Services Network (RESNET) moving towards adopting the use of EnergyPlus in its Home Energy Rating System (HERS) index. California Energy Commission (CEC) has adopted EnergyPlus for developing and maintaining the standards since the 2013 code cycle. The Alternative Calculation Method (ACM) of the CA Title-24 standard for building performance compliance is currently in the transition to EnergyPlus from its predecessor DOE2. More information regarding the current state of EnergyPlus and its future development is available in [1].

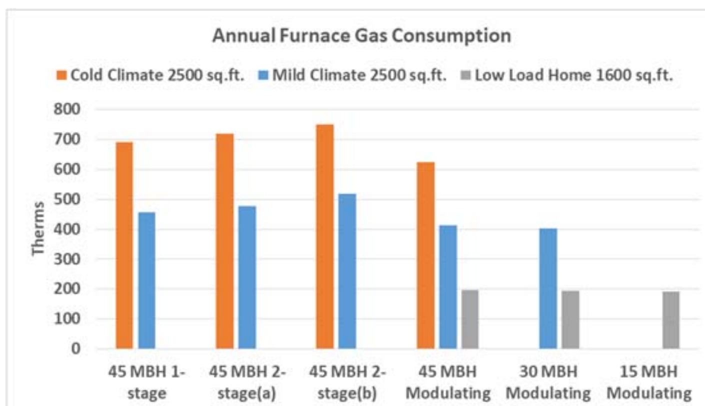

Figure 1. Advanced condensing furnace performance predictions form Phase 1 simulations and analysis

EnergyPlus is open source, with DOE providing the primary support for its maintenance and development. While in development for nearly two decades, portions of the software have not been updated since the first release. For instance, the principal aspects of a residential furnace model can be traced back to DOE2 development [2], and the model can no longer accurately capture the performance of modern condensing furnaces, which entered the market after the first release of EnergyPlus. Worse yet, most often only the AFUE is used to predict their performance, which does not account for part-load cycling penalties and the impact of oversizing the furnace. In Phase 1 of this project, using performance maps obtained in the GTI Virtual Test Home, it was demonstrated how condensing modulating furnace can save up to 10% on gas compared to its single- and two-stage counterparts, Figure 1. Right sizing the furnace, especially important for low-load homes, could save an addition 2%.

For progressive gas heating technologies such as tankless and gas absorption heat pumps (GAHP) based combis, no simulation capabilities in EnergyPlus exist, e.g., [3]. At the same time, models of electric heating appliances have been extensively updated in the last 10 years, supported by funding from DOE, e.g., [4]. An issue therefore arises if a decision maker wants to consider the best HVAC options for a building or in policy development, they would have significantly limited options for comparing advanced gas appliances to their electric counterparts.

1.1 Objectives:

The primary objective of this project was to address the limitations of EnergyPlus in simulating advanced residential space heating equipment by developing and advancing the state-of-the-art methods for simulating advanced condensing furnaces, gas heat pumps, and combined space and water heating systems. Specific objectives for Phase 2 were:

1. Refine simulation methods for advanced residential gas heating equipment with new performance data, collected in the GTI's Virtual Test Home and in the field
2. Develop and adapt tools to automated simulations and of advanced gas heating systems to enable more expansive technoeconomic analyses with respect to locations and use cases
3. Perform a technical and economic potential analysis on advanced gas heating systems for the US single-family housing market
4. Disseminate the outcomes of this work publicly though direct updates to EnergyPlus and peer-reviewed journal publications and conference presentations

Figure 2 – Advanced heating systems modeled in EnergyPlus, including tankless combi, gas heat pumps, and advanced condensing furnaces

2. Simulating Advanced Tankless Combis

One of the main objectives for Phase 2 of this project was to expand EnergyPlus simulation capabilities to predict the performance of tankless combis. These heating systems are very attractive from an economic perspective because they meet both the space and water heating demand with a single combustion system. While condensing furnaces have achieved a high market penetration, the water heating market lags behind due to hard economics for condensing appliances. Combis offer the opportunity to increase the market penetration of condensing water heating technologies while reducing its cost.

While EnergyPlus contains modules that can represent a hydronic air handler, it has inadequate capability to simulate tankless water heaters. In all instances where a tankless water heater is simulated in EnergyPlus, it is represented as a storage water heater with a one gallon storage capacity and a constant steady state efficiency equal to the Uniform Energy Factor (UEF). This approach is very limiting because it cannot capture the impact of different usage cases (gal/day) or the impact of mains water temperature (Btus/day). It is also completely inadequate to predict the performance of combined space and water heating systems.

Multiple field and laboratory studies in the last fifteen years have demonstrated that the Energy Factor is a poor predictor of actual water heater performance, e.g., [3] [5] [6]. Oddly enough, the storage water heater model in EnergyPlus is robust enough to accurately predict their performance, while the tankless approach has been very crude. Even in residential simulation tools such as BEopt [7], the most that is done is to de-rate the performance of the tankless water heater by 8%.

The challenge for this task was to find a method for simulating tankless water heaters that could also be used to predict the performance of tankless combis. The overall desirable features of a tankless combi model are:

- Easy and fast to integrate such that the model can be readily used with calculators and tools such as EnergyPlus
- Have few parameters that can be determined from limited testing in the laboratory
- Be able to capture the impacts of part-load operation and the heating capacity oversize factor
- Capture the interaction between the air-handler and the heating plant
- Capture the impact of different control strategies
- Accurately predict the energy consumption of the tankless in DHW only mode

Appendices A and B describe in detail the theoretical framework for tankless combis that was developed to attain the above features. The data used for validation was collected as part of two parallel projects focused on assessing the performance of tankless water heaters and advanced combis. The theoretical approach overall is based on a Lumped Heat Capacity (LHC) method first proposed as a means of simulating tankless water heaters by Burch et al. [8]. The work done as part of this project is the first time the LHC method has been validated and used effectively to predict the energy consumption of tankless and combis. The results of this work have been presented at the 2019 American Council on Energy Efficiency and Economy Hot Water Forum and a full journal paper is being prepared. The remainder of this section highlights the major findings of the techno-economic analyses performed for tankless water heaters and advanced tankless combis.

2.1 Predicting Annual Tankless Water Heater Energy Use

8760-hour building simulations were performed using realistic domestic how water (DHW) draw patterns, in different climates and use cases. A custom model was developed for tankless water heaters based on the Lumped Heat Capacity (LHC) model developed at NREL [8]. This model was combined with DHW loads generated by BEopt [7] and EnergyPlus [9]. A detailed description of the model development is provided in Appendix A.

Ten locations were considered overall in the analysis and three different use cases were investigated, high, medium, and low which approximate homes that are 4 bed 3-bath, 3 bed - 2 bath, and 2 bed – 1 bath. Four water heating options were simulated including a minimum efficiency 0.62 UEF non-condensing storage, a 0.82 UEF non-condensing tankless, 0.96 UEF condensing tankless, and for additional comparison a 0.82 UEF condensing storage water heater. The last option represents an alternative high-efficiency water heater choice that could yield energy savings on a similar order of magnitude but at potentially reduced installed costs. It was included in this study for comparison as an intermediate option. The annual gas consumption for each option in the high usage case is compared in Figure 3.

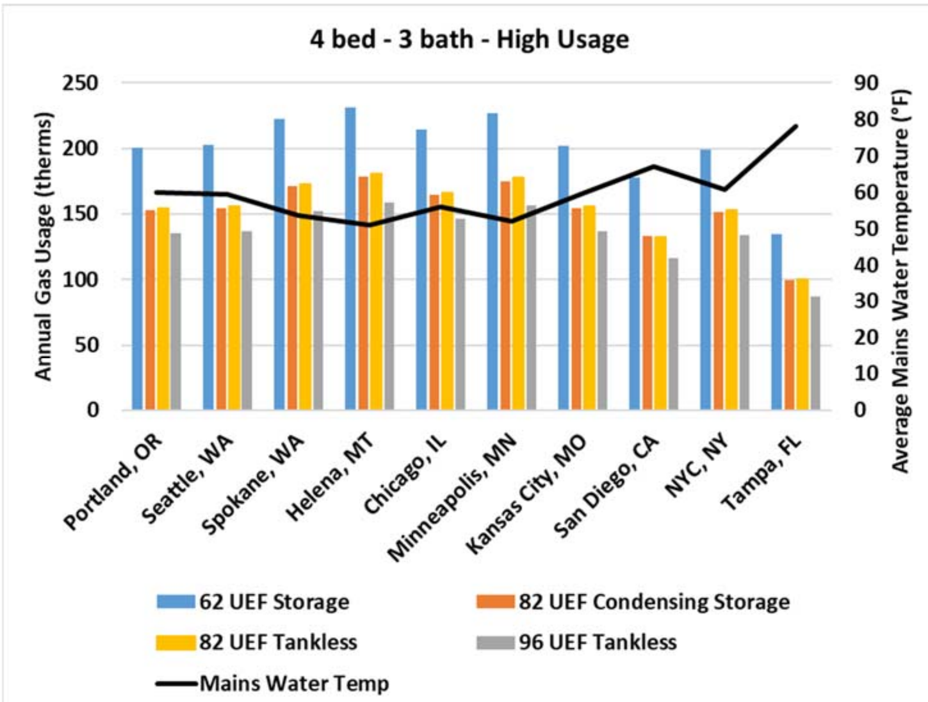

Figure 3. Annual gas consumption for all water heater options considered.

Water heater energy consumption is strongly correlated with average annual mains water temperature, despite the same draw patterns being used. More DHW was needed to temper mains supply in colder climates. Being able to predict this effect is a unique feature of the LHC simulation approach developed.

With respect to energy savings, the condensing tankless offered the greatest average savings of 33%, while the condensing storage and non-condensing tankless both offered approximately 23% energy savings compared to the 0.62 UEF baseline. The relative savings were independent of the climate, but varied with use cases, summarized in Figure 4.

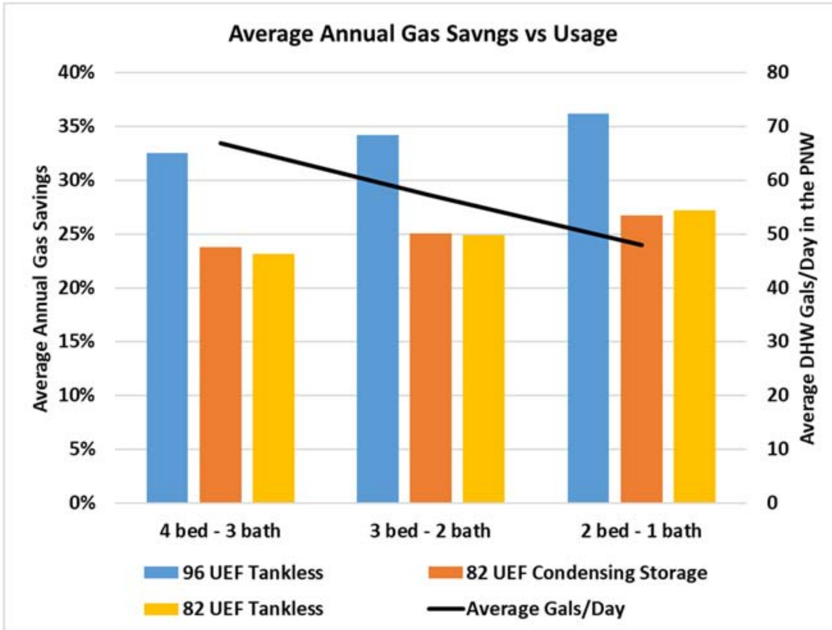

Figure 4. Relative energy savings for different use cases

Relative savings are higher for lower use cases due to increased penalty of standby heat losses of the 0.62 UEF storage water heater. These results are based on installations inside the conditioned space. If installed inside unconditioned space such as a garage, the savings for all high efficiency water heaters were approximately 2% higher. No other usage pattern changes were considered/ Using the 2016 state average natural gas prices from Energy Information Administration, the annual operating cost savings for each high efficiency water heater are compared in Figure 5.

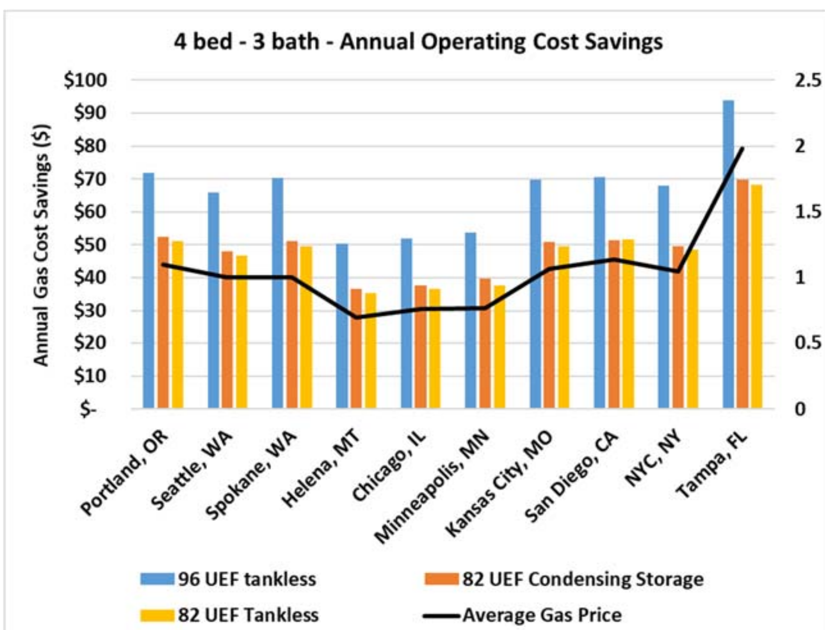

Figure 5. Annual operating cost savings

2.1.1 Simplified Approach for Predicting Tankless Energy Use

The previous section and Appendix A describe the approach utilized in the present study to simulate tankless water heaters and predict their real-world energy consumption. While the LHC model is less complex than other approaches, e.g., [10], it can still be impractical since it requires numerical integration. Frequently, only the EF rating is used to estimate energy consumption and relative savings as described earlier. Prior studies have shown that energy consumption estimates based on the EF rating can be underestimated by 10% or more, with worse results being seen for storage water heaters. The Uniform Energy Factor (UEF) evolved from the EF rating and attempts to better account for real world water heater performance by implementing realistic draw patterns with typical usage of 84, 55, 38, and 10 gal/day. However, it was found as part this study that the draw patterns utilized in the UEF test may still not be representative of real-world performance. Figure 6 plots the predictions of the LHC model of the present study for the different UEF draw patterns.

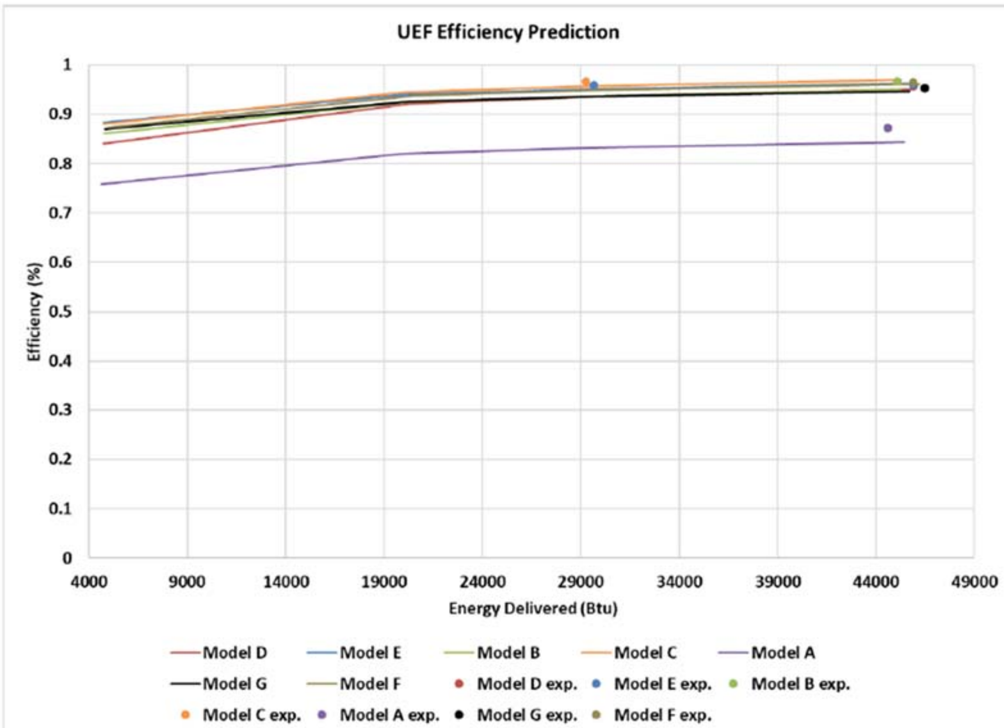

Figure 6. Simulated UEF tests using the LHC model compared to experimental measurements

Simulations of the UEF tests suggest that tankless water heaters would only experience an 8-9% decrease in performance in the lowest usage cases. However, real-world performance of tankless water heaters in very low usage cases has been documented to be as much as 20% lower than the rating. Figure 7 compares LHC model predictions to real world performance data collected as part of a study by Minnesota Center of Energy and Environment (MN CEE) [5].

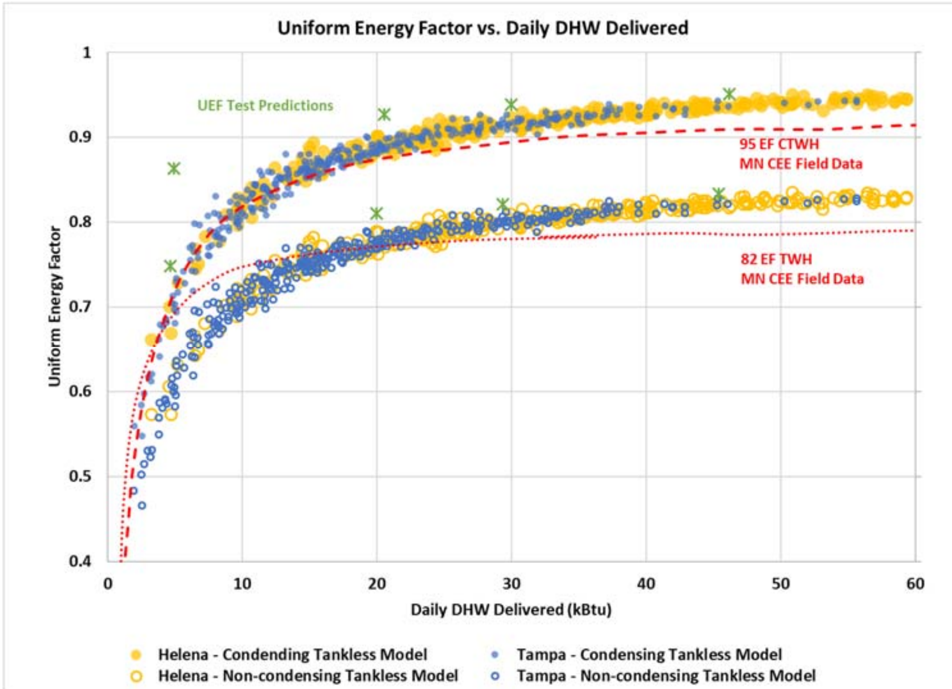

Figure 7. Predicted energy efficiency compared to available field measurement correlations from [5]

The LHC model is in good agreement with the field data correlations and shows a rapid decline in efficiency during low use days. In contrast, the UEF rating would underpredict energy consumption on these days by 25% or more. These results indicate a deficiency that is still present in the UEF rating.

An alternative simple method for estimating daily energy consumption is to use an input-output correlation developed from experimental data and simulations [5]. These correlations can accurately reproduce the data such as plotted in Figure 7. Using the LHC simulation results from this study, new correlations curves were developed for the 0.96 UEF and 0.82 UEF tankless water heaters. These correlations are provided in Figure 8.

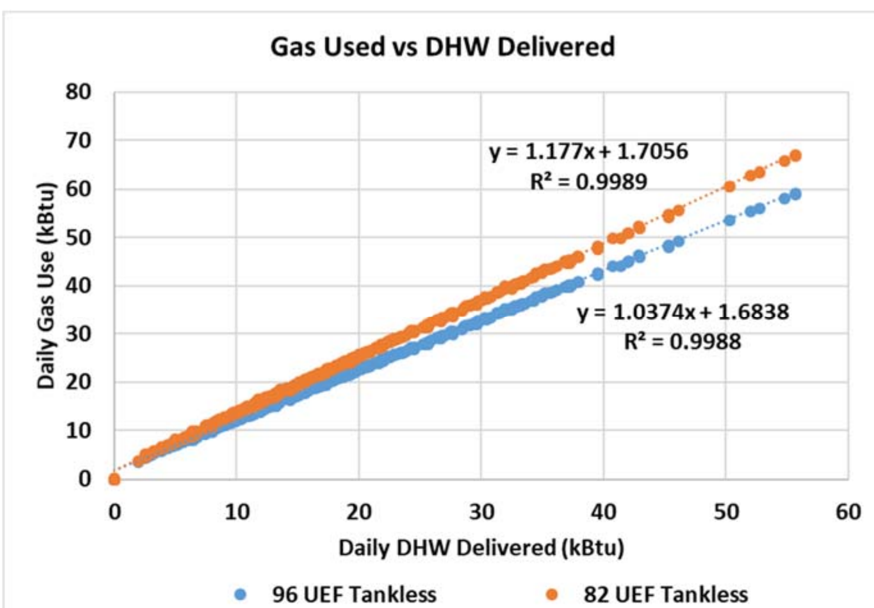

Figure 8. Input-output correlations to predict gas use for tankless products

2.2 Predicting Annual Tankless Combi Energy Use

The previous section illustrates the effectiveness of of the LHC model for predicting the energy consumption of tankless water heaters. Given the similarities between the construction of a tankless water heater and the hydronic air handler, it was hypothesized that the LHC method could be expanded to simulate a tankless combi as well. Appendix B describes in detail how the theoretical framework can be expanded to simulate tankless combis and compares the models predictions to the energy use of a real advanced tankless combi. This section describes the major findings from an energy savings analysis for combi tankless systems using the new LHC model.

Figure 9 presents the variation in seasonal efficiency of a standard tankless combi that is installed "properly", i.e., the system is configured to always achieve condensing efficiency when operating at steady state, [11]. The simulations are based on a 3000 sq-ft, 4-bed, 3-bath, single family home circa 2006 with an attached 2-car garage. Building model (Building 1) assumptions are summarized in Appendix D.

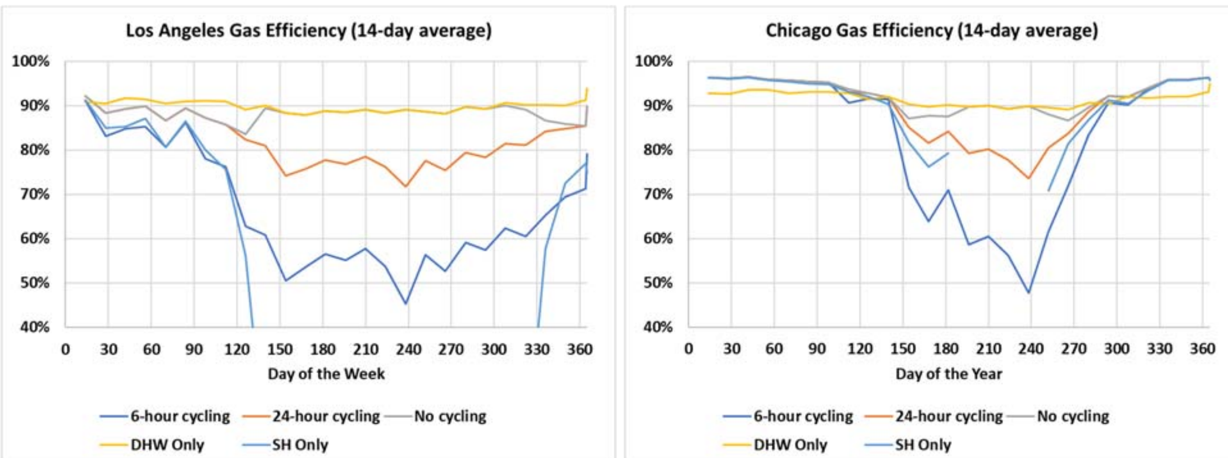

Figure 9. Seasonal variation of efficiency of a tankless combi in different operating modes. Cycling refers to off-cycle combi cycling to heat the water trapped in the hydronic air handler to kill legionella (assuming an open-loop system).

Early tankless combi field trials suffered from low performance due two primary issues. The main cause of lower efficiencies has been high return water temperatures to the tankless preventing them from achieving condensing efficiencies. This issue has largely been addressed with better designed tankless water heaters and hydronic air handler controls. The second major issue in some cases has been local code requirements to cycle the hydronic air handler to heat the trapped water to 120°F in order to kill legionella when there hasn't been a space heating call for more than 6-hours. In instances when required, this has resulted in significant energy efficiency penalties, [12]. Figure 9 illustrates the predicted seasonal variation of a tankless combi when operating on either a 6-hour or a 24-hour off-cycle heating. The results agree well with observations made in the field. 6-hour off-cycle heating in the warmer months significantly impacts the efficiency of the tankless combi. If the off-cycle period can be increased to every 24-hours, the efficiency penalty is significantly lower.

Figure 9 also illustrates the impact of running the tankless combi in space heating (SH) or (DHW) only, as well as their interaction when running as a combi. In DHW only, the tankless water heater experiences only a small decline in average efficiency in the warmer month in both locations. For SH only, the efficiency in the shoulder months declines significantly. However, given that only a small portion of the overall heat is delivered during these months, the annual efficiency is not impacted as significantly, Figure 10. The comparison between Chicago and Los Angeles is made because the former location is space heating dominated while the latter is water heating dominated. When operating in combi mode, the LHC model predicts a slight boost in annual gas efficiency in Chicago. In Los Angeles, the combi achieves an intermediate efficiency between DHW and SH only operation. The overall trend is an increasing efficiency with an increasing SH/DHW load, hence the same system in Chicago can achieve a higher annual efficiency than in Los Angeles.

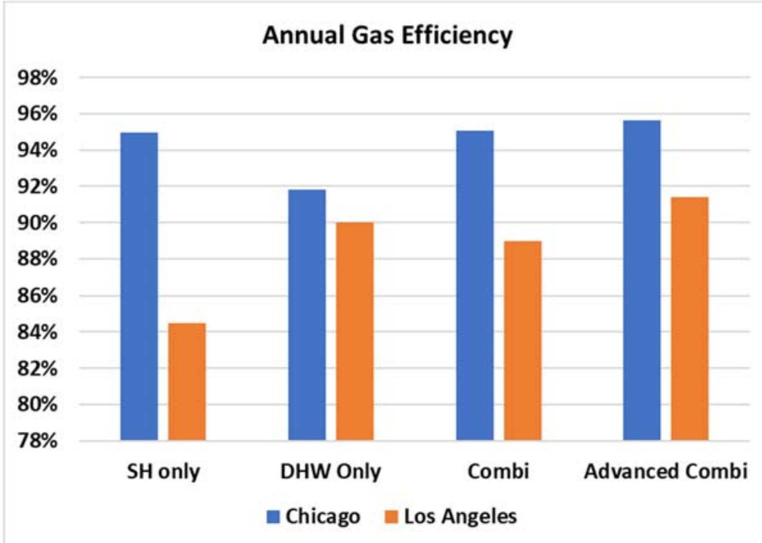

Figure 10. Predicted annual gas efficiency for a tankless combi in different operating modes

Figure 10 also plots the predicted efficiency for an "advanced" tankless combi. GTI has recently conducted a thorough investigation of emerging combi technologies, including advanced air handlers optimized for combi operation. These air handlers minimize the amount of residual heat left in the system after a space heating call. This has been shown to provide an additional boost to efficiency in laboratory testing, which is also predicted by the LHC combi model. Using the advanced combi as the state of the art, an energy and cost savings potential analysis was performed for multiple locations around the United States. The predicted annual efficiencies in different locations is plotted in Figure 11. The building model considered in all cases is the same 3000 sq-ft, circa 2006 single family home (Building 1 described in Appendix D).

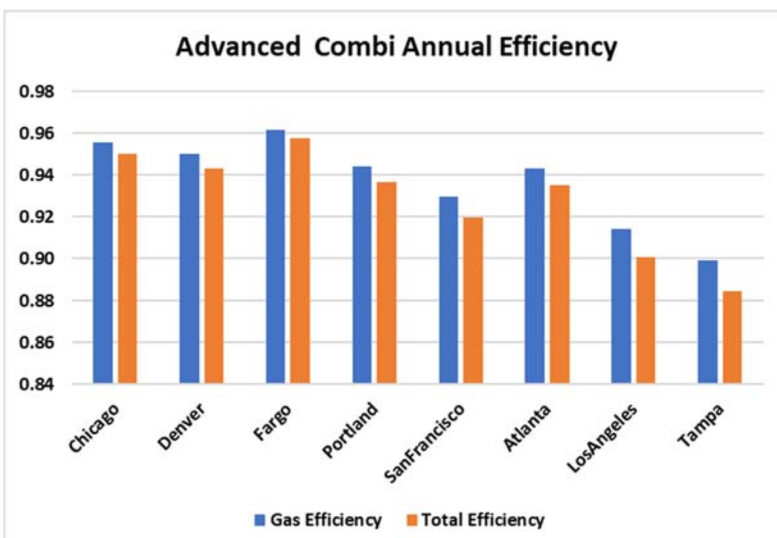

Figure 11. Predicted annual efficency for an advanced tankless combi in different locations

Figure 11 further reinforces an earlier finding that the best performance will be seen for high SH and DHW loads, which will be observed in colder climates. Prior field trials have observed efficiencies that were lower than 90% in many cases [13], below what may be expected for a standalone condensing furnace and a condensing tankless water heater. Energy use predictions from the advanced combi analysis were compared to predicted energy use of three alternative gas furnace scenarios:

- Baseline gas: 80% AFUE furnace, 0.62 UEF storage water heater
- Better Gas: 95% AFUE furnace, 0.62 UEF storage water heater
- Best Gas: 95% AFUE furnace, 0.96 UEF tankless water heater

More detailed assumptions regarding these cases are discussed in Section 8 of this report. Figure 12 summarizes predicted advanced tankless combi savings when compared to the different furnace cases above. This plot illustrates that an advanced tankless combi can provide comparable or better energy gas savings in all locations when compared to the condensing furnace/water heater scenario, something earlier tankless combis struggled to achieved. This trend holds for predicted operating cost and CO2-equivalent emissions for the advanced tankless combis, plotted in Figure 13 and Figure 14.

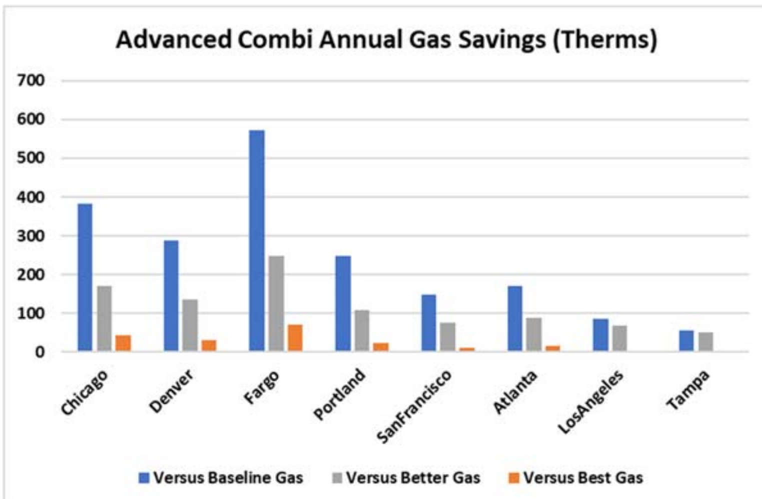

Figure 12. Predicted advanced tankless combi gas savings

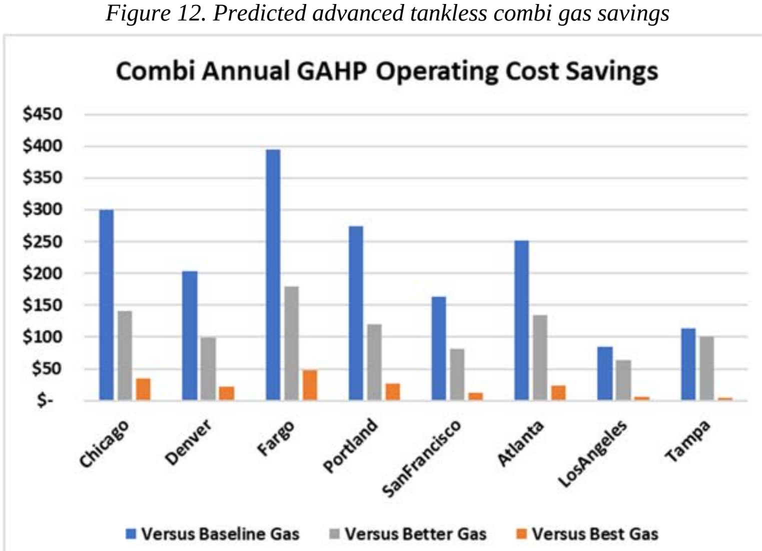

Figure 13. Predicted advanced tankless combi operating cost savings

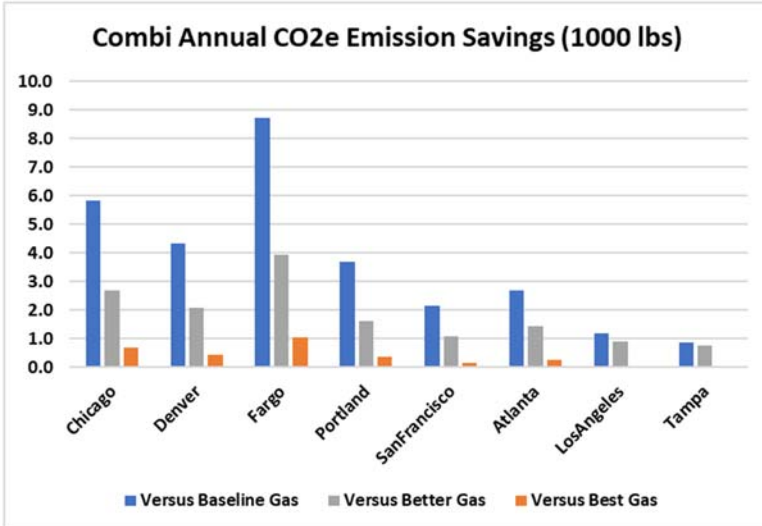

Figure 14. Predicted advanced tankless combi CO2-equivalent emissions savings

The simulations and analysis of tankless combis presented here is the first time such analysis has been performed. The results of this work are being prepared into a conference paper (ASHRAE 2021 Winter Conference – Chicago, IL) in order to socialize the new theoretical framework and to make the results of the analysis publicly available.

3.0 Simulating GAHP Combi

The model for a GAHP combi developed as part of Phase 1 had a few limitations which needed to be addressed before widespread dissemination:

- A single performance curve was used to capture the performance of the heat pump, which had limited ability to extrapolate performance to conditions not tested
- The model did not account for defrost operation of the heat pump
- The model did not account for cycling penalties
- The model used a mixed storage tank sub-model, which could not accurately predict return water temperature to the GAHP
- The GAHP capacity had to be sized manually
- The model was difficult to apply to new buildings models and the analysis performed was therefore limited in scope
- The data used for the performance map was based on early prototypes of the GAHP from Stone Mountain Technologies (SMTI)

One of the objectives of Phase 2 was to refine the GAHP combi model developed previously to address the above limitations and to revise the performance map based on new pre-commercial prototype data. Additionally, the model's portability was improved by developing Python scripts that could automate the application of the model to new buildings as well as to size the GAHP based on the design heating load and outdoor conditions when it occurs.

Using the new model and tools, a detailed energy and cost savings analysis was performed for the US single family housing market. This analysis included 13 cities, covering all US climate zones, and three different building sizes. Appendix C describes the revised theoretical model for the GAHP combi. Appendix D describes the building model and economic assumptions used in the analysis. The remainder of this section summarizes the major findings of this analysis.

3.1 Energy and Cost Savings Analysis Results

The energy savings analysis was performed in part to support the first Trane-SMTI field trial in Wisconsin, which was partially supported by UTD Project 1.13.F. The analysis focused on cold climate cities for that project but was expanded to include all US climate zones for this project. The analysis was performed using a combination of BEopt [7], EnergyPlus [9], and a custom GAHP combi model that uses a performance map based on laboratory and field data. BEopt was used to develop prototypical residential building models and as a source of performance data of electric heat pumps (used for comparison). Three different homes sizes were simulated, in thirteen different locations, and six different HVAC scenarios. Table 1 summarizes the high-level building characteristics used in the analysis. The building models were built to approximately International Energy Conservation Code (IECC) 2006 building code. The "Simulation Assumptions" sub-section provides detailed building model assumptions.

Table 1 – Locations and buildings simulated

<table>
<tr><th>City</th><th>Climate Zone</th><th>Building 1</th><th>Building 2</th><th>Building 3</th><th>Type</th><th>Foundation</th></tr>
<tr><td>Fargo, ND</td><td>7 -dry</td><td rowspan="13">3000 sq-ft</td><td rowspan="5">2400 sq-ft</td><td rowspan="2"></td><td rowspan="13">2-story, 4-bed, 3 bath, 2-car attached garage</td><td rowspan="6">unfinished basement</td></tr>
<tr><td>Rochester, NY</td><td>6-moist</td></tr>
<tr><td>Minneapolis, MN</td><td>6-moist</td><td rowspan="2">1800 sq-ft</td></tr>
<tr><td>Chicago, IL</td><td>5-moist</td></tr>
<tr><td>Philadelphia, PA</td><td>5-moist</td><td rowspan="9"></td></tr>
<tr><td>Denver, CO</td><td>5-dry</td><td rowspan="8"></td></tr>
<tr><td>Portland, OR</td><td>4-marine</td><td>slab</td></tr>
<tr><td>Louisville, KY</td><td>4-moist</td><td>unfinished basement</td></tr>
<tr><td>San Francisco, CA</td><td>3-marine</td><td>slab</td></tr>
<tr><td>Atlanta, GA</td><td>3-moist</td><td>slab</td></tr>
<tr><td>Albuquerque, NM</td><td>4-dry</td><td>slab</td></tr>
<tr><td>Los Angeles, CA</td><td>3-dry</td><td>slab</td></tr>
<tr><td>Tampa, FL</td><td>2-moist</td><td>slab</td></tr>
</table>

Table 2 summarizes the HVAC scenarios considered in the analysis. All HVAC system models were taken directly from BEopt with minor modifications. The baseline storage water heater (62 EF) model is a custom option added to BEopt to reflect the current federal minimum. The variable speed heat pump option was modified to size the equipment based on the maximum load (as opposed to cooling load only), to better reflect how a "cold-climate" heat pump would be sized. The furnace models were modified to include part-load efficiency curves $Normalized\ Efficiency = 0.9 + 0.1 * PLR$ for the condensing furnace and $Normalized\ Efficiency = 0.8 + 0.2 * PLR$ for the non-condensing furnace, where $PLR = load/capacity$. These modifications were made to better account for cycling efficiency losses of typical furnaces. These curves were added directly to the EnergyPlus models generated by BEopt and simulated separately.

The GAHP combi was simulated by modifying the "Best Gas" scenario model with a custom GAHP plant model and new performance curves. The subsection "GAHP Combi Model Assumptions" describes the GAHP model assumptions in detail. The model itself applied a control strategy similar to the real combi system, following a temperature setback curve for heating and operating in DHW priority.

Table 2 – HVAC cases simulated. The air conditioner for all non-heat pump cases was a SEER 13 unit.

Case	Space Heating	Water Heating
Baseline Gas	80% AFUE Furnace, autosized for max heating load	62 EF, 47.5 gal storage water heater
Better Gas	95% AFUE Furnace, autosized for max heating load	62 EF, 47.5 gal storage water heater
Best Gas	95% AFUE Furnace, autosized for max heating load	96 EF, 199 MBH tankless water heater*
GAHP Combi	45 MBH min., autosized for peak heading load	65 gal indirect storage tank
Standard Electric	7.7 HSPF Heat Pump (SEER 13), autosized to meet cooling load*	92 EF, 59.4 gal electric storage water heater*
Best Electric	10 HSPF Var. Speed Heat Pump (SEER 22), autosized for max heating load*	2.3 EF, 80 gal, Electric HPWH*
*Standard BEopt 2.8 options (unmodified)		

Figure 15 plots the annual performance predicted for the GAHP Combi in each location for Building 1. The annual coefficient of performance (COP) is the ratio of space heating and hot water delivered to the gas used for COPgas and gas + electricity use for the COP. The results are comparable to field observations and align with expected performance in cold climates.

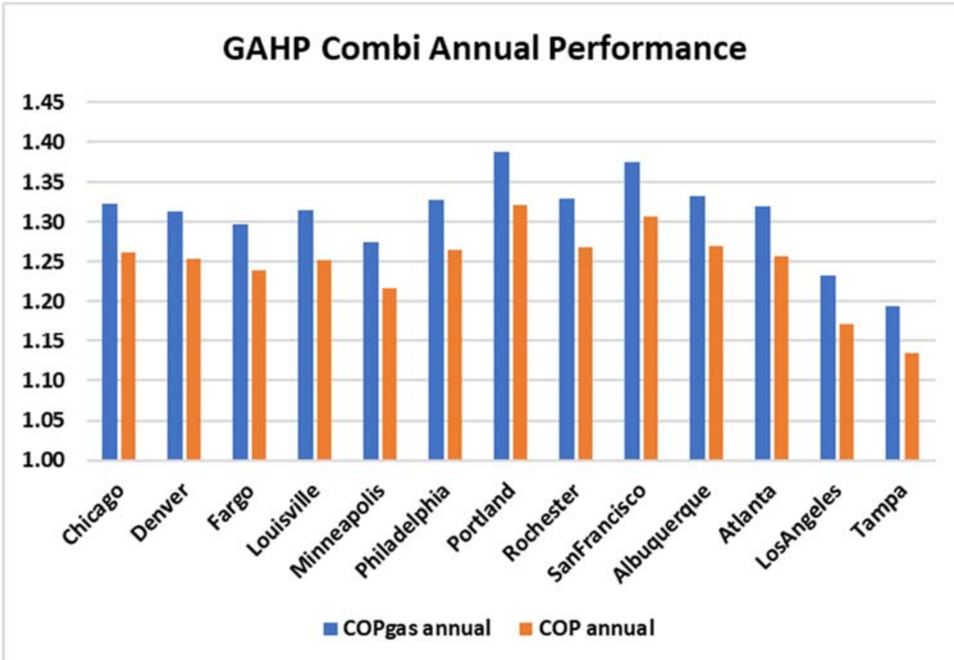

Figure 15 – Annual GAHP performance for Building 1 in different locations. COPgas = (space and water heating delivered) / GAHP gas use, COP = (space and water heating delivered) / GAHP gas and electricity use.

The variation in annual performance is largely correlated with the amount of annual space heating performed. DHW water usage is the same in each case, approximately 65 gal/day. However, due to cycling penalties attributed to short DHW recovering, DHW only performance is lower than SH performance, therefore lowering the overall annual COP in warmer climates. In addition, the minimum capacity of the GAHP was set to 45 MBH to ensure that sufficient hot water could be provided. This resulted in higher cycling penalties in warmer climates as well. Figure 16 plots the variation of the annual COPgas by location and building size.

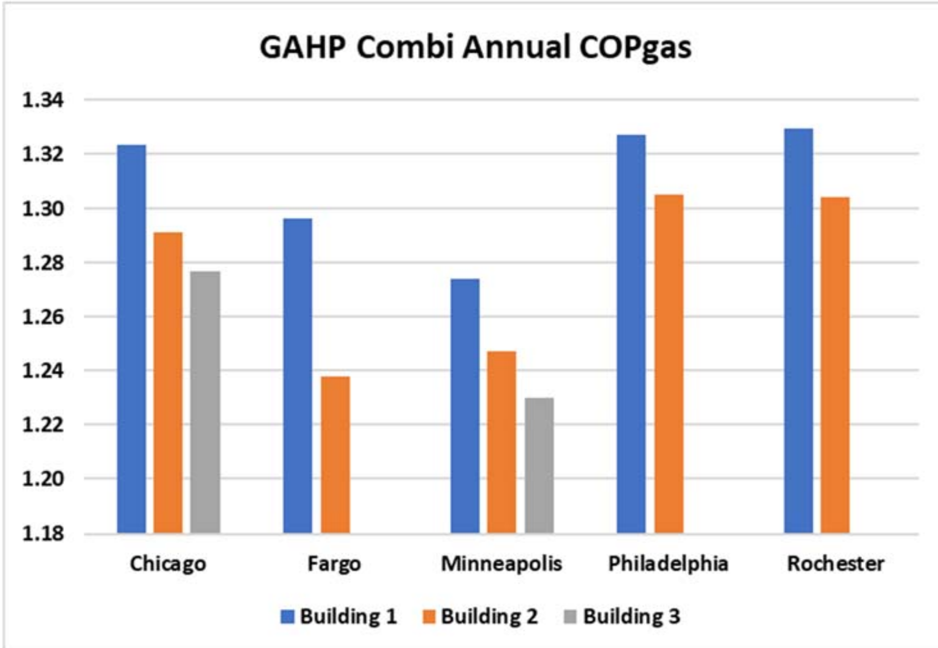

Figure 16 – Annual GAHP performance for Buildings 1, 2, and 3

Figure 17 through Figure 18 plot the predicted gas, CO_2 equivalent emission, and operating cost savings for the GAHP combi when compared to all three gas HVAC scenarios. The emission and operating cost savings account for total HVAC energy use, including space and water heating, space cooling, and fan energy use. Details about the economic analysis assumptions are provided in sub-section Appendix D.

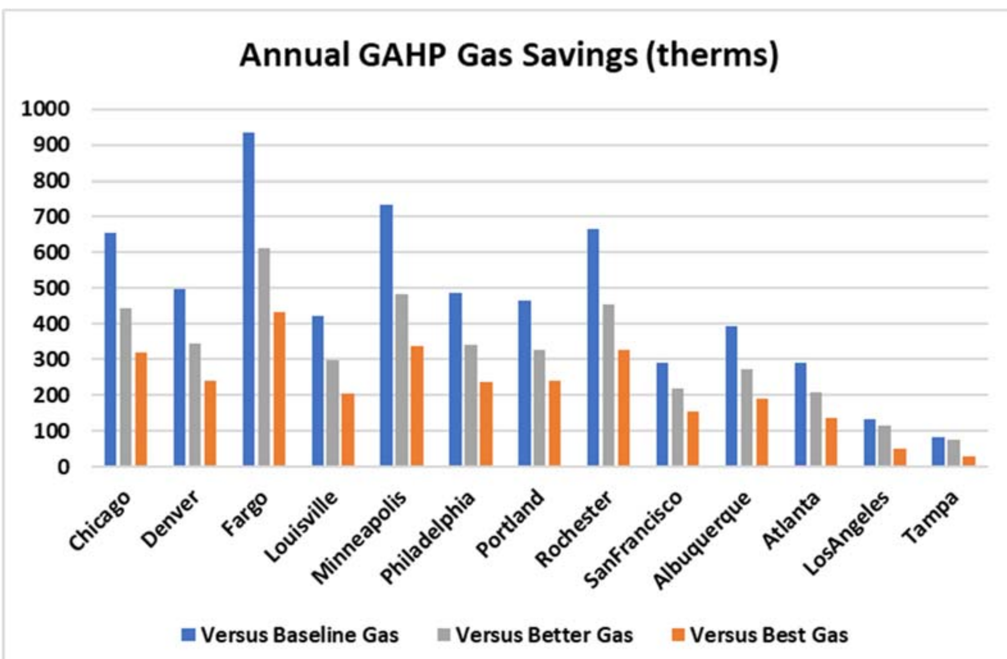

Figure 17 – Projected GAHP Combi gas savings for Building 1 against the alternative gas cases. Includes space and water heating.

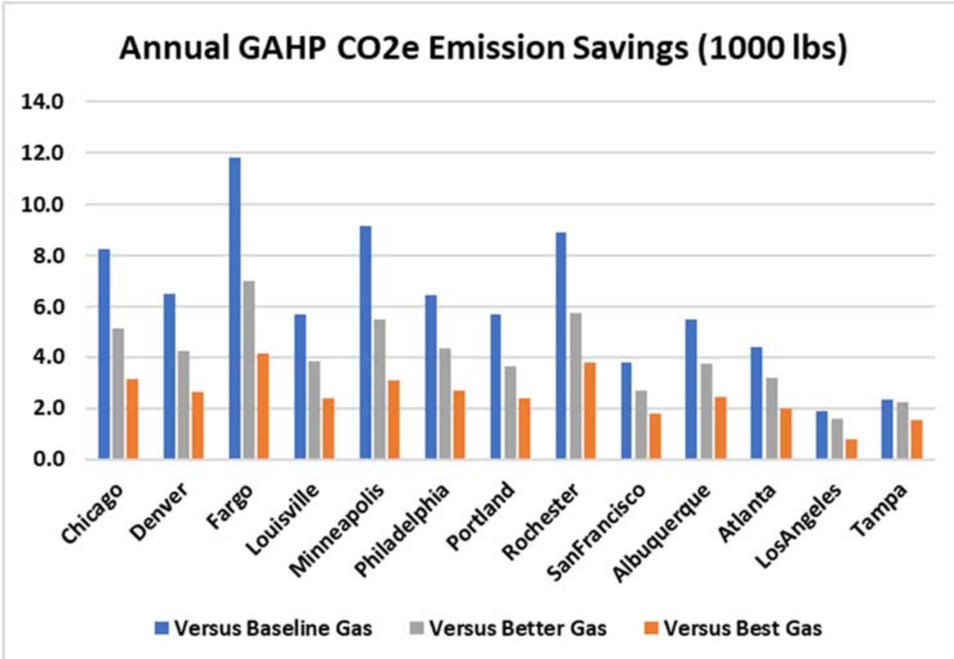

Figure 18 – Projected GAHP Combi CO_2 equivalent emission savings for Building 1 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

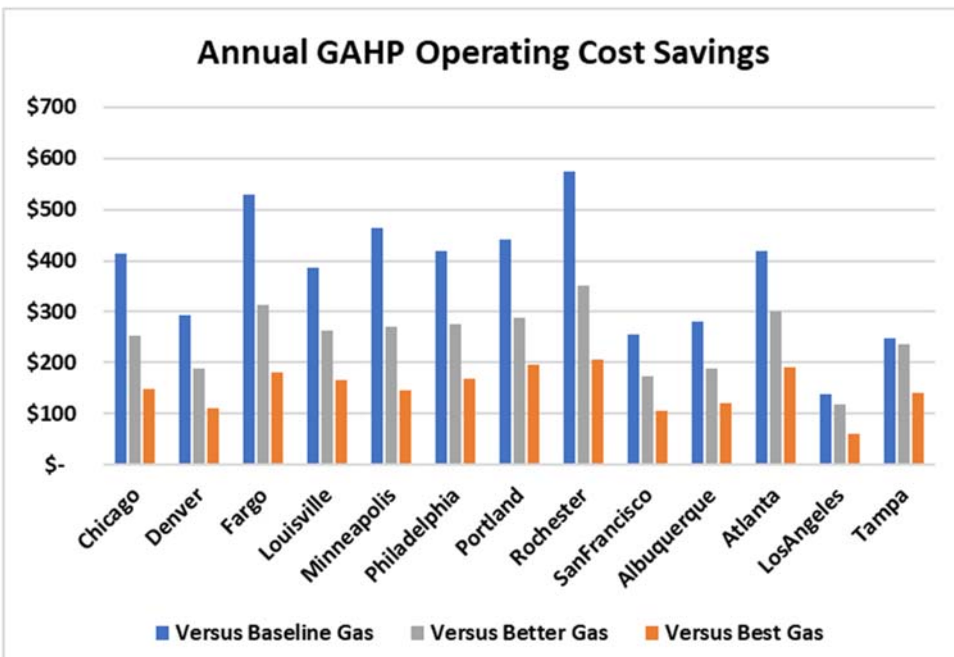

Figure 19 – Projected GAHP Combi operating cost savings for Building 1 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

The projected GAHP energy and cost savings are the highest compared to the baseline gas case which uses both non-condensing space and water heating technologies. The savings are the lowest when compared to the "Best Gas" scenario. This scenario represents the best alternative gas space and water heating technologies available today. As demonstrated in Section 7, this case is also very comparable to an advanced tankless combi savings as well. However, due to the tough economics for tankless water heaters, e.g., 20+ year payback periods [5], this is not a likely retrofit scenario to occur. With increasing prevalence of condensing furnaces and low penetration of high-efficiency water heating gas technologies, the “Better Gas” scenario is the more likely retrofit scenario to be encountered in the near future. Figure 20 and Figure 21 plot the predicted operating cost and CO_2 equivalent emissions savings for the GAHP as compared to the “Better Gas” scenario for different building sizes.

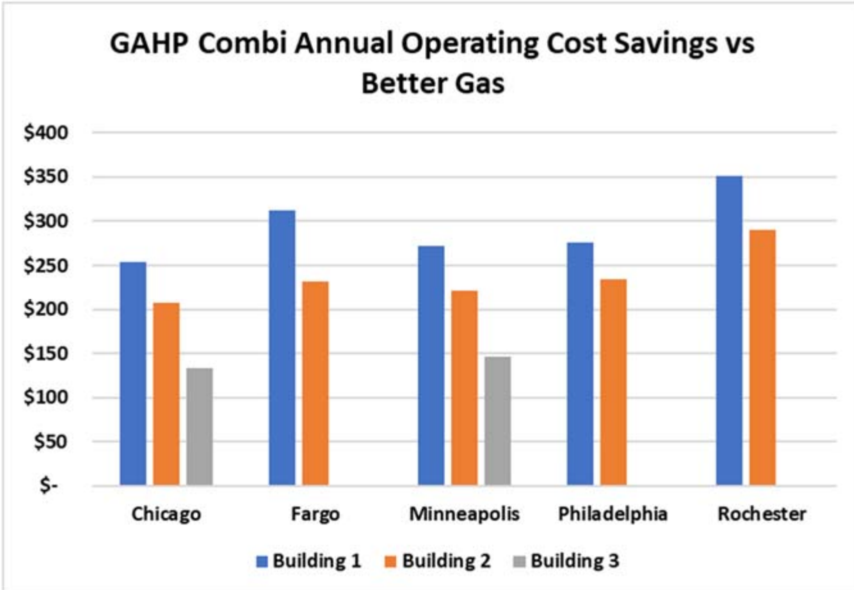

Figure 20 – Annual GAHP operating cost savings for Buildings 1, 2, and 3 as compared to the “Better Gas” scenario

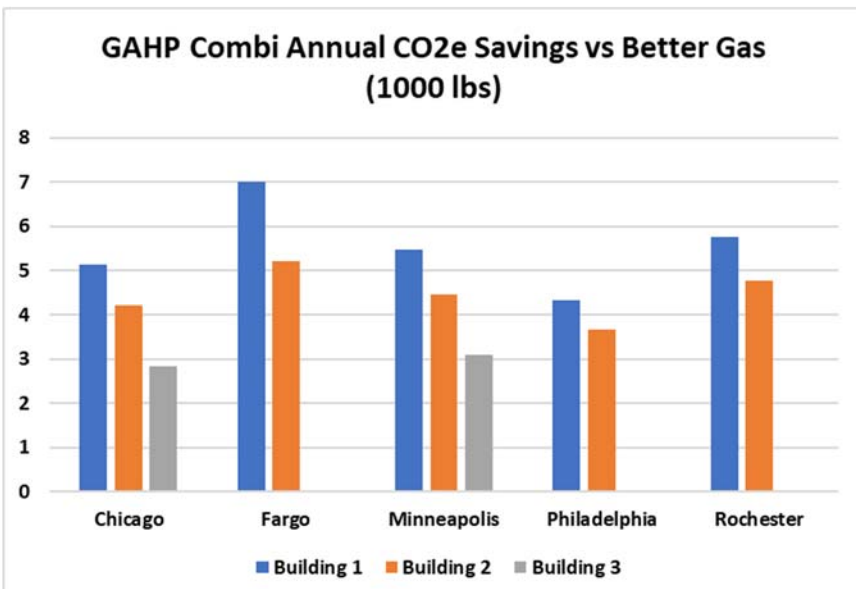

Figure 21– Annual GAHP CO2e emission savings for Buildings 1, 2, and 3 as compared to the “Better Gas” scenario

Figure 22 and Figure 23 compare the predicted operating cost and CO_2 equivalent emissions for the GAHP Combi and the electric scenarios against the “Better Gas” case.

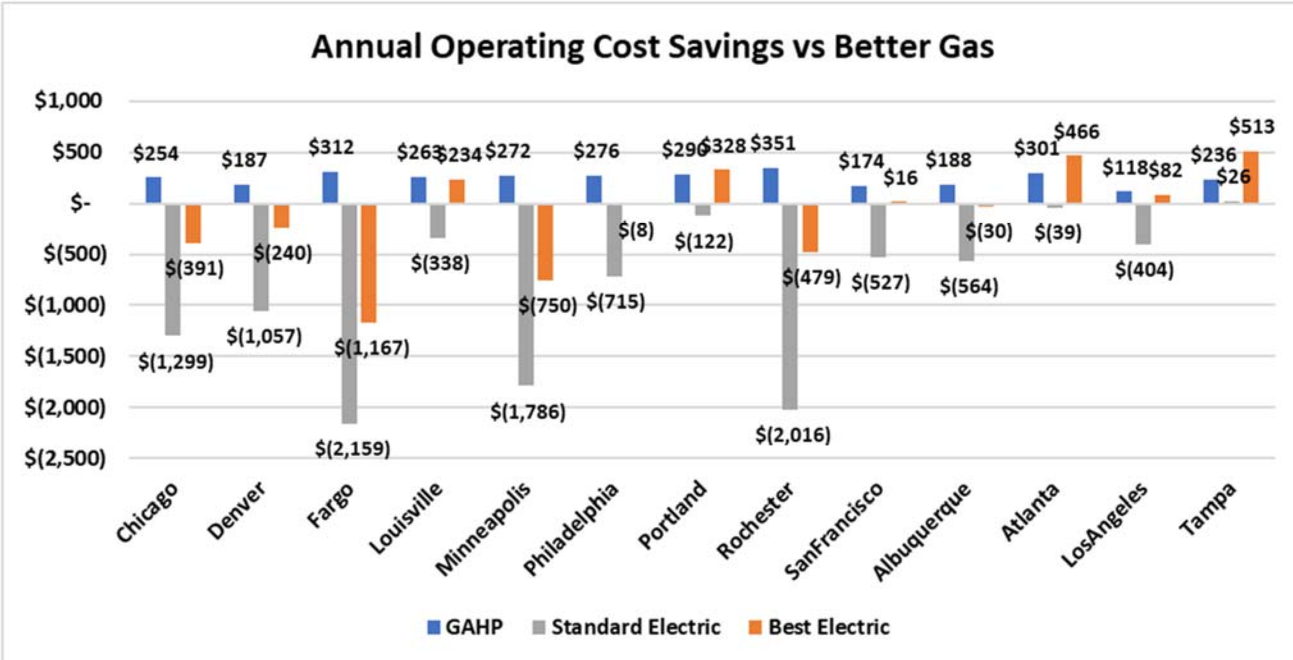

Figure 22 – Projected operating cost savings for the GAHP and the electric options versus the better gas case for Building 1. Includes heating, cooling, water heating, and fan energy use.

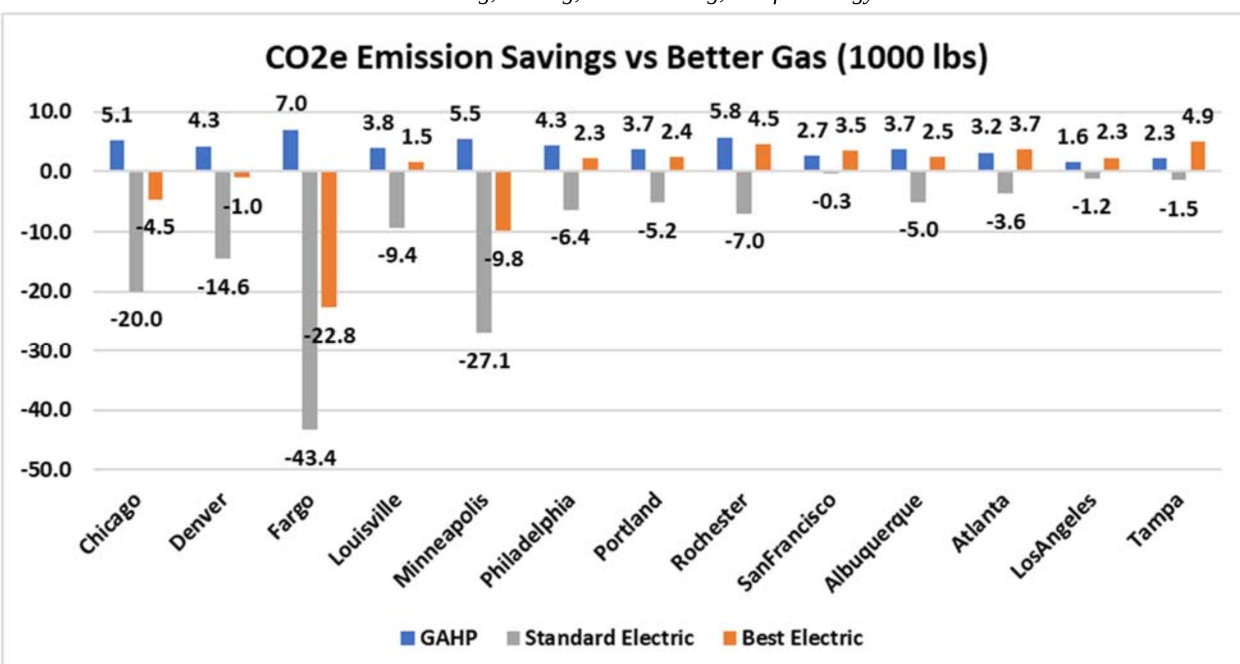

Figure 23 – Projected CO_2 equivalent emission savings for the GAHP and the electric options versus the better gas case for Building 1. Includes heating, cooling, water heating, and fan energy use.

Given the present residential energy prices (summarized in the next section) and the carbon intensity of the power generation grid (non-baseload/marginal power plants in all cases), the GAHP Combi is predicted to be the best and most cost-effective option for carbon reduction in residential retrofits in cold and mild climates. In most cases, the electric alternatives are predicted to have a negative savings for operating costs and CO_2 equivalent emissions. However, these results are very sensitive to the energy prices and carbon intensity of the electric grid. If natural gas price rose to $2/Therm, the annual operating cost savings of the "Best Electric" case would be comparable or better than the GAHP Combi. Similarly, a rise in electricity prices would push the operating cost savings of the electric options further into negatives.

3.2 Additional Simulation Results

This subsection presents additional simulation results for Buildings 2 and 3, not discussed elsewhere in the section.

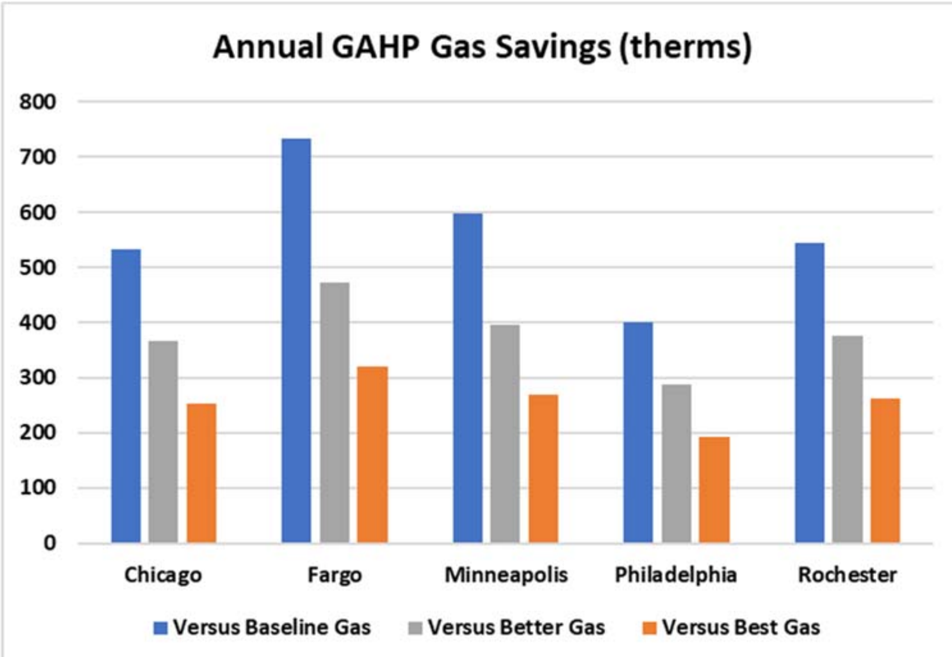

Figure 24 – Projected GAHP Combi gas savings for Building 2 against the alternative gas cases. Includes space and water heating.

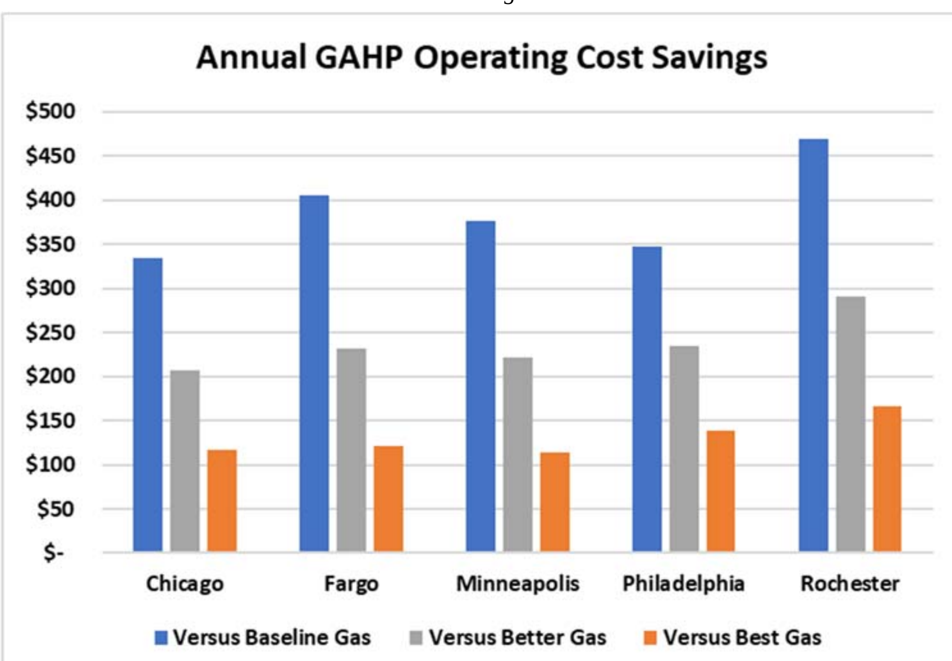

Figure 25 – Projected GAHP Combi operating cost savings for Building 2 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

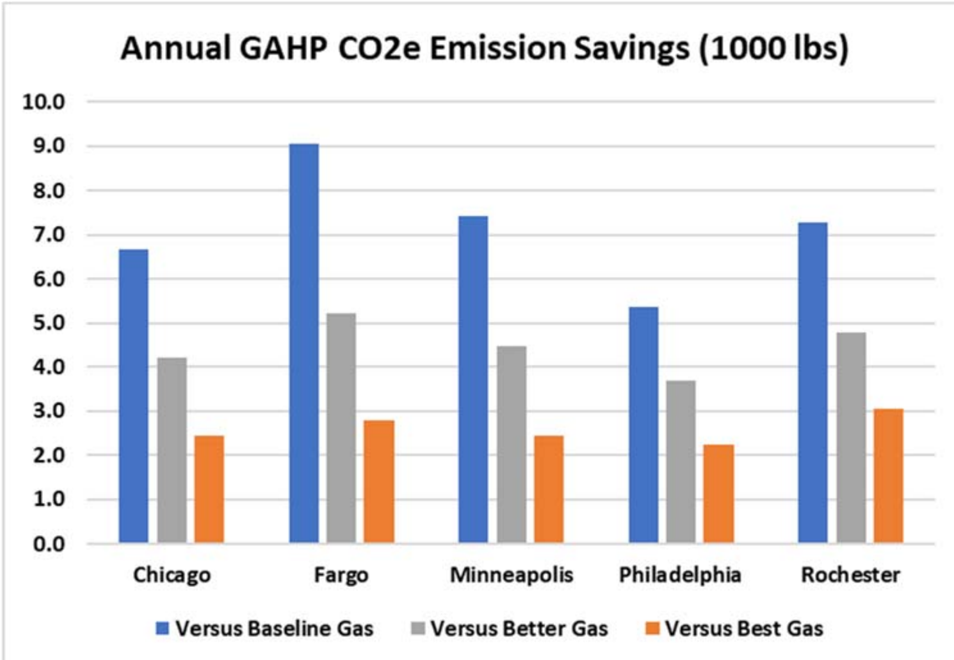

Figure 26 – Projected GAHP Combi CO_2 equivalent emission savings for Building 2 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

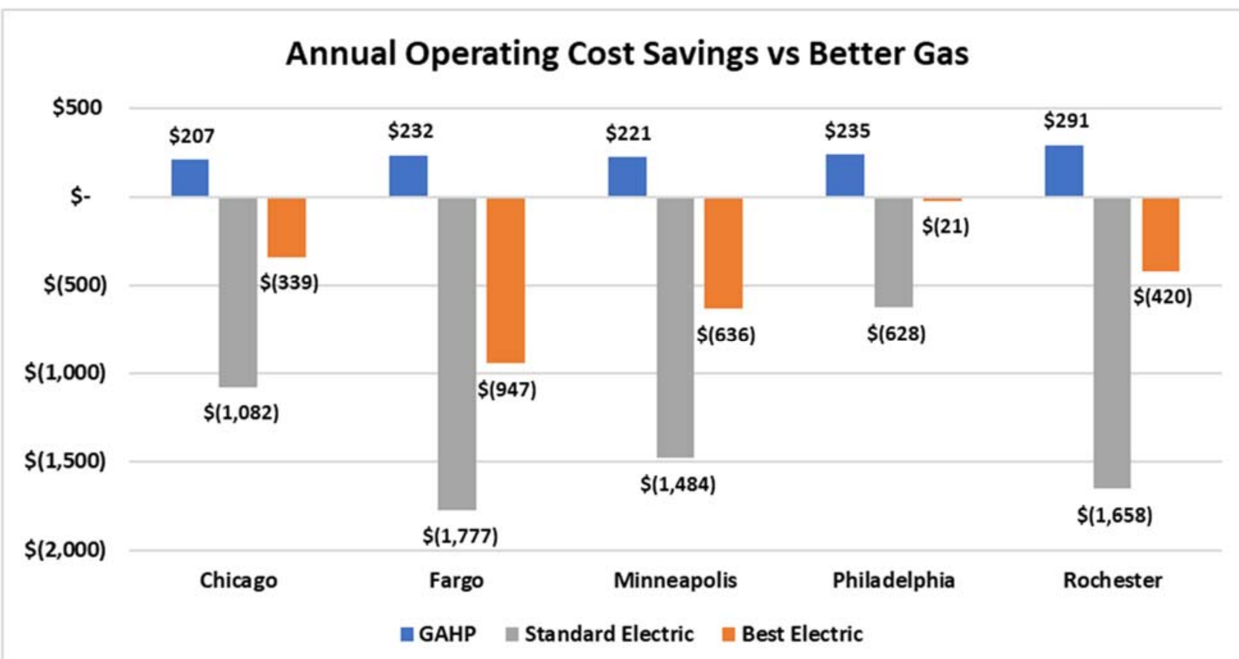

Figure 27 – Projected operating cost savings for the GAHP and the electric options versus the better gas case for Building 2. Includes heating, cooling, water heating, and fan energy use.

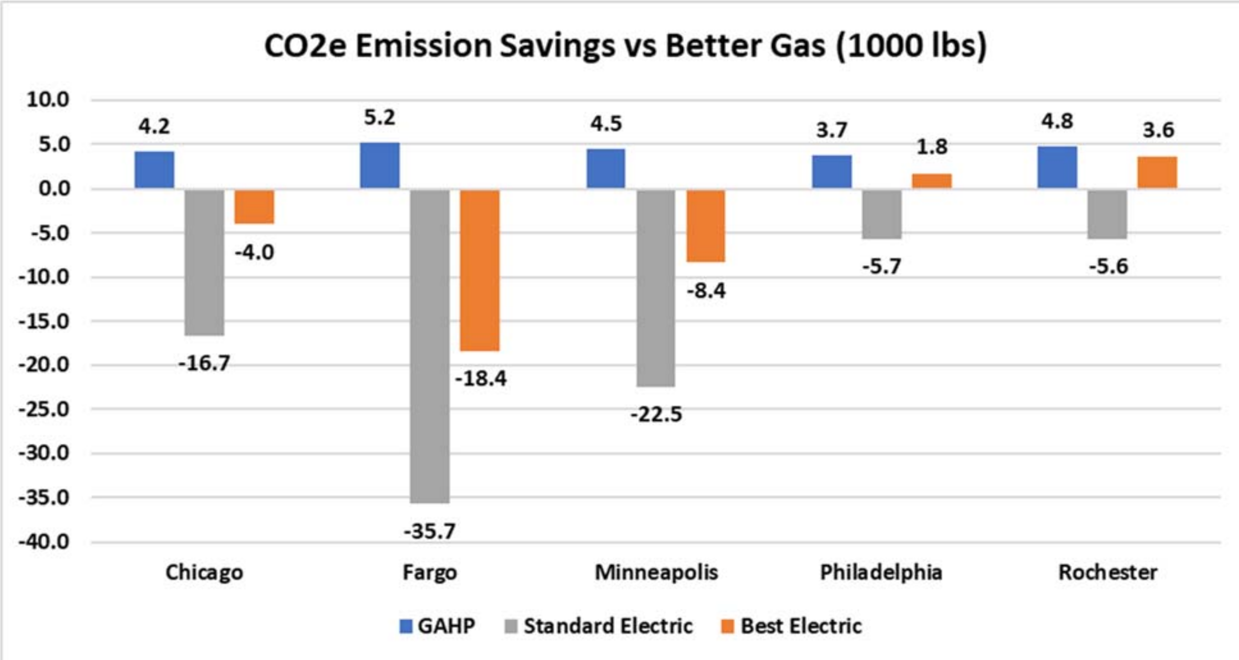

Figure 28 – Projected CO_2 equivalent emission savings for the GAHP and the electric options versus the better gas case for Building 2. Includes heating, cooling, water heating, and fan energy use.

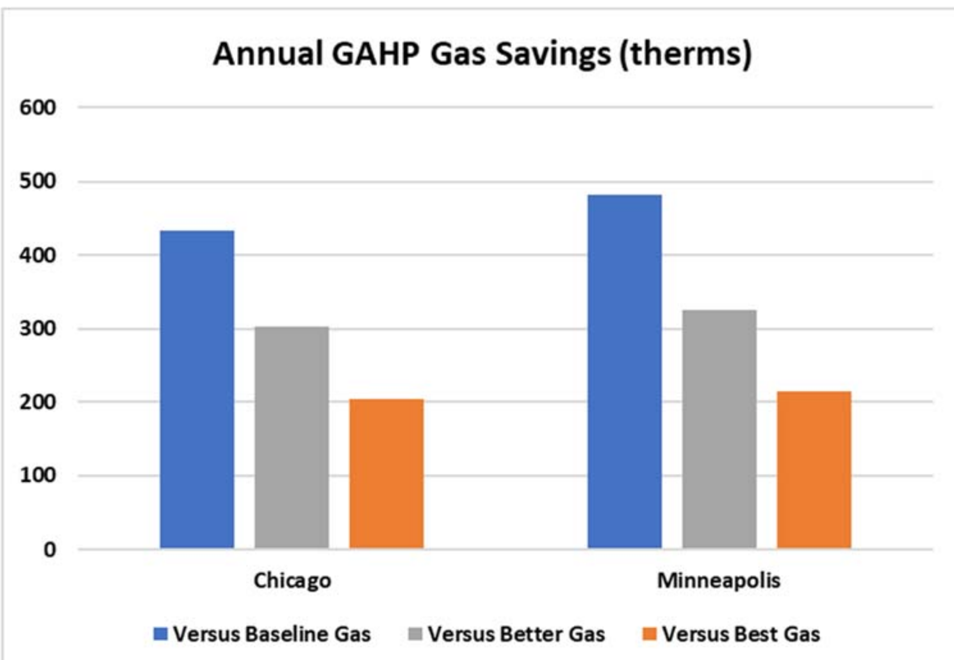

Figure 29 – Projected GAHP Combi gas savings for Building 3 against the alternative gas cases. Includes space and water heating.

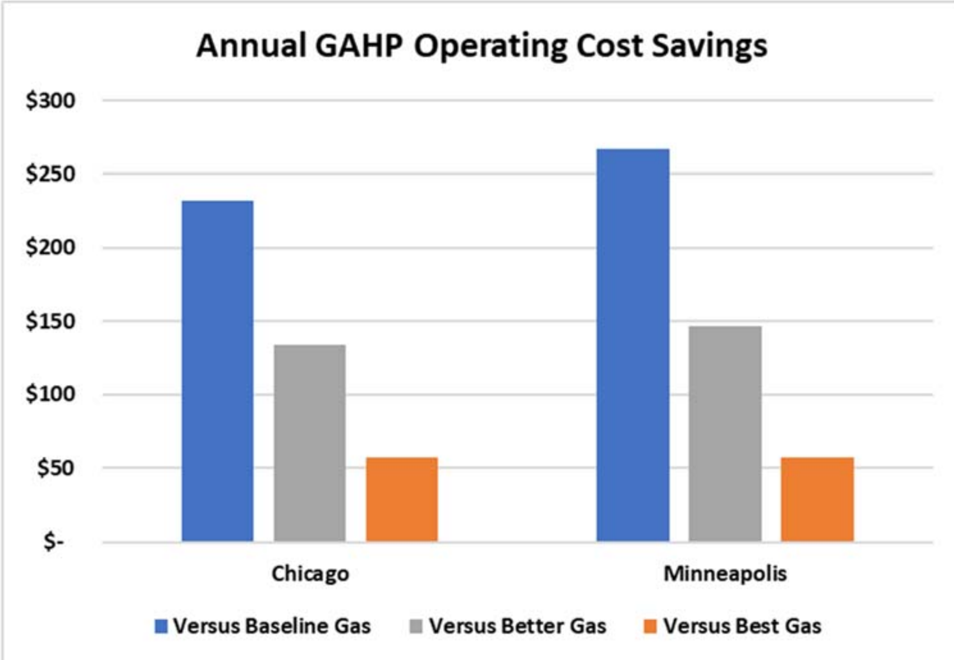

Figure 30 – Projected GAHP Combi operating cost savings for Building 3 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

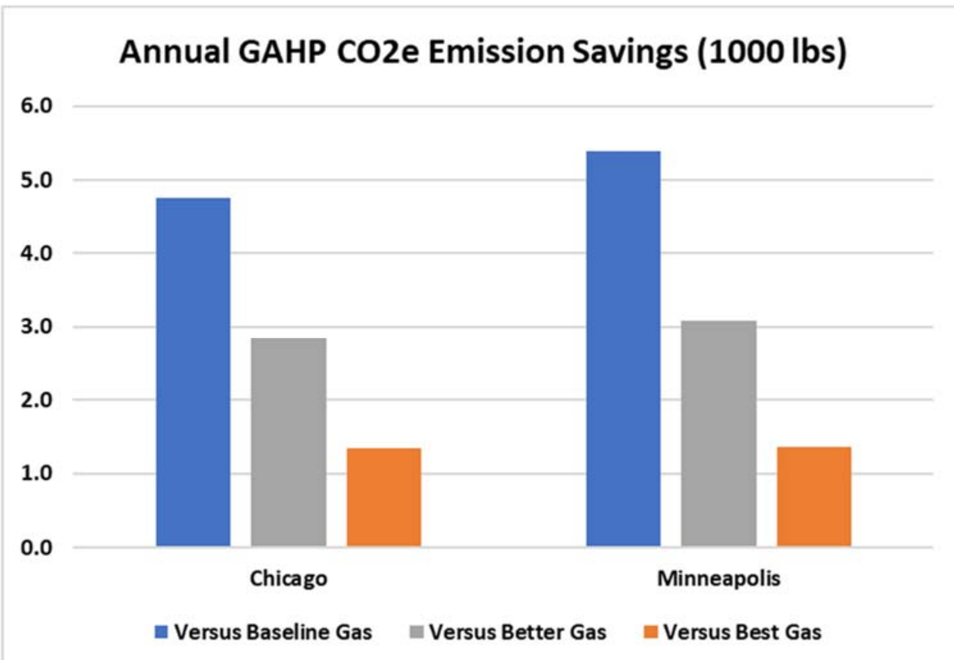

Figure 31 – Projected GAHP Combi CO_2 equivalent emission savings for Building 3 against the alternative gas cases. Includes heating, cooling, water heating, and fan energy use.

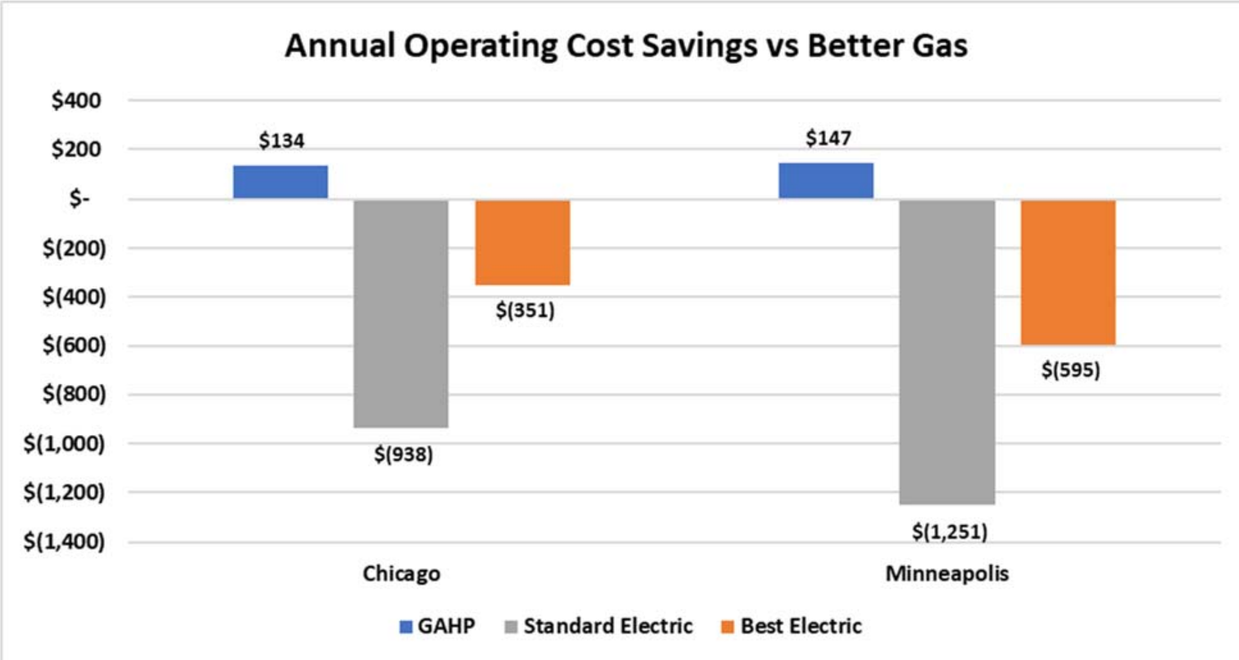

Figure 32 – Projected operating cost savings for the GAHP and the electric options versus the better gas case for Building 1. Includes heating, cooling, water heating, and fan energy use.

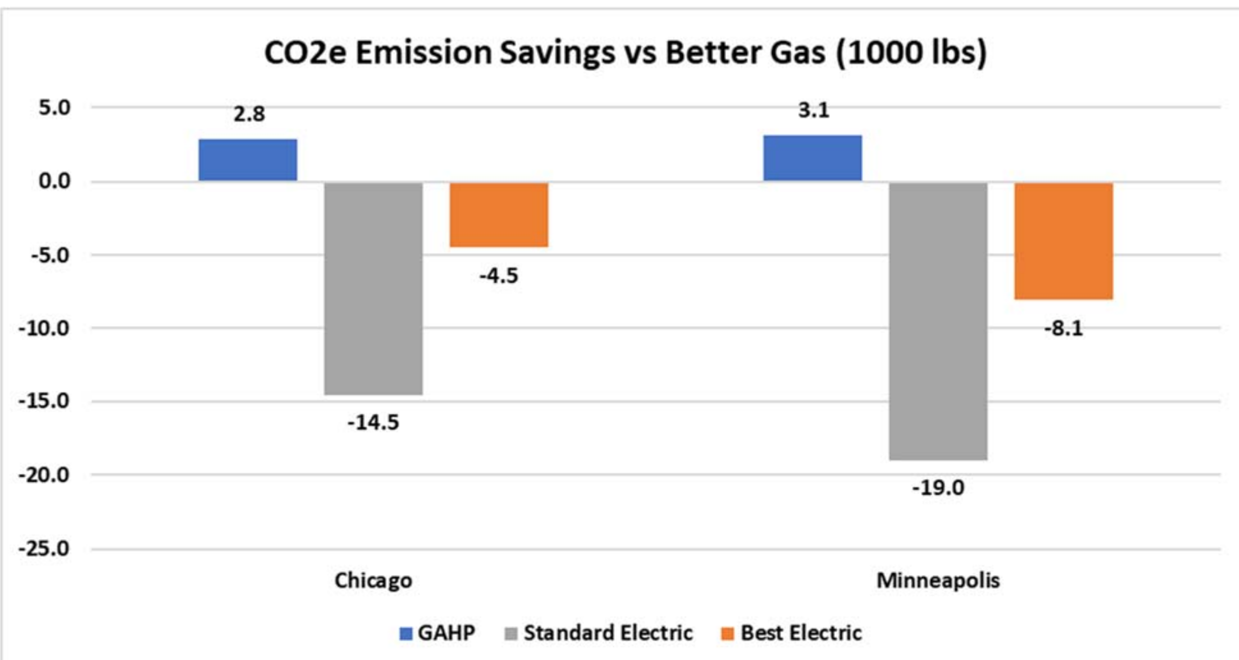

Figure 33 – Projected CO_2 equivalent emission savings for the GAHP and the electric options versus the better gas case for Building 3. Includes heating, cooling, water heating, and fan energy use.

4. Conclusions and Recommendations

The objective of this overall project is to address limitations within EnergyPlus in simulating advanced residential gas heating systems, including condensing furnaces, gas heat pumps, and combined space and water heating systems. In development for almost 20 years, EnergyPlus has emerged as the pre-eminent tool for estimate a buildings energy consumption and the impact of different energy efficiency measures, including envelop and HVAC. Given its open source nature, the onus of accurately representing gas HVAC systems has historically fallen on the industry. With support from UTD, this project has proceeded through two phases.

In Phase 1, GTI leveraged extensive data collected in the Virtual Test Home to advance EnergyPlus simulation capability for condensing furnaces and gas absorption heat pumps. Major accomplishments of Phase 2 include:

- A whole new mathematical framework was developed for simulating tankless based combis. Existing methods used in EnergyPlus were found to be inadequate at the onset of Phase 2. An extensive energy and cost savings analysis demonstrated the efficacy of the novel framework and how advanced tankless combi can produce energy and cost savings comparable to condensing furnace/water heater alternatives, something tankless combis struggled with in the past.
- The GAHP combi model was refined with new data for the latest pre-commercial prototypes. The new model was used in an extensive energy and cost savings analysis. The major conclusion was that the GAHP is the best and most cost-effective option right now (and for the foreseeable future) for reducing CO_2-equivalent emissions in majority of location around the US.
- Public dissemination of the results of this project has begun through conference presentations and journal articles being prepared for 2020-2021 publication.

The recommended next step is to push the results of Phase 1 and Phase 2 out to the public through direct updates to EnergyPlus. Additionally, a review of how current modeling and simulation tools are being used has highlighted a need for even simpler tools and calculators for estimating the energy consumption of advanced gas heating systems. Also proposed for Phase 3 is to develop simple correlations and estimators for combis and GAHPs to use with tools such as GTI's Energy Planning Analysis Tool, HERS Rating, and CBECC Res. Methods and tools developed as part of this project can also be expanded to analysis and model developed of commercial gas heating options. Further work on this topic should focus more broadly on gas and gas-electric hybrid heating systems in residential AND commercial applications.

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Appendices

Appendix A – Lumped Heat Capacity Tankless Simulation Method

To predict the energy consumption of tankless water heaters for this study, an accurate thermodynamic model was needed. While a variety of models exist with different levels of complexity, e.g., [10], the Lumped Heat Capacity (LHC) model originally developed at NREL [8] offered the right mix of complexity and simplicity. The advantage of this model is that it can be used to accurately predict the energy consumption of the water heater when subjected to realistic draw patterns and mains temperatures, which would otherwise be very time consuming to do in the lab [14] [6]. At the same time, this model can be readily implemented with tools such as EnergyPlus and to predict annual gas consumption in different climates and use cases.

The LHC model (1) is typically characterized by just three parameters.

$$C\frac{dT_{\mathrm{TWH}}}{dt} = \eta\dot{Q}_{\mathrm{gas}} - \dot{m}c_p(T_{\mathrm{TWH}} - T_{in}) - UA(T_{\mathrm{TWH}} - T_{env}) \quad (1)$$

- C – thermal capacitance of the heat exchanger
- η – steady state combustion efficiency
- UA – standby loss coefficient of the heat exchanger relative to ambient

The other terms in equation (1) are T_{TWH} tankless outlet temperature, $\dot{Q}_{\mathrm{gas}}$ is the firing rate, $\dot{m}$ is the mass flow rate of water, c_p is the specific heat of water, T_{in} is the inlet water temperature, and T_{env} is the temperature of the ambient environment. The model was integrated using the forward Euler method with 5-second draw data from the expeirments and 1-minute DHW demand data from EnergyPlus.

Special tests were conducted as part of task one to infer these parameters, illustrated in Figure 34. Two larger draws and two small draws with 2-hour standby periods in between were used as a training data set to provide an initial estimate of the LHC model parameters. It was found that a fourth parameter, $Qoverfire$, was needed to accurately predict heat delivered as well. This parameter accounts for slightly increased firing rate at the beginning of a draw.

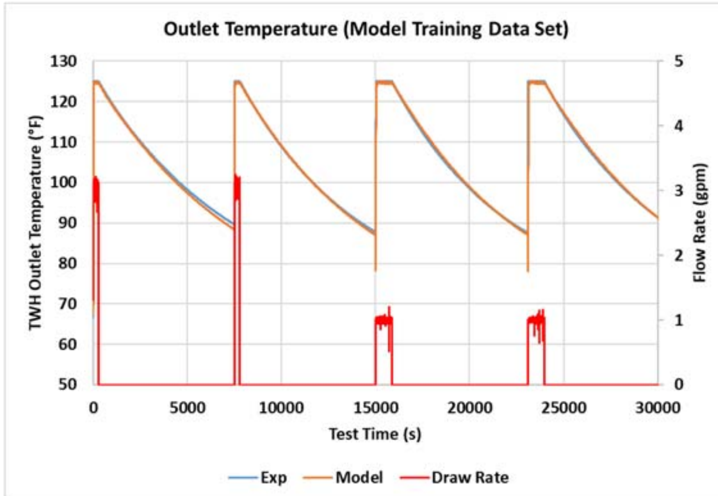

Figure 34 Model predictions compared to the training data set

The LHC model for each water heater was then optimized against the 24-hour UEF tests, using the training data set results as the initial guess. The optimization was performed using the nonlinear, generalized reduced gradient algorithm. Final model fits, while not perfect, could predict gas consumption and heat delivered to within 3% or less. Figure 35 and Figure 36 illustrate the quality of the fit and the predictive capability of the LHC model for the Model D water heater.

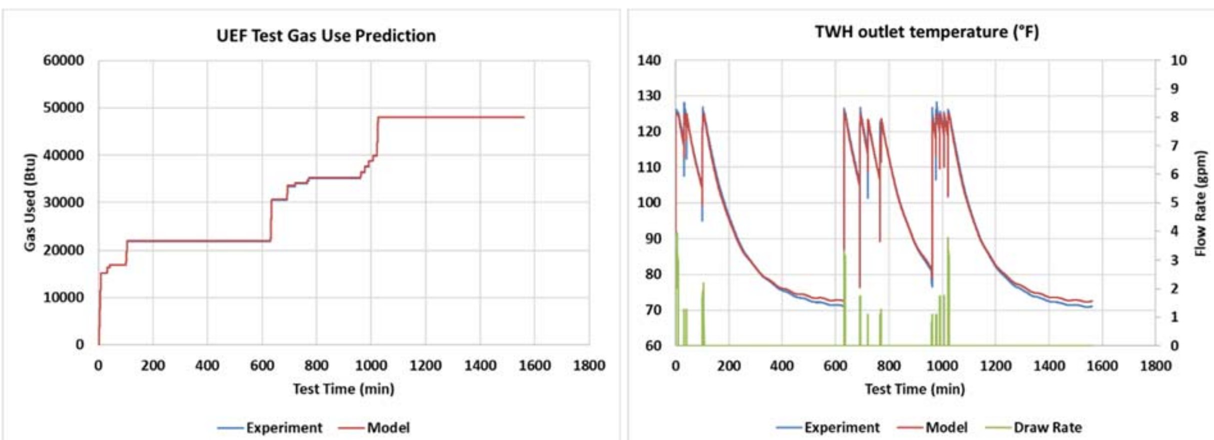

Figure 35. Predicted and experimental gas use (Left) and overall tankless temperature (Right) during the 24-hour UEF test

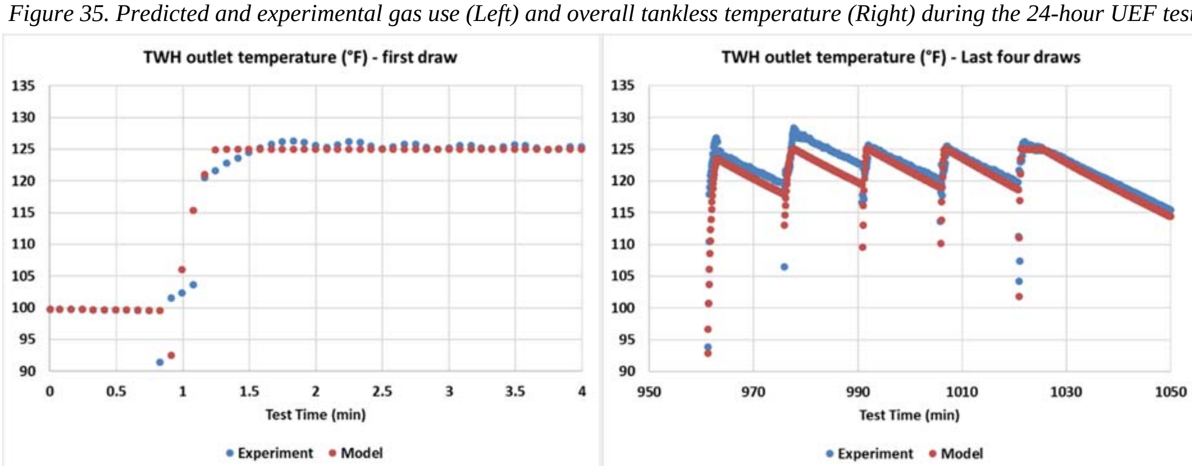

Figure 36. Predicted tankless outlet temperature compared to experimental measurements

Table 3 summarizes the inferred LHC model parameters for each tankless water heater tested. These parameters are similar in magnitude to prior studies [14] [8], however it is interesting to note that all of the parameters are similar in magnitude, despite differences in the actual water heater models. This is likely due to a statistical coupling between all four parameters in the optimization algorithm.

Table 3. LHC Model parameters for each water heater

Water heater	C [Btu/°F]	UA [Btu/hr-°F]	η_{ss}	Qoverfire [Btu/hr-gpm][2]
Model A	4.713	2.730	86.7	38534
Model B	4.559	2.375	97.3	35477
Model C	4.478	2.263	99.3	34251
Model D	5.675	3.029	98.2	36085
Model E	4.221	2.050	98.4	34102
Model F	4.522	2.270	98.5	36357
Model G	3.893	1.930	96.6	34878

[1]Used in energy savings and economic assessment
[2]Used only for estimate heat delivered

The model predictions of each water heater are compared in Figure 6. Despite the differences in rated UEF values, the performance characteristics of all the condensing tankless water heaters were similar. Model F water heater had performance characteristics that split the difference between the other models. For this reason, its LHC parameters were chosen for the energy savings analysis in this study.

Appendix B – Lumped Heat Capacity Method of Tankless Combis

The previous section demonstrated how all of the desirable combi model features were provided by a simple lumped heat capacity (LHC) model for tankless water heaters. Given that the hydronic air handler (AHU) is very similar in construction to a tankless, i.e., some volume of stored water ad metal heat exchangers, the LHC model can be applied to the AHU as well. It can be coupled to the tankless model through a shared term. Starting with the tankless LHC model (described in more detail in Appendix A), a term for heat supplied to the AHU ($\dot{Q}_{AHU}$) is added:

$$C_{TWH}\frac{\partial T_{\mathrm{TWH}}}{\partial t} = \eta\dot{Q}_{\mathrm{gas}} - \dot{Q}_{DHW} - UA_{TWH}(T_{\mathrm{TWH}} - T_{env}) - \dot{Q}_{AHU}$$

Using the same format and similar assumption, the AHU LHC governing equation is:

$$C_{AHU}\frac{\partial T_{\mathrm{AHU}}}{\partial t} = \dot{Q}_{AHU} - \dot{Q}_{\mathrm{SH}} - UA_{AHU}(T_{\mathrm{AHU}} - T_{env})$$

Where, C_{AHU}, T_{AHU}, and UA_{AHU} are the thermal mass, internal temperature, and overall heat transer coefficient for the air handler. $\dot{Q}_{SH}$ is the instantaneous space heating demand. Combining the two into a single energy balance equation, yields:

$$C_{AHU}\frac{\partial T_{\mathrm{AHU}}}{\partial t} + C_{TWH}\frac{\partial T_{\mathrm{TWH}}}{\partial t} = \eta\dot{Q}_{\mathrm{gas}} - \dot{Q}_{DHW} - \dot{Q}_{\mathrm{SH}} - UA_{TWH}(T_{\mathrm{TWH}} - T_{env}) - UA_{AHU}(T_{\mathrm{AHU}} - T_{env})$$

Similar to the tankless LHC model, it assumed that a single temperature can characterize the stored energy inside the AHU and TWH. Combustion efficiency is assumed constant. Heat transfer on the water side is assumed to be fast and therefore can be ignored. This above model necessarily assumes proper installation of the tankless combi, i.e., it is optimized to achieve condensing efficiency at all conditions by minimizing the return water temperature and maximizing combustion exhaust dew point.

During numerical integration using the Forward Euler method, this equations exists in two “states”. When there is a space and water heating call, if it assumed that the AHU and TWH reach their target temperatures quickly. The only unknown is $\dot{Q}_{\mathrm{gas}}$, and the equation is solved to determine the firing rate at each time step. In abscene of space heating calls, the above combi model reduces down to just a tankless LHC model.When there is no space or water heating call, the equation reduces down to:

$$C_{AHU}\frac{\partial T_{\mathrm{AHU}}}{\partial t} + A_{AHU}(T_{\mathrm{AHU}} - T_{env}) = 0 = C_{TWH}\frac{\partial T_{\mathrm{TWH}}}{\partial t} + \ UA_{TWH}(T_{\mathrm{TWH}} - T_{env})$$

This permits the individual temperatures of the AHU and TWH to be solved for during the standby period.

In order to validate this approach and to estimate the magnitude of the thermal mass and standby loss coefficienct for the AHU, the model was calibrated again GTI Virtual Test Home data for an advanced tankless combi. Using a simulated 24-hour space and water heating test profile, $\dot{Q}_{SH}$ and $\dot{Q}_{DHW}$ determined for 10-minute intervals, Figure 37. The the AHU LHC model parameters were then tuned to best reproduce cumulative gas use for the 24-hour period. Predicted gas use and AHU internal temperature are compared in Figure 38. The is able to accuretly predict the gas use but only qualitatively predicts the internal temperature of the AHU. This is an inherent limitation the approach since it represents the entirety of stored residual energy as a single temperature.

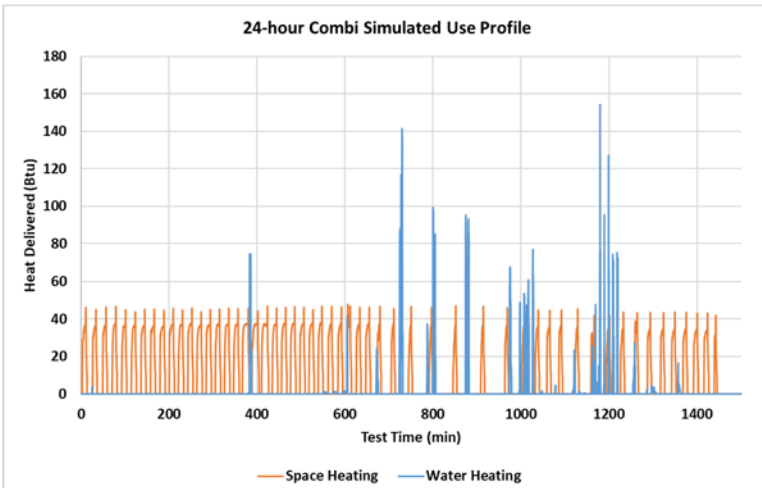

Figure 37. 24-hour simulated use Virtual Test Home profile for an advanced iFLOW tankless combi

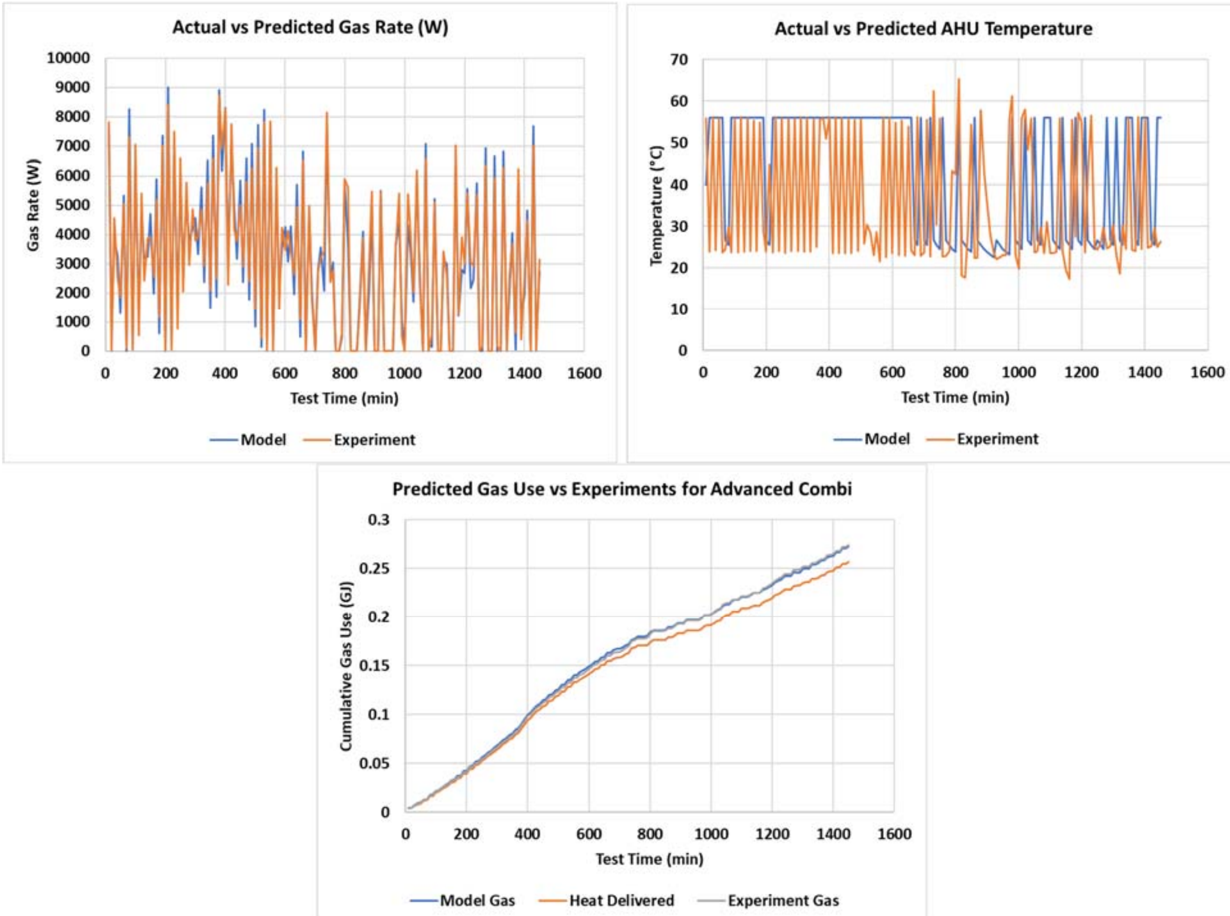

Figure 38. Predicted versus actual gas rate for the 24-hour Virtual Test Home combi test (TL). Predicted AHY temperature versus experimental measurements (TR). Predicted cumulative gas use compared to experimental mesurements during the 24-hour simulated use test.

Appendix C – GAHP Combi Model Assumptions

The GAHP combi was simulated by modifying the "Best Gas" scenario BEopt model (Section 8). The gas heating coil was replaced with a hot water heating coil to represent the hydronic air handler. The storage water heater was replaced with a stratified 9-node storage tank model, indirectly heated by the GAHP, and with heat loss characteristics similar to the tanks used in the field. The GAHP itself was modeled as a user-defined plant component and a custom Energy Runtime Language (ERL) script within the EnergyPlus input file. The "Best Gas" scenario was chosen as the basis to accurately capture the reduced infiltration of closed combustion heating systems. The duct heat-loss model as implemented in BEopt was preserved such that the overall space heating demand was not impacted.

The GAHP plant model acted as a simple heating device responding to demand from the space and water heating branches. The maximum heating capacity and the efficiency of the GAHP was determined using six unique performance curves, following a similar approach used in EnergyPlus for electric heat pumps[1]. The overall heating capacity of the GAHP was determined from the rated heating capacity and a function (CAPFT) of outdoor dry bulb temperature ($Tamb$) and hydronic return temperature ($Tret$):

$$GAHP\ Heating\ Capacity = Rated\ Heating\ Capacity * CAPFT$$

$$CAPFT = a1 * Tamb + b1 * Tamb^2 + c1 * Tret + d1 * Tret^2 + e1 * Tret * Tamb + f1$$

Table 4 – CAPFT coefficients

a1	b1	c1	d1	e1	f1
0.00428	-8.6E-05	0.004093	-0.00014	2.26E-06	1.011452

Knowing the maximum heating capacity of the GAHP for a given condition, the part load ratio (PLR) was determined according to:

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

The minimum modulation level of the GAHP is 25%, with a minimum cycle time of 45 minutes, resulting in a minimum PLR of ~0.2. If the requested load was below the minimum PLR, the GAHP would not activate. At other conditions, the GAHP would meet the heating load and consume gas according to the following equation:

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

Where, $EIRFT$ is the energy input ratio function of outdoor dry bulb and hydronic return water temperatures:

$$EIRFT = a2 * Tamb + b2 * Tamb^2 + c2 * Tret + d2 * Tret^2 + e2 * Tret * Tamb + f2$$

Table 5 – EIRFT coefficients

a2	b2	c2	d2	e2	f2
-0.00318	6.6E-05	0.011763	-6.1E-05	-4.8E-05	0.382999

$EIRFPLR$ is the energy input ratio function of the part load ratio:

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

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

To account for the defrost performance penalty (up to 4% near -2.8°C), an additional energy input ratio function of outdoor dry bulb temperature was use:

$$EIRDEFROST = -0.0011 * Tamb^2 - 0.006 * Tamb + 1.0317 \; for - 8.89°C \leq Tamb \leq 3.333$$

Between the minimum modulation rate at $PLRmin = 0.25$ and the minimum cycle time at $PLR = 0.2$, the GAHP is expected to cycle to meet load. An additional cycling penalty function was defined to account for increased energy use in this range:

$$CRF = 0.4167 * CR + 0.5833$$

Where CR is the cycling ratio, defined by:

$$CR = \frac{PLR}{PLRmin} \; for \; 0.2 \leq PLR \leq 0.25$$

Figure 39 through Figure 40 compare the predicted heating capacity, and coefficient of performance as a function of outdoor dry bulb temperature and part load ratio.

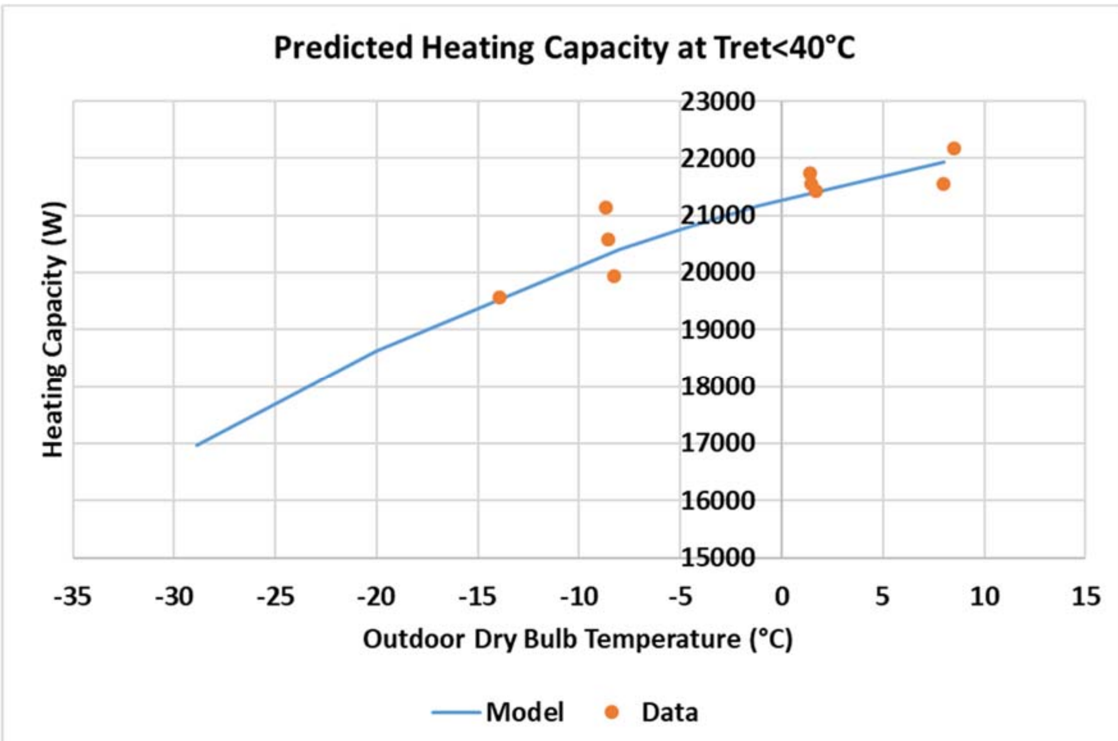

Figure 39 – Predicted heating capacity of the GAHP as a function of outdoor dry bulb temperature for a fixed return water temperature of 37°C

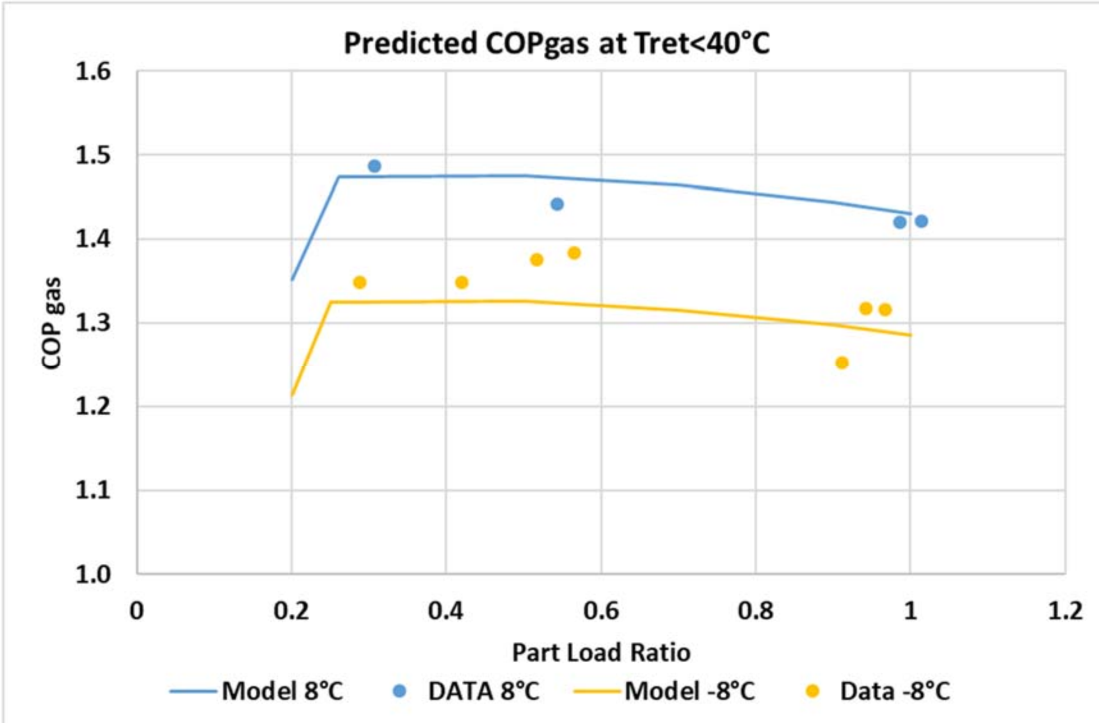

Figure 40 – Predicted COPgas for the GAHP as a function of part load ratio (PLR = load/capacity) for a fixed return water temperature of 37°C

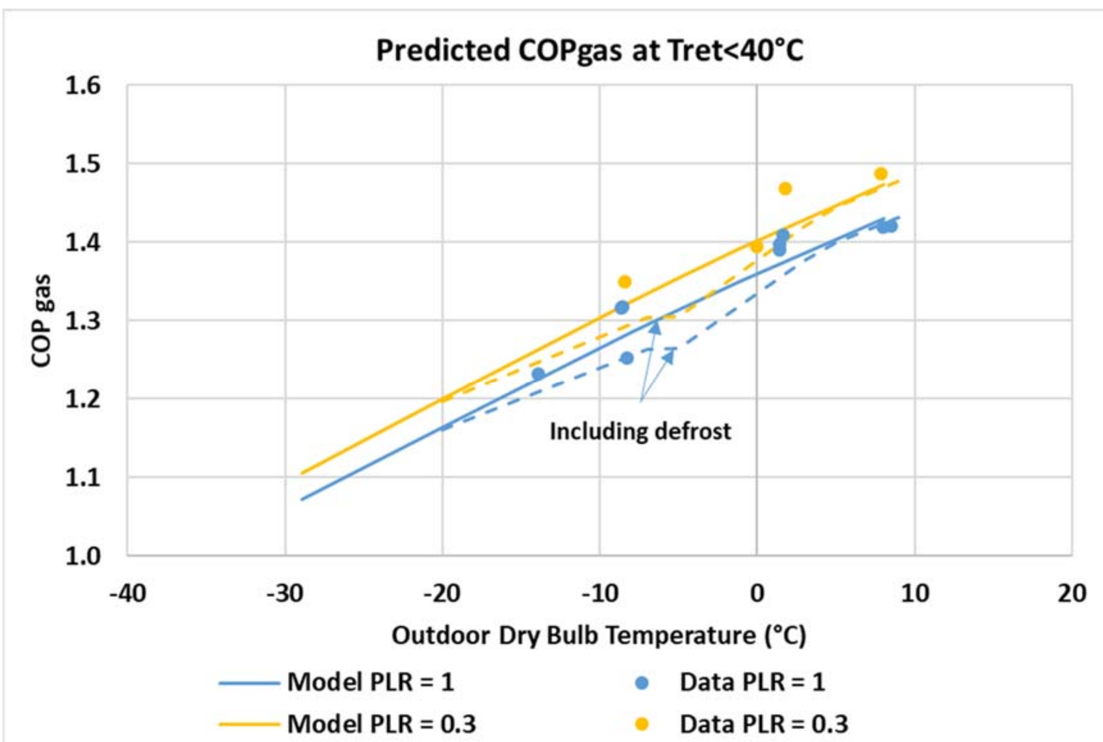

Figure 41 – Predicted COPgas as a function of outdoor dry bulb temperature for a fixed return water temperature of 37°C

The electricity use of the GAHP was modeled using a simple approach. The GAHP outdoor unit electricity usage was taken to be 2.7% of the heat delivered. The pump energy of the GAHP Combi was taken to be 1% of the heat delivered.

The supply temperature setpoint for the GAHP followed an outdoor air temperature reset for space heating, summarized in Table 6. The supply water temperature setpoint was fixed at 54.4°C for DHW recovery, to meet the mid-tank setpoint target of 51.67°C.

Table 6 – Outdoor air temperature reset strategy

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

The balance of the EnergyPlus model, e.g., tank and water heating coil heat transfer effectiveness, was tuned to achieve a typical return water temperature of ~105°F, as observed at the field demonstration sites.

For each location and building type, the rated heating capacity of the GAHP was autosized to better match the other HVAC scenarios which were all autosized by BEopt and to ensure that the GAHP could meet the peak heating load over the course of the year. This capacity was determined by dividing the maximum observed hourly heating load by the output of the $CAPFT$ function at the corresponding outdoor dry bulb temperature and an assumed return water temperature of 37°C. The minimum rated capacity of the GAHP was fixed at 13.2 kW to ensure that there was enough capacity to meet the DHW demand.

Appendix D – Building Model Assumptions

The building models used in GAHP and tankless combi analysis were developing using BEopt 2.8. The primary building characteristics are summarized in Table 1. The overall construction followed the IECC 2006 requirements for each climate zone[2]. *Table 7* summarizes all common and unique building envelope assumptions, as used with BEopt. Where not prescribed in IECC 2006 codes, default assumptions of the Building America House Simulation Protocols were used[3]. Typical home construction varies significantly by vintage, location, and extent to which energy efficiency retrofits have been performed, making it difficult to state definitively what is a "typical" retrofit scenario in each location. The IECC 2006 code was therefore chosen as the common reference point between newest construction and older construction homes.

Table 7 – Building model assumptions for each climate zone, as used with BEopt 2.8

Category Name	Climate Zone 7	Climate Zone 6	Climate Zone 5 + 4-marine	Climate Zone 4	Climate Zone 2, 3
	Walls				
Wood Stud	R-21 Fiberglass Batt, 2x6, 24 in o.c.	R-19 Fiberglass Batt, 2x6, 24 in o.c.	R-19 Fiberglass Batt, 2x6, 24 in o.c.	R-13 Fiberglass Batt, 2x4, 16 in o.c.	R-13 Fiberglass Batt, 2x4, 16 in o.c.
Wall Sheathing	OSB				
Exterior Finish	Vinyl, Light				
Interzonal Walls	R-13 Fiberglass Batt, 2x4, 16 in o.c.				
	Ceilings/Roofs				
Unfinished Attic	Ceiling R-49 Fiberglass, Vented	Ceiling R-49 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-30 Fiberglass, Vented
Roof Material	Asphalt Shingles, Medium				
Radiant Barrier	None				
	Foundation/Floors				
Foundation	Whole Wall R-10 XPS - Basement	Whole Wall R-10 XPS - Basement	Whole Wall R-10 XPS - Basement	Whole Wall R-10 XPS - Basement	Uninsulated slab
Carpet	40% Carpet				
	Thermal Mass				
Floor	Wood Surface				
Exterior Wall	1/2 in. Drywall				
Partition Wall	1/2 in. Drywall				
Ceiling	1/2 in. Drywall				
	Windows & Doors				
Window Areas (Fraction of Exterior Facade)	F15 B15 L15 R15				

2 National Energy and Cost Savings for New Single– and Multifamily Homes: A Comparison of the 2006, 2009, and 2012 Editions of the IECC, US DOE Building Technologies Program, 2012, PNNL-21329

3 Wilson, E., Horowitz, S., Building America Housing Simulation Protocols, NREL/TP-5500-60988

Windows	Low-E, Double, Non-metal, Air, M-Gain
Interior Shading Fraction	Summer = 0.7, Winter = 0.7
Door Area	20 ft^2
Doors	Steel
Eaves	2 ft
Overhangs	None
	Airflow
Air Leakage	8 ACH50
Mechanical Ventilation	None
Natural Ventilation	Year-Round, 3 days/wk
	Space Conditioning
Central Air Conditioner	Case Specific
Space Heating	Case Specific
Ducts	15% Leakage, R-8
Ceiling Fan	National Average
Dehumidifier	None
	Space Conditioning Schedules
Cooling Set Point	76 F
Heating Set Point	71 F
Humidity Set Point	None
	Water Heating
Water Heater	Case Specific
Distribution	Uninsulated, Trunk Branch, Copper
Lighting, Appliances, and Miscellaneous loads and schedules are Building America 2010 reference design	

Economic assumptions including electric grid carbon intensity factors and energy prices are summarized in *Table 8*. This information was obtained from the Source Energy and Emissions Analysis Tool[4], which itself aggregates information from the US Environmental Protection Agency Emissions & Generation Resource Integrated Database, US Energy Information Administration, and US Department of Energy national laboratory data sources.

4 http://seeatcalc.gastechnology.org/ (December 2019).

Table 8 – Economic assumptions used in the present analysis. Source: http://seeatcalc.gastechnology.org/ (December 2019)

Location	Gas Winter Price ($/Therm)	Annual Average Electricity Price ($/kWh)	Electric Grid CO2e* (lbms/MMbtu)	Gas CO2e Emissions (lbms/Mmbtu)	Site-to-Source Gas*	Site-to-Source Electric *
Chicago	$ 0.76	$ 0.125	627	148	1.09	3.27
Denver	$ 0.69	$ 0.121	588			3.21
Fargo	$ 0.67	$ 0.102	618			3.25
Louisville	$ 0.98	$ 0.105	585			3.15
Minneapolis	$ 0.77	$ 0.127	618			3.25
Philadelphia	$ 0.98	$ 0.139	496			3.1
Portland	$ 1.10	$ 0.107	527			3.04
Rochester	$ 1.05	$ 0.176	386			2.75
San Francisco	$ 1.14	$ 0.174	362			2.68
Albuquerque	$ 0.77	$ 0.120	494			2.93
Atlanta	$ 1.41	$ 0.115	488			2.93
Los Angeles	$ 1.14	$ 0.174	362			2.68
Tampa	$ 1.98	$ 0.110	425			2.80
*Non-baseload (marginal) power plants						