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Executive Summary

EnergyPlus™ is the US Department of Energy's 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.

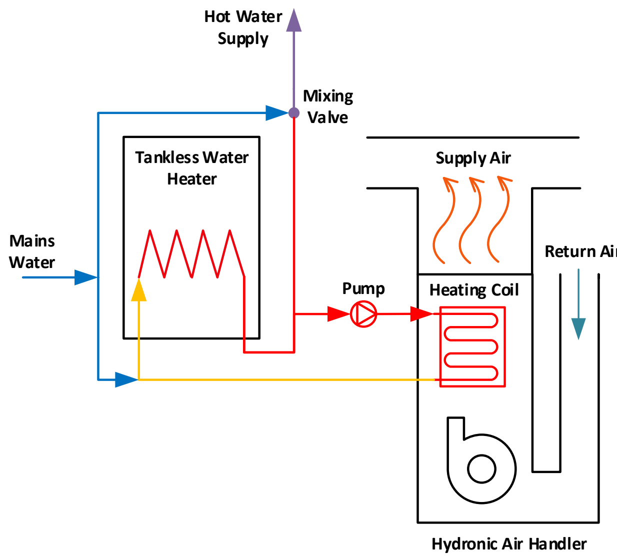

Figure E1. Gas Heat Pump testing at GTI Energy (L) and Tankless Combi schematic (R), both the focus of new model development

The primary objective of this project is to provide decision-makers accurate and reliable simulation tools for gas heating systems and to enable equitable comparisons of competing technologies. Phases 1 and 2 of this project focused on developing performance curves and models for condensing furnaces, gas absorption heat pumps (GAHPs), and tankless-based combis. Phase 3 of this project, described in this report, focused on dissemination of findings from prior phases as updates to EnergyPlus, as well as expanding into commercial HVAC modeling, and building energy model validation using real-world Zero Net Energy homes in California. Phase 3 highlights and accomplishments include:

Model Deployment With EnergyPlus

GTI published two peer-reviewed articles on modeling details of GHPs and tankless combis. The team then worked with a subcontractor to deploy a heating and cooling GAHP model in

EnergyPlus, which is available to beta testers as of writing of this report and will be fully available publicly as part of EnergyPlus 23.1 in March of 2023.

Reduced Order System Modeling

One of the key accomplishments of this task is the development of simple linear and quadratic correlations for annual gas consumption of GAHP combis, tankless combi, and several other gas heating scenarios. These new correlations permit relative savings to be quickly computed for these advanced gas heating systems in single family homes, without the need for detailed EnergyPlus runs.

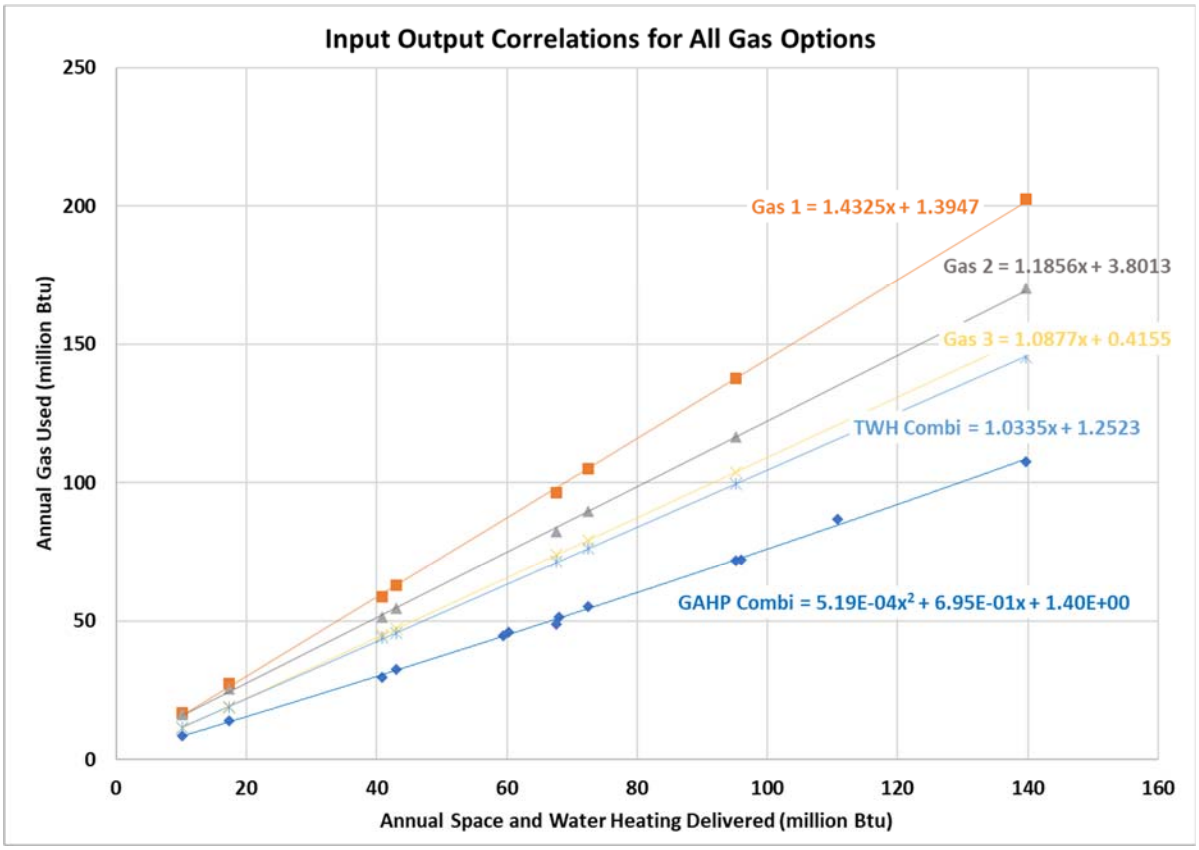

Figure E3. Input-Output correlations for different gas heating scenarios as a function of the annual space and water heating load.

ZNE All-electric and Mixed-fuel Home Modeling

GTI had the opportunity to monitor two Zero Net Energy homes in California and to perform a detailed building energy model calibration as well as validation of the tankless combi and electric heat pumps models. The field measurements generally showed good agreement with model predictions, for both mixed-fuel and all electric homes. These data provide validation for analyses GTI has performed under Phases 1 and 2 of this project, and the building models will be utilized in future efforts when modeling high-performance homes.

Figure E4. The two ZNE homes under construction in 2020. One was an all-electric home, while the second used a tankless combined space and water heating system. Both were monitored and used for validation of building energy models in this phase of the project.

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 can be used directly, it is more commonly used on the backend of other building energy software including OpenStudio, DesignBuilder, Autodesk Insight 360, and TRANE 3D Plus.

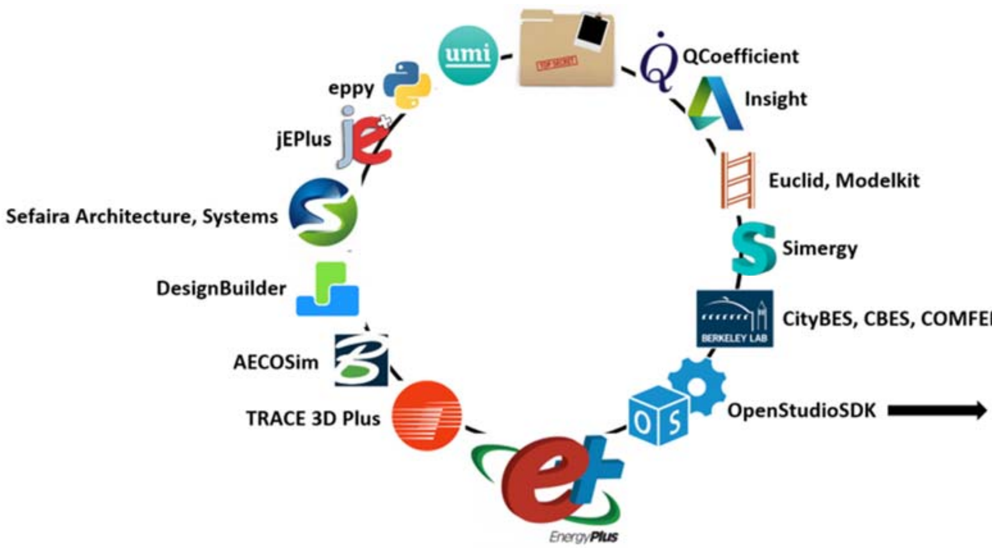

Figure 1. EnergyPlus ecosystem of dependent tools and services[1]

In development for over 20 years, it has become 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 do regional differences such as weather, building construction, vintage, and state adoption of energy building codes affect system efficiency? EnergyPlus permits the extrapolation of limited experimental data to the analysis of how different buildings consume energy throughout the year.

EnergyPlus has extensive support for building code compliance and ratings, e.g., Leadership in Energy and Environmental Design (LEED) and Residential Energy Services Network (RESNET) recently adopting the use of EnergyPlus in its Home Energy Rating System (HERS) rating 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

[1] EnergyPlus | Department of Energy

from its predecessor DOE2. More information regarding the current state of EnergyPlus and its future development is available in on its website[2].

EnergyPlus is open source, with DOE providing the primary support for its maintenance and development through National Renewable Energy Laboratory (NREL). In development for over two decades, portions of the software have not been updated since first release, with some modules tracing their roots to legacy building energy modeling software (e.g., DOE2 and BLAST). While regular updates to EnergyPlus are deployed on a semi-annual basis, the majority of the updates are bug fixes and performance improvements. New features and capabilities are added on a more limited basis, primarily driven by demand from the manufacturers, national labs, and consultants[3]. Most new features and improvements for equipment in EnergyPlus in the last 15+ years have been on electric systems, with a heavier focus on commercial HVAC. Therefore, the onus falls on the gas industry to contribute to the EnergyPlus project to ensure that gas heating and cooling systems are accurately represented, and models are deployed for emerging technologies like gas heat pumps.

Background and Objectives

The primary objective of this project is to provide decision-makers accurate and reliable simulation tools for gas heating systems and to enable equitable comparisons of competing technologies. Prior to the first phase of this project (2016-2017), EnergyPlus had a limited ability to model advanced gas heating systems, specifically, modulating furnaces, GAHPs, and combi systems. To address these limitations of EnergyPlus, GTI Energy leveraged technology performance data collected as part of other projects to develop the necessary performance curves and sub-models for GAHPs and condensing furnaces, permitting a detailed performance analysis to be performed, e.g., Fig. 2.

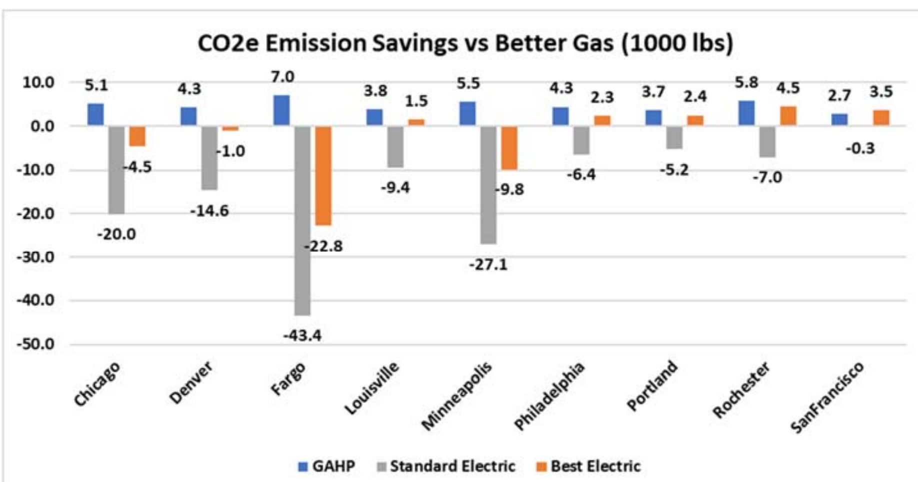

Figure 2. Predicted GAHP combi CO_2 equivalent savings (in thousands of pounds) in cold climate cities, compared to electric alternatives, with a condensing gas furnace baseline from modeling performed in Phases 1 and 2.

[2] https://energyplus.net/

[3] See example new feature requests for 2023: EnergyPlus_Prioritized_Feature_Requests_FY23.pdf

In Phase 2 (2018-2020), the furnace and GAHP models were further refined with new laboratory and field data collected by GTI Energy. To accurately simulate combis based on tankless water heaters, a whole new theoretical model was developed for tankless water heaters and combis for use with EnergyPlus (something completely missing previously). The fidelity of the new approach can be used as a research tool to predict the impact of regulatory requirements for open-loop combis.

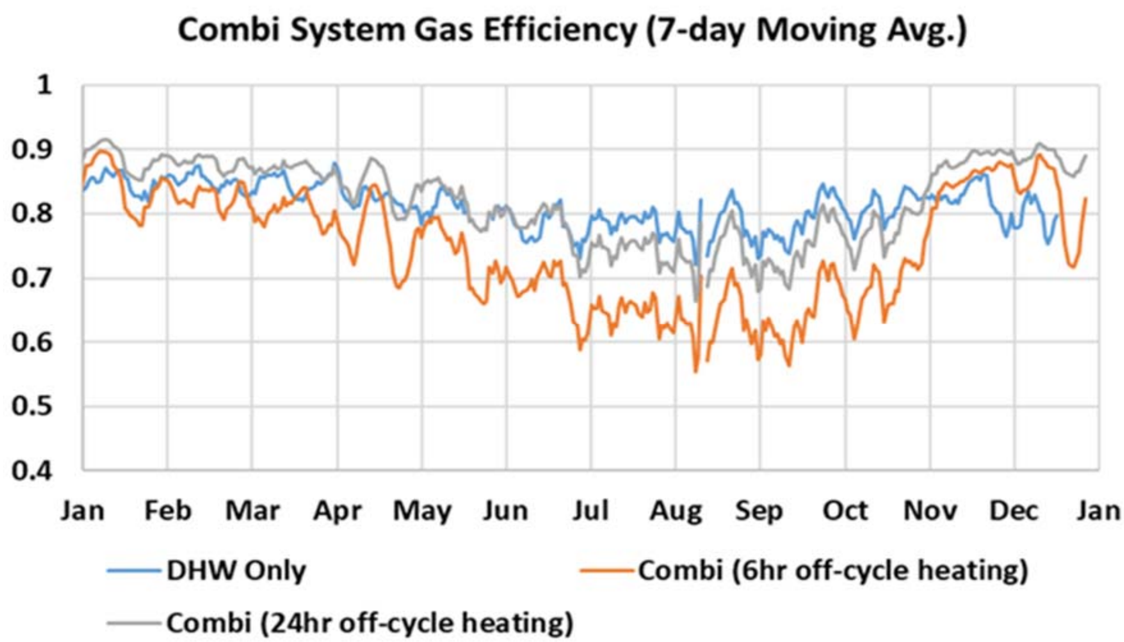

Figure 3. Predicted tankless combi performance and the impact of legionella management requirements, based on simulations performed in Phase 2 of this project.

This report summarizes the findings from the third phase of this project (2020-2022), that included the specific objectives of:

1. Disseminate project findings and models developed in Phases 1 and 2, including Gas Absorption Heat Pumps (GAHP) and tankless water heaters and combis, through direct updates to EnergyPlus.
2. Model validation using field measurements of a side-by-side comparison of an all-electric and mixed-fuel Zero Net Energy (ZNE) homes in California.

The following report sections provide an overview of major findings from each project task associated with these goals. Where needed, the report appendices provide additional detail on methods and results. This public version of the report excludes some additional analysis performed on other topics, since those results were of a preliminary nature.

Model Deployment with EnergyPlus

The primary objective of this task was to deploy the models developed for the GAHP and tankless combis in Phases 1 and 2 of this project with EnergyPlus, pictured in Figure 4. The key outcome of this work was to make the results of prior phases available to the EnergyPlus community as well as the broader public.

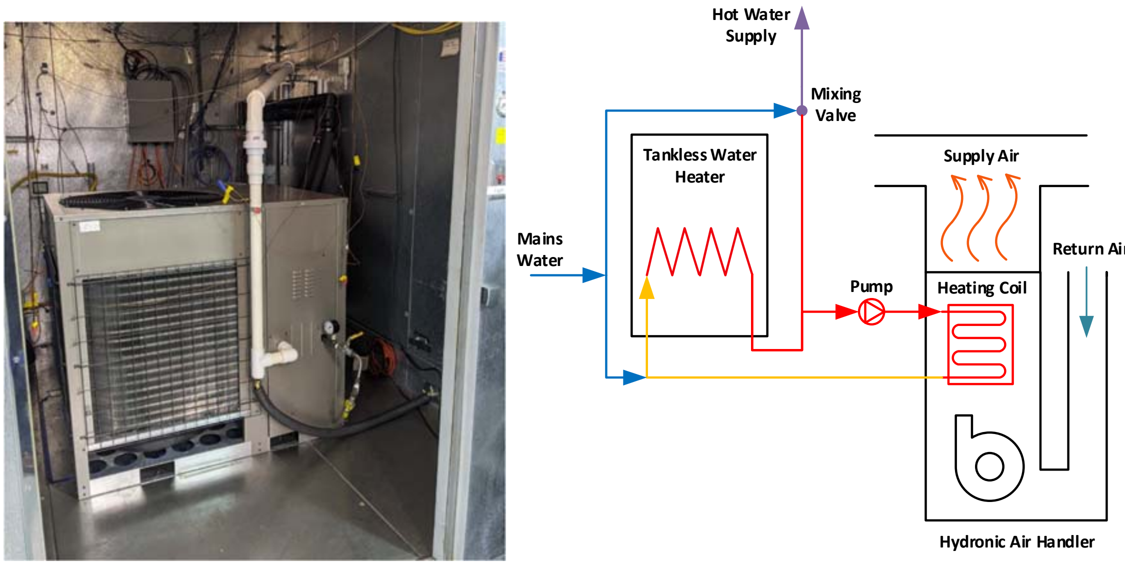

Figure 4. SMTI GAHP testing at GTI Energy (L) and Tankless Combi schematic (R)

GTI Energy first developed the results from prior phases into “Engineering Documentation” for these models in the form of peer-reviewed publications. This effort resulted in two peer-reviewed publications and presentations:

1. Fridlyand, A., Glanville, P. and Garrabrant, M., 2021. Pathways to Decarbonization of Residential Heating. *Proceedings of the International High Performance Buildings Conference,* 2021, Purdue University, https://docs.lib.purdue.edu/ihpbc/354/
2. Fridlyand, A., Guada, A.B., Kingston, T. and Glanville, P., 2021. Modeling Modern, Residential, Combined Space and Water Heating Systems Using EnergyPlus. ASHRAE Transactions, 127(1).

With publication of these papers, GTI Energy engaged the EnergyPlus DOE project leads at National Renewable Energy Laboratory about deploying new EnergyPlus features based on these efforts. For the Tankless Combis, the primary limitation that resolved in Phase 2 of the project was the lack of a realistic tankless water heater model. The building energy modeling team at NREL was able to secure funding directly from DOE to deploy an update to the tankless water heater model in EnergyPlus, based on the work performed on this project. While GTI was ready to share data and provide support, project delays at NREL have pushed out the development of these planned features. As of the writing of this report, an updated tankless water heater model was a "high priority" new feature for 2023[4], which GTI Energy will support under Phase 4 of this project.

For the GAHP combi model, GTI Energy engaged an approved EnergyPlus developer to translate the model GTI Energy developed into an EnergyPlus model. The published paper, as well as other notable efforts by the industry like the GHP roadmap and pilots, were used as the justification for why the new feature was necessary. GTI Energy then worked with the subcontractor to develop the model specification as well as further documentation. The subcontractor then wrote the code, completed the EnergyPlus team review process, and as of the submission of this report, the new model features are included in the "feature frozen" release of EnergyPlus 23.1, prior to the full public release at the end of March 2023. This version of EnergyPlus is available for beta testers on GitHub[5]. The details of the new feature as well as the outcomes of the review can be found on GitHub as well[6].

```
doc/acknowledgments/src/notices-and-acknowledgments/other-acknowledgments.tex
@@ -9,3 +9,5 @@ \section{Other Acknowledgments}\label{other-acknowledgments}
 The HAMT (Heat And Moisture Transfer) model was supported by the Engineering and Physical Sciences Research Council (EPSRC), the UK government agency for funding research and training in engineering and the physical sciences.

 The SQLite output module was funded by Building Synergies, LLC and was made possible by inclusion of software code from the SQLite project (\url{http://www.sqlite.org/}).
+
+The fuel-fired absorption heat pump (HeatPump:AirToWater:FuelFired:Heating and Cooling) model development was funded by Utilization Technology Development (\url{https://www.utd-co.org}) on a subcontract with GTI Energy (\url{https://www.gti.energy/}). See Pull Request 9405 (\url{https://github.com/NREL/EnergyPlus/pull/9405}).
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Figure 5. Code snippet attributing the contribution to UTD and GTI Energy.

The final contribution consists of the model code, performance curves from the GTI Energy publication (based on the SMTI prototype GAHP combi), as well as EnergyPlus documentation, and example files. The GAHP model itself was deployed as a more generic "Fuel-Fired Air to Water Heat Pump" for both heating and cooling applications. In anticipation of future GHP products, the model itself is written in a flexible performance-curve based formulation that should be able to accommodate any air-to-water fuel-fired heat pump (e.g., Robur, Vicot, and ThermoLift). With the final EnergyPlus 23.1 release, the new model will also begin to propagate to other tools based on EnergyPlus, likely in the second half of 2023. Continued work at GTI Energy under Phase 4 will focus on developing more performance data for different GHPs as well as more case studies for the GHP in multi-family and commercial applications.

[4] EnergyPlus_Prioritized_Feature_Requests_FY23.pdf
[5] Release EnergyPlus 23.1.0 IOFreeze · NREL/EnergyPlus · GitHub
[6] Gas-Fired Absorption Heat Pump (GAHP) model by jcyuan2020 · Pull Request #9405 · NREL/EnergyPlus · GitHub

Reduced Order System Modeling

The objective of this task is to use the results of a large parametric analysis for GAHPs and tankless combis to enable easy estimation of energy consumption of these systems without the use of EnergyPlus. While EnergyPlus is a powerful tool, it can be cumbersome to use, especially for when all that's necessary are simple estimates of performance and energy savings potential. To address this limitation, GTI Energy has performed a detailed data analysis on all simulations performed for GAHPs, tankless combis, and furnaces for residential applications to develop simple correlations and reduced-order model fits that could provide a first-order approximation of annual performance of these systems in different climates, similar to how equipment ratings are used.

Additionally, with these correlations, it will be easier to integrate advanced gas heating options into tools used for rating and compliance such as CBECC-Res, Rem/Rate (HERS Index Rating), and GTI's Energy Planning Analysis Tool ("EPAT")[7]. These specific tools, and many other simple calculators, do not rely on EnergyPlus to determine HVAC energy use; they tend to be far more rudimentary and often rely on appliance ratings and simple correlations. This task sought to address the limitation of these tools in being unable to simulate advanced gas HVAC options for single family homes.

Methods

This task repurposes GAHP and tankless combi simulations previously performed under Phase 2 of this project, as well as under UTD project 1.18.H. The detailed simulations performed previously covered all major North American climate zones, multiple home sizes, as well as several different HVAC scenarios. The details of the detailed simulations performed are summarized in Phase 2 final report as well publications by NEEA[8], ASHRAE[9], and Purdue University[10]. A summary of locations considered, home sizes, as well the gas HVAC scenarios considered are provided in Table 1 and Table 2.

[7] Welcome - Energy Planning Analysis Tool (gti.energy)

[8] Northwest Energy Efficiency Alliance (NEEA) | Lab Testing of Tankless...

[9] Fridlyand, A., Guada, A.B., Kingston, T. and Glanville, P., 2021. Modeling Modern, Residential, Combined Space and Water Heating Systems Using EnergyPlus. *ASHRAE Transactions*, *127*(1).

[10] Fridlyand, A., 2022. Load-based Testing of Heating and Cooling Equipment Informed by Detailed Energy Models.

Table 1. Locations and heating loads for a IECC 2006, 3000 sq-ft home, with 4 bedrooms, and 3+ baths.

Location	Climate Zone	Degree Days (EnergyStar 2019)	SH Del (mmBtu)	DHW Del (mmBtu)
Fargo	7-dry	9293	124	16
Minneapolis	6-moist	7821	96	15
Rochester	6-moist	6359	82	14
Chicago	5-moist	6184	81	14
Philadelphia	5-moist	5209	55	13
Denver	5-dry	5934	59	13
Louisville	4-moist	4151	49	12
Portland	4-marine	3940	55	13
Albuquerque	4-dry	3944	47	12
Atlanta	3-moist	2895	32	11
San Francisco	3-marine	2592	29	12
Los Angeles	3-dry	1002	7	10
Tampa	2-moist	403	2	8

Table 2. Gas HVAC scenarios considered in the present analysis.

HVAC Scenario	Space Heating	Water Heating
Gas 1	Gas Furnace – 80% AFUE	62 UEF, 50-gal water heater
Gas 2	Gas Furnace – 95% AFUE	62 UEF, 50-gal water heater
Gas 3	Gas Furnace – 95% AFUE	96 UEF, Tankless Water Heater
Tankless combi	96 UEF, Tankless Water Heater + Hydronic Air Handler Unit	
GAHP combi	Air-to-water GAHP + Hydronic Air Handler Unit + Indirect Storage Tank	

The performance-curve based model developed in Phase 2 and deployed with EnergyPlus in 2023 is itself a simple model. However, it requires the knowledge of hourly space and water heating loads and some simplified assumptions about the heat exchangers to be utilized. This is indeed the approach used in the current version of GTI Energy's EPAT[7]. Therefore, the simplification developed here addresses the scenario for when the hourly loads are not available, but the annual space and water heating loads are known. In absence of this information, Table 1 can be used to get an estimate.

In addition to developing correlations for GAHP and Tankless combis, similar correlations were developed for the other typical gas HVAC scenarios in Table 2. This is necessary because using the correlations described below with standard ratings for furnaces and water heaters would underestimate the potential savings of the advanced systems. Standard ratings for furnaces and water heaters are inadequate for estimating annual gas usage accurately. It is therefore expected that any calculation performed with the combi correlations would include all the HVAC scenarios for comparison.

The correlations developed here are based on simple "Input – Output" relationships. This is an effective approach frequently used when daily space and water heating loads are known[8]. The primary difference here is that the "Input" is annual space and water heating delivered (in million

Btus), while the "Output" is annual gas use (in millions Btu). While more complicated relationships with more terms were evaluated, the simplest "Input – Output" relationships proved to be most accurate for all HVAC scenarios. Figure 6 plots the Output vs Input relationship for all the GAHP combi scenarios considered, indicating how well the data aligns with a simple linear (or quadratic) relationship, regardless of location or home size.

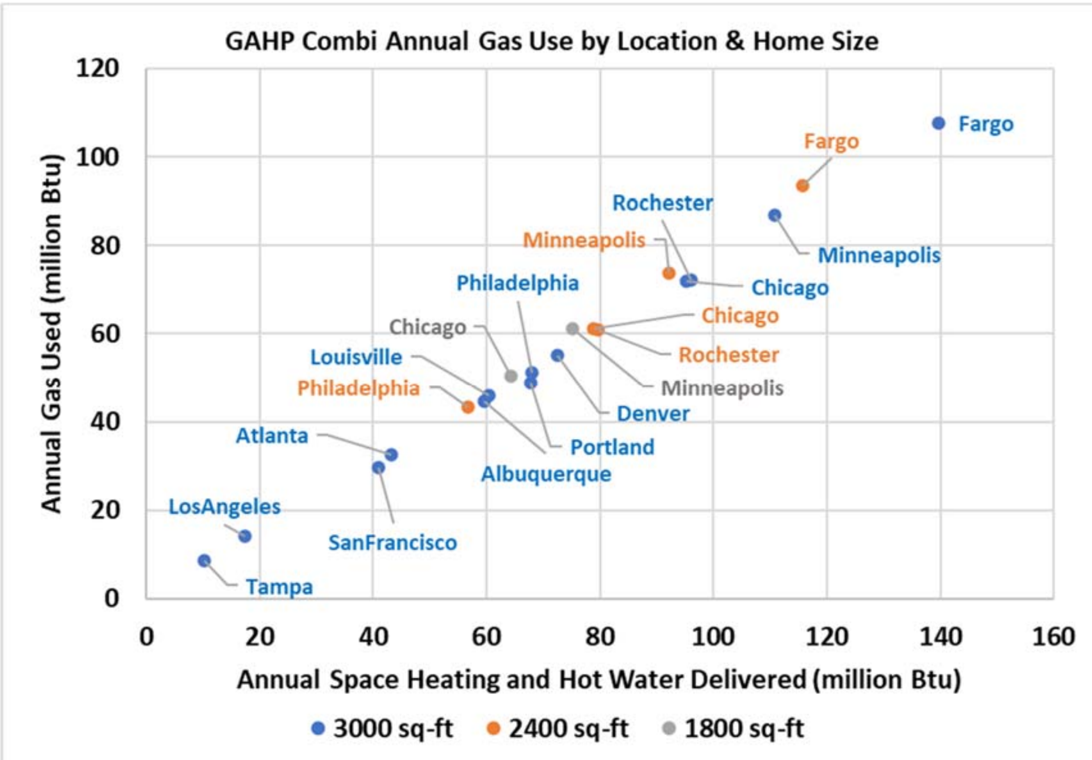

Figure 6. Relationship between GAHP combi annual gas use, building space and water heating load, and home size. Most significant factor in determining heating load is the location, followed by home size.

Major Findings

The Input – Output relationships developed are summarized in Figure 7. It is important to emphasize that the Input is the combined space and water heating load (in million Btus). While not as important for Gas 1 – 3 cases, given the interaction of space and water heating loads for the combi systems, combined loads were used for the correlations. If instead the annual gas efficiency is desired instead of the gas, it can be calculated by dividing the "Input" by the "Output" values from each correlation. Figure 8 plots the outcome of this calculation and compares the GAHP combi gas efficiency with the detailed model results from Phase 2. The overall fit is satisfactory, with a maximum error of ~3% for the GAHP combi.

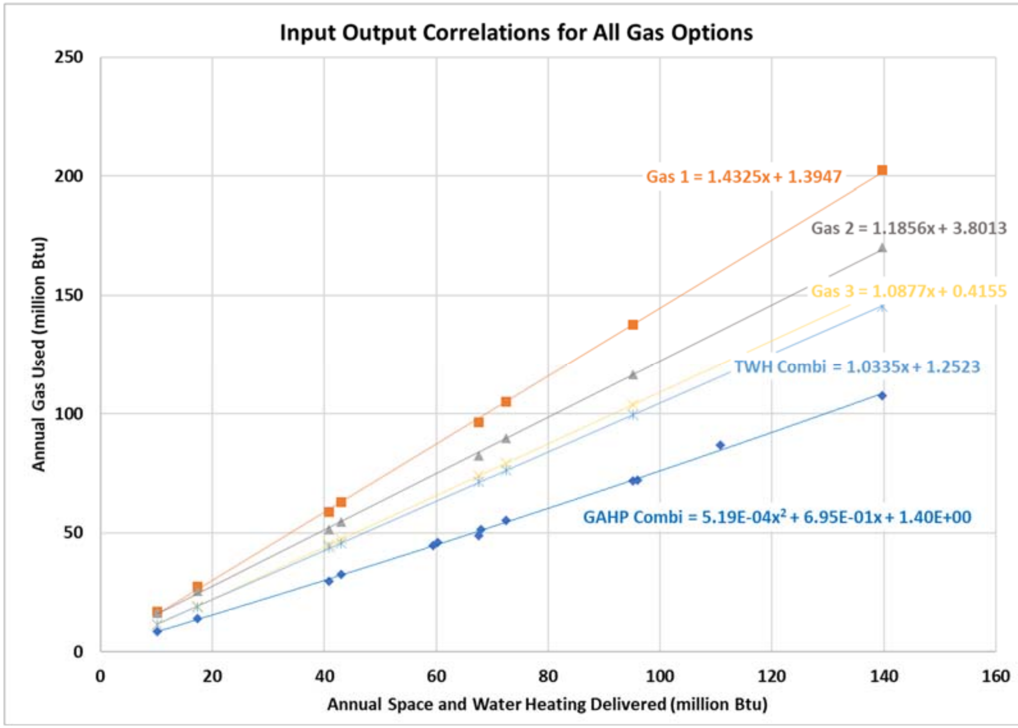

Figure 7. Input Output correlations for different gas heating scenarios as a function of the annual space and water heating load.

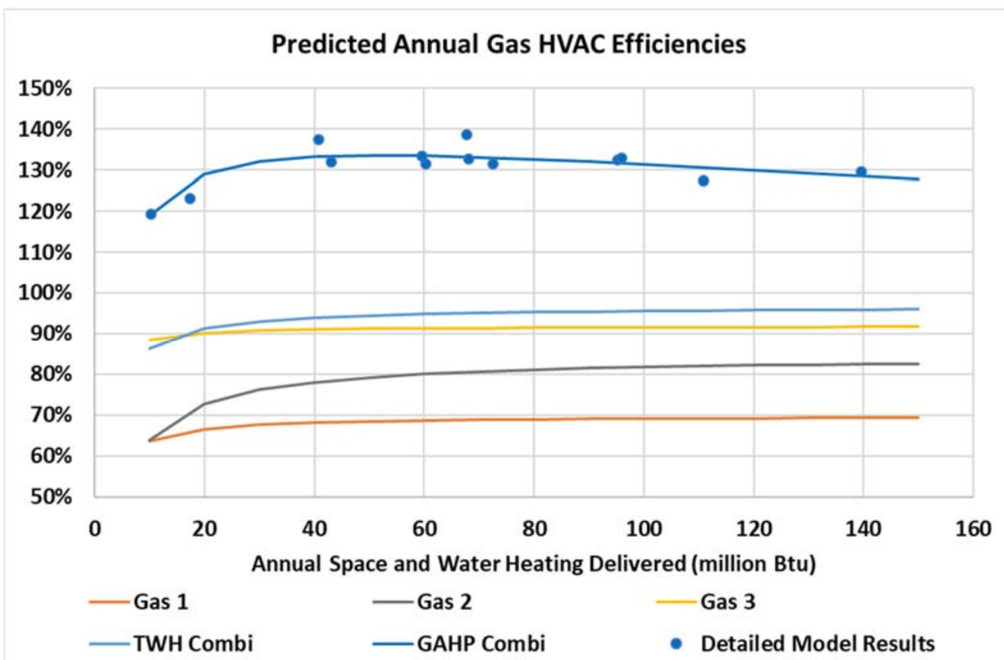

Figure 8. Predicted annual gas efficiency for different HVAC options considered

It is also important to note the assumptions and potential limitations of these correlations:

1. These correlations are based on detailed models. Any limitations of the detailed models are true for these correlations as well.

2. These correlations are true for right-sized HVAC equipment and typical hot water usage patterns. They will not hold for scenarios with extremely oversized equipment or for cases with extreme high or low hot water usage.
3. They were developed for single-family homes based on IECC 2006 building code in each location. While the results here show good agreement, regardless of home size, it is not guaranteed that the correlations will hold for all building types. For instance, these correlations are unlikely to work for passive homes with ultra-low space heating loads.
4. Correlations for cases with tankless water heaters will not work for scenarios where continuous hot water recirculation is used. Different correlations would be needed.
5. The correlation for GAHP combi is based on performance data available for the Stone Mountain Technologies (SMTI) 80k heat pump. It is also reflective of the controls and the optimizations of the SMTI system. While the correlation may hold for other GAHPs that come to market in the future, it is likely to be incidental. Additional correlations would be necessary, which may be developed in the future.

The next step for these correlations is further integration into analyses that GTI Energy performs for other UTD research projects as well as other government and industry sponsors. In Phase 4 of this project, GTI Energy is looking to help improve GAHP simulation capabilities for the HERS Index Rating software, where these correlations are likely to be used. While the current version of GTI Energy's EPAT tool uses the performance curves from Phase 2 of this work, it is unable to predict the annual combi performance. These new correlations will be integrated into future versions of EPAT to address these limitations.

All-electric and Mixed-fueled ZNE Home Models

Two side-by-side Zero Net Energy (ZNE) homes were built during 2019-20 for a California Energy Commission (CEC) funded project, one mixed-fuel and one all-electric. The preliminary design of these homes included modeling and analysis using BEopt, prior to the start of Phase 3 of this project. To validate the preliminary calculations as well as modeling methods used in this and prior phases of this project, this task focused on monitoring the gas and electricity consumption in these two homes and using the data obtained to build and validate EnergyPlus building models that incorporate advanced combi systems as well as best-in-class electric equipment. At the completion of this phase of the project, only about seven months of data (June 22 – January 23) had been collected due to delays on the CEC project in moving new residents into the homes. However, as shown below, this is sufficient data to validate the building and HVAC models, which will be used in Phase 4 of this project as well.

Methods

The two homes built for the CEC projects are pictured in Figure 9. The construction details are provided in Appendix A. For the field demonstration, all individual appliances as well plug loads were sub-metered, permitting all aspects of the building's internal loads to be characterized. The building envelopes were identical in each case. The only differences between the homes were any occupant behavior differences, the HVAC and DHW systems utilized, as well as the size of the PV system for ZNE operation, described in more detail shortly. For all simulation results that follow, BEopt 2.8[11] was used for simulations with EnergyPlus. In cases where envelope or HVAC options did not match those of the real buildings, custom measures were created.

Figure 9. The two ZNE homes under construction in 2020. One was an all-electric home, while the second used a tankless combined space and water heating system.

Major Findings

ZNE All-Electric Home

The ZNE all-electric home was equipped with a 4.5 kW PV system and a mini-split HVAC system to support the cooling and heating loads of this home. Figure 10 shows the modeled ZNE all-electric home in BEopt. Though these homes were built by the end of 2020, there was a delay in having them occupied which happened during mid-2022. The data is successfully being

[11] BEopt: Building Energy Optimization Tool | Buildings | NREL

monitored as of June 2022 and has been used to validate the ZNE all-electric home model, as described below.

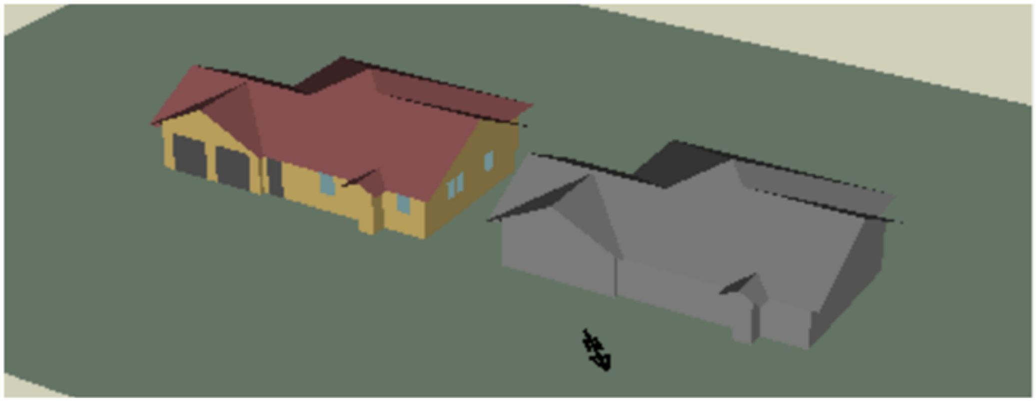

Figure 10. BEopt model of ZNE All-Electric Home

The BEopt model for the all-electric home was simulated for an entire year with a CA climate zone 12 which closely represents the area where this home was built. The model data was captured for an entire calendar year which was compared to an approximately seven months of field data. Due to difference in data lengths, these data sets were modified to capture the HVAC energy usage as a function of heating degree days and cooling degree days, with a base temperature of 65°F. The last few days of the data monitoring period had days where both heating and cooling systems were turned on. Usage as such days was segregated while accounting for the daily HVAC cooling energy usage and HVAC heating energy usage for both the model and the field data. Figures 2 and 3 show the modeled HVAC data and field HVAC data as a function of heating and cooling degree days.

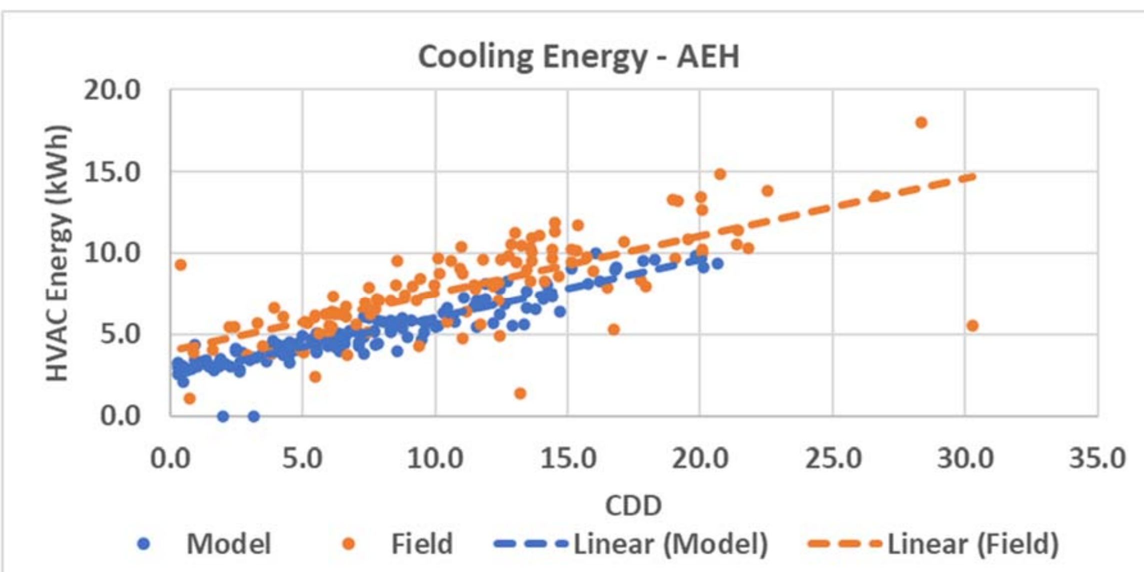

Figure 11. *HVAC Cooling Energy Usage vs. Cooling Degree Days (All-Electric)*

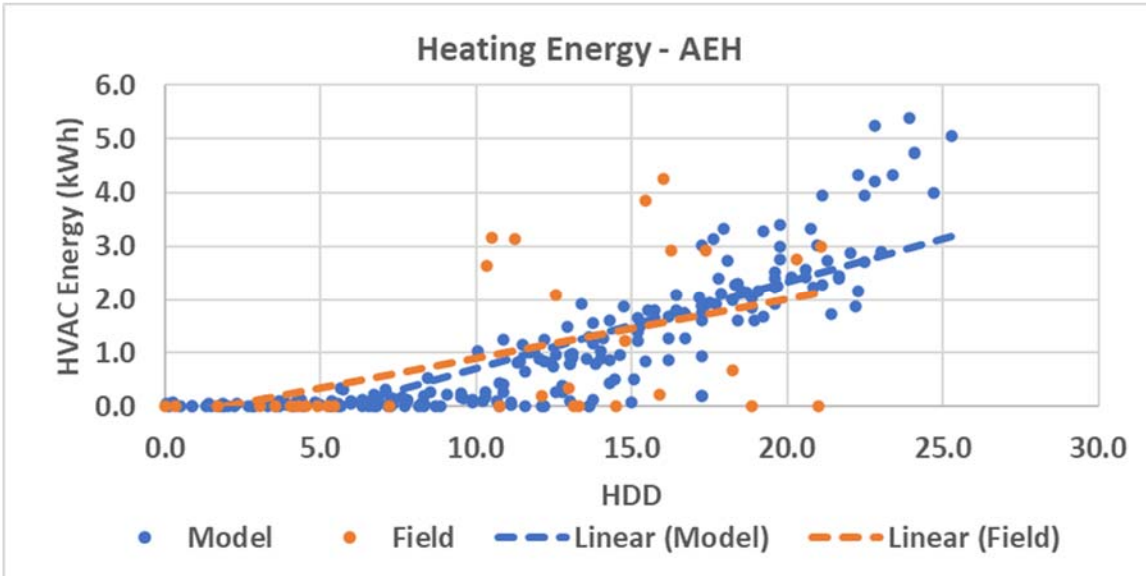

Figure 12. HVAC Heating Energy Usage vs. Heating Degree Days (All-Electric)

Due to most of the monitoring period covering the cooling season, heating data validation is more limited. The results obtained (Figure 11 and Figure 12) clearly show a similar trend between the HVAC energy usage data obtained for the model and from the field. The distribution of the data also significantly overlaps both the model and the field data. Given the remaining uncertainties about building occupant behavior as well as discrepancies between modeled and "real-world" air-conditioner and HPWH performance, the agreement is acceptable. Note that typically, energy usage can disagree by as much as 50% between modeled and real buildings[12].

The trendlines obtained show a rise in HVAC energy usage with increasing temperature for both heating and cooling degree days. However, the HVAC energy for space cooling at lower cooling degree days (below 5°F) is significantly higher, whereas for space heating the HVAC energy usage does not start to kick-in until the temperature difference between outdoor and indoor temperatures is about 7°F. Both observations hold true for model and field date. This shows the capability of the building envelope towards resisting colder temperatures.

Despite having fewer points for the heating degree days, the trendlines obtained for both field and model HVAC heating energy data also showed similar trends and distribution of data points over the range of heating degree days. The all-electric HVAC and HPWH models used in this analysis were directly from BEopt. However, these models have been extensively used by GTI Energy when comparing performance of gas and electric HVAC systems. Therefore, this exercise provides valuable validation of prior analyses on gas vs electric systems.

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[12] Based on private communications with Building Energy Modeling professionals.

ZNE Mixed-Fuel Home

The ZNE mixed-fuel home was equipped with a 3 kW PV system, a 1-ton air conditioning system to support the cooling load and with a tankless combi HVAC system to support the space and heating loads of this home. Figure 13 shows the modeled ZNE mixed-fuel home in BEopt. Note that the primary difference in the geometry are the neighboring homes, which cast shadows during different times of the day. Similar to the all-electric home, occupancy was delayed until mid-2022. The data is successfully being monitored from June 2022 and has been used to validate the ZNE mixed-fuel home model.

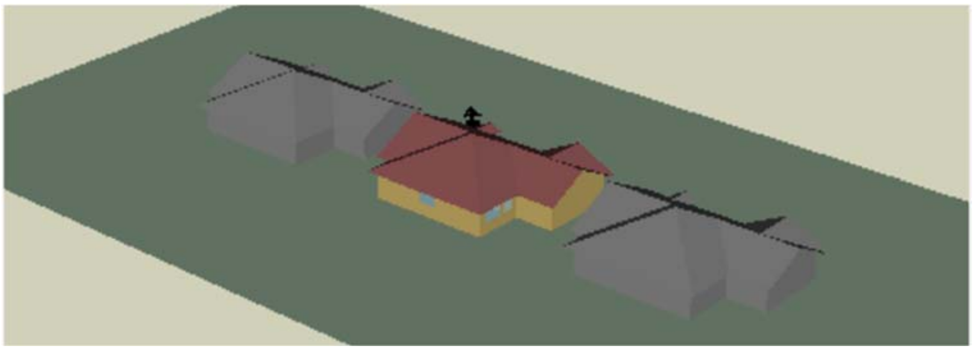

Figure 13. BEopt model of ZNE Mixed-Fuel Home

The BEopt model for the mixed-fuel home was simulated for an entire year with a CA climate zone 12 which closely represents the area where this home was built. The model data was captured for an entire calendar year which was compared to an approximately 7 months of field data. Due to difference in data lengths, these data sets were modified to capture the HVAC energy usage during heating degree days and cooling degree days. The last few days of the data monitoring period had days where both heating and cooling systems were turned on. These days were binned based on whether most of the time the HVAC system was heating or cooling. The HVAC energy usage simulated by the model and the energy usage captured from the field date were compared based on the heating and cooling degree days. Figure 14 and Figure 15 show the modeled and field HVAC data as a function of heating and cooling degree days with a 65°F base.

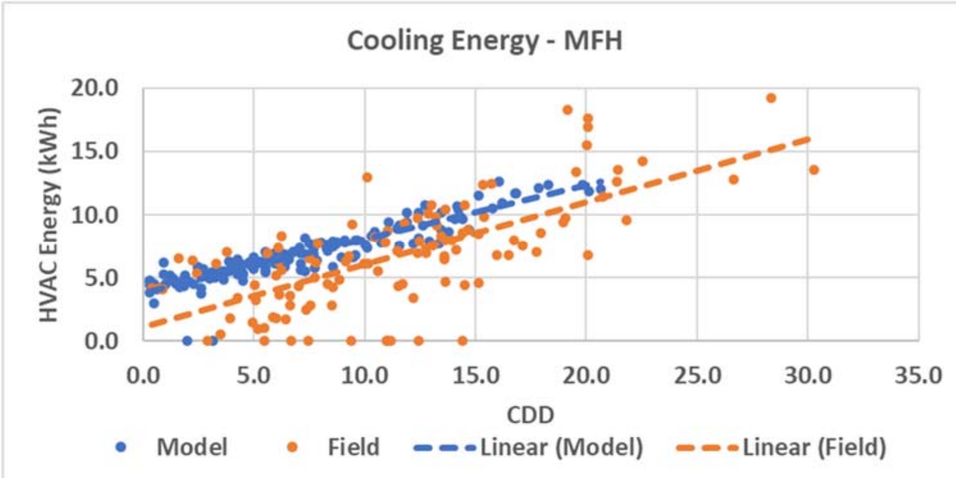

Figure 14. HVAC Cooling Energy Usage vs. Cooling Degree Days (Mixed-Fuel)

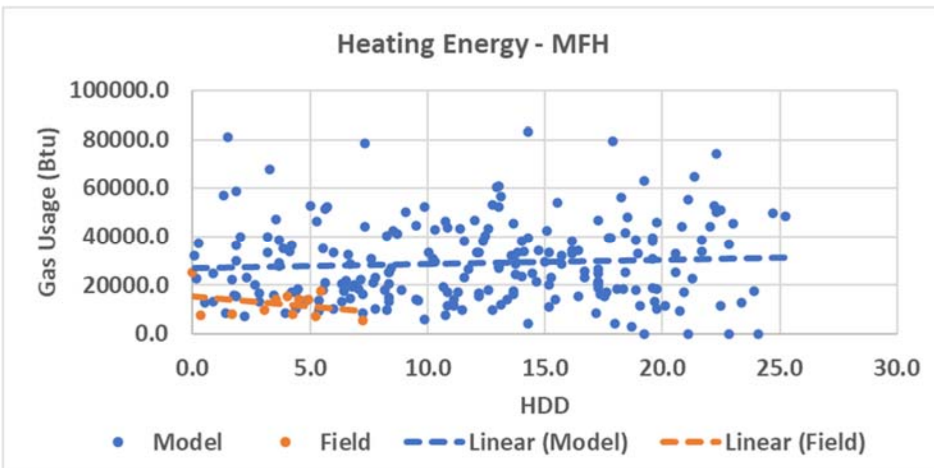

Figure 15. *HVAC Heating Energy Usage vs. Heating Degree Days (Mixed-Fuel)*

Similar to the all-electric home, a major portion of the field data monitoring period occurred during the cooling season, thus a large number of data points were obtained to validate the HVAC cooling energy usage. The HVAC cooling energy usage corresponds to the electrical energy usage of the 1-ton air conditioning system and the results obtained can be seen in Figure 14. This figure clearly shows a similar trend between the HVAC energy usage data obtained for the model and from the field. The distribution of the data also significantly overlaps for both the model and the field data. Like the all-electric home, given the remaining uncertainties in how the real home operates, the agreement is reasonable.

Unlike in the all-electric home, the mixed-fuel home has a gas tankless combi system which supports the space and water heating loads of the home. For this reason, it was not possible to separate the gas usage data corresponding to space heating from water heating. The data presented in Figure 15 combines the space and water heating usage from the model to compare with the field data. What both the model and field data confirm is that these homes, given their construction and location, are in cooling dominated climates. While space heating takes place, it is a smaller compared to water heating. The high degree of scatter in the modeled results in Figure 15 are directly related to the variance in water heater usage. The water heater draw profiles could not be taken directly from the sites given the coarse time resolution of the field data. Instead, the model used realistic draw patterns developed by NREL[13] and built into BEopt. While the difference in results and poor correlation with heating degree days prevent a quantitative comparison of the measured and modeled data, within the range of prediction by the model, there is reasonable agreement with field measurements.

[13] Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings (nrel.gov)

Conclusions

The primary objective of this project is to provide decision-makers accurate and reliable simulation tools for gas heating systems and to enable equitable comparisons of competing technologies. Phases 1 and 2 of this project focused on developing performance curves and models for condensing furnaces, gas absorption heat pumps (GAHPs), and tankless-based combined space and water heating systems. Phase 3 of this project described in this report, focused on dissemination of findings from prior phases as updates to EnergyPlus as well as expanding into building energy model validation using real-world Zero Net Energy homes in California.

Project highlight and accomplishments include:

1. Model deployment with EnergyPlus
    a. Using the results of Phase 2 of this project, GTI Energy published two peer-reviewed articles on modeling details of GHPs and tankless combis.
    b. GTI Energy's subcontractor deployed a heating and cooling GAHP model in EnergyPlus, which is available to beta testers as of writing of this report and will be fully available publicly as part of EnergyPlus 23.1 in March of 2023.
    c. While not fully deployed under this phase, the tankless water heater model, which is key to the modeling tankless combis, is a "high priority" new feature for the NREL EnergyPlus development team for 2023. GTI will continue to provide support under Phase 4 of this project (2022 start).
2. Reduced Order System Modeling
    a. One of the key accomplishments of this task is the development of simple linear and quadratic correlations for annual gas consumption of GAHP combis, tankless combi, and several other gas heating scenarios. The correlations take annual space and water heating loads as input and provide estimate of annual gas consumption.
    b. These new correlations permit relative savings to be quickly computed for these advanced gas heating systems without the need for detailed EnergyPlus runs.
    c. Under Phase 4 of this project, GTI Energy will work towards disseminating the use of these correlations with HERS Index rating software as well as integration into GTI Energy's Energy Parametric Analysis Tool.
3. ZNE All-electric and Mixed-fuel Home Modeling
    a. GTI Energy had the opportunity to monitor two Zero Net Energy homes in California and to perform a detailed building energy model calibration as well as validation of the tankless combi and electric heat pumps models.
    b. Despite a limited set of heating data collected by the completion of this project, GTI Energy was able to make quantitative comparison between the measured building energy consumption and modeling results. The field measurements generally showed good agreement with model predictions, for both mixed-fuel

and all electric homes. These data provide validation for analyses GTI Energy has performed under Phases 1 and 2 of this project, and the building models will be utilized in future efforts when modeling high-performance homes.

Appendix A – ZNE Homes Construction Details

<table>
<tr><th>Parameter</th><th>ZNE All Electric</th><th>ZNE Mixed Fuel</th></tr>
<tr><td>Wood Stud</td><td rowspan="10">Exterior Walls are 2x6 with R-21 cavity insulation, R-5 continuous exterior insulation (U = 0.038 for opaque walls) and incorporate advanced framing techniques.</td><td rowspan="10">Exterior Walls are 2x6 with R-21 cavity insulation, R-5 continuous exterior insulation (U = 0.038 for opaque walls) and incorporate advanced framing techniques.</td></tr>
<tr><td>Double Wood Stud</td></tr>
<tr><td>Steel Stud</td></tr>
<tr><td>CMU</td></tr>
<tr><td>SIP</td></tr>
<tr><td>ICF</td></tr>
<tr><td>Other</td></tr>
<tr><td>Wall Sheathing</td></tr>
<tr><td>Exterior Finish</td></tr>
<tr><td>Interzonal Walls</td></tr>
<tr><td>Unfinished Attic</td><td rowspan="3">Attic is vented, with R-42 insulation at the ceiling and an exposed radiant barrier</td><td rowspan="3">Attic is vented, with R-42 insulation at the ceiling and an exposed radiant barrier</td></tr>
<tr><td>Roof Material</td></tr>
<tr><td>Radiant Barrier</td></tr>
<tr><td>Crawlspace</td><td rowspan="2">Crawlspace foundation has a minimum of R-21 cavity insulation under the floor, plus continuous R-5 rigid insulation under the floor joists</td><td rowspan="2">Crawlspace foundation has a minimum of R-21 cavity insulation under the floor, plus continuous R-5 rigid insulation under the floor joists</td></tr>
<tr><td>Carpet</td></tr>
<tr><td>Floor Mass</td><td>Wood Surface</td><td>Wood Surface</td></tr>
<tr><td>Exterior Wall Mass</td><td>1/2 in. Drywall</td><td>1/2 in. Drywall</td></tr>
<tr><td>Partition Wall Mass</td><td>1/2 in. Drywall</td><td>1/2 in. Drywall</td></tr>
<tr><td>Ceiling Mass</td><td>1/2 in. Drywall</td><td>1/2 in. Drywall</td></tr>
<tr><td>Number of Windows</td><td rowspan="6">10% glass area, Windows are high performance, with low-E coating and an average U-factor of 0.27 and SHGC of 0.24. Windows are sized to fit within the 24" o.c. framing modules.</td><td rowspan="6">10% glass area, Windows are high performance, with low-E coating and an average U-factor of 0.27 and SHGC of 0.24. Windows are sized to fit within the 24" o.c. framing modules.</td></tr>
<tr><td>Window Area</td></tr>
<tr><td>Window Material</td></tr>
<tr><td>Interiror Shading</td></tr>
<tr><td>Number of doors</td></tr>
<tr><td>Door Area</td></tr>
</table>

Door Material		
Eaves		
Overhangs		
Air Leakage	2 ACH50	2 ACH50
Mechanical Ventilation	Ducted ERV, Panasonic (FV-10VEC1), 50-100 CFM	Ducted ERV, Panasonic (FV-10VEC1), 50-100 CFM
Natural Ventilation	None	None
Central Air Conditioner	None	1-ton american condensing unit 16 SEER/13 EER
Room Air Conditioner	None	None
Furnace	None	Combined hydronic air handler, First Company 30CDXQ, 2.5-ton
Boiler	None	None
Electric Baseboard	None	None
Air Source Heat Pump	None	None
Mini-Split Heat Pump	Ducted mini-split Fujitsu 3/4 ton (09RLF)	None
Ground Source Heat Pump	None	None
Ducts	Ducts and HVAC equipment located in conditioned space for thermal efficiency	Ducts and HVAC equipment located in conditioned space for thermal efficiency
Ceiling Fan	None	None
Dehumidifier	None	None
Cooling Setpoint	70 F	70 F
Heating Setpoint	70 F	70 F
Humidity Setpoint	None	None
Water Heater	Split System HPWH, VKIN (VRHA-12AN1DCTS50) with 50-gallon storage tank	Condensing tankless, 0.95 EF
Distribution	Uninsulated, TrunkBranch, Copper	Uninsulated, TrunkBranch, Copper

Solar Water Heating	None	None
Solar Water Heating Azimuth	None	None
Solar Water Heating Tilt	None	None
Lighting	100% LED, Low Efficacy	100% LED, Low Efficacy
Refrigerator	Top Freezer, EF = 17.6	Top Freezer, EF = 17.6
Cooking Range	Electric	Gas
Dishwasher	None	None
Clothes Washer	EnergyStar	EnergyStar
Clothes Dryer	Electric, Heat Pump, Ventless	Gas
Hot Water Fixtures	25 gal/unit/day	25 gal/unit/day
Refrigerator Schedule	Standard	Standard
Cooking Range Schedule	Standard	Standard
Clothes Dryer Schedule	Standard	Standard
Plug Loads	1997 kWh/unit/yr	1997 kWh/unit/yr
Extra Refrigerator	None	None
Freezer	None	None
Pool Heater	None	None
Pool Pump	None	None
Hot Tub/Spa Heater	None	None
Hot Tub/Spa Pump	None	None
Well Pump	None	None
Gas Fireplace	None	None
Gas Grill	None	None
Gas Lighting	None	None
Plug Loads Schedule	Standard	Standard
Extra Refrigerator Schedule	Standard	Standard

Freezer Schedule	Standard	Standard
Pool Heater Schedule	Standard	Standard
Pool Pump Schedule	Standard	Standard
Hot Tub/Spa Heater Schedule	Standard	Standard
Hot Tub/Spa Pump Schedule	Standard	Standard
Well Pump Schedule	Standard	Standard
Gas Fireplace Schedule	Standard	Standard
Gas Grill Schedule	Standard	Standard
Gas Lighting Schedule	Standard	Standard
PV System	4.5 kW	3 kW
PV Azimuth	Southwest	Southwest
PV Tilt	Roof, Pitch	Roof, Pitch