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Design Approach and Performance Analysis of a Small Integrated Heat Pump (IHP) for Net Zero Energy Homes (ZEH)

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ABSTRACT

This paper describes the design and performance analysis of a variable-capacity heat pump system developed for a small [1800ft² (167 m²)] prototype net ZEH with an average design cooling load of 1.25 tons (4.4 kW) in five selected US climates. The heat pump integrates space heating and cooling, water heating, ventilation, and humidity control (humidification and dehumidification) functions into a single integrated heat pump (IHP) unit. The design approach uses one small variable-capacity compressor to meet all the above functions in an energy efficient manner. Modal performance comparisons to an earlier IHP product are shown relative to the proposed new design for net ZEH application. The annual performance analysis approach using TRNSYS in conjunction with the ORNL Heat Pump Design Model is discussed. Annual performance projections for a range of locations are compared to those of a base system consisting of separate pieces of equipment to perform the same functions. The ZEH IHP is projected to reduce energy use for space heating & cooling, water heating, dehumidification, and ventilation for a net ZEH by about 50% compared to that of the base system.

1. INTRODUCTION

The US Department of Energy's (DOE's) strategic goal for residential buildings technology is to develop ZEH or net ZEH technology by 2020. A net ZEH is defined as "a home with greatly reduced needs for energy through efficiency gains (60% to 70% less than conventional practice), with the balance of energy needs supplied by renewable technologies." To achieve this goal will require energy service equipment that can meet the space heating and cooling (SH and SC), ventilation (V), water heating (WH), dehumidification (DH), and humidification (H) needs while using 50% less energy than current equipment. One promising approach to meeting this requirement is through an integrated appliance or "integrated heat pump" (IHP) – a single system based on heat pumping technology. The energy benefits of an IHP result from the ability to provide high efficiency water heating from heat pumping and recovery. The IHP utilizes outdoor source and otherwise wasted outdoor sink energy (e.g., heat rejected by the space cooling operation can be used for water heating) with the same high efficiency modulating components used for space conditioning. With the greater energy savings the cost of the more energy efficient components required for the IHP can be recovered more quickly than would be the case if they were applied to individual pieces of equipment to meet each individual energy service need.

The IHP can be designed to utilize either outdoor air (AS-IHP) or the ground (GS-IHP) as the heat source/sink. Figure 1 is an illustration of an AS-IHP installation. In the present design, dedicated dehumidification is provided through use of a hot water tempering coil in the indoor air handler as described by Baxter *et al.* (2008). Heat-pump-heated water for air humidification in winter is also provided from the domestic water tank. Details of the modeled design arrangement are given in Murphy *et al.* (2007a, 2007b).

A laboratory prototype was developed and tested over a range of operating modes and conditions. Test data from the laboratory prototype system was used to calibrate a detailed heat pump system design model or HPDM (Murphy, *et al.* 2007a). This calibrated model was then used to develop target performance levels for the different operation modes. Details of these target performance ranges are discussed and compared with the performance of an earlier integrated heat pump. The HPDM was then linked to TRNSYS, a time-series-dependent simulation model and used to calculate the yearly performance of IHP system designs optimized for R-410A in five major cities, representing key climate zones of interest within the United States. Summary results from these calculations are presented.



Figure 1: Conceptual installation of a residential air-source integrated heat pump.

2. PERFORMANCE ANALYSIS

2.1 Heat Pump Design Model Calibration and Application to IHP Design

A lab prototype IHP was tested over a range of operating conditions and modes to provide performance data for calibration of the predictions of a detailed heat pump design model or HPDM (Rice and Jackson 2002). The test prototype arrangement and test results are discussed in detail by Murphy *et al.* (2007a). The measured refrigerant and indoor air flows were used with a data reduction program to calculate the delivered capacities of system heat exchangers (HXs), the heat losses and gains and pressure losses in the connecting lines and to deduce the airflows across the outdoor coil at various fan speeds from the condenser energy balance. The performance map for the lab prototype compressor was adjusted for the effects of inverter efficiency and reduced speeds based on the measured power and mass flow data. This adjusted compressor map was input to the HPDM and initial predictions of the lab tests conducted. HPDM predictions were compared to the actual lab results and, through an iterative process, the HPDM predictions were calibrated to the range of space cooling and water heating tests performed.

Using the calibrated HPDM, IHP design optimization and control assessments were conducted to establish target optimized compressor and fan speed control relationships based on the laboratory R-22 compressor, air-moving, and heat exchanger components. Subsequently a suitable compressor map for a state-of-the-art R-410A variable-speed rotary compressor was obtained and input to the calibrated HPDM. Optimal speed and control ranges were then established for both the air-source and ground-source IHPs using this preferred HFC refrigerant R-410A. Variable-speed blowers and pumps and condenser subcooling were controlled as a function of compressor speed. Details of the selected operating speed ranges and control relationships are described by Murphy *et al.* (2007a, 2007b).

2.2 Modal IHP Performance Comparisons

Comparison of predicted performance of the ZEH air-source IHP (AS-IHP) to that of an earlier commercial variable-speed air-source IHP product, or C-IHP, (Carrier 1989) shows significant performance improvements with the higher efficiency rotary compressors presently available. This is shown in the following figures for the current R-410A ZEH AS-IHP design of 1.25 ton (4.4 kW) nominal cooling capacity as compared with the published HydroTech 2000 product performance data for the Carrier 2-ton (7 kW) C-IHP design using R-22.

The first comparison is for space cooling operation. Here the Carrier HydroTech product was rated at low, intermediate, and high (design cooling) speeds (32, 40, and 55 Hz in the cooling mode for the 2-ton design). The intermediate speed is, by rating procedure convention, one-third of the way between the low and high speeds. We evaluated the ZEH AS-IHP design for a similar set of speeds, although with the wider available speed range.

The cooling mode speed ranges relative to rated design cooling speed were from 0.58 to 1 for the Carrier 2-ton design versus 0.35 to 1 for the ZEH AS-IHP.

Figure 2 shows the comparative cooling capacities for the ZEH AS-IHP vs. the C-IHP, with the AS-IHP design of similar relative speed given by the dashed lines with the same symbol. Here the capacity trends are seen to be similar for the three speed levels, with the differing nominal capacities of 1.25 tons (4.4 kW) and 2 tons (7 kW), respectively, being obtained at high speed and 95°F (35°C) ambient.

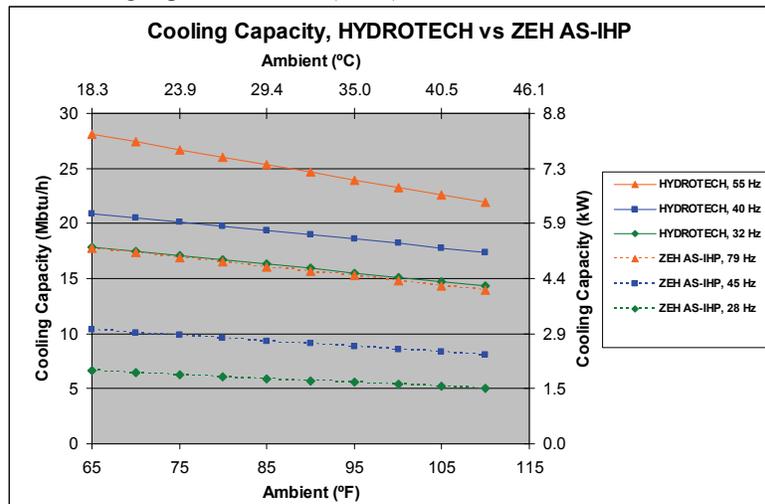


Figure 2: Comparison of space cooling capacities for 2-ton (7 kW) HydroTech vs. 1.25-ton (4.4 kW) ZEH AS-IHP

Comparative space cooling efficiency levels for the two systems are shown in Figure 3. Efficiency of the ZEH AS-IHP is seen to be much higher, especially at the intermediate and low speeds where most of the operating hours occur. This higher predicted performance is due in part to the wider low-end of the speed modulation range and in part from the higher efficiency of the current variable-speed rotary compressors.

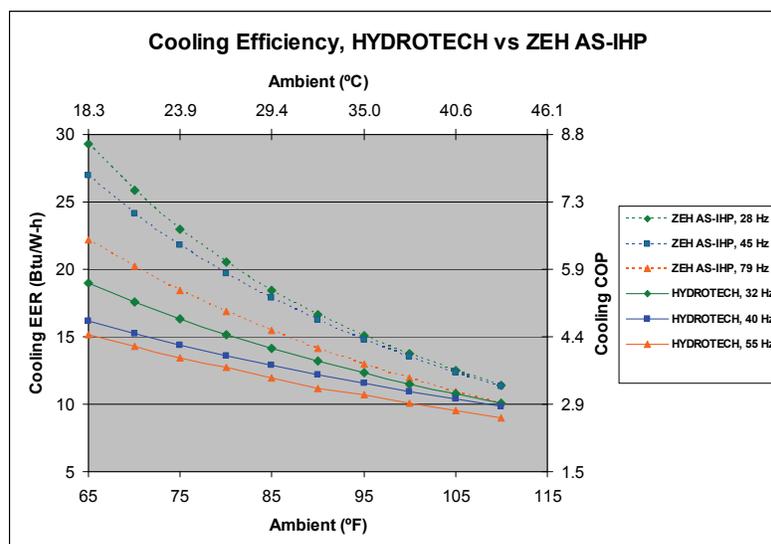


Figure 3: Comparison of space cooling efficiencies for ZEH AS-IHP vs. HydroTech

Figures 4 and 5 illustrate the space heating mode performance comparisons. The heating speed ratios referenced to the nominal cooling speed are 0.58 to 1.33 for the C-IHP and 0.35 to 1.5 for the ZEH AS-IHP. Because of the higher overspeed capability of the current rotary compressor, the capacity of the ZEH AS-IHP at lower ambient temperature conditions approaches that expected of the larger capacity C-IHP. Note also that the slope of the capacity dropoff at lower ambients is less for the current rotary than for the reciprocating compressor of the earlier design. This is expected due to the poorer volumetric efficiency trend of the reciprocating compressor from the larger clearance volume re-expansion at higher pressure ratios as compared to that used in the ZEH AS-IHP.

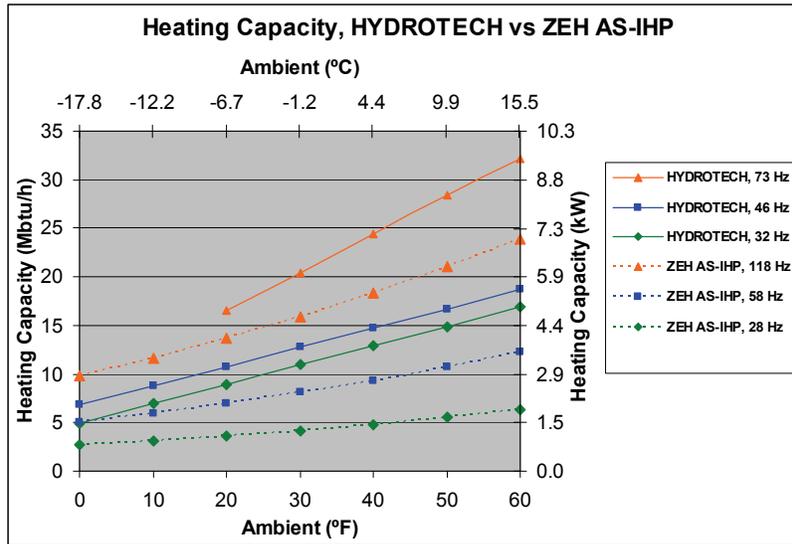


Figure 4: Comparison of space heating capacities for 2-ton (7 kW) HydroTech vs. ZEH AS-IHP

The relative space heating efficiency levels for the ZEH AS-IHP (Figure 5) are seen to be much higher than that of the C-IHP, including the intermediate and low speeds where the bulk of the operating hours occur. Again the wider low-end of the speed modulation range and higher efficiency of the current variable-speed rotary compressors are believed to be the major contributors here.

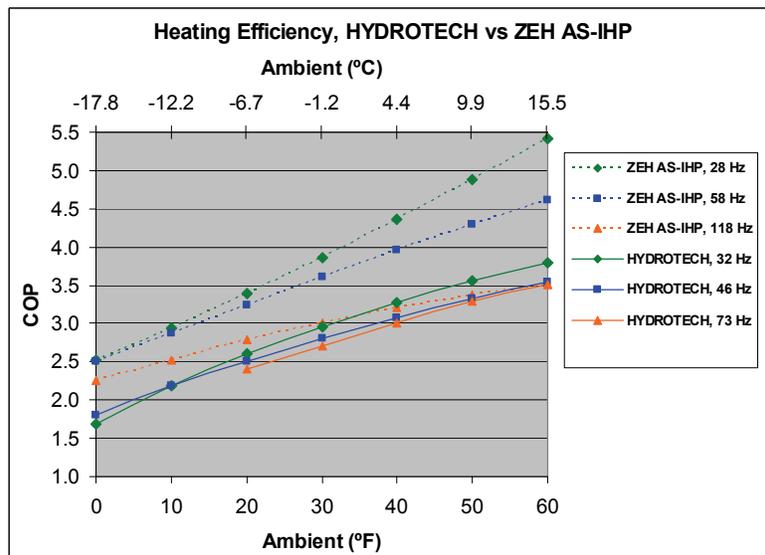


Figure 5: Comparison of space heating efficiencies for ZEH AS-IHP vs. HydroTech

Figure 6 compares dedicated water heating capacity of the two systems. An entering water temperature (EWT) of 108°F (42.2°C) from the domestic water heater was used for this comparison.

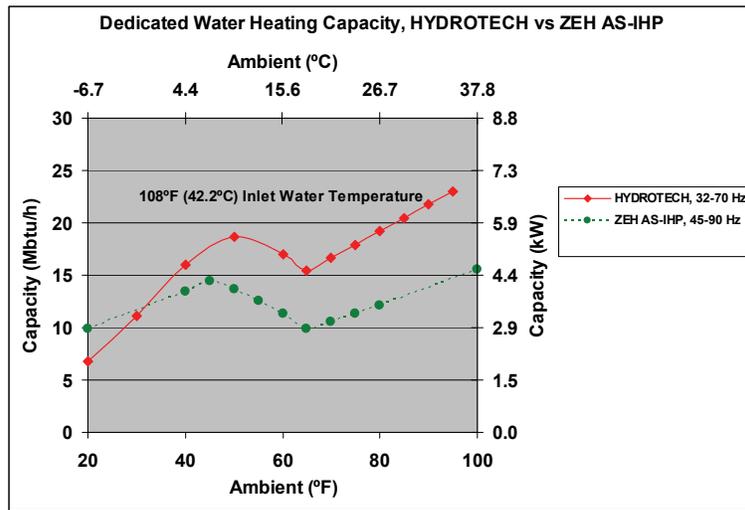


Figure 6: Comparison of dedicated water heating capacities for 2-ton (7 kW) HydroTech vs. ZEH AS-IHP

From observing the published HydroTech capacity trends with ambient, it is estimated that the compressor speed was at the 70 Hz maximum water heating speed at around 50°F (10°C) and below, then decreasing to the minimum speed of 32 Hz as the ambient increased from 50 to 65°F (10 to 18.3°C). In comparison, the simulated water heating speeds for the ZEH AS-IHP are 90 Hz at 45°F (7.2°C) and below, decreasing to a minimum of 45 Hz at 65°F (18.3°C). The capacity trends of the two systems are seen to be similar, but with a faster drop-off in capacity for the C-IHP unit below 40°F (4.4°C), for reasons discussed earlier regarding Figure 4. The comparative water heating COPs are shown in Figure 7. At 50°F (10°C), the COP advantage is the narrowest for the ZEH AS-IHP system at 37%, increasing to between 47 and 53% higher between 60 and 80°F (15.6 and 26.7°C).

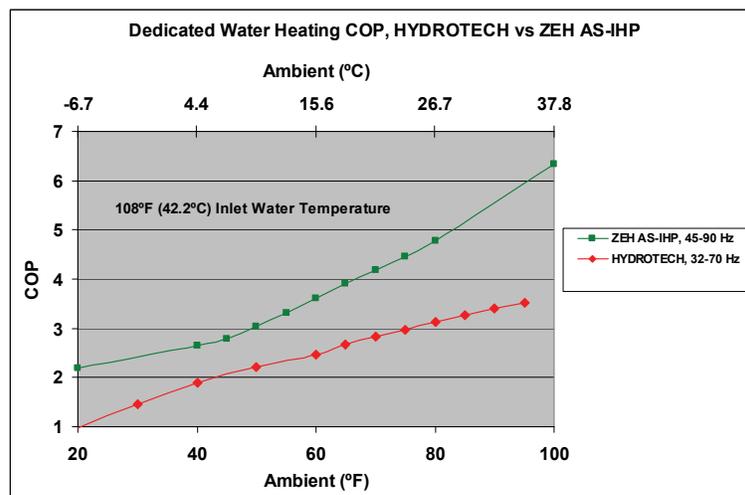


Figure 7: Comparison of dedicated water heating COPs for ZEH AS-IHP vs. HydroTech

For the case of combined space cooling and heat recovery water heating, the C-IHP design rejects heat from both the water-to-refrigerant condenser and the outdoor condenser operating in series. As such, combined mode cooling performance is a function of ambient temperature. In contrast, the proposed ZEH AS-IHP design employs full heat recovery and so performance is independent of ambient temperature at a fixed compressor speed. As a result, the combined cooling and water heating performance is somewhat higher, as shown in Figs. 8 and 9. As before, the water heating performance is calculated for a constant inlet water temperature to the water-to-refrigerant HX of 108°F (42.2°C).

The delivered space cooling and water heating outputs for the two designs are compared in Fig. 8. The 2-ton (7 kW) rated HydroTech unit provides a nearly constant 7000 Btu/h (2.1 kW) of water heating while that of the ZEH AS-IHP increases along with unit cooling output from about 6000 to over 17,000 Btu/h (1.8 to 5 kW) at the design cooling condition of 95°F (35°C) ambient.

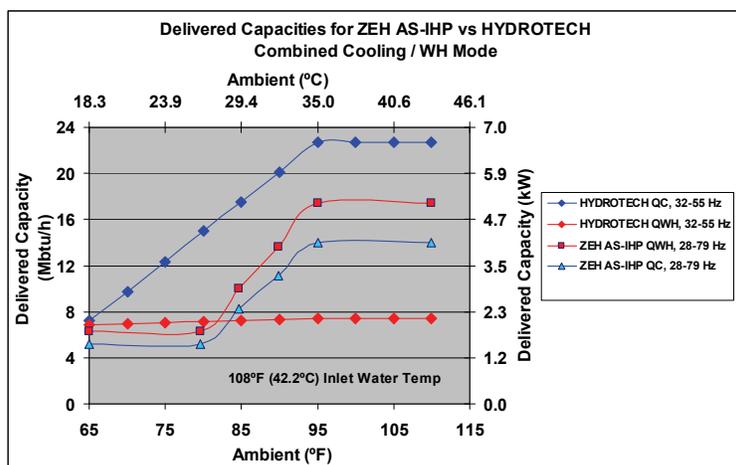


Figure 8: Space cooling and water heating capacities vs. ambient, dual mode

Figure 9 compares the combined efficiency of each system, calculated as the sum of the useful cooling and water heating output divided by the input power. The ZEH AS-IHP system shows much higher performance with combined EERs ranging from 24 to 22 (COPs from 7 to 6.5) as the ambient increases vs. EERs of 10 to 13.5 (COPs of 2.9 to 4) for the C-IHP. This is due to the much higher water heating output from the full waste heat recovery operation for the present ZEH AS-IHP design, which more than offsets the higher condensing temperatures required. A similar design approach was taken for the ZEH GS-IHP with narrower speed ranges needed for space conditioning due to the more moderate maximum source and sink conditions (Murphy *et al.* 2007b).

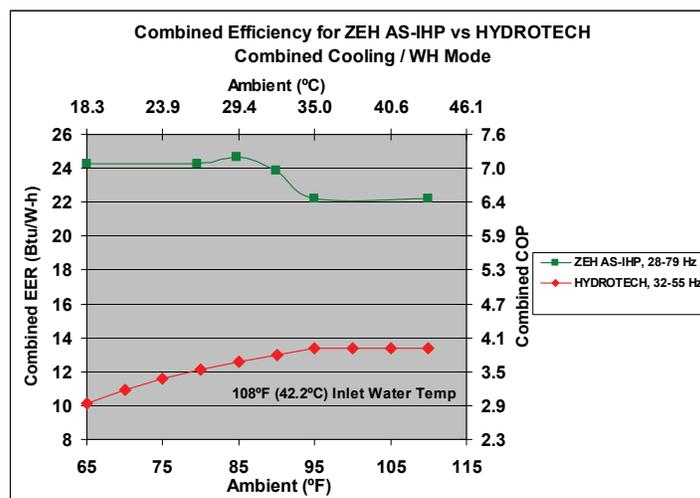


Figure 9: Combined efficiency for total cooling / water heating outputs vs. ambient, dual mode

2.3 TRNSYS/HPDM Simulation Approach

Once the modal designs were fully determined for the IHPs, the next challenge was to estimate the IHP annual energy use in a net ZEH for a range of climates representative of most US locations. A sub-hourly analysis tool was needed to most accurately account for the competing IHP operating modes and to provide representative inlet conditions that will be seen by the heat pump condenser while heating water. This was accomplished linking the HPDM with TRNSYS (Solar Energy Laboratory *et al.* 2006). An extensive effort was undertaken to couple the two

codes so that the outputs of the TRNSYS from modeling the time-dependent ZEH indoor space and water heater conditions would become inputs to the HPDM. In turn, the HPDM output conditions of the indoor air and water leaving the equipment heat exchangers are coupled back to the TRNSYS house and water heater modules to update their operating states. Initially we directly linked the HPDM to TRNSYS for the needed assessment capabilities. This worked well enough but required a call of the HPDM at each simulation time step causing the run time to be very long. To alleviate the long run time and improve the robustness of the combined TRNSYS/HPDM model, a map-based approach combined with multi-dimensional interpolation was used.

A full set of IHP performance maps are generated for all available modes of operation at the outset of an annual performance simulation using the HPDM model in map generation mode, and written to disk for later reuse. During the simulation, the HPDM module in the TRNSYS/HPDM code performs multi-parameter interpolations (of three to four independent parameters depending on the mode of operation) of heat pump performance for the active operation mode. Further details of the house and controls modeling and the HPDM/TRNSYS linkage approach are described by Murphy *et al.* (2007a and 2007b).

2.4 Annual Simulation Results

The TRNSYS/HPDM was used to calculate estimates of annual performance (using 3-minute time steps) for air-source and ground-source IHP systems as well as a baseline system. A standard split-system air-to-air heat pump with USDOE-minimum required efficiencies (SEER 13 and HSPF 7.7 – cooling and heating seasonal performance COPs of 3.8 and 2.26, respectively) provides space heating and cooling under control of a central thermostat that senses indoor space temperature. It also provides dehumidification (DH) when operating in space cooling mode but does not separately control space humidity. A standard 50 gallon (0.189 m³) electric storage water heater (WH) with USDOE minimum mandated energy factor (EF=0.90) provides domestic hot water needs. Ventilation (V) to meet the requirements of ASHRAE Standard 62.2-2004 (ASHRAE 2004) is provided using a central exhaust fan. A separate stand-alone dehumidifier (DH) is used to meet dehumidification needs during times when the central heat pump is not running to provide space cooling. A DH efficiency or energy factor (EF_d) of 1.4 L/kWh (0.0014 m³/kWh) was used based on the USDOE proposed minimum requirement for 2012. A whole-house humidifier (H) accessory was included with the heat pump to maintain a minimum 30% relative humidity (RH) during the winter.

Table 1 provides a summary of the results for the baseline HVAC system for the net ZEH. Table 2 provides results for the ZEH air-source (AS) and ground-source (GS) IHPs. For the ZEH AS-IHP, the simulation results show ~46 to 67% energy savings vs. the baseline depending upon location. For the ZEH GS-IHP, the simulations show over 50% savings in all locations, with a range of ~52 to 65%.

Table 1: Annual site HVAC/WH system energy use and peak for 167-m² ZEH house with Baseline system

Location	Heat pump cooling capacity tons (kW)	HVAC site energy use, kWh
Atlanta	1.25 (4.4)	7,230
Houston	1.25 (4.4)	7,380
Phoenix	1.5 (5.3)	6,518
San Francisco	1.0 (3.5)	4,968
Chicago	1.25 (4.4)	10,773

Table 2: Annual site HVAC/WH system energy use and peak for 167-m² ZEH with IHPs

Location	Heat pump cooling capacity tons (kW)	AS-IHP HVAC site energy use, kWh	GS-IHP HVAC site energy use, kWh	% energy savings vs. Baseline HVAC	
				AS-IHP	GS-IHP
Atlanta	1.25 (4.4)	3,349	3,007	53.7	58.4
Houston	1.25 (4.4)	3,418	3,290	53.7	55.4
Phoenix	1.5 (5.3)	3,361	2,909	48.4	55.4
San Francisco	1.0 (3.5)	1,629	1,699	67.2	65.8
Chicago	1.25 (4.4)	5,865	5,126	45.6	52.4

3. CONCLUSIONS

The following specific conclusions are highlighted.

1. The ZEH air-source IHP system (using R410A) simulation results showed ~46 to 67% energy savings vs. the baseline system suite of equipment depending upon location. The lowest savings were for the Chicago location. In Chicago, energy service loads are dominated by space and water heating requirements and the air-source IHP heating efficiency suffers during the extremely low ambient temperature conditions encountered. Similarly, the space cooling efficiency of the current R-410A air-source design is not quite high enough at the extremely high ambient temperatures experienced in Phoenix to enable the IHP to achieve 50% annual savings.
2. For the ZEH ground-source IHP design (also using R-410A), the simulation showed over 50% savings vs. the baseline system suite in all locations with a range of ~52 to 66%.

Further investigation is planned for more advanced designs with the potential to improve hot climate and dual-mode performance for additional energy savings.

NOMENCLATURE

AS	air-source	HSPF	heating seasonal performance factor
COP	coefficient of performance	IHP	integrated heat pump
EER	energy efficiency ratio (cooling)	SEER	seasonal EER (cooling)
GS	ground-source	ZEH	net zero energy home

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