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Business Case Analysis of Two Integrated Heat Pump HVAC Systems for Near-Zero-Energy Homes

Van Baxter

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Engineering Science and Technology Division

Business Case Analysis of Two Integrated Heat Pump HVAC Systems for Near-Zero-Energy Homes (NZEH)

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August 2006

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1. INTRODUCTION

The long range strategic goal of the Department of Energy's Building Technologies (DOE/BT) Program is to create, by 2025, technologies and design approaches that enable the construction of net-zero energy homes at low incremental cost (DOE/BT 2005). A net zero energy home (NZEH) is a residential building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies. While initially focused on new construction, these technologies and design approaches are intended to have application to buildings constructed before 2025 as well resulting in substantial reduction in energy use for all building types and ages. DOE/BT's Emerging Technologies (ET) team is working to support this strategic goal by identifying and developing advanced heating, ventilating, air-conditioning, and water heating (HVAC/WH) technology options applicable to NZEHs.

Although the energy efficiency of heating, ventilating, and air-conditioning (HVAC) equipment has increased substantially in recent years, new approaches are needed to continue this trend. Dramatic efficiency improvements are necessary to enable progress toward the NZEH goals, and will require a radical rethinking of opportunities to improve system performance. The large reductions in HVAC energy consumption necessary to support the NZEH goals require a systems-oriented analysis approach that characterizes each element of energy consumption, identifies alternatives, and determines the most cost-effective combination of options. In particular, HVAC equipment must be developed that addresses the range of special needs of NZEH applications in the areas of reduced HVAC and water heating energy use, humidity control, ventilation, uniform comfort, and ease of zoning.

In FY05 ORNL conducted an initial Stage 1 (Applied Research) scoping assessment of HVAC/WH systems options for future NZEHs to help DOE/BT identify and prioritize alternative approaches for further development. Eleven system concepts with central air distribution ducting and nine multi-zone systems were selected and their annual and peak demand performance estimated for five locations: Atlanta (mixed-humid), Houston (hot-humid), Phoenix (hot-dry), San Francisco (marine), and Chicago (cold). Performance was estimated by simulating the systems using the TRNSYS simulation engine (Solar Energy Laboratory et al 2006) in two 1800-ft^2 houses — a Building America (BA) benchmark house and a prototype NZEH taken from BEopt results at the take-off (or crossover) point (i.e., a house incorporating those design features such that further progress towards ZEH is through the addition of photovoltaic power sources, as determined by current BEopt analyses conducted by NREL). Results were summarized in a project report, *HVAC Equipment Design options for Near-Zero-Energy Homes – A Stage 2 Scoping Assessment,* ORNL/TM-2005/194 (Baxter 2005).

The 2005 study report describes the HVAC options considered, the ranking criteria used, and the system rankings by priority. Table 1 summarizes the energy savings potential of the highest scoring options from the 2005 study for all five locations.

Table 1. Estimated energy savings potential of highest-scoring electric HVAC system options for 1800-ft^2 NZEH (savings expressed as percent compared to central baseline), from FY05 scoping assessment (Baxter 2005)

System	Atlanta	Houston	Phoenix	San Francisco	Chicago
Central systems					
13SEER heat pump with 0.9 EF electric WH (baseline)	-	-	-	-	-
18 SEER 2-spd heat pump with desuperheater	21	23	31	20	25
GCHP with desuperheater	26	22	24	21	30
GCHP with desuperheater and solid water sorbent (SWS) enhanced horizontal GHX	26	22	24	21	30
2-spd GCHP with desuperheater	30	30	38	22	36
Air-source IHP	53	52	50	61	50
Ground-source IHP	58	56	55	62	58
Zoned systems					
13 SEER minisplit heat pump each zone with 0.9 EF electric WH (base zoned system)	8	5	6	8	12
Multisplit heat pump (MSHP) with integrated demand WH module	34	24	22	54	22
MSHP with exhaust-air heat pump for WH&V	31	31	28	33	32
Zoned IHP, air-source	55	55	51	63	58
Zoned IHP, ground-source	60	58	56	66	64

All system options were scored by the ORNL building equipment research team and by William Goetzler of Navigant Consulting. These scores were reviewed by DOE/BT's Residential Integration program leaders and Building America team members. Based on these results, the two centrally ducted integrated heat pump (IHP) systems (air source and ground source versions) were selected for advancement to Stage 2 (Exploratory Development) business case assessments in FY06. This report describes results of these business case assessments.

2. ASSESSMENT APPROACH

This assessment work has involved several steps:

- Collaboration with the National Renewable Energy Laboratory (NREL) to define appropriate Regional Standard Practice (RSP) house descriptions and descriptions of identically sized prototype NZEH houses at the 50%+ savings level as determined by BEopt analyses at the photovoltaic (PV) take-off point. [NOTE: savings relative to the Building America research benchmark house as of July 2005, with benchmark as defined in Hendron, et al. (2004) and Hendron (2005).]

- Definition of baseline HVAC and water heating systems: a baseline set of equipment of legally minimum efficiency: SEER 13 and HSPF 7.7 centrally ducted split-system air-to-air heat pump for heating and cooling, a mass-market, standard dehumidifier that operates on demand when by-product latent cooling by the heat pump is insufficient, a standard electric storage water heater with energy factor of 0.90, and mechanical ventilation system satisfying ASHRAE 62.2.

- Using computer analyses (based on TRNSYS simulations of the houses and HVAC options), the hourly space heating, space cooling (latent and sensible), ventilation, and water heating loads that will need to be met by the HVAC equipment were determined.

- Using TRNSYS analyses the energy consumption to meet the RSP and NZEH loads was determined for the baseline system and IHPs in five locations – Atlanta (mixed-humid climate zone), Houston (hot-humid), Phoenix (hot-dry), San Francisco (marine), and Chicago (cold). (NOTE: only the baseline system energy consumption was computed for the RSP house.)

- The IHP options were scored against the weighted criteria factors outlined below. The quantitative analysis supported scoring of the primary should-meet criterion, which is potential to achieve peak demand and 50% annual energy savings relative to baseline. The other criteria were scored qualitatively based on the expert opinions of the scorers.

Technology Option Ranking Criteria

The criteria consist of four must-meet criteria and ten should-meet criteria:

1. Must-meet:

   a. In alignment with one of the components of strategy for achieving the HVAC and water heating objective.

   b. Has potential for significant energy savings with the sum of utility and mortgage costs in new housing construction remaining the same, or enables other technologies in a whole-house package to do so.

   c. Unlikely to be developed by the private sector alone.

   d. Technically feasible (there is a reasonable likelihood that the product can be developed and produced).

2. Should-meet:
   (The 10 criteria are each scored 1-10, criterion scores are averaged across all scoring participants, then the criterion weights are applied to arrive at an overall project score. The best possible score is 100.):

   a. (Weight: 2.5) Equipment has the potential to achieve 50% energy savings versus baseline in a range of climates (all climates would get best score).

b. (Weight: 1.25) Equipment can meet ZEH energy service needs (e.g., cooling/ heating/dehumidification/fresh air ventilation/domestic hot water), which may be quite different in magnitude and relative proportions from those of current buildings, and come with additional expectations for uniform comfort and indoor environmental quality (IEQ).

c. (Weight: 1.25) There do not appear to be any high costs, such as high-cost components or other factors, that would preclude the use of the equipment in new housing construction by 2015, with the sum of utility and mortgage costs remaining the same versus baseline.

d. (Weight: 1.0) Private sector enterprises can be identified that should have an interest in the new product concept based on degree of strategic fit, competitive advantage, in-house core competencies, existing business units, market niches served, existing paths to market, entrepreneurial track record, etc.

e. (Weight: 1.0) The program element has prospects for resources of sufficient critical mass to fund early phase research and to cost-share the mid-phases in order to attract private partners for the new product concept.

f. (Weight: 0.75) Equipment is based on off-the-shelf components that are mass produced now, or are likely to become common and mass produced due to the support of markets other than NZEH (i.e., Building Technologies program resources are not expected to be needed in order for the components to reach this level of commercialization).

g. (Weight: 0.75) Equipment is easily installed and maintained without necessitating substantial additional training for installers or requiring additional trades personnel.

h. (Weight: 0.5) Equipment serves the new NZEH market but can also satisfy the conditions for participation in the broad new housing construction market for equipment.

i. (Weight: 0.5) Equipment serves the new NZEH market but can also satisfy the conditions for participation in the broad residential equipment replacement markets, including the immediacy requirement for some equipment replacements upon failure.

j. (Weight: 0.5) Equipment has the potential to achieve significant peak energy demand reduction versus baseline in a range of climates (all climates would get best score).

Failing to meet all the must-meet criteria implies “no-go.” If the must-meet criteria are met numerical scores (maximum of 100) are generated based on the “should-meet” criteria. DOE/BT management, the RI program staff, and BA team members can then use the rankings and management discretion to determine whether either or both of the IHP options are “go” for further RD&D steps.

3. HOUSE DESCRIPTIONS

For the previous scoping assessment (Baxter 2005), the current Building America Research benchmark house [benchmark as defined in Hendron, et al. (2004) and Hendron (2005)] was used as the baseline house configuration. For the present study it was decided to examine a baseline house construction more indicative of typical 2006 practice. Therefore, in consultation with NREL Regional Standard Practice (RSP) house descriptions were defined. Table 2 lists the ceiling and wall cavity insulation values, window U-factors, and solar heat gain coefficients (SHGC) used in the RSP houses for each location. Requirements as outlined in the 2006 International Energy Conservation Code (IECC 2006, Table 402.1.1) were generally followed with exceptions as described in the Table 2 footnotes.

Table 2. Wall and ceiling cavity insulation minimum R-values, maximum window U-factors, and SHGC for Regional Standard Practice (RSP) baseline houses[a]

City	Walls (IECC 2006 minimum)	Walls (values used for present analysis)[b]	Ceiling (IECC 2006 minimum)	Window U-factors (IECC 2006)	Window SHGC (IECC 2006)
Atlanta	13	13 cavity + R5 sheathing	30	0.65	0.40
Houston	13	13 cavity + R5 sheathing	30	0.75	0.40
Phoenix	13	13 cavity + R5 sheathing	30	0.75	0.40
San Francisco	13	13 cavity + R5 sheathing	30	0.65	0.40
Chicago[c]	13 cavity + R5 sheathing (2x4 stud, 16" OC, 25% frame factor)	19 cavity + R5 sheathing (2x6 stud, 24" OC, 20% frame factor)	40[d]	0.35	No IECC requirement

[a]Balance of construction (sheetrock, studs, ceiling framing factor of 11%, etc., same as for BA benchmark house from 2005 study)
[b]IECC minimum yields lower total wall R than for BA benchmark house
[c]For Chicago basement wall insulation is R10 (continuous)
[d]IECC minimum is R38

Prototype NZEH houses were used for the IHP energy savings estimation analyses. These were as determined in July 2005 by NREL using their Building Energy Optimization (BEopt) analyses tool (Christensen 2005, Anderson, et al 2004) at the PV take-off point. Figure 1 illustrates mortgage plus utility cost results from NREL's BEopt simulation for Atlanta. The y-intercept point on the left vertical axis represents this cost parameter for the BA benchmark. The prototype NZEH for Atlanta was taken from the point on the curve at about 55% energy savings vs. the BA benchmark as indicated by the vertical dashed line. The blue solid vertical line superimposed on Figure 1 indicates the approximate energy savings of the RSP baseline house relative to the BA benchmark.

A key objective of identifying design concepts that can save up to 50% relative to current baseline systems is to move the point of break-even mortgage and utilities cost on Figure 1 from around 55–60% to 70–85% energy savings. This will in turn reduce the net cost premium required to meet the net zero energy goal.

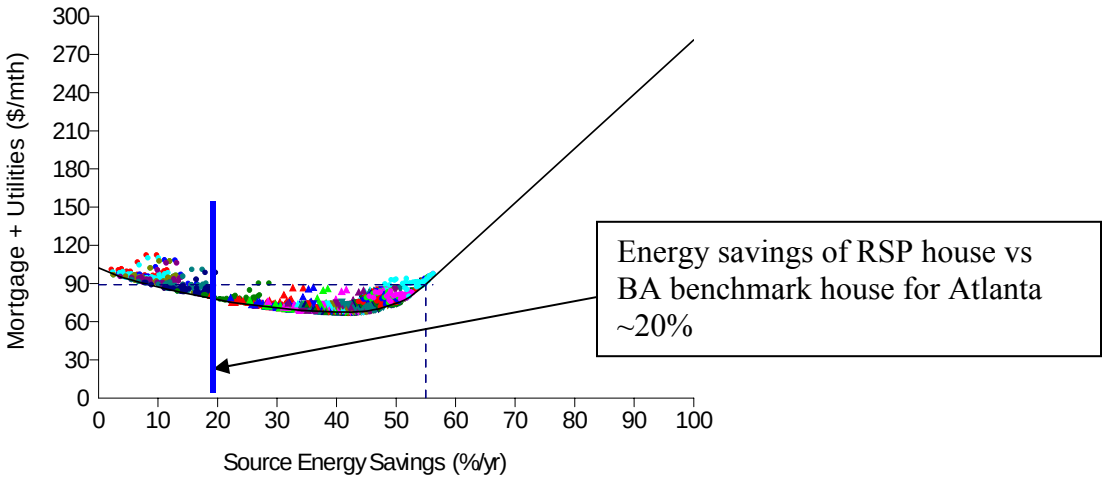

Fig. 1. Net mortgage and utilities cost vs. source energy savings for 1800-ft^2 house in Atlanta with BA benchmark at 0% energy savings point and prototype NZE house at ~55% energy savings point (i.e., take-off point).

TRNSYS representations were developed for both the RSP and NZE houses. Thermostat control was single-zone with set points of 71°F heating, 76°F cooling, and 120°F water heating as provided in the DOE 2.2 BDL files from NREL. In the BEopt analyses, it was assumed that the occupants of the house would open windows to take advantage of free cooling whenever ambient air temperature was low enough during the cooling season. This was followed in the TRNSYS representations & simulations as well. Figures 2 and 3 give a comparison of the computed NZEH heating and cooling loads, respectively, from the BEopt analysis (DOE2.2-based) and from the TRNSYS analysis. In general the absolute loads computed by the TRNSYS simulation are higher for heating and lower for cooling with closer agreement (percentage-wise) where loads are higher. The trends are in close agreement.

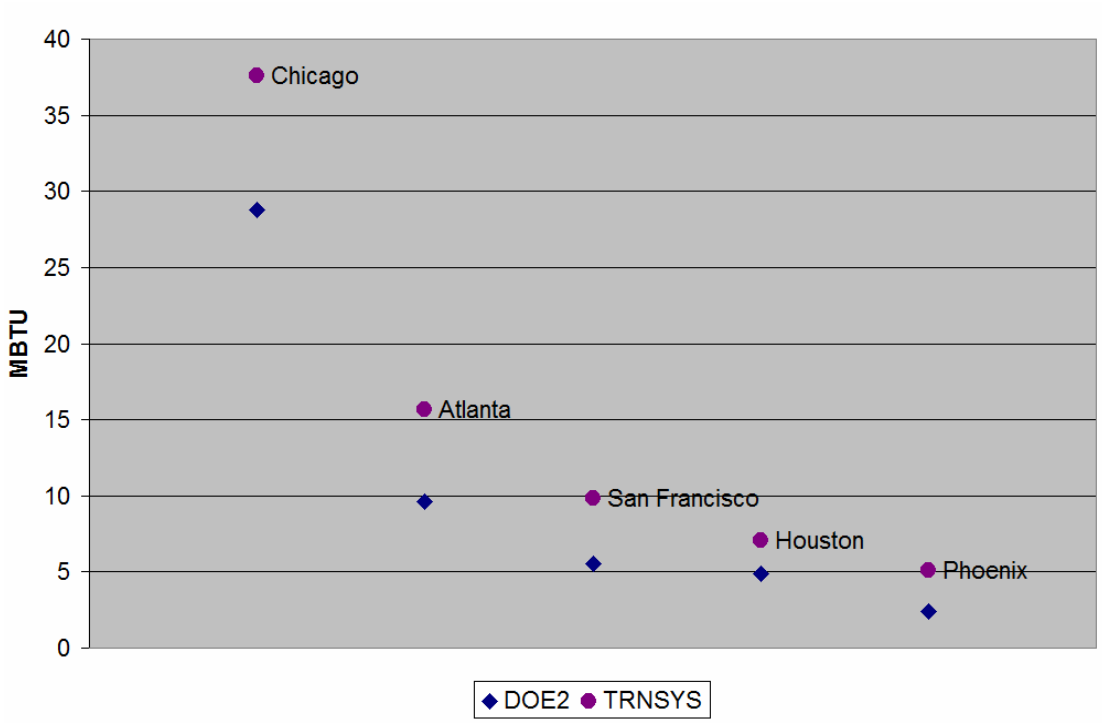

Fig. 2. DOE2 vs. TRNSYS heating loads for 1800-ft^2 NZEH.

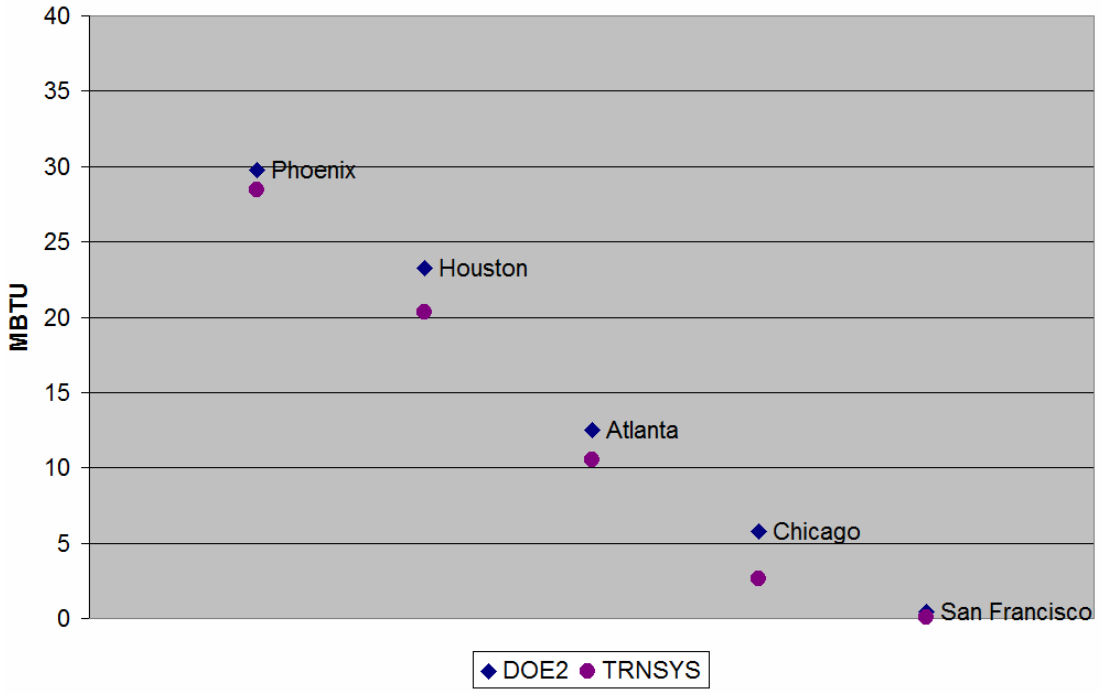

Fig. 3. DOE2 vs. TRNSYS cooling loads for 1800-ft^2 NZEH.

4. DESCRIPTION OF HVAC SYSTEM OPTIONS

4.1 Baseline (Electric)

A standard split-system (separate indoor and outdoor sections), air-to-air heat pump provides space heating and cooling under control of a central thermostat that senses indoor space temperature. It also provides dehumidification when operating in space cooling mode but does not separately control space humidity. Rated system efficiencies were set at the DOE-minimum required levels (SEER 13 and HSPF 7.7) in effect for 2006. Water heating is provided using a standard 50 gallon capacity electric storage water heater with energy factor (EF) set at the current DOE-minimum requirement (EF = 0.90) for this size WH. Ventilation meeting the requirements of ASHRAE Standard 62.2-2004 (ASHRAE 2004) is provided using a central exhaust fan. A separate dehumidifier (DH) is included as well to meet house dehumidification needs during times when the central heat pump is not running to provide space cooling. A humidistat with a set point of 50% RH was used for the DH control.

Dehumidifier location, sizing, and efficiency level. Rudd, et al (2005) indicates that perhaps the most cost effective approach for adding separate dehumidification capability to a house is to locate a stand-alone dehumidifier in the conditioned space, preferably in close proximity to the main HVAC system return air grill. That is the approach adopted in the present analysis. A manufacturer of typical stand-alone DH's, Heat Controller, includes a table on their web site that suggests a 30-50 pint/day (7-12 L/d) capacity would be sufficient for a 2000 ft^2 house (http://www.heatcontroller.com/products/pdf/dehumidbroch.pdf). A 40 pt/d size was chosen and this proved to be adequate for the NZE house in the Atlanta, Chicago, Phoenix, and San Francisco locations. In this case adequate was taken to mean that indoor RH levels would exceed 60% for no more than about 10% of the year. Since window openings were allowed it was assumed that allowing the RH to rise above 60% for this amount of time was acceptable for the occupants. In examining the results, most of these hours occurred early or late in the cooling season during periods of very mild ambient conditions. However, for Houston the interior house space exceeded 60% RH for almost 25% of the time. So, a larger DH (65 pt/d) was used in Houston to keep the total hours above 60% RH down to about 10% of the year.

There is currently no DOE-mandated minimum efficiency value for residential dehumidifiers. However, amendments to the Energy Policy and Conservation Act (EPCA) of 1975 included in the Energy Policy Act of 2005, P.L. 109-58, expanded DOE's energy conservation program to include certain commercial equipment and residential products, including dehumidifiers. In compliance with this directive, DOE/BT has recently specified a default minimum dehumidifier energy factor (EF_d) for 40 pt/d DHs of 1.3 L/kWh effective 2007 and a default minimum of 1.4 L/kWh effective 2012 (DOE/BT 2006). According to comments submitted by Whirlpool to EPA regarding their recent revision of the Energy Star

requirements for dehumidifiers the 35-54 pt/d capacity range represents nearly 60% of all dehumidifier shipments (Hoyt 2005). DOE will focus its rulemaking analysis for DH's on the 35-45 pt/d size range only. The Energy Star website (http://www.energystar.gov/index.cfm?c=dehumid.pr_dehumidifiers) indicates that the current efficiency of ES-qualified dehumidifiers of the above capacity range from 1.3 to 1.5 L/kWh (rated at 80 °F and 60% RH indoor conditions). Based on the above it was decided to use $EF_d = 1.4$ for the baseline system dehumidifier efficiency in the present analysis.

4.2 Centrally Ducted Air-Source Integrated Heat Pump (AS-IHP)

This option is the air-source version of the integrated heat pump (IHP) currently in the breadboard laboratory prototype stage at ORNL. This concept, as shown in Figure 4, uses one variable-speed (VS) modulating compressor, two VS fans, one VS pump, and a total of four heat exchangers (HXs: two air-to-refrigerant, one water-to-refrigerant, and one air-to-water) to meet all the HVAC and water heating (WH) loads.

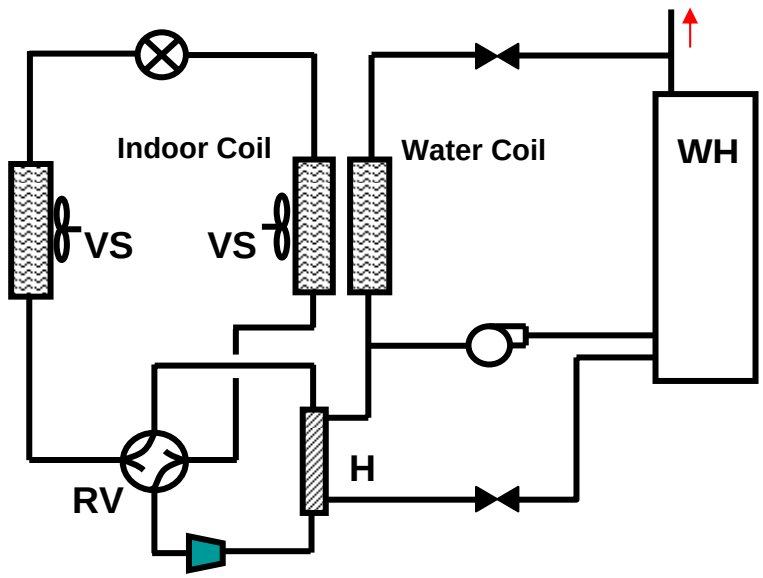

Fig. 4. Conceptual diagram of a central forced-air electric air-source integrated heat pump, showing operation in space-cooling mode.

One unique aspect is that the ventilation air is conditioned by the heat pump in both space cooling and space heating modes, and on demand if neither heating nor cooling is required. The unit also cycles on demand to dehumidify the space whether or not heating or cooling is required. The air-to-water HX uses waste hot water generated in the space cooling, dehumidification, and ventilation cooling modes to temper the ventilation air, as needed, for space neutral conditions. Compressor, indoor fan, and water pump speed modulation is used to control both indoor humidity and temperature, when needed. (Note that both water heating and ventilation air tempering can be done at the same time.) The system concept is described more fully by Tomlinson et al (2005).

Another potentially attractive aspect of the IHP concept is that, being a single equipment package, it is better suited than the baseline suite of equipment for being able to curb demand when the grid is stressed in response to a utility or ISO radio signal.

4.3 Centrally Ducted Ground-Source Integrated Heat Pump (GS-IHP)

This technology is similar to the AS-IHP above but with the outdoor air coil replaced with a refrigerant-to-water HX and pumped secondary fluid to a conventional high-density polyethylene (HDPE) ground heat exchanger (HX), making a ground-coupled version of the IHP. As with other ground-source heat pumps the GS-IHP does not require a defrost cycle and with a properly sized ground HX operates with heat source and sink temperatures that are friendlier than outdoor air all year long. We plan to assess this option with both a vertical bore ground HX and a horizontal loop ground HX with SWS enhancement.

5. ANALYSIS APPROACH

The annual energy use simulations for the baseline and IHP HVAC systems were performed using the TRNSYS 16 platform (Solar Energy Laboratory, et al. 2006). This required conversion of the 1800-ft^2 RSP house and prototype NZEH descriptions to TRNSYS Type 56 representations. Performance of each of the IHP systems was estimated based on experimental performance maps generated for a laboratory prototype IHP at ORNL (Tomlinson et al 2005).

Annual, hour-by-hour simulations were performed for the baseline system for both the RSP and prototype NZEH buildings for five locations - Atlanta, mixed-humid; Houston, hot-humid; Phoenix, hot-dry; San Francisco, marine; and Chicago; cold). Annual simulations for the IHP systems were limited to the NZE houses only.

6. SYSTEMS ENERGY CONSUMPTION RESULTS

Table 3 provides results of the TRNSYS simulations for the baseline HVAC system for the RSP house for each of the five locations examined in this study. Table 4 provides the same information for the prototype NZEH house. Tables 5 and 6 provide results for the AS-IHP and GS-IHP, respectively. Peak kW demand in Tables 5 and 6 are hourly integrated values. Maximum peaks generally occurred in the winter. Summer peaks are somewhat lower and generally occurred in July.

Table 3. Annual site HVAC/WH system energy for 1800-ft^2 RSP benchmark house with Baseline HVAC/WH system

Location	HVAC site energy use, kWh	HVAC peak integrated hourly kW (winter/summer)	Percent savings vs. RSP/Baseline HVAC
Atlanta	11,234	15.8/8.4	-
Houston	13,632	8.4/8.8	-
Phoenix	9,841	8.7/8.5	-
San Francisco	7,784	6.8/4.9	-
Chicago	12,495	14.6/6.9	-

Table 4. Annual site HVAC/WH system energy for 1800-ft^2 NZEH house with Baseline HVAC/WH system

Location	HVAC site energy use, kWh	HVAC peak integrated hourly kW (winter/summer)	Percent savings vs. RSP/Baseline HVAC
Atlanta	8,753	9.6/6.9	22.1
Houston	11,028	5.9/5.7	19.1
Phoenix	7,149	6.2/4.8	27.4
San Francisco	5,678	5.7/4..9	27.1
Chicago	11,209	9.7/6.4	10.3

Table 5. Estimated annual site HVAC/WH system energy use and peak for 1800-ft^2 NZEH house with AS-IHP system (from Baxter 2005)

Location	HVAC site energy use, kWh	HVAC peak integrated hourly kW (winter/summer)	Percent energy savings vs. NZEH/Baseline HVAC
Atlanta	4149	5.8/4.1	52.6
Houston	5271	4.1/4.0	52.2
Phoenix	3582	4.3/3.4	49.9
San Francisco	2226	4.5/3.9	60.8
Chicago	5571	5.8/3.8	50.3

Table 6. Estimated annual site HVAC/WH system energy use and peak for 1800-ft^2 NZEH house with GS-IHP system (from Baxter 2005)

Location	HVAC site energy use, kWh	HVAC peak integrated hourly kW (winter/summer)	percent savings vs. NZEH/Baseline HVAC
Atlanta	3685	5.8/4.1	57.9
Houston	4808	4.1/4.0	56.4
Phoenix	3203	4.3/3.4	55.2
San Francisco	2152	4.5/3.9	62.1
Chicago	4730	5.8/3.8	57.8

Individual system efficiencies needed to reach annual energy savings goal: A reasonable question to ask is "How efficient must individual pieces of equipment be to match the annual energy savings potential of the IHPs noted in tables 5 and 6?" The best available efficiencies for the individual units that compose the baseline system (sans the ventilation fan) are as follows.

> Central air conditioners/heat pumps — A recent *ACH&R News* article noted that at least one central AC product was available with a rated SEER of 23 for a unit with variable-speed compressor (*ACH&R News* 2006). A search of ARI's online directory found six split system heat pump models (all ductless-type products) with certified HSPF ratings of 10 or higher (www.aridirectory.org/index.html; accessed August 16, 2006). No heat pump products were found in the directory with both a 23 SEER and HSPF ≥10.
>
> Water heaters — An integral-type (heat pump components mounted to water storage tank) heat pump water heater (HPWH) product marketed in the early 2000's achieved a rated EF of 2.4 (www.ecrinternational.com/secure/upload/document/76.pdf). The maker has removed this product from the market recently.
>
> Dehumidifiers — The Energy Star website (www.energystar.gov/index.cfm?c=dehumid.pr_dehumidifiers) notes one stand-alone DH product with an EF_d of 2.0 (50 pt/d capacity).

Applying these efficiencies to the NZE house loads and estimating the resulting energy consumption yields about 42.5% annual energy savings vs. the baseline system suite in Atlanta. To reach the 50% target savings level with a suite of individual equipment will thus require that efficiency of one or more of the individual units be increased. One combination of unit efficiency levels that would accomplish this would be a HPWH EF of 3, a DH EF_d of 3, and a variable-capacity heat pump with 23 SEER and 10 HSPF. A suite of equipment with these efficiencies could yield about 51% annual savings for the Atlanta location. It will also exceed the 50% target in Houston (53%), Phoenix (51%), and San Francisco (57%). It will just reach the target in Chicago (50%) assuming the heat pump has enough over-capacity capability during winter to offset the need for electric resistance backup heating. To achieve the HPWH and DH efficiencies noted would require a significant RD&D effort to develop small-capacity, fractional-horsepower compressors with much higher efficiency than available today.

Alternatively, central heat pumps (of 1-1.5 ton nominal capacity) must be developed with much higher SEER and HSPF ratings than commercially available today. Assuming a suite of equipment that includes the best available HPWH and DH efficiencies noted above, my estimate is that the central heat pump would have to have rated SEER and HSPF of 33 and 15, respectively, to ensure meeting the 50% savings target in all five study locations. The IHP energy savings estimates are based on demonstrated efficiency of a laboratory proof-of-concept prototype that used commercially available, variable-capacity compressor technology being manufactured in large quantities today.

7. SYSTEM COST ESTIMATES

7.1 Baseline System Estimated Costs

Central heat pump; minimum estimate: From the 2002 technical support document (TSD/heat pump) for DOE's central heat pump efficiency standards (DOE/BT 2002), the estimated cost to manufacture a 13SEER 3-ton split system heat pump in 1998 dollars was $743.36. Data from the US Department of Labor indicates that the Producer Price Index (PPI) for finished goods less food and energy has inflated by 10.8% from 1998 to 2006. Applying this factor to the 1998 cost estimate yields an estimated cost to manufacture of $823.64 in 2006 dollars. The TSD/heat pump also estimated mark up factors for manufacturer, distributor, and dealer of 1.23, 1.26, and 1.27, respectively. Applying these factors to the manufacturing cost estimate yields an estimated selling price for a 3-ton heat pump of $1621.13 (2006 dollars). Pricing data obtained on May 16, 2006 from the Smarterway.com web site (www.smarterwayinc.com/), a source used by NREL in obtaining cost data for BEopt analyses, indicates that 1.5 ton systems are on average about 80.5% of the cost of 3-ton models. So, an estimate for the selling price of a 1.5 ton heat pump is $1305.01 in 2006 dollars.

Central heat pump; maximum estimate: Average pricing data for four (4) different manufacturers from the Smarterway.com site is plotted in Figure 8 for 13SEER heat pumps from 1.5 - 4.0 tons. Price increases linearly with capacity above the 2-ton level. Average price for the 1.5-ton models from this source is virtually the same (about $21 less) as that for the 2-ton size. It is assumed that these prices include manufacturer, distributor and dealer mark ups.

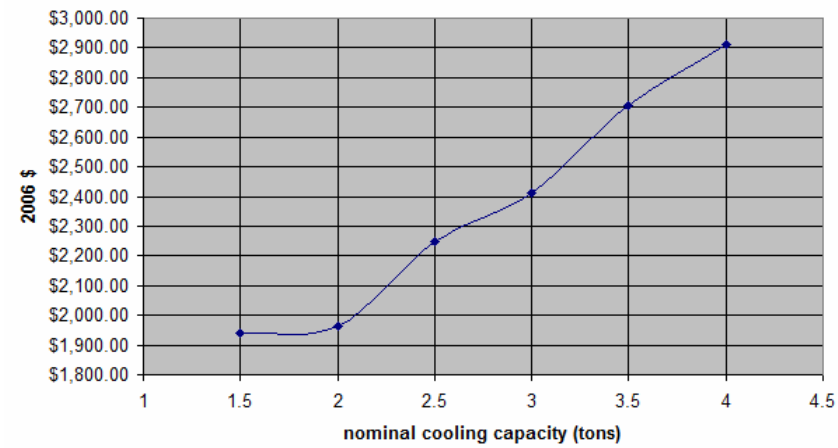

Fig 5. Average 2006 selling prices for 13SEER split system heat pumps. (Source: www.smarterwayinc.com, 5/16/2006.)

Central heat pump; installation cost estimate: The TSD/heat pump estimated average 1998 installation costs for a central heat pump of $2280 with no differentiation for size. The Consumer Price Index (for all items less food and energy) was used to inflate this cost to 2006 dollars. Between 1998 and 2006 the CPI has increased about 18.3%, thus the estimated installation cost for a baseline central heat pump in 2006 dollars is about $2690.

Water heater: From the 2000 technical support document (TSD/WH) for DOE's water heater efficiency standards (DOE/BT 2000), the estimated cost to manufacture a 50-gallon electric storage water heater in 1998 dollars was $166.60. This cost includes the following efficiency enhancement features needed to reach the prescribed efficiency level: a heat trap, 2.5" of foam insulation, and foam insulation on the tank bottom. Applying the 1998-2006 PPI of 1.108 (above), the estimated manufacturing cost is $184.60 in 2006 dollars. The TSD/WH estimated an overall mark up factor of 1.7 for manufacturer to consumer which yields an estimated selling price of $313.82 in 2006 dollars. 1998 installation costs estimated in the TSD/WH are $160, and after inflating using the 1998-2006 CPI (above) this yields an installation cost of $188.8 in 2006 dollars. The overall estimated cost to the consumer for a 50-gallon storage electric water heater in 2006 dollars is therefore $502.62.

Dehumidifier: Costs for a 50 pt/d stand-alone dehumidifier are estimated at $400 (2001 dollars) based on data presented by Rudd, et al. (2005). This includes cost of the dehumidifier, an overflow drain pan, and running a condensate line to nearest drain. The CPI inflated by an estimated 10% for the period from 2001 to 2006 (U.S. Dept. of Labor) so this cost would be $440 in 2006 dollars. The web site of "AC for sale" (http://acforsale.com), another source of cost data for BEopt, includes recent prices for dehumidifiers to enable estimation of the relative cost of a 40 pt/d model compared to the 50 pt/d size. Based on this data, stand-alone 40 pt/d dehumidifier cost in 2006 dollars is estimated to be about $415.

Ventilation fan: The minimum continuous ventilation rate for an 1800 ft^2 (167 m^2) house with three bedrooms is 48 cfm per ASHRAE Standard 62.2-2004 (ASHRAE 2004). A typical 50-cfm exhaust fan ducted to the nearest exterior wall is assumed to be used to provide this function, with makeup air provided by infiltration through the building envelope. RSMeans Mechanical Cost Data (Means 2005) indicates that the installed cost of this item (assuming 4 ft of 6-inch-diameter duct and exterior weather cap) in 2005 dollars is about $300. Since the CPI increase from January 2005 to January 2006 was about 1.9%, the cost in 2006 dollars would be about $305.

Total baseline HVAC/WH/DH system cost estimate: Table 7 provides the baseline system costs for the NZEH at each of the five locations used in this study. Table 8 provides similar cost estimates for baseline systems for the RSP houses.

Table 7. Estimated installed costs for NZE house baseline HVAC/WH system (2006 dollars)

City	Heat pump nominal cooling capacity (tons)	DH size (pts/d)	Heat pump cost	DH cost	WH cost	Vent fan cost	Total cost
Atlanta	1.25	40	$3985-4621	$415	$503	$305	$5208-5844
Houston	1.25	65	$3985-4621	$490	$503	$305	$5283-5919
Phoenix	1.50	40	$3995-4631	$415	$503	$305	$5218-5854
San Francisco	1.00	40	$3974-4610	$415	$503	$305	$5197-5833
Chicago	1.25	40	$3985-4621	$415	$503	$305	$5208-5844

Table 8. Estimated installed costs for RSP house baseline HVAC/WH system (2006 dollars)

City	Heat pump nominal cooling capacity (tons)	DH size (pts/d)	Heat pump cost	DH cost	WH cost	Vent fan cost	Total cost
Atlanta	3.00	40	$4311-5100	$415	$503	$305	$5534-6323
Houston	3.50	65	$4509-5395	$490	$503	$305	$5807-6693
Phoenix	4.00	40	$4649-5602	$415	$503	$305	$5872-6825
San Francisco	2.00	40	$4009-4652	$415	$503	$305	$5232-5875
Chicago	2.25	40	$4106-4796	$415	$503	$305	$5329-6019

7.2 AS-IHP Cost Estimate

An artist's concept of the AS-IHP system is given in Figure 6. The basic heat pump system (compressor, indoor and outdoor coils, indoor blower, outdoor fan, refrigerant piping, flow controls, etc.) is similar to the baseline heat pump. While three separate sections (indoor air handler, outdoor coil, and compressor section) are shown in Figure 6, the system could conceivably be packaged in two sections like conventional split system heat pumps and air conditioners. To complete the IHP system, a water heater (with backup electric elements & controls), a refrigerant/water heat exchanger (for water heating), a multi-speed hot water circulation pump, connecting piping between the water heater and heat pump, a water/air heat exchanger coil (for tempering heating during dehumidification operation), and a short duct with motorized damper for ventilation air are added to the basic heat pump.

Cost estimates for each of these elements were developed as described below. Where costs were estimated using Means (2005) they have been inflated to 2006 dollars by the factor of 1.019 (increase in the CPI from January 2005 to January 2006).

1. For the basic heat pump, the author obtained relative costs between a SEER 13 system and a SEER 18 system in the process of replacing his own home heat pump. The SEER 18 unit included dual compressors and a variable-speed indoor blower and its installed cost excluding ductwork was about 1.8 times that of the SEER 13 unit (same manufacturer). Since the IHP system would include a single variable-speed compressor and variable-speed indoor and outdoor fans, thus requiring three inverter speed controllers, we conservatively estimated that a split system heat pump with these same features would be twice the cost of the base 13 SEER system - $2610 to $3882 for a 1.5 ton system.
2. The water heater tank for the IHP was assumed to be identical to that used in the baseline system, and with the same installed cost - $503.
3. Prices for refrigerant/water heat exchangers (R-W HX in figure 6) were obtained from a major water-source heat pump manufacturer (Ellis 2006). Quantity costs for high-efficiency heat exchangers to a WSHP OEM were estimated at $180 each by the manufacturer. To obtain an estimate of the cost to the consumer as

assembled into the IHP package the markup factors for manufacturer, distributor, and dealer from the TSD/heat pump (DOE/BT 2002) were assumed to apply. Total estimated cost for this item is $355 as assembled into the IHP package.

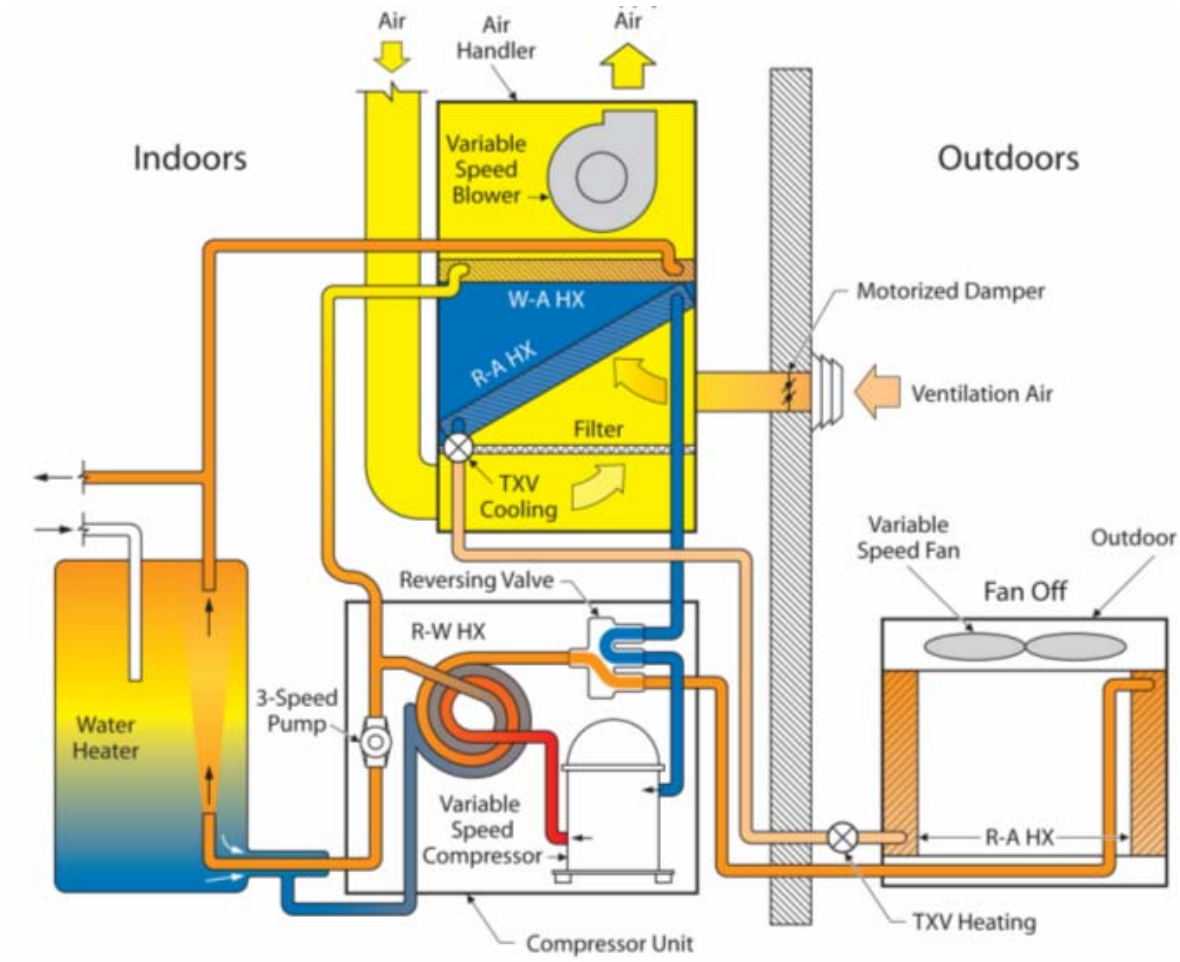

Fig. 6. Schematic of AS-IHP system, dedicated dehumidification mode.

4. The cost of the multi-speed hot water circulating pump was estimated to be about $70 based on the price quoted for a replacement pump for our laboratory IHP prototype. The markup factors from the TSD/heat pump were assumed to apply giving an estimated cost to consumer of $136 as assembled into the IHP package.

5. It is assumed that the WH tank and heat pump would be installed in very close proximity so that minimal interconnecting water tubing runs would be required. Based on data in Means (2005) and assuming that a total of 50 ft of ½ inch insulated copper tubing would be required, cost of installing the water piping is estimated at $700.

6. Water/air heat exchanger (W-A HX in Figure 6) costs were estimated starting with data from Means for a 10 in by 24 in, 2-row, 8 fins/in coil - $345 (2005$). Since the HX used in the lab prototype IHP system (Tomlinson 2005) had only one row this cost was multiplied by 0.5 and the markup factors from the TSD/heat

pump along with the 2005-2006 CPI adjustment were applied. Total estimated cost for this item came to $350 as assembled into the IHP package.

7. For the vent line with motorized damper and exterior weather cap, cost data from Means (assuming a 2-foot long, 6 inch diameter line) resulted in a cost estimate for this item of $194.
8. Installation of the basic heat pump was assumed to be the same as that of the baseline system SEER 13 heat pump, but a 10% increase was assumed to cover miscellaneous contingencies in the IHP case – total $2959.

Estimated costs for the AS-IHP system in each city are given in Table 9. Included in the table are estimated energy cost savings computed using electricity costs for each city from BEopt along with estimated simple payback periods vs. the baseline system *in the ZEH*.

Table 9. Estimated installed costs for NZE house AS-IHP system (2006 dollars)

City	Heat pump nominal cooling capacity (tons)	Total cost	Premium over baseline system	Energy cost savings over baseline system	Simple payback over baseline system, years
Atlanta	1.25	$7793-9058	$2585-3214	$330	7.8-9.7
Houston	1.25	$7793-9058	$2510-3139	$498	5.0-6.3
Phoenix	1.50	$7807-9079	$2589-3225	$281	9.2-11.5
San Francisco	1.00	$7779-9038	$2582-3205	$371	7.0-8.6
Chicago	1.25	$7793-9058	$2585-3214	$418	6.2-7.7

7.3 GS-IHP Cost Estimate

Cost for the basic heat pump portion of the GS-IHP (with a refrigerant/water heat exchanger and pump replacing the outdoor air coil and fan, but with outdoor fan/coil enclosure, refrigerant line set, and defrost cycle with its associated controls all eliminated) was assumed to be 10% less than that for the AS-IHP above. Costs for items 2-7 in the above list were assumed to be identical as for the AS-IHP. Installation of the GS-IHP (exclusive of the ground HX) should be somewhat less involved than for the AS-IHP since there would be no outdoor fan/coil enclosure (eliminates need for labor/materials for the mounting pad, setting the enclosure on the pad, and installation of the associated electrical power/control wiring and refrigerant line set). Installation costs for the GS-IHP package were therefore estimated to be 15% less than for the AS-IHP, or $2515. For the vertical bore ground HX option, the installed cost of the ground heat exchanger (including hookup to the GS-IHP package) was estimated at $1000/ton based on input from a large, experienced installation contractor (Schoen 2006). Total system cost estimates for each city are given in Table 10. Estimated energy cost savings and simple paybacks are included.

Table 10. Estimated installed costs for NZE house GS-IHP system (2006 dollars) – assuming vertical bore ground HX at $1000/ton installed

City	Heat pump nominal cooling capacity (tons)	Total cost	Premium over baseline system	Energy cost savings over baseline system	Simple payback over baseline system, years
Atlanta	1.25	$8338-9476	$3130-3632	$363	8.6-10.0
Houston	1.25	$8338-9476	$3055-3557	$538	5.7-6.6
Phoenix	1.50	$8602-9747	$3384-3893	$310	10.9-12.6
San Francisco	1.00	$8074-9333	$2877-3500	$379	7.6-9.2
Chicago	1.25	$8338-9476	$3130-3632	$480	6.5-7.6

7.4 GS-IHP/SWS Cost Estimate

The solid-water-sorbent- (SWS-) enhanced environmental coupling concept (Ally 2006a) is being investigated for its potential to reduce the size (and cost) of the ground HX required for the GS-IHP. Results of field experiments conducted at a research house in the Lenoir City, TN Habitat for Humanity (HfH) site indicate that a horizontal ground HX of about 700 ft of ¾ inch HDPE pipe surrounded by 80 lb of SWS material and 3200 lb of water enclosed in a vapor barrier surrounding the pipe would be sufficient to handle the peak heat rejection load from a 1-ton heat pump system. A 1200-ft^2 HfH house (30 ft by 40 ft footprint) at the site has a ground-coupled heat pump with a ground HX of 1500 ft of ¾-inch HDPE that was installed completely within the excavation needed for the house foundation. The HX pipe length was determined per design by Bob Brown of WaterFurnace (Brown 2006). Thus the test results indicate that use of the SWS could potentially reduce the required HX length for that house by a factor of two. A horizontal HX for the GS-IHP/SWS should fit comfortably within the available foundation and utility service trench length for the ZEH's used in this study (30-ft by 30-ft footprint).

The results further indicate that the performance of the SWS-enhanced heat exchanger in the experiment is achieving heat transfer efficiency equivalent to that of soil with a thermal conductivity seven times greater than the native soil at the site (Ally 2006b). Parametric analyses conducted as part of the FY05 scoping study (Baxter 2005) indicated that SWS enhancement equivalent to a thermal conductivity increase of 10 – 15 times greater than native soil would be needed to achieve energy efficiency equal to that of a vertical loop ground HX. This would require doubling the amounts of SWS material and water to 160 lb and 6400 lb, respectively, for a 1-ton system. It is further assumed for purposes of this study that the ground HX peak heat rejection capacity could be doubled again by doubling the SWS and water (to 320 lb SWS and 12,800 lb water) enabling the HX length to be cut in half. Using these assumptions together with HDPE pipe costs of $0.21/ft (Schoen 2006), SWS costs of $0.69/lb (Ally 2006b), and vapor barrier costs of $25 (Ally 2006b) a rough estimate of an SWS-enhanced GS-IHP system was developed. Details of the cost estimate are given in Table 11.

Table 11. Cost estimate details for GS-IHP/SWS ground HX

Cooling capacity tons	SWS lb/cost	HDPE pipe length, ft/cost	HX installation cost	Vapor barrier cost	Total cost
1 (San Francisco)	160/$110 320/$221	700/$147 350/$74	$455 $228	$25	$737 $548
1.25 (Atlanta, Houston, Chicago)	200/$138 400/$276	900/$189 450/$$94	$585 $293	$25	$937 $688
1.5 (Phoenix)	240/$166 480/$331	1100/$231 550/$116	$715 $358	$25	$1137 $830

The installation cost in Table 11 is based on $0.65/ft and was arrived at as follows. The 1500-ft HDPE HX in the HfH house noted above cost $1500 to install (Christian 2006). This included laying and headering three 500-ft pipe loops in the trench, installing a pump, connecting pump and HX to the heat pump, and leak checking the HX. The loop contractor was from Blountville, Tennessee, approximately 120 miles from the job site, and made three trips to the site. For purposes of this estimate it was assumed that a local contractor could do the job in one day, saving three round trips or 720 miles of travel. DOE allows business travelers to claim $0.445/mile for personal car mileage, so at this rate $320 could be deducted from the cost. The GS-IHP package is assumed to include the ground loop pump so no expense for pump purchase and installation is required. $200 is deducted from the cost to cover elimination of pump cost and labor for mounting, connecting HDPE piping, and making electrical power and control connections. This reduces the installation cost estimate to $980, or $0.65/ft based on the 1500-ft installation at HfH. This is assumed to cover the cost of laying the plastic vapor barrier in the trench, laying and headering the pipe, adding the SWS material and water, covering the pipe and SWS–water mixture with the plastic vapor barrier sheet, and securing the vapor barrier. Since we assume the pipe is laid in the house foundation and/or utility service trenches, trench backfilling is not charged to the ground HX.

Total system cost estimates for each city are given in Table 12 assuming the maximum SWS usage (least pipe length). If, as we believe, the assumed level of ground HX enhancement can be achieved with the SWS backfill the GS-IHP costs could be reduced to about the same level as for the AS-IHP. Estimated energy cost savings and simple paybacks are included.

Table 12. Estimated installed costs for NZE house SWS-enhanced GS-IHP system (2006 dollars)

City	Heat pump nominal cooling capacity (tons)	Total cost	Premium over baseline system	Energy cost savings over baseline system	Simple payback over baseline system, years
Atlanta	1.25	$7776-8914	$2568-3170	$363	7.1-8.7
Houston	1.25	$7776-8914	$2493-2995	$538	4.6-5.6
Phoenix	1.50	$7932-9077	$2714-3223	$310	8.8-10.4
San Francisco	1.00	$7622-8881	$2425-3148	$379	6.4-8.3
Chicago	1.25	$7776-8914	$2568-3170	$480	5.3-6.6

7.5 Cost Sensitivities

The simple paybacks in Tables 9, 10, and 12 assume no favorable tax incentives or utility rate structures designed to promote use of IHPs or other highly efficient HVAC/WH system options. An estimate of the sensitivity of IHP payback vs. the base system to these factors was developed for two levels of tax incentive and a postulated time-of-use (TOU) + demand charge utility rate structure.

Early in 2006, the Internal Revenue Service issued guidelines for a new, two-year program of tax incentives for energy conservation (http://www.irs.gov/newsroom/article/0,,id=154657,00.html). These incentives include a $300 tax credit to home owners for purchase of "energy efficient property" including air-source heat pumps which have a minimum SEER of 15, HSPF of 9, and rated EER at 95°F (EER_{95}) of 13. Based on the AS-IHP lab system tests last year (Tomlinson 2005), its estimated SEER and HSPF are 17.9 and 11.3, respectively, both well in excess of the rebate requirements. IHP peak reduction potential was estimated at 20 – 40% for combined space conditioning and water heating in last year's scoping study (Baxter 2005). In comparison, the average EER_{95} of 57 single-speed heat pump models with 13 SEER is 11.3 according to Southern California Edison (2005) in their Database for Energy Efficiency Resources (DEER) study for the California Energy Commission (CEC). So the 13 EER_{95} requirement represents about a 6% peak efficiency improvement or peak power reduction on average (12 vs. 11.3). Again the projected peak reduction for the IHP is well in excess of this requirement. With a $300 credit, simple paybacks for the IHP systems reduce by 0.6 – 1.0 years depending upon location. If the credit could be increased to $1000, paybacks would fall by 2-3 years. These results are summarized in Table 13.

Table 13. Sensitivity of AS-IHP and GS-IHP system payback vs. baseline system to assumed tax credits and TOU/demand electricity pricing

City	Heat pump nominal cooling capacity (tons)	Total cost	Premium over baseline system	Energy cost savings over baseline system	Simple payback over baseline system, years
$300 system tax credit					
AS-IHP					
Atlanta	1.25	$7493-8758	$2285-2914	$330	6.9-8.8
Houston	1.25	$7493-8758	$2210-2839	$498	4.4-5.7
Phoenix	1.50	$7507-8779	$2289-2925	$281	8.1-10.4
San Francisco	1.00	$7479-8738	$2282-2905	$371	6.2-7.8
Chicago	1.25	$7493-8758	$2285-2914	$418	5.5-7.0
GS-IHP, vertical ground HX					
Atlanta	1.25	$8038-9176	$2830-3332	$363	7.8-9.2
Houston	1.25	$8038-9176	$2755-3257	$538	5.1-6.1
Phoenix	1.50	$8302-9447	$3084-3593	$310	9.9-11.6
San Francisco	1.00	$7774-9033	$2577-3200	$379	6.8-8.4
Chicago	1.25	$8038-9176	$2830-3332	$480	5.9-6.9

GS-IHP, SWS-enhanced					
Atlanta	1.25	$7476-8614	$2268-2870	$363	6.2-7.9
Houston	1.25	$7476-8614	$2193-2695	$538	4.1-5.0
Phoenix	1.50	$7632-8777	$2414-2923	$310	7.8-9.4
San Francisco	1.00	$7322-8581	$2125-2848	$379	5.6-7.5
Chicago	1.25	$7476-8614	$2268-2870	$480	4.7-6.0
$1000 system tax credit					
AS-IHP					
Atlanta	1.25	$6793-8058	$1585-2214	$330	4.8-6.7
Houston	1.25	$6793-8058	$1510-2139	$498	3.0-4.3
Phoenix	1.50	$6807-8079	$1589-2225	$281	5.7-7.9
San Francisco	1.00	$6779-8038	$1582-2205	$371	4.3-5.9
Chicago	1.25	$6793-8058	$1585-2214	$418	3.8-5.3
GS-IHP, vertical ground HX					
Atlanta	1.25	$7338-8476	$2130-2632	$363	5.9-7.3
Houston	1.25	$7338-8476	$2055-2557	$538	3.8-4.8
Phoenix	1.50	$7602-8747	$2384-2893	$310	7.7-9.3
San Francisco	1.00	$7074-8333	$1877-2500	$379	5.0-6.6
Chicago	1.25	$7338-8476	$2130-2632	$480	4.4-5.5
GS-IHP, SWS-enhanced					
Atlanta	1.25	$6776-7914	$1568-2170	$363	4.3-6.0
Houston	1.25	$6776-7914	$1493-1995	$538	2.8-3.7
Phoenix	1.50	$6932-8077	$1714-2223	$310	5.5-7.2
San Francisco	1.00	$6622-7881	$1425-2148	$379	3.8-5.7
Chicago	1.25	$6776-7914	$1568-2170	$480	3.3-4.5
$1000 system tax credit + TOU/demand rates					
AS-IHP					
Atlanta	1.25	$6793-8058	$1585-2214	$589	2.7-3.8
Houston	1.25	$6793-8058	$1510-2139	$641	2.4-3.3
Phoenix	1.50	$6807-8079	$1589-2225	$445	3.6-5.0
San Francisco	1.00	$6779-8038	$1582-2205	$411	3.8-5.4
Chicago	1.25	$6793-8058	$1585-2214	$667	2.4-3.3
GS-IHP, vertical ground HX					
Atlanta	1.25	$7338-8476	$2130-2632	$617	3.5-4.3
Houston	1.25	$7338-8476	$2055-2557	$676	3.0-3.8
Phoenix	1.50	$7602-8747	$2384-2893	$474	5.0-6.1
San Francisco	1.00	$7074-8333	$1877-2500	$417	4.5-6.0
Chicago	1.25	$7338-8476	$2130-2632	$716	3.0-3.7
GS-IHP, SWS-enhanced					
Atlanta	1.25	$6776-7914	$1568-2170	$617	2.5-3.5
Houston	1.25	$6776-7914	$1493-1995	$676	2.2-3.0
Phoenix	1.50	$6932-8077	$1714-2223	$474	3.6-4.7
San Francisco	1.00	$6622-7881	$1425-2148	$417	3.4-5.2
Chicago	1.25	$6776-7914	$1568-2170	$716	2.2-3.0

To estimate the potential impact of a TOU + demand utility costs, a rate structure was postulated as shown in Table 14. The TOU rate itself is patterned after a residential structured that was in use on a trial basis in Laredo, TX in the early 1990's (Goldman, et al, 1995). A demand charge of $10/peak kW/month was added to the TOU hourly use rates for purposes of this present sensitivity analysis. Applying this postulated rate structure to the baseline and IHP ZEH systems in the five study locations yielded increased annual energy cost savings. Table 13 includes simple payback impacts from combining the TOU + demand rates with a $1000 tax credit. In this scenario, simple paybacks for the IHP ranged from about 2 – 6 years depending upon location.

Table 14. Postulated TOU + demand rate structure used for IHP simple payback sensitivity assessment

Season	Time of day	Rate as fraction of average rate	Demand charge, $/peak kW/m
Summer	1 p.m. – 4 p.m.	1.375	10
	4 p.m. – 5 p.m.	4.375	
	5 p.m. – 7 p.m.	1.375	
	7 p.m. – 1 p.m.	.7125	
Winter	1 p.m. – 7 p.m.	.9125	10
	7 p.m. – 1 p.m.	.7125	

7.6 Approximate IHP System Target Prices

Using the BEopt program developed by NREL (Anderson et al., 2004) analyses for 1800-ft^2, all-electric houses in all five locations were performed. Plots of the sum of incremental mortgage costs plus utility costs from this analysis are presented in figures 7 – 11.

Using the energy savings for HVAC/WH computed for the IHP systems and their estimated installed costs from above, mortgage + utility costs for IHP-equipped houses were estimated and their locations shown on Figures 7-11. The procedure used to estimate the IHP mortgage + energy costs is as follows:

- HVAC/WH-related energy consumption & monthly costs for the ZEH from the BEopt analysis were extracted from the detailed BEopt output;
- HVAC/WH-related energy use and costs were estimated for the ZEH assuming baseline system efficiencies;
- IHP system energy savings were applied to the ZEH with baseline system HVAC/WH-related energy uses;
- IHP system incremental monthly mortgage costs were estimated based on the monthly mortgage cost and total system cost at the ZEH point (100% savings) from the BEopt output;
- IHP system monthly utility costs were estimated based on the monthly utility costs at the zero energy savings (BA benchmark) point from the BEopt output; and
- Total IHP system mortgage + utilities costs for the ZEH with IHP were estimated.

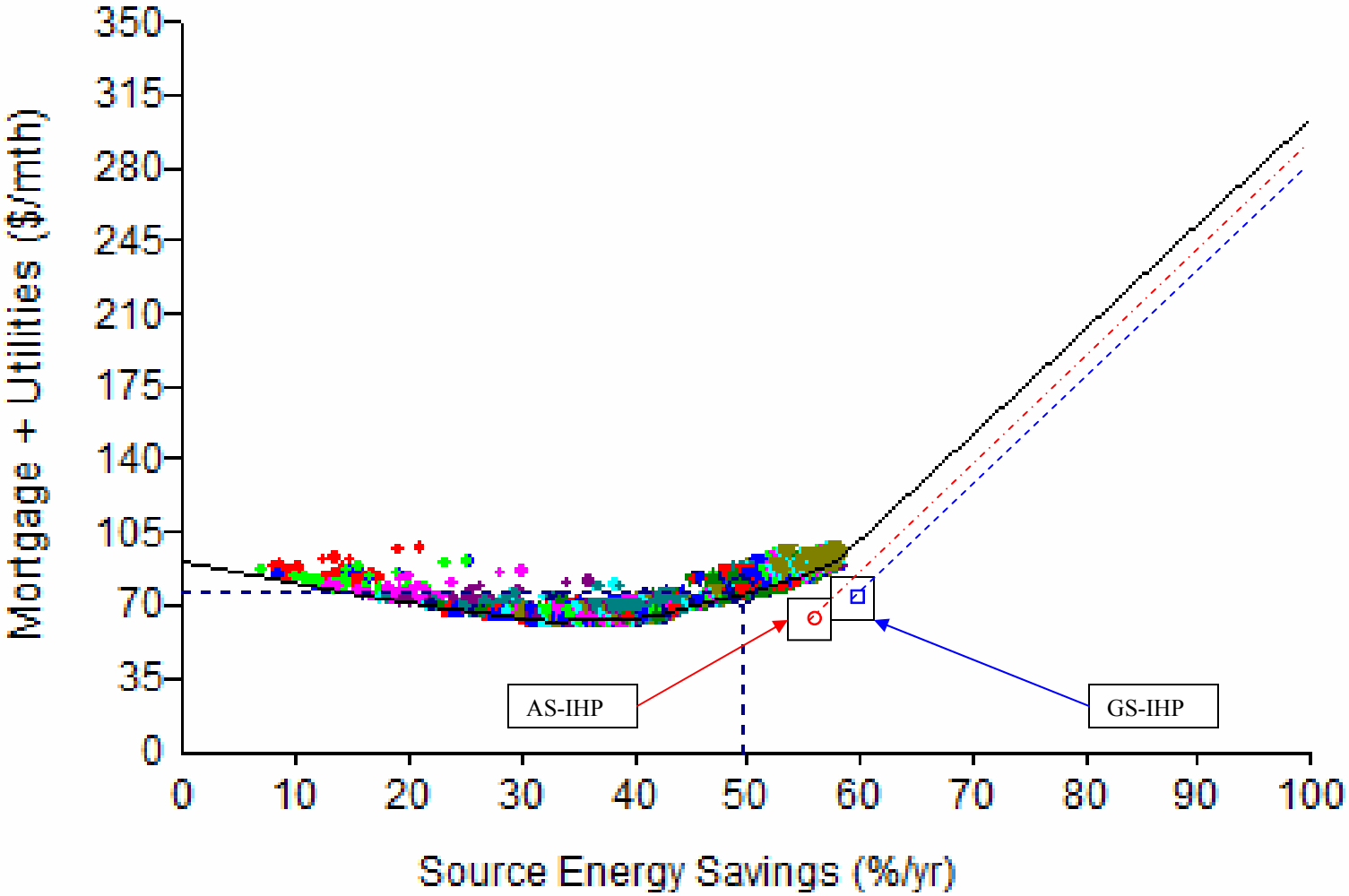

Fig. 7. Incremental mortgage + utilities costs for 1800-ft^2 ZEH in Atlanta (from NREL BEopt analysis).

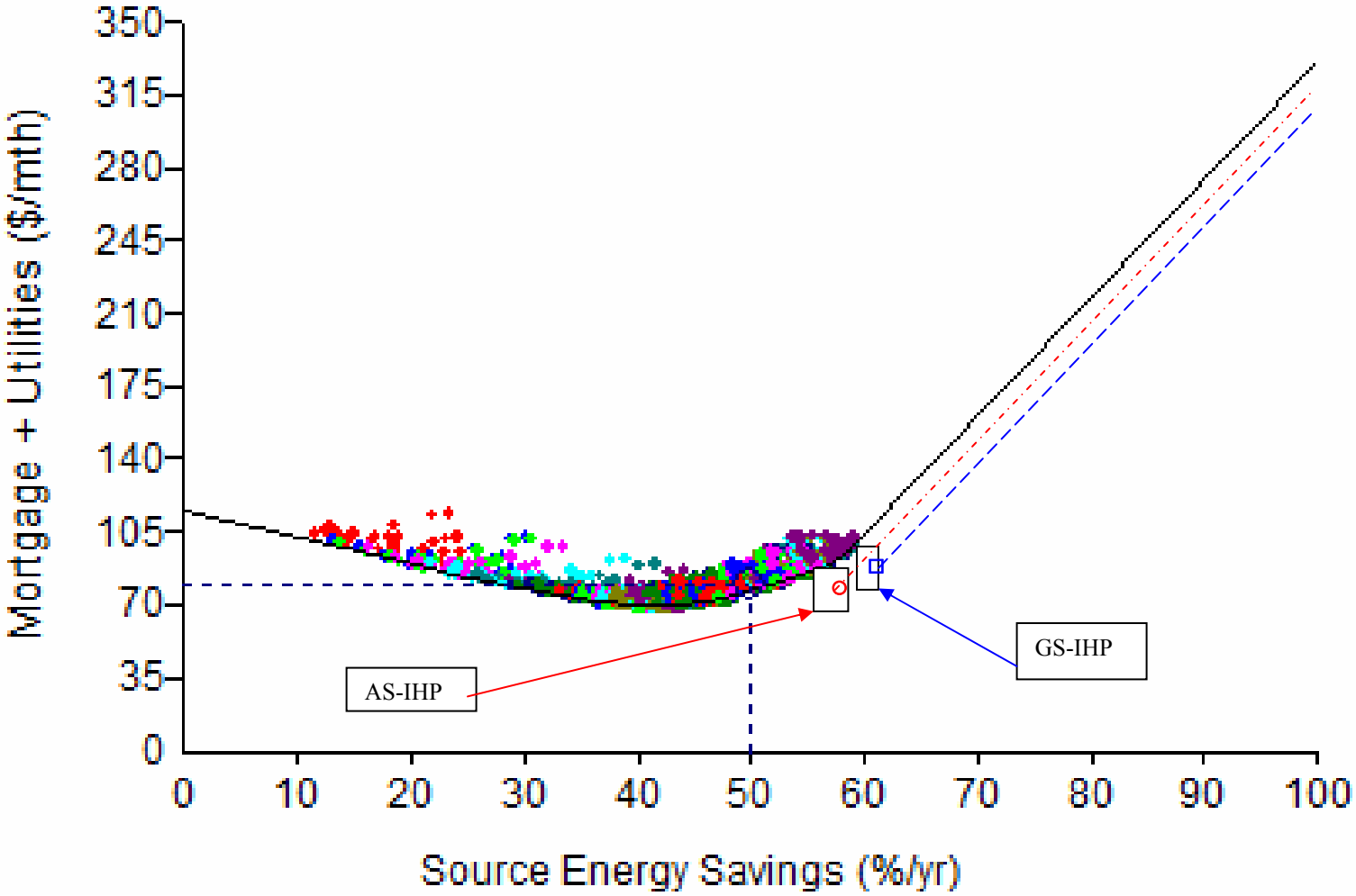

Fig. 8. Incremental mortgage + utilities costs for 1800-ft^2 ZEH in Houston (from NREL BEopt analysis).

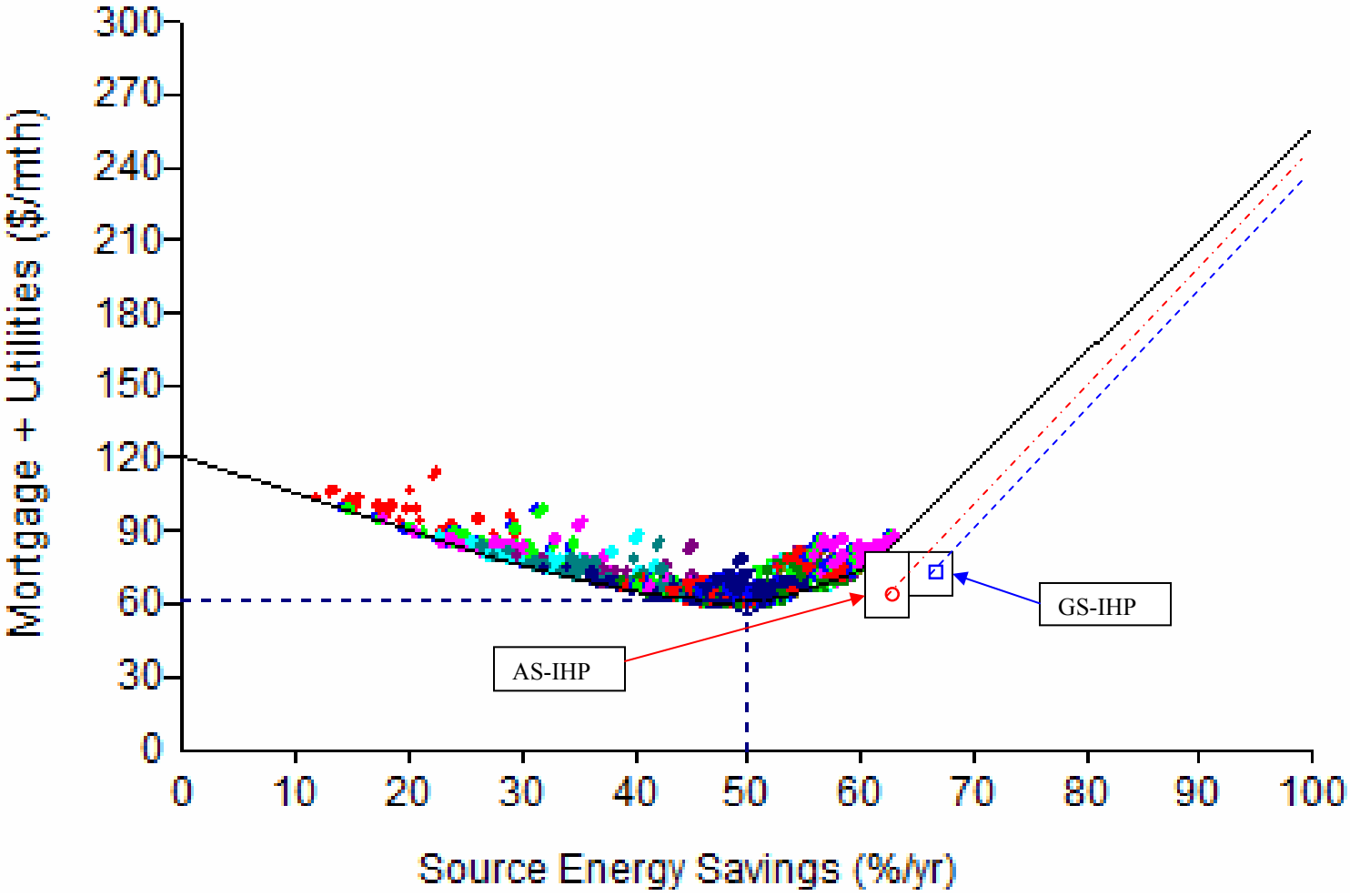

Fig. 9. Incremental mortgage + utilities costs for 1800-ft^2 ZEH in Phoenix (from NREL BEopt analysis).

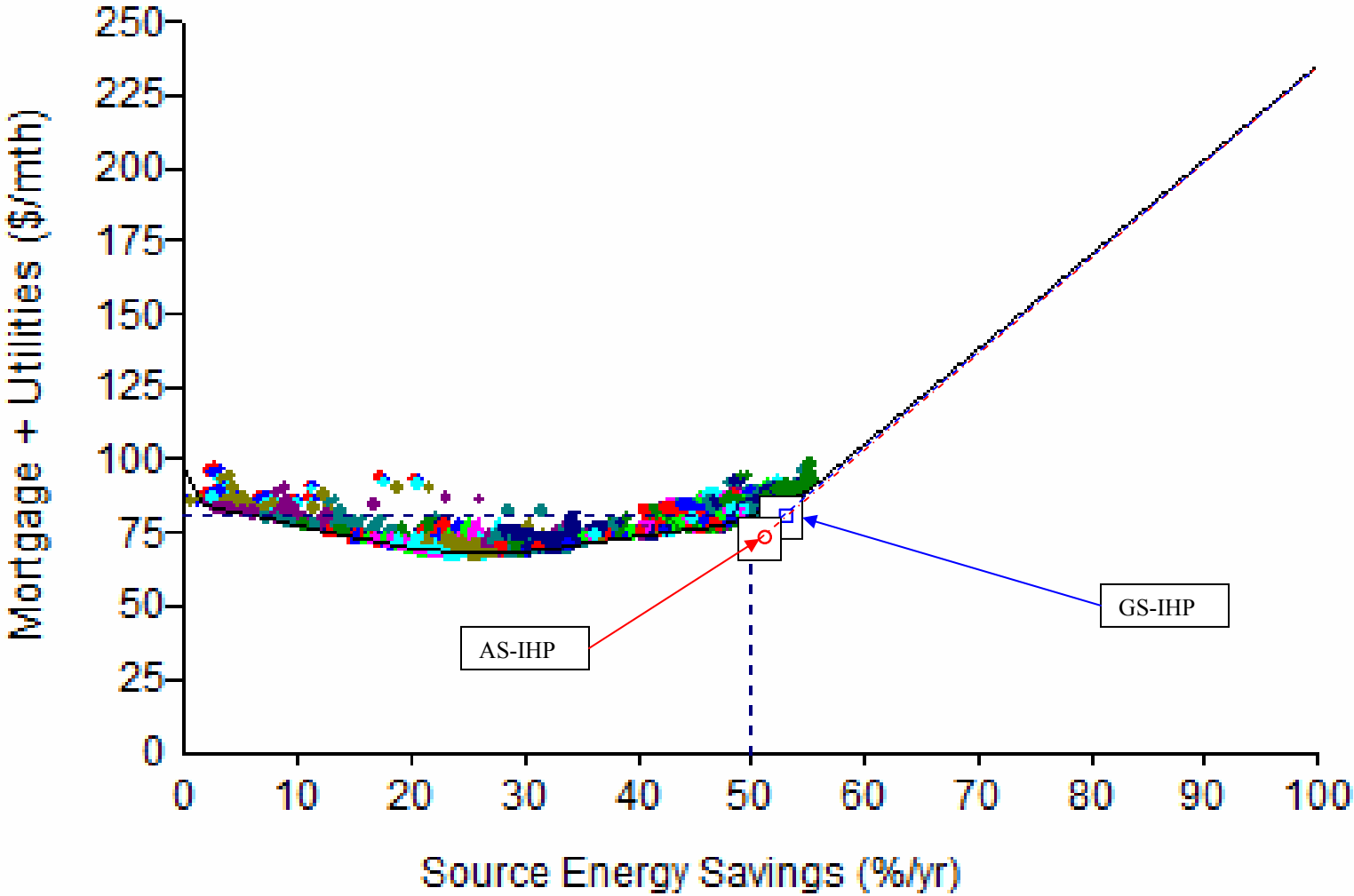

Fig. 10. Incremental mortgage + utilities costs for 1800-ft^2 ZEH in San Francisco (from NREL BEopt analysis).

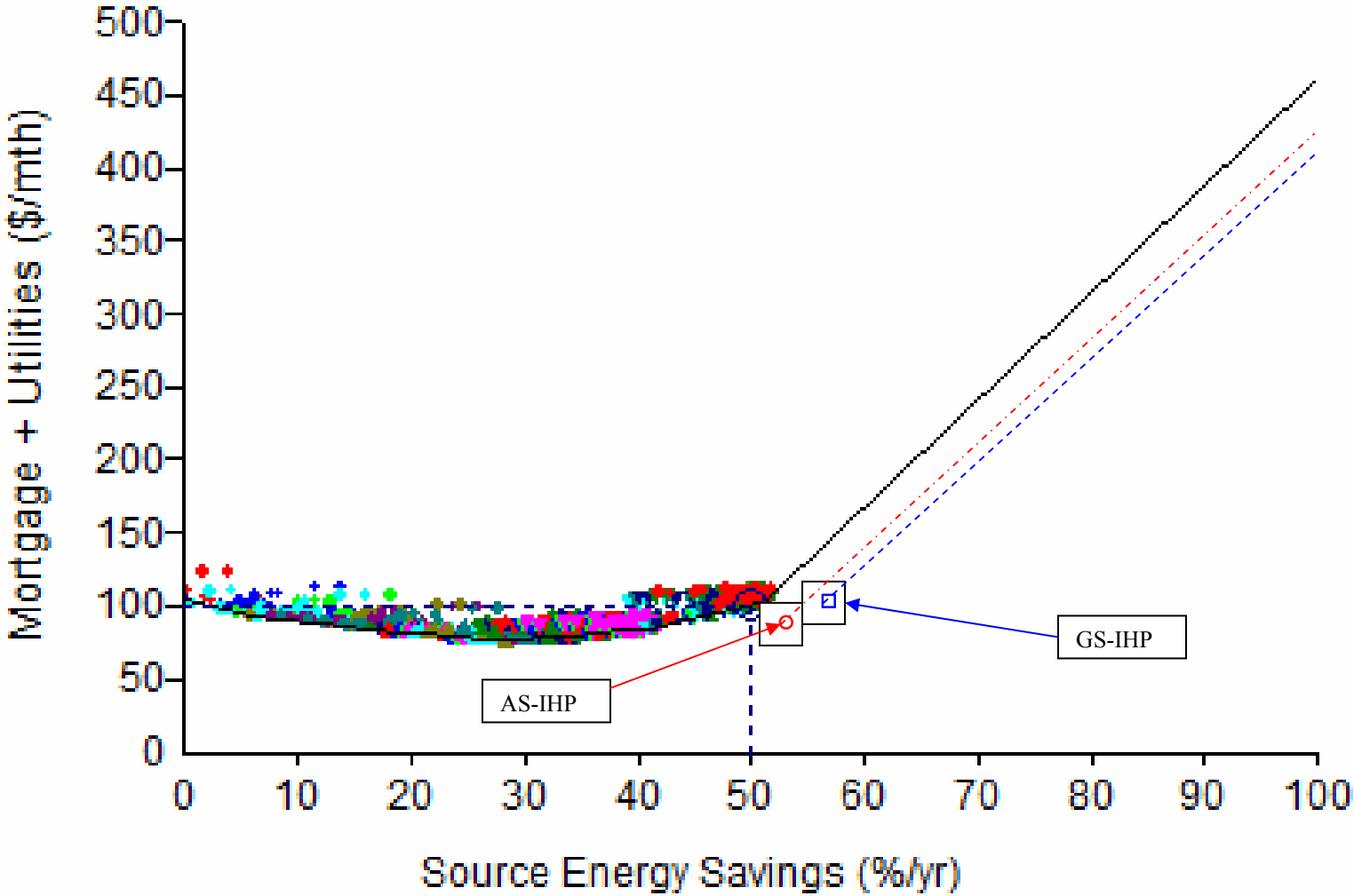

Fig. 11. Incremental mortgage + utilities costs for 1800-ft^2 ZEH in Chicago (from NREL BEopt analysis).

Note that in every location, the estimated IHP mortgage+utility costs are below the least cost curve generated by the BEopt analysis and in many cases to the right as well. Table 15 summarizes the results. The reduced overall system monthly cost estimates for the AS-IHP and GS-IHP resulted in estimated reductions in PV system costs required to reach the ZEH (100% savings) point from a low of $2700 in San Francisco to a high of $14,000 in Chicago. In every location studied, the PV savings exceed the maximum estimated IHP installed cost increments given above – by as much as a factor of four depending upon location. Based on this observation it appears that both IHP systems have potential to significantly reduce the total cost required for a ZEH in all the climate locations considered.

Table 15. Estimated PV cost savings from use of AS-IHP or GS-IHP for a ZEH

City	Maximum estimated IHP incremental cost		Estimated PV cost reduction	
	AS-IHP	GS-IHP	AS-IHP	GS-IHP
Atlanta	$3214	$3632	$6,700.00	$7,700.00
Houston	$3139	$3557	$6,700.00	$8,300.00
Phoenix	$3225	$3893	$6,800.00	$7,000.00
San Francisco	$3205	$3500	$3,300.00	$2,700.00
Chicago	$3214	$3632	$10,300.00	$14,000.00

8. SCORING OF OPTIONS VERSUS CRITERIA

Both options have been scored using the criteria and weighting factors described earlier in this report by the ORNL equipment research team, which is one perspective. Detailed results are given in Appendix A. Each system option received essentially identical scores and based on this result the ORNL team recommends that both be advanced to the next appropriate development steps. It is DOE's prerogative to revisit the criteria and obtain scoring from additional perspectives as part of its decision making process. If the criteria change, the ORNL team will be happy to re-score.

9. CONCLUSIONS AND RECOMMENDATIONS

The two top-ranked HVAC/WH systems arising from the FY05 scoping study (Baxter 2005) have been applied to prototype 1800-ft^2 NZE houses in five cities (Atlanta, Houston, Phoenix, San Francisco, and Chicago) and their energy and peak power savings estimates from the FY05 study refined. In addition, initial estimates of the installed costs for each system were prepared along with estimates of the amount of required PV power reductions. These energy and cost estimates were compared to those of a suite of baseline equipment required to meet all the energy service requirements of a ZEH (space heating, space cooling, ventilation, water heating, and demand dehumidification).

Base scenario (no system cost reduction or utility cost incentives) simple payback of the IHP systems vs. the baseline system *in the ZEH* were, perhaps predictably, relative high ranging from about 5 to 12 years for the AS-IHP and 6 to 13 years for the GS-IHP (with

vertical bore ground HX). For a scenario of a $1000 system tax credit combined with a favorable TOU + demand utility rate structure, these paybacks fall to about 2-5 years and 3-6 years, respectively.

However, in every location studied, both IHP systems showed significant potential to reduce the total cost required for a ZEH.

Using the long-term criteria as proposed, and based on scoring by the ORNL team, both systems achieved essentially the same priority ranking. Based on this result the ORNL team recommends that both be advanced to the next appropriate development steps. The rankings based on the ORNL team scores represent one perspective. It is DOE's prerogative to revisit the criteria and obtain scoring from additional perspectives as part of its decision making process. If the criteria change, the ORNL team will be happy to re-score.

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APPENDIX A

The scoring of options versus the criteria is summarized in Table A1. The composite team score is shown in the "criteria" column, the criteria weighting factor is in the "weight" column, and the "score" is the product of the previous two columns.

Table A1. HVAC longer-term option assessment scores

	AS-IHP			GS-IHP		
Longer-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet						
a. Technically feasible	yes			Yes		
b. Aligned w/at least one strategy component	yes			Yes		
c. Potential for Energy savings without additional mortgage, utility cost …	Yes			Yes		
d. Sole private sector development unlikely	Yes			Yes		
Should meet						
a Achieve 50% energy savings w.r.t baseline	10	2.5	25	10	2.5	25
b. Meets ZEH service needs	9	1.25	11.25	9	1.25	11.25
c. No high cost component to jeopardize baseline cost	7	1.25	8.75	6	1.25	7.5
d. Identified private sector interest	5	1	5	5	1	5
e. Resources available for R&D	5	1	5	5	1	5
f. Based on off-the-shelf components	10	0.75	7.5	10	0.75	7.5
g. Equipment easily installed/maintained w/o acquiring new skills	5	0.75	3.75	5	0.75	3.75
h. Serves new NZEH and broad residential markets	3	0.5	1.5	3	0.5	1.5
i. Satisfies immediacy replacement criteria in NZEH and broad residential markets	2	0.5	1	2	0.5	1
j. Significant peak demand reduction potential	9	0.5	4.5	10	0.5	5
TOTAL SCORE			73.25			72.5