Economic and Environmental Analysis of Residential Heating and Cooling Systems: A Study of Heat Pump Performance in U.S. Cities

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Abstract

As more efficient heat pump systems have been introduced in the residential HVAC market over the past few years, including systems that rely on inverter (INV) technologies or variable speed motors, policymakers and energy efficiency program administrators have started to pay close attention to these technologies as key efficiency measures to reduce energy consumption, CO_2 and air pollution.

In a recent study, Synapse Energy Economics (Synapse) examined the hypothetical operation of two "efficient" HVAC technology options—a 2-stage heat pump and an inverter heat pump—for single family homes that were built around 1990 and that require replacement of a ducted HVAC system. Synapse then compared those options to a reference-case option—consisting of an efficient natural gas furnace and a central air conditioning system—on the basis of energy, environmental, and economic impacts for 11 U.S. cities with varied climates.

This was one of the first studies, if not *the first*, to use detailed performance curves of a ducted inverter heat pump system in the U.S., and to analyze and compare the energy and environmental impacts of these HVAC options on an hourly or seasonal basis.

This paper discusses the methodologies and results of our analysis. Key findings include the following:

- **Which options are most cost-effective?** In all cities studied, the INV heat pump SEER 16 option had the shortest payback, the highest benefit cost-ratio, and offered the largest net benefits to consumers.
- **Which provided the greatest CO_2 reductions?** The INV heat pump saw significantly more CO_2 savings across all studied cities (except Chicago and Minneapolis) than the 2-stage heat pump option.
- **In which cities are consumers, the society, or both likely to gain the most benefit from installing one of the studied HVAC technologies?** Among all cities studied, we found that Atlanta and Houston provided the best balance among all analysis results, including customer payback, benefit cost ratio, and net benefits and CO_2 reduction.

The Case Studies

Three single-family-home replacement HVAC technology options (or combinations of options) were selected for this analysis, which are summarized in Table 1. Option 1, which consists of a central air conditioning unit (CAC) plus a natural gas (NG) furnace, is a reference case against which the energy, environmental, and economic impacts of the other options are compared. These technology options are intended to represent the choices that owners of single-family homes with a ducted HVAC system are likely to face when they plan to replace their heating and cooling systems. All of the heat pumps shown are 4-ton units (or 48,000 Btu).

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[1] Mike Duclos, a HERS Rater and a Certified Passive House Consultant, analyzed annual heating and cooling energy loads using the REM/Rate™ model as a subcontractor to Synapse for the original analysis upon with this paper was based.

Table 1: Studied HVAC Systems[2]

	Option 1: CAC & NG Furnace	**Option 2: 2-stage HP (SEER 16)**	**Option 3: INV HP (SEER 16)**
Cooling	SEER 13 CAC	SEER 16 2-stage heat pump (ducted)	SEER 16 inverter heat pump (ducted)
Heating	95% AFUE NG furnace	HSPF 9.5 2-stage heat pump; 95% AFUE NG furnace backup at 15°F	HSPF 9.5 inverter heat pump; 95% AFUE NG furnace backup at 5°F

As noted in Table 1, our study assumed a 2-stage heat pump switches its operation to a back-up gas furnace at 15°F, and an inverter heat pump switches its operation to a back-up furnace at 5°F.[3]

The 11 cities addressed in this analysis include Atlanta, Boston, Chicago, Houston, Los Angeles, Miami, Minneapolis, New York City, Phoenix, Portland, and Salt Lake City. These cities were selected to cover broad climate regions, and to include cities and states that have aggressive state and utility energy efficiency programs.

Figure 1 shows a map of the selected cities and their respective climate zones based on heating degree days (HDD) and cooling degree days (CDD).

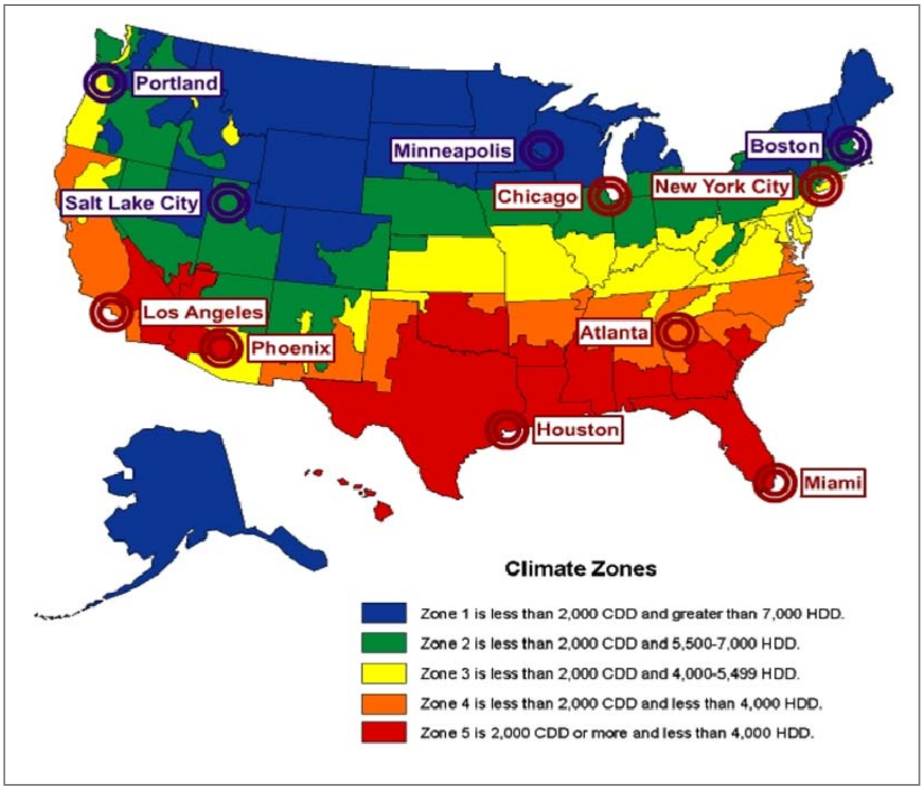

Figure 1: The selected cities superimposed on a climate map of the U.S. [1]

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[2] SEER and HSPF stand for Seasonal Energy Efficiency Ratio and Heating Seasonal Performance Factor, respectively. SEER is a standard efficiency metric used in the U.S. for the cooling performance of air conditioners. HSPF is a standard efficiency metric used in the U.S. for the heating performance of heat pumps. Both SEER and HSPF are calculated as Btu energy output over Wh electrical input during one season at certain test conditions. AFUE represents efficiency of furnaces and boilers and stands for Annual Fuel Utilization Efficiency.

[3] These temperature thresholds were set to minimize the source energy consumption in the two coldest cities for this study, Boston and Minneapolis.

Methodology and Assumptions

HVAC Performance Data

HVAC performance data for CAC and the 2-stage heat pump were obtained from publicly available data sources. We reviewed manufacture specifications from Goodman, Carrier, and Acadia as well as the DOE building energy simulation software's underlying data, and decided to use Goodman's manufacturer data sets for central AC and the 2-stage heat pump because (a) they are comprehensive and reflected changes in performance given changes in indoor humidity and ambient temperature; and (b) the company has significant market share in heat pump technologies. Detailed performance data for the inverter heat pump were obtained from a global HVAC manufacture company which is developing inverter heat pumps for the U.S. market. Comparisons of heating and cooling performance for these HVAC options are presented in Figure 2 and Figure 3. Figure 2 shows that INV heat pump systems perform significantly better on average than the reference CAC and 2 stage heat pump systems for cooling when they are operating at partial load conditions and at non-extreme temperatures, as indicated by "INV Low" lines.

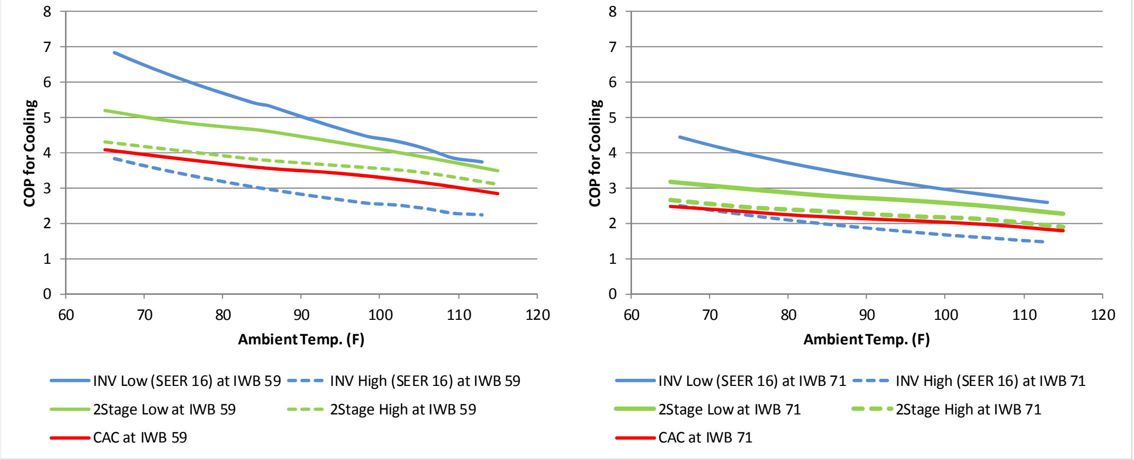

Figure 2: Cooling performance comparison between INV HP SEER 16, 2-stage HP (at Indoor Wet Bulb or IWB 59 on left, at IWB 71 on right), and CAC (at IWB 59 on left, at IWB 71 on right).[4,5] [2],[3],[4]

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[4] While Figure 2 uses indoor wet bulb (IWB) 59 and 71, data for other IWB points were also obtained and used.

[5] Sensible cooling outputs were used to estimate COP values. Sensible output over total output ratios for the 2-stage HP were used to estimate COP and consumption for the INV HP because sensible output data for the INV HP were not available.

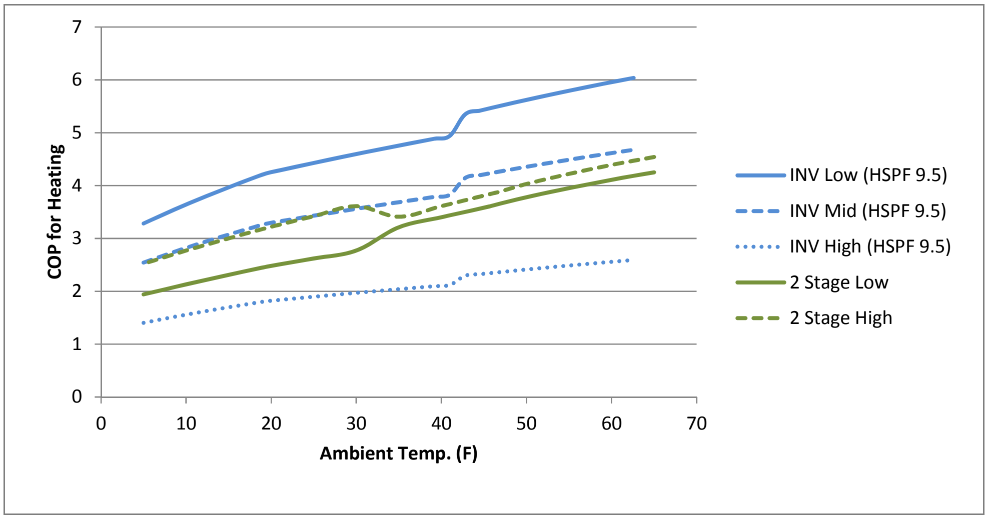

Figure 3: Heating performance comparison between HSPF 9.5 INV HP and HSPF 9.5 2-stage HP [3],[4]

Synapse's Building HVAC Energy Analysis Model

Synapse developed its own integrated, spreadsheet-based model (the Synapse Building HVAC Energy Analysis Model) to estimate energy consumption and energy savings, and to analyze the associated economic and environmental impacts for single family houses in the 11 U.S. cities. This model provides a rigorous first-cut analysis of efficient heat pumps and natural gas furnaces, built upon detailed analysis of climate data, building characteristics, HVAC performance curves, avoided energy costs, retail energy prices, and avoided emission factors for each study region. The model is composed of two major components: (a) the HVAC Energy Consumption Model, and (b) the HVAC Economic and Environmental Analysis Model.

HVAC Energy Consumption Model

This model was used to estimate hourly consumption for each technology option in each city based on hourly average heating and cooling sensible load factors (kBtu/F per house), hourly climate data (e.g., temperature and humidity), HVAC performance, and heating back-up temperature setting. A detailed model house was developed for each city to specify building structure, insulation levels for various parts of the house, appliances, and equipment based on publicly available data sources and the authors' experience with building energy codes and practices. Synapse incorporated the model house for each city in REM/Rate™, a widely used building energy model for code compliance, and estimated annual load by city in order to produce annual total energy consumption.[6][5] Annual total consumption was then divided by total hourly heating and cooling degree hours to estimate hourly "average" sensible load factors (kBtu/°F/hr). Hourly climate data were obtained from the Typical Meteorological Year 2 (TMY2) data set, available from the National Solar Radiation database.[6] The load factors were then applied to temperature in each hour to estimate hourly load. HVAC curves which account for latent load were then used to estimate hourly consumption based on hourly load.

HVAC Economic and Environmental Analysis Model

This model was used to estimate the economic and environmental impacts for each "efficient" HVAC option in terms of total energy costs, HVAC costs, and CO_2, NOx, and SO_2 emissions caused by an on-site reduction or increase in energy consumption (as compared to the reference case).

For the economics of efficient HVAC systems, we analyzed simple payback years, benefit cost ratios, and net benefits from both the consumer and societal or regional perspectives. The Total Resource Cost (TRC) test, which is the tool most widely used to evaluate the economics of utility programs in

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[6] The consumption outputs from REM/Rate™ do not include consumption associated with latent cooling load.

the U.S., was used to evaluate the total lifecycle benefits and costs of efficient HVAC systems from a regional or societal perspective, which includes the impacts on all utility customers. The TRC benefits and costs in our analysis are represented as avoided electricity and natural gas cost impacts, plus the difference in the installed costs between efficient measures and the reference measures. The Participant Cost (PC) test was used to evaluate the economics of energy efficiency from the perspective of consumers who install efficient systems. The PC benefits and costs are represented as energy bill impacts based on “retail rates,” plus the difference in the installed costs between the efficient options and the reference option, minus any program incentives.

Some key assumptions and methods are presented as follows:

- Our economic and environmental analyses reflect the cost and benefit of operating HVAC equipment for its entire life, which we assume to be 18 years. A real discount rate of 6 percent was used to estimate the present value of benefits and costs.
- Consumer benefits were estimated based on historical regional retail electricity and natural gas rates based on the Edison Electric Institute (EEI) Typical Bills report and the regional electric cost forecasts available in the Energy Information Administration (EIA)’s Annual Energy Outlook (AEO) 2010. Further seasonal natural gas retail prices were developed using historical price data.[7]
- Societal or regional benefits were estimated based on our estimates of avoided energy costs for electricity and natural gas. Avoided costs represent the costs *all* energy customers (including those who invested in energy efficiency and those who did not) could avoid. However, as a conservative measure, our analysis did not include avoided transmission and distribution capacity costs and various other benefits.[7]
- Avoided natural gas cost is best represented by the wholesale natural gas price plus a certain portion of the retail margin price, both of which vary by season.[8] The retail margin is the difference between residential prices and wholesale prices; we assumed 35 percent of retail margin can be avoided.[9] [9] Finally, we applied seasonal price variation factors based on NYMEX natural gas future monthly prices and estimated levelized seasonal costs for each city.[10]
- Our avoided electricity cost consisted of avoided electricity costs and avoided power plant capacity costs. Seasonal and peak and off-peak avoided electricity costs were estimated based primarily on (a) the wholesale electricity prices in 2010, (b) regional electricity price projections, and (c) seasonal and time-of-use price factors, available from the AEO 2010 [11], the Federal Energy Regulatory Commission’s website [12] and the Independent System Operators (ISOs).
- Our avoided capacity cost was $100/kW-year, which roughly represents the cost of a natural gas peaking unit.[13]
- The costs of the HVAC systems except the INV heat pump are based on data from a U.S.-wide commercial HVAC distributor.[14] The costs we decided to use for the natural gas furnace, the central AC, and the 2-stage heat pump are $1374, $2005, and $3858, respectively. Based on our discussion with the HVAC company that provided the INV performance data, we decided it is reasonable to assume the cost of the INV heat pump is equal to the cost of a 2-stage heat pump at the same SEER and HSPF level.

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[7] A more comprehensive TRC test should include other benefits such as avoided transmission and distribution costs, avoided cost of environmental compliance and avoided emissions, and quantifiable non-energy benefits (e.g., water savings, increased property values, improved safety and comfort).[8]

[8] The AEO 2010 regional natural gas prices for the electric power sector was used as a proxy for city gate wholesale natural gas prices.

[9] A study called Avoided Energy Supply Costs in New England determined 70% of the retail margin is avoidable. However, how much can be avoided depends on region and whether and how fast the industry is growing and increasing natural gas sales. Considering this fact, we adopted a more conservative approach and used 35% as an avoidable retail margin factor across the study cities.

Average retail prices and avoided costs for electricity and natural gas are presented in Table 2.

Table 2: Summary of Average Retail Price and Costs for Electricity and Natural Gas

	Elec. Price (cents/kWh)	Average Avoided Elec. Cost (cents/kWh)[10]	Average NG Price ($/mmBtu)	Average Avoided NG Cost ($/mmBtu)
Atlanta	8.7	3.9	14.1	10.7
Boston	15.3	5.0	15.1	10.4
Chicago	10.5	3.6	10.7	7.8
Houston	7.6	3.9	11.1	8.2
Los Angeles	15.3	4.1	11.5	8.6
Miami	9.7	4.9	14.1	10.7
Minneapolis	9.1	2.8	10.8	8.2
New York City	21.2	5.5	13.1	9.4
Phoenix	10.5	3.5	10.8	8.5
Portland	10	3.8	11.5	8.6
Salt Lake City	8.1	3.8	10.8	8.5

Avoided emission rates for NO_x, SO_2, and CO_2—which were used to estimate emissions avoided due to a reduction in energy consumption with efficient HVAC options—are based on our analysis of historical hourly emissions data. In this analysis, we determined the mix of marginal generation units during each hour for each U.S. EPA eGrid region.[15][11] The weighted average emissions rate from this marginal mix is an estimate of the displaced emissions rate. In this analysis, the marginal (or avoidable) emissions rate was estimated empirically by quantifying which units had a marginal behavior—i.e., ramp with changes in demand on a regular basis. The method used the Continuous Emissions Monitoring (CEMS) data of the US EPA's Clean Air Market Division (CAMD).[16] This CAMD dataset contains hourly reported generation, CO_2, SO_2, and NO_x emissions for fossil boilers over 50 MW in size.

Energy Savings and Consumption Analysis Results

Cooling Energy Savings

Figure 4 below shows annual cooling energy savings results 1) in MMBtu (on the left side), and 2) as a percent of the reference case's total energy consumption (i.e., CAC + NGFurnace) on the right side. Overall, the cities with hot climates, such as Houston, Miami, and Phoenix, had three to four times more annual savings than the other cities in absolute terms (MMBtu). Average temperature, maximum temperature, cooling degree days (CDD), and degree days above 87°F for these cities (along with the other cities) are presented in Table 3. Key findings for each of the efficient HVAC options are summarized below:

- **2-stage Heat Pump:** The annual cooling energy savings for the 2-stage HP relative to the reference case consumption was about 20% for each city, and ranged from 0.5 MMBtu per year in Portland to about 3.6 MMBtu per year in both Phoenix and Miami.
- **INV HP SEER 16:** The cooling energy savings for the INV HP SEER 16 was more than 30% for the majority of the cities, except Los Angeles, Phoenix, and Salt Lake City. The absolute

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[10] The values do not include the avoided capacity cost of $100/kW-year. For example, the annual avoided capacity value for the INV HP SEER 16 is $52 in New York City given that our model estimates that the system provides 0.56 kW peak savings.

[11] Marginal units respond to fluctuations in demand and price. As the demand for electricity grows during a typical day, more expensive units are added as required; consequently, if less energy is demanded, these expensive units will drop off sequentially and are hence "avoided."

savings ranged from 0.7 MMBtu in Portland to 7 MMBtu in Miami. Houston had the second highest cooling savings at 4.8 MMBtu.

In general, for all the heat pump technologies, cities with humid, hot climates saw the most cooling savings compared to the reference case, and cities with dry, hot climates saw the least cooling savings compared to the reference case. Cities with cooler climates tended to see intermediate savings compared to the reference case. In Phoenix, a city with an extremely hot climate, the inverter heat pump did not perform as well as it did in other cities (relative to the reference case), while the 2-stage heat pump maintained a lower, but more standard percent savings across all cities, as shown in Figure 4. This is mainly because the INV HP performance has a more significant decrease than the performance of the 2-stage HP in Phoenix's extremely hot climate. (See Figure 2 for the HVAC performance, and Table 3 for the climate data for the study cities.)

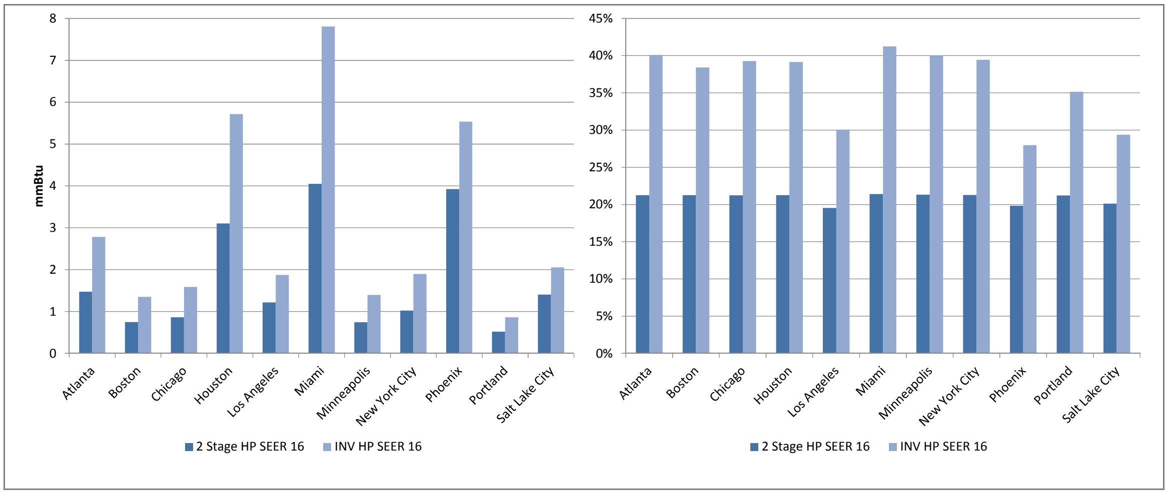

Figure 4: Annual Cooling Site Energy Savings in MMBtu (left) and as a Percent of the Reference Case Energy Consumption (right)[12]

Table 3: Climate Statistics by City [6][13]

	Annual Average Temp (F)	**Max**	**Min**	**HDD at 65°F**	**Degree Days under 32°F**	**CDD at 70°F**	**Degree Days above 86°F**	**Average Rel. Humidity (%)**
Atlanta	61	97	12	3,265	18	904	8	65
Boston	51	92	5	5,959	56	346	2	59
Chicago	50	96	-9	6,586	78	520	5	58
Houston	68	97	14	1,771	5	1,798	29	72
Los Angeles	63	98	35	1,707	0	427	3	53
Miami	76	93	38	218	0	2,557	19	72
Minneapolis	45	95	-21	8,049	109	422	3	60
New York City	54	95	4	5,159	45	563	4	59
Phoenix	73	115	27	1,535	0	3,216	90	27
Portland	53	92	20	4,813	8	241	2	43
Salt Lake City	52	101	0	5,919	61	825	19	27

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[12] Consumption is presented as consumption to serve sensible load.

[13] "Average Rel. Humidity (%)" refers to average humidity during cooling degree days for each city, and is different from annual average humidity.

Heating Energy Savings

Figure 5 shows total annual “site” heating energy savings in MMBtu in the left chart, and total annual “source” energy savings as a percent of the reference case consumption in the right chart. The reason to show “source” energy savings instead of “site” energy savings, in relative terms, is to give an alternative comparison between consumption by electricity and consumption by natural gas. Site electricity consumption does not reflect energy lost between electricity generation and delivery to houses.

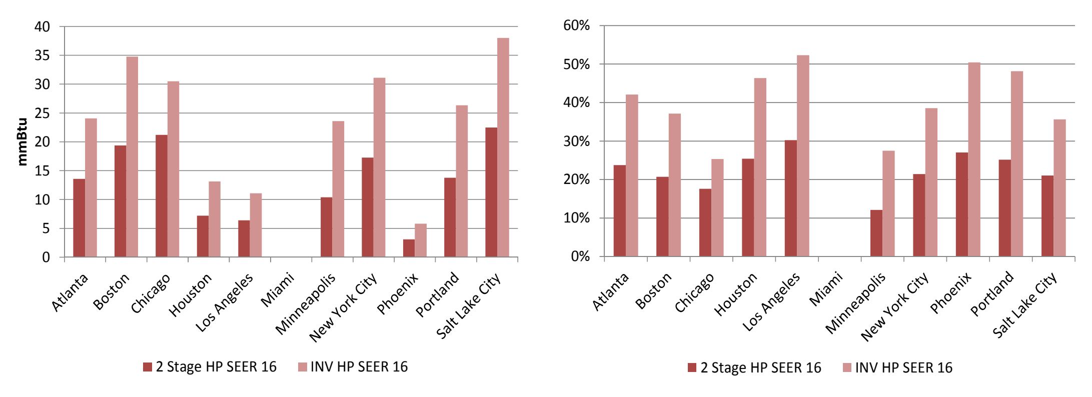

Figure 5: Annual Heating “Site” Energy Savings in MMBtu (left) and Annual Heating “Source” Energy Savings as a Percent of the Reference Case Consumption (right)[14]

The cities with the greatest absolute site heating energy savings were cities with cooler/cold climates such as Boston, Chicago, Minneapolis, New York City, and Salt Lake City. (See Table 3 for the climate statistics for heating). The energy savings for those cities ranged from about 50 to 80 MMBtu, which is roughly five to eight times greater savings than cities with hot climates such as Houston, Los Angeles, and Phoenix. However, the warmer cities had much greater savings when viewed as a percentage of the reference case, as presented in the right-hand chart in **Error! Reference source not found.**. This ability to perform well compared to the reference case is due to the fact that for heating, heat pumps work more efficiently in less extreme weather. Key findings for each of the efficient HVAC options are summarized below:

- **2-stage Heat Pump:** Minneapolis, the coldest city, had the lowest relative source energy savings potential (12%) for the 2-stage HP (excluding Miami, with no heating requirement), while the other cities saved about 20 to 30%.
- **INV HP SEER 16:** All cities (excluding the coldest cities, Minneapolis and Chicago) saved 40 to 50% of the reference case energy consumption.

Economic and Environmental Analysis

Economic Analysis

Figure 6 and Figure 7 present the results of our economic analyses from the consumers’ perspective. Based on our review of these results, we found that the INV HP SEER 16 was the most attractive investment for all of the study cities for consumers. This is mainly because (a) the cost of the technology is equal to or smaller than the costs of the 2-stage HP, and (b) the energy savings resulting from this HVAC option are significantly higher than the savings from the 2-stage HP.

Additional economic findings (from the consumer perspective) are summarized below:

- **Simple payback:** The INV HP SEER 16 had the best (i.e., shortest) payback for all cities, averaging approximately 2 to 3 years in all cities except New York. (See Figure 6) New York had a long payback period or did not pay back at all, depending on the HVAC system,

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[14] We assume on-site electricity utilizes only 35% of the primary energy input at power generation

because the lifetime costs for these systems exceed the lifetime benefits. The higher lifetime costs in New York were due to the city's highest retail electricity rate among the study cities, along with an average retail natural gas rate.

- **Benefit cost ratio:** The INV HP SEER 16 provided the highest benefit cost ratio for all cities. (See the left chart in Figure 7.) For example, a dollar investment in the INV HP SEER 16 (i.e., the incremental cost of the system over the reference case system) yielded about eight dollars return in Houston, while a dollar investment in the other technology yielded slightly above a dollar return.
- **Net benefits:** In terms of net benefits to consumers, the 16 SEER Inverter HP was the best option for all cities. (See the right-hand chart in Figure 7.) The largest net benefit was slightly over $6,500 with the INV HP SEER 16 in Atlanta.
- **Consumer economics:** The top five cities with good consumer economics with the INV HP SEER 16 were Atlanta, Houston, Portland, Phoenix, and Salt Lake City, due to a combination of favorable retail energy rates for heat pumps, the level of energy savings, and/or low incremental HVAC system costs.

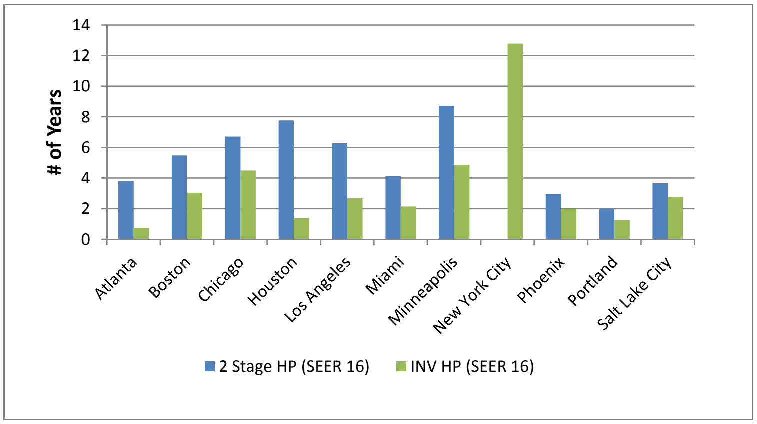

Figure 6: Simple Payback Year Comparison

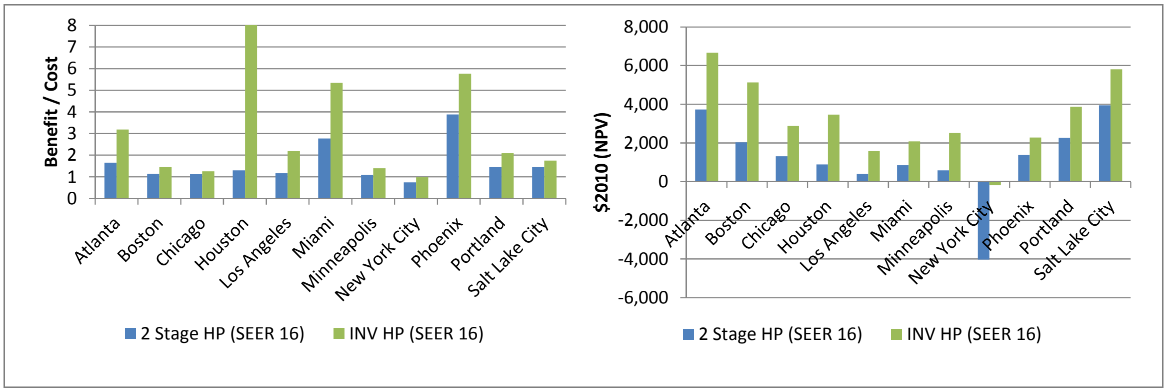

Figure 7: Benefit/Cost Analysis (left) and Net Benefits (right) with the Participant Cost Test

Figure 8 shows the benefit cost ratio and net benefits from the societal/Total Resource Cost (TRC) perspective by HVAC system and city. The TRC perspective differs from the consumer perspective in that the INV HP SEER 16 had the highest benefit cost ratio and highest net benefits among HVAC options for all cities except Portland. This is mainly because (a) the cost of the technology was set equal to the cost of the 2-stage HP, and (b) the energy savings of this HVAC option were significantly higher than savings from the 2-stage HP. Portland is in a winter electricity peaking region, and the use of heat pumps during the winter period for heating requires extra generating capacity. This adds extra costs to the electricity grid instead of providing benefits in terms of reducing peak load.

Among cities, the TRC ratios for the INV HP SEER 16 systems were particularly high in Atlanta, Houston, Miami, and Phoenix, where the INV systems do not require a back-up furnace, and the electricity consumption increase for heating is largely offset by the electricity savings for cooling.

Interestingly, the cities with the highest TRC benefit cost ratios for the INV HP SEER 16 are Houston, Miami, Los Angeles, and Phoenix, which had *lower* net benefits than other cities. Heat pump systems in these cities were relatively small as the mild winter climate in these cities did not require back-up furnaces. Alternately, cities such as Atlanta, Boston, Chicago, and Salt Lake City, which had low benefit cost ratios, provided very high net benefits to consumers across different HVAC types. It appears that these cities had either high energy savings (especially heating savings) or favorable avoided energy costs for heat pumps (i.e., low avoided electricity and high avoided natural gas costs), or both.

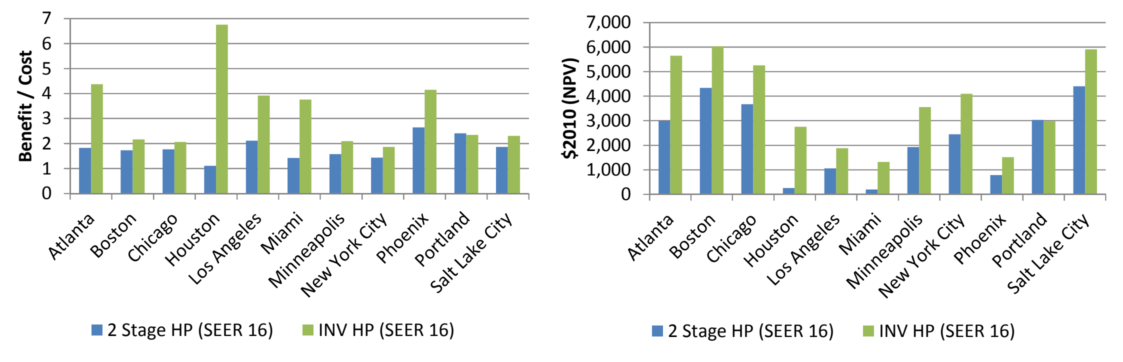

Figure 8: Benefit/Cost Analysis (left) and Net Benefits (right) with the TRC

Environmental Analysis

In terms of lifetime emissions impacts, many cities saw significant CO_2 and NO_x savings with heat pumps, but almost all cities except Miami saw SO_2 emission increases, and Los Angeles and Phoenix saw negligible SO_2 emission increases or decreases. In addition, the cities in the Midwest (Chicago and Minneapolis) saw a significant increase in all emissions (CO_2, NO_x, and SO_2) because this region has significant amounts of coal-fired electric generation on the margin (Figure 9).[15]

Additional environmental findings are summarized below:

- **CO_2 savings:** The INV heat pump saw significantly more CO_2 savings across all cities (except Chicago and Minneapolis) than the 2-stage HP option.
- **NO_x savings:** The INV heat pump option saved NO_x emissions in all cities except Chicago, Minneapolis, and Salt Lake City. The 2-stage HP saved NO_x emissions in all cities except Chicago, Minneapolis, Atlanta, Portland, and Salt Lake City. Among all cities, Boston and New York (which have low emission rates and high energy savings) saved the most emissions.
- **SO_2 savings:** In many of the study cities, SO_2 emissions increased with both HP options because the baseline SO_2 emission rate estimates based on a natural gas furnace are negligible. The increase was again particularly acute in Chicago and Minneapolis. Cities with significant cooling energy savings relative to heating energy savings (i.e., Miami, Los Angeles, and Phoenix) saw some positive SO_2 emission reduction or negligible SO_2 emission increase with INV heat pumps.

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[15] This means that marginal emissions from electricity in the region are so high that they exceed emissions from natural gas per mmBtu "heating load."

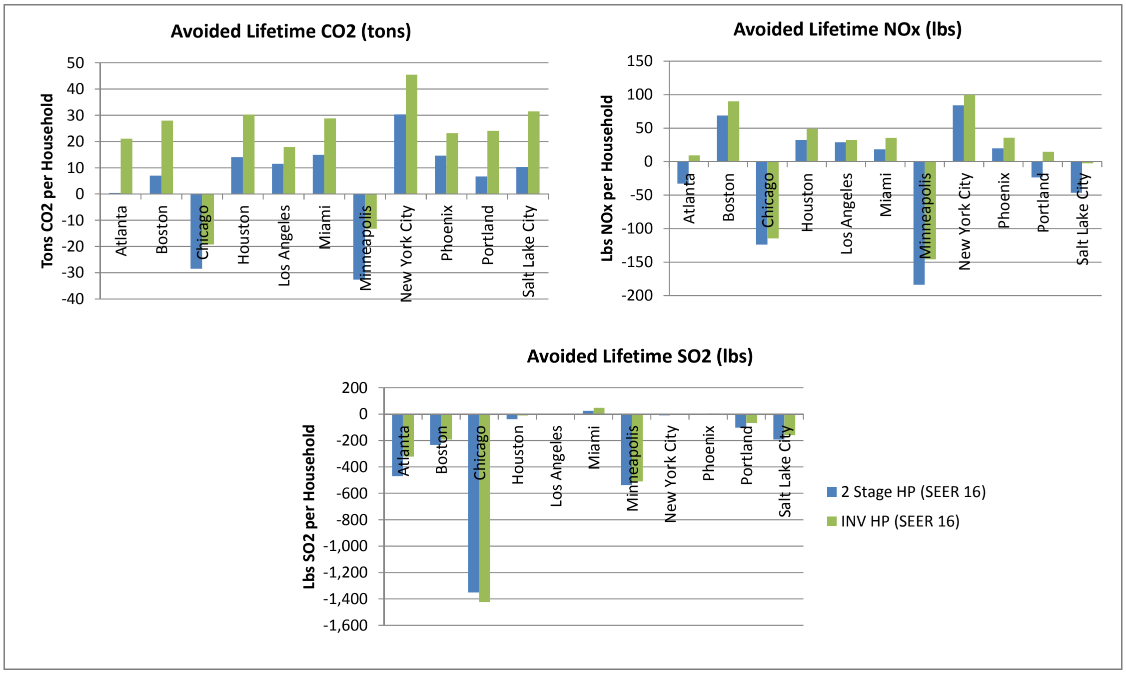

Figure 9: Avoided Lifetime CO2, NOx, and SO2 Emissions (tons or lbs.)

Synthesis of Economic and Environmental Impacts from Consumer and Societal Perspectives

Ultimately, the type of heat pump that makes the most economic and environmental sense for each city depends on the perspective the analysis is being conducted from—particularly whether it is from the consumers' or the societal perspective. Given that our analysis of the different HVAC options found that the INV HP SEER 16 provided the greatest benefits across all cities with a few exceptions, we took a closer look at the energy and environmental impacts of the INV HP by city, and synthesized the results as one total score for each city as shown in Table 4 (below). The higher the score, the better for each analysis category in the table. For example, Atlanta received a score of 11 for payback because it had the shortest payback period among all cities for this technology option, and New York received the lowest score of 1 because the payback for the city was the longest.

Among all cities, we found that Atlanta and Houston provided the best balance among all analysis results, including customer payback, benefit cost ratio, and net benefits with the Participant Cost Test and CO_2 reduction. Salt Lake City, Portland, and Boston rounded out the top five cities.

However, when we consider NOx emission impact, Salt Lake City, the third ranked city, showed reduced benefit from investment in heat pumps (as shown in Figure 9) , In contrast, Houston, the second ranked city, saved a great deal of NO_x emissions with heat pump technologies.

In terms of lifetime SO_2, emissions increased in all cities except Phoenix and Miami with the use of heat pumps, while Los Angles saw negligible emissions increase.

The cities with the lowest total scores were Minneapolis, New York City, and Chicago. The benefit cost ratios and simple payback years were very low for these cities. Additionally, lifetime CO_2 emissions increased for both Chicago and Minneapolis with the use of heat pumps due to the high electricity marginal emission rates in the Midwest region

Also note that New York was the only city that the benefit cost ratios for the 2-stage HP and the INV SEER 16 were below 1 from the consumer perspective, while the ratio for the INV is very close to 1. This means that these technologies do not provide net benefits to consumers in this city. However, lifetime CO_2 and NO_x emission savings in New York were the highest among all cities across all HVAC options, which implies that the net benefits could be significantly increased if monetary values were assigned to such avoided emissions.

Table 4: Economic and Environmental Scores for the INV HP SEER 16 by City

	Payback	PTC Ratio	PTC Net Benefit	TRC Ratio	TRC Net Benefit	CO_2	Total Score
Atlanta	11	8	11	10	9	4	53
Houston	9	11	7	11	4	9	51
Salt Lake City	5	5	10	5	10	10	45
Portland	10	6	8	6	5	6	41
Boston	4	4	9	4	11	7	39
Phoenix	8	10	4	9	2	5	38
Miami	7	9	3	7	1	8	35
Los Angeles	6	7	2	8	3	3	29
Chicago	3	2	6	2	8	1	22
New York City	1	1	1	1	7	11	22
Minneapolis	2	3	5	3	6	2	21

Recommendations

Our analysis shows that when replacing an aging central AC and natural gas furnace system, the INV HP SEER 16 in a single family house with a ducted HVAC system is a very attractive investment from both the consumer and societal perspectives, and also reduces CO_2 emissions. However, more research is needed to verify this finding and detailed results from this analysis. In particular:

a. More heat pump models need to be investigated for their performance, including field data, to ensure that performance data are reasonably accurate.

b. Electricity and fuel price forecasts need to be updated to reflect the most recent forecasts.

c. Avoided emissions analysis could be improved by using updated emissions data and a more sophisticated avoided emission model, such as the U.S. EPA's Avoided Emissions and Generation Tool (AVERT).

d. More precise hourly load factors may provide more accurate results.

e. Adding benefits not included in this analysis will improve the economic analysis of HVAC systems. An expanded analysis could include T&D avoided costs; current and expected environmental compliance costs for NOx, SO_2, and CO_2; and other non-energy benefits.

Nonetheless, the results of our analysis offer valuable information to policymakers, consumers, and HVAC companies by identifying HVAC options that are more economically and environmentally advantageous than a NG heating + central AC combination system, and to what extent.

Based on the results of our analysis, Synapse recommends that policymakers further investigate the benefits of these technologies, particularly the 16 SEER Inverter HP system, and consider them for inclusion in energy efficiency programs at the state and federal levels. State governments and utility or third-party energy efficiency program administrators may want to consider including INV heat pumps as a technology eligible for incentives (e.g., rebates). Additionally, the Federal Government could consider adopting higher federal heat pump standards that reflect the energy efficiency attained by inverter heat pump technologies.

In considering INV heat pumps (particularly the INV HP SEER 16), state agencies and energy efficiency program administrators should consider paying particular attention to Houston, Los Angeles, Phoenix, and regions/states with similar building and climate characteristics due to the societal benefits provided in those cities. Minneapolis and Chicago should be considered last. In light of consumer economics, the regions covering Atlanta, Houston, Salt Lake City, Portland, and Boston are also good places to consider promoting the INV HP SEER 16.

Private companies—such as manufacturers, wholesale HVAC companies, and local HVAC contractors—can utilize the information in this study to effectively market their products and provide useful information to customers who are considering replacing their current HVAC system with one that is more efficient. The information from this study would be particularly useful to customers with homes similar to those analyzed in this analysis: single family homes with a ducted natural gas and central AC system. Private companies may want to begin by promoting these technologies in Atlanta, Houston, Portland, Phoenix, and Salt Lake City, where the consumer economics are strongest.

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