Air Source Integrated Heat Pump Simulation Model for EnergyPlus

Authors: Bo Shen, Joshua New, Van Baxter

ABSTRACT

Air Source Integrated Heat Pump (ASIHP) is an air source, multi-functional space-conditioning unit with water heating function (WH), which can lead to significant energy savings by recovering condensing waste heat in the cooling season and providing dedicated or desuperheating heat pump water heating in the remaining months. This paper summarizes development of the EnergyPlus ASIHP model. It introduces the physics, sub-models, working modes, and control logic. Based on the model, building energy simulations were conducted to demonstrate greater than 50% annual energy savings, in comparison to a baseline heat pump with electric water heater, over 10 US cities, using the EnergyPlus quick-service restaurant template building. We assessed water heating energy saving potentials using ASIHP versus gas heating, and identified the climate zones where ASIHPs are promising. In addition, a grid integration strategy was investigated to reveal further energy saving and electricity cost reduction potentials, via increasing the water heating set-point temperature during off-peak hours and using larger water tanks.

ACRONYMS

ASIHP	Air Source Integrated Heat Pump
COP	coefficient of performance
DOE	U.S. Department of Energy
DWH	dedicated water heating
HVAC	heating, ventilating, and air-conditioning
IDF	EnergyPlus input data file
SC	space cooling
SCDWH	space cooling and water heating with desuperheating
SCWH	space cooling and water heating
SH	space heating
SHDWH	space heating and water heating with desuperheating
WH	water heating (function)

1. INTRODUCTION

An Air Source Integrated Heat Pump (ASIHP) is an air source, multi-functional space-conditioning unit with water heating function (WH), as shown in Figure 1, which generally uses a variable-speed compressor, indoor blower, and outdoor fan. It has an outdoor unit and indoor air handler with air-to-refrigerant heat exchangers (R-A HX) just as a typical heat pump unit. The addition is a water heater, using a double-walled tube-in-tube or brazed heat exchanger (R-W HX) to heat water in a storage tank. Some ASIHP products may circulate the hot water in a water-to-air heat exchanger (W-A HX) downstream of the indoor R-A HX to temper the indoor supply air during an enhanced dehumidification mode. By recovering the condenser waste heat for water heating and by providing dedicated heat pump water heating capability, ASIHPs are able to achieve significant energy savings. While the waste heat recovery is not free due to the elevated condensing temperatures required to meet domestic hot water needs in full condensing WH operation, the combined mode is quite efficient as both space cooling and full condensing water heating are delivered from one compressor power input.

Murphy et al (2007) conducted sub-hourly annual energy use simulations to compare the performance of the ASIHP system concept to that of a baseline suite of individual systems; 3.8 W/W Cooling Season Performance Factor (CSPF) [13.0 Btu/Wh Seasonal Energy Efficiency Ratio (SEER)]) heat pump with humidifier option, 0.90 W/W energy factor (EF) electric WH, a standalone space dehumidifier of 1.4 EF). The TRNSYS 16 (Klein, 2010 [10]) system simulation software platform (Solar Energy Laboratory, et al. 2010) was used to conduct these analyses for five US locations - representing cold (Chicago), mixed humid (Atlanta), hot humid (Houston), hot dry (Phoenix), and marine (San Francisco) climate zones. A tight, very well insulated house was used for the analyses. Results of these analyses showed that the estimated annual energy savings for the initial ASIHP concept prototype design ranged from about 46% in Chicago to almost 70% in San Francisco. In addition, estimated summer afternoon peak demand for the ASIHP ranged from 20% to ~60% lower than that of the baseline system depending on location.

Rice et al. (2014) [12] introduced development of a residential ASIHP in partnership with a U.S. manufacturer. A nominal 10.6 kW (3-ton) cooling capacity variable-speed unit, the system provides both space conditioning and water heating. This multifunctional unit can provide domestic water heating in either full condensing (dedicated water heating or simultaneous space cooling and water heating) or desuperheating operation modes. Laboratory test data were used to calibrate a vapor compression simulation model for each mode of operation. The model was used to optimize the internal control options for efficiency while maintaining acceptable comfort conditions and refrigerant-side pressures and temperatures within allowable compressor operating envelopes. Annual simulations were performed with the ASIHP installed in a well-insulated house in five U.S. climate zones, using TRNSYS 16. The system was predicted to use 45 to 60% less energy than a DOE minimum efficiency baseline system while meeting total annual space conditioning and water heating loads.

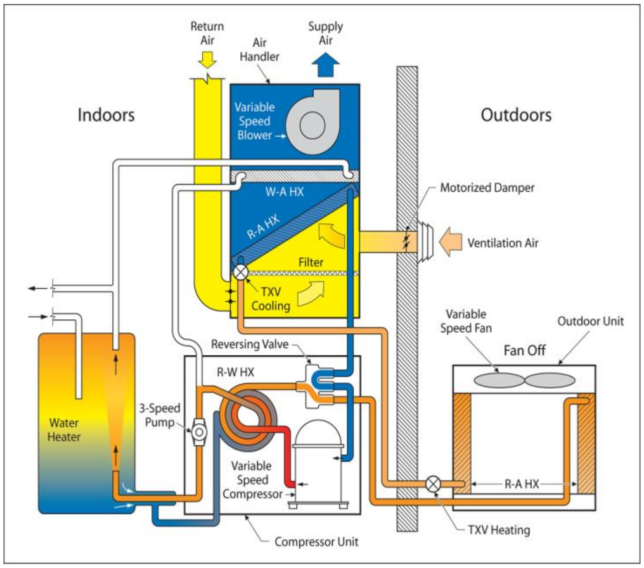

Figure 1. Schematic of Air Source Integrated Heat Pump.

The energy saving of an integrated heat pump is mainly due to heat recovery using condenser heat for water heating. Heinz et al. (2016) [7] developed a numerical model for a heat pump condenser and desuperheater integrated to a water storage tank. The model was used to conduct both design calculations of the condenser/desuperheater and annual simulations of the system integrated into a whole heating system. The water tank model is a one-dimensional stratified model. The authors compared laboratory measurements with codenser/desuperheater and water tank temperatures. Hengel and Heinz (2016) [8] performed extensive analyses for in a combined solar and air-source heat pump system for a residential building having low heating load. They investigated numerous control strategies for the desuperheater using a TRNSYS heat pump model coupled with a buffer storage tank, a thermal solar collector and the heat distribution and heat dissipation system. The TRNSYS (Klein, 2010) [10] building energy simulation predicted around 4% energy saving, in comparison to a baseline heat pump. Justin et al. (2017) [9] used TRNSYS to simulate an integrated solar heat pump using an ice slurry tank for latent energy storage. They conducted annual energy simulations in four Canadian climate zones and revealed 17% to 28% energy savings, compared to a baseline air-to-water heat pump. Claudia and Enzo (2017) [3] modelled a multi-functional heat pump with condenser heat recovery for water heating. The energy saving by the heat recovery in cooling season was reported up to 30%. Fucci et al. (2016) [6] studied a heat pump for heat recovery in a ventilation system, to use the exhaust air as the source and use the condenser heat to warm up the ventilation air. They conducted experiments via varying outdoor air temperature from -5 to 10°C and controlling the indoor air at 20°C. The measured overall system COP reached 9.5. The literature search indicates that studies on a full-version of multi-functional ASIHP are still lacking, i.e. a unit capable of all the space heating, space cooling and water heating modes. In particular, a freely available building energy simulation tool, which is able to reveal ASIHPs' energy saving potentials in various climate zones, needs to be developed.

The U.S. Department of Energy (DOE) has invested in developing such an advanced, cutting-edge technology for years and now it is ready to be launched to the market. Due to premium variable-speed compressors and fans applied, the initial cost of an ASIHP is rather high. However, the payback period should be acceptable due to its significant energy saving potential, i.e., >50%. EnergyPlus [4] is a building energy modeling tool developed and maintained by DOE. In support of DOE's goal to promote energy saving technologies, EnergyPlus has been recently enhanced to accurately simulate ASIHPs and estimate their annual energy savings and payback periods. This will help provide justifications to end-consumers for selecting the highly efficient product.

EnergyPlus is able to simulate the individual working modes of the ASIHP using the following modules (included in the code since 2014): 1) variable-speed cooling coil (Coil:Cooling:DX:VariableSpeed), 2) variable-speed heating coil (Coil:Heating:DX:VariableSpeed), and 3) variable-speed water heating coil (Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed). The EnergyPlus ASIHP model reported here is the collection of the variable-speed air-source heat pump and water heating modules along with the parent feature of ASIHP which integrates these modes and simulates the multi-functional ASIHP operations.

The Variable-Speed DX (Direct Expansion) Cooling Coil (Coil:Cooling:DX:VariableSpeed) is a collection of performance curves that represent the cooling coil at various speed levels. EnergyPlus uses off-design performance curves to consider cooling capacity changing with ambient and indoor return air wet-bulb conditions at each speed level as shown in Equations 1 and 2,

$$CAPFT_{coil,cooling} = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_o) + e(T_o)^2 + f(T_{wb,i})(T_o) \quad (1)$$

$$\dot{Q}_{coil(i),cooling,total} = \dot{Q}_{coil(i),cooling,rated}\left(CAPFT_{coil,cooling}\right) \quad (2)$$

Where $CAPFT_{coil,cooling}$ = Coil Cooling Capacity Correction Factor (function of temperature); $\dot{Q}_{coil(i),cooling,total}$ = unit total (sensible + latent) cooling capacity [W]; $\dot{Q}_{coil(i),cooling,rated}$ = rated total (sensible + latent) cooling capacity [W]; $T_{wb,i}$ = wet-bulb temperature of the air entering the cooling coil (°C); T_o= temperature of the air entering an outdoor heat exchanger (°C); and $a-f$ = bi-quadratic equation coefficients for Cooling Capacity Correction Factor.

The DX cooling coil energy input ratio (EIRFT) also depends on the wet-bulb temperature of the air entering the cooling coil and ambient temperature.

$$EIRFT_{cooling} = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_o) + e(T_o)^2 + f(T_{wb,i})(T_o) \quad (3)$$

$$COP_{cooling} = COP_{cooling,rated} / EIRFT_{cooling} \quad (4)$$

$EIRFT_{cooling}$ = the cooling energy input ratio correction factor (function of temperature). $COP_{cooling,rated}$ is the unit rated COP. The rated conditions for obtaining the capacities, COPs and SHRs are at an indoor dry-bulb temperature of 26.67 ˚C (80 ˚F), wet bulb temperature of 19.44 ˚C (67 ˚F), and condenser entering air temperature of 35 ˚C (95 ˚F).

The performance curves should be generated from Reference Unit data, published in a product literature. This is an equation-fit model that resembles a black box with no heat transfer equations. On the other hand, the model uses the bypass factor approach to calculate sensible heat transfer rate, similar to the one used in the single-speed DX coil. The number of speed levels can range from 1 to 10. The cooling coil has two indoor air-side connections, one inlet and one outlet node, and one optional condenser air node connection (such as to a precooling unit). The user needs to specify a nominal speed level at which the rated total cooling capacity, and rated volumetric air rate are sized. The rated capacity and rated volumetric flow rate represent the field situation in the air loop and are used to determine and flow rates at various speed levels in its parent object, e.g. of AirLoopHVAC:UnitaryHeatPump:AirToAir, etc. It should be noted that the performance correction curves, i.e. the temperature and flow fraction correction curves, should be normalized to the rated capacity and flow rate at each individual speed and at the rated conditions, similar to the performance curves used in the single-speed DX coil. The performance values, e.g. capacities, COPs, SHRs and flow rates at individual speed levels, should be given in reference to a specific unit from the Reference Unit catalog data.

The Variable-Speed Air-to-Air Heating DX Coil (Coil:Heating:DX:VariableSpeed) is a collection of performance curves that represent the heating coil at various speed levels. The format of energy performance curves in heating mode is similar to the cooling DX coil, simply replacing the indoor wet bulb temperature with the indoor dry bulb temperature. The performance curves should be generated from the heat pump Reference Unit catalog data, again as black box equation –fit models. The number of speed levels can range from 1 to 10. The heating coil has two air-side node connections, one at the coil inlet and the other at the outlet. The user needs to specify a nominal speed level, at which the rated capacity and rated volumetric air flow rate are sized. As for the cooling coil model, the performance correction curves, i.e. the temperature and flow fraction correction curves, should be normalized to the capacity and flow rate at each individual speed and at the rated operating conditions, similar to the performance curves used in the single-speed DX coil. The performance values at individual speed levels, e.g. capacities, COPs and flow rates, should be given regarding a specific unit from the Reference Unit catalog data. The rated conditions for obtaining the heating capacities and COPs are at indoor dry-bulb temperature of 21.1 ˚C

(70 ˚F) and the source side entering air temperature of 8.3 ˚C (47 ˚F).

Variable-Speed Heat Pump Water Heating Coil (Coil:WaterHeating:AirToWaterHeatPump: VariableSpeed) withdraws source energy from the outdoor air for the ASIHP or from an indoor conditioned zone. To simulate the variable-speed water heating coil, the number of speed levels and the corresponding curve sets are expanded up to ten. The format of energy performance curves in water heating mode is similar to the space heating mode, simply replacing the indoor dry bulb temperature with the water temperature entering the heat pump water heater. The user can provide speed levels of any number from 1 to 10. The more curves the more accurate with linear interpolation. The object fits into the parent object of WaterHeater:HeatPump:PumpedCondenser, to be connected with other components, i.e. water heater tank, evaporator fan, etc. The user can replace an existing single-speed water heating coil by switching to the name and object type of a variable-speed water heating coil, i.e. Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed versus Coil:WaterHeating:AirToWater-HeatPump in the same parent object.

When a variable-speed unit cycles, i.e. operating below its minimum speed, the variation of electrical power input to the unit is considered as a function of the part load ratio (PLR, actual load/steady-state capacity for the minimum speed), in the same way as in the EnergyPlus single-speed DX coil model. If the load is higher than the capacity given by the maximum speed, the variable-speed unit operates at the top speed. If the load can be matched by operating between the minimum and maximum speeds, the model will do linear interpolation between two neighboring speeds and find an exact speed level to match the building or water heating load. Furthermore, using linear interpolation and providing air and water flow rates at individual speed levels facilitates arbitrary relationships of flow rates as a function of the compressor speed. Other detailed descriptions of the variable-speed heating, cooling and water heating coils can be seen in the EnergyPlus Engineering Reference.

2. Control and Operation of ASIHP

Control and operation of ASIHPs are more complicated than those of standard air source heat pumps because they have more operating modes, including: (1) space cooling (SC), (2) space heating (SH), (3) dedicated water heating (DWH), (4) combined space cooling and water heating with full condensing (SCWH), (5) combined space cooling and water heating with desuperheating (SCDWH), and (6) combined space heating and water heating with desuperheating (SHDWH). The SC mode has the same operation as the object of Coil:Cooling:DX:VariableSpeed. The SH mode has the same operation as the object of Coil:Heating:DX:VariableSpeed. The DWH mode uses outdoor air as the heating source, which can be represented by an object of Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed. The

SCWH mode uses indoor air as the heating source and full condenser heat for water heating, which can be simulated using an object of Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed.

The SCDWH mode uses the superheated section of an outdoor condenser to heat the water. In this combined SCDWH mode, the cooling function is simulated using an object of Coil:Cooling:DX:VariableSpeed, containing temperature correction curves as a function of the indoor air and ambient temperatures at each speed level. Corrections for SC capacity and power in the SCDWH mode are included in the coiling coil object separate from the SC cooling coil object. The water heating function is simulated using an object of Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed, having temperature correction curves as a function of the ambient air temperature and entering water temperature at each speed level. It should be noted that the rated power and power correction curves are contained in the Coil:Cooling:DX:VariableSpeed object to account for the total power consumption in the combined mode. Thus, the power values and curves in the Coil:WaterHeating: AirToWaterHeatPump:VariableSpeed are not used. That means the power consumption at each speed level of the SCDWH mode is accounted by the SCDWH cooling coil part.

The SHDWH uses the superheated section of an indoor condenser to heat the water. In this combined mode, the heating function is simulated using an object of Coil:Heating:DX:VariableSpeed, having temperature correction curves as a function of the indoor air and ambient temperatures at each speed level. Corrections for SH capacity and power in the SHDWH mode are included in the heating coil object separately from the standard SH heating coil object. The water heating function is simulated using an object of Coil:WaterHeating: AirToWaterHeatPump:VariableSpeed, having temperature correction curves as a function of the ambient air temperature and entering water temperature at each speed level. It should be noted that the rated power and power correction curves are contained in the Coil:Heating:DX:VariableSpeed object to account for the total power consumption in the combined mode. Thus, the power values and curves in the Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed are not used. That means the power consumption at each speed level of the SHDWH mode is accounted by the air heating coil part. The Coil:Heating:DX:VariableSpeed object calculates the total heating capacity added to the indoor air flow. Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed calculates the total heating capacity added to the water stream.

The parent object of the ASIHP is named as CoilSystem:IntegratedHeatPump:AirSource, which is a collection of all the sub-models as above. Also, CoilSystem:IntegratedHeatPump:AirSource facilitates mode switch and control algorithms.

2.1 Working Modes

The ASIHP is a collection of working modes, i.e., objects, as described below:

Space Cooling Mode (SC):

Coil object: Coil:Cooling:DX:VariableSpeed contained in CoilSystem:IntegratedHeatPump:AirSource.

Loop object: AirLoopHVAC:UnitaryHeatPump:AirToAir, which refers to the CoilSystem:IntegratedHeatPump:AirSource object.

Load matching: the same as a regular variable-speed air source heat pump in cooling mode.

Space Heating Mode (SH):

Coil object: Coil:Heating:DX:VariableSpeed contained in CoilSystem:IntegratedHeatPump:AirSource.

Loop object: AirLoopHVAC:UnitaryHeatPump:AirToAir, which refers to the CoilSystem:IntegratedHeatPump:AirSource object.

Load matching: the same as a regular variable-speed air source heat pump in heating mode

Dedicated Water Heating Mode (DWH):

Coil object: Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed contained in CoilSystem:IntegratedHeatPump:AirSource. The water heating coil uses outdoor air as the heating source.

Loop object: WaterHeater:HeatPump:PumpedCondenser, which refers to the CoilSystem:IntegratedHeatPump:AirSource object.

Load matching: the same as a regular variable-speed heat pump water heating coil with outdoor air source.

Combined Space Cooling and Water Heating with Full Condensing Mode (SCWH):

Coil object: Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed contained in CoilSystem:IntegratedHeatPump:AirSource. The water heating coil uses indoor air as the heating source.

Loop object:

- Air side: the same loop object as the SC mode, i.e., AirLoopHVAC:UnitaryHeatPump:AirToAir, which refers to the CoilSystem:IntegratedHeatPump:AirSource object.
- Water side: the same loop object as the DWH mode, i.e., WaterHeater:HeatPump: PumpedCondenser, which refers to the CoilSystem:IntegratedHeatPump:AirSource object.

Load matching:

- If one chooses to match the space cooling load, iterate the AirLoopHVAC object, and the water heating capacity in the water tank object is resultant.
- If one chooses to match the water heating load, iterate the water tank object, and the space cooling capacity is resultant.

Combined Space Cooling and Water Heating with Desuperheating Mode (SCDWH):

Coil object: use two coil objects, Coil:Cooling:DX:VariableSpeed and Coil:WaterHeating:-AirToWaterHeatPump:VariableSpeed, contained in CoilSystem:IntegratedHeatPump:AirSource. The desuperheater heat is used for water heating, which changes with the compressor speed and operating conditions. This is a dual-function coil, which provides both space cooling and water heating, so performance curves for the dual functions will be included in the coil objects, respectively. These should be different objects from the SCWH mode and SC mode. The water heating coil contains temperature correction curves as a function of the ambient air and entering water temperatures.

It should be noted that the rated power and power correction curves are contained in the Coil:Cooling:-DX:VariableSpeed object. Thus, the power values and curves in the Coil:WaterHeating:-AirToWaterHeatPump:VariableSpeed are not used. That means the power consumption at each speed level of the SCDWH mode is accounted by the cooling coil part.

Loop object:

- Air side: the same loop object as the SC mode, i.e., AirLoopHVAC:UnitaryHeatPump:AirToAir.
- Water side: the same loop object as the DWH mode, i.e., WaterHeater:HeatPump:PumpedCondenser.

Load matching: Always match the space cooling load by iterating the AirLoopHVAC object and the water heating amount in the water tank object is resultant.

Combined Space Heating and Water Heating with Desuperheating Mode (SHDWH):

Coil object: use two coil objects, Coil:Heating:DX:VariableSpeed and Coil:WaterHeating:-AirToWaterHeatPump:VariableSpeed, contained in CoilSystem:IntegratedHeatPump:AirSource. The desuperheater heat is used for water heating, which changes with the compressor speed and operating conditions. This is a dual-function coil, which provides both space heating and water heating, and so performance curves for the dual functions will be included in the coil objects, respectively.

It should be noted that the rated power and power correction curves are contained in the Coil:Heating:DX:VariableSpeed object. Thus, the power values and curves in the Coil:WaterHeating:-AirToWaterHeatPump:VariableSpeed are not used. That means the power consumption at each speed level of the SHDWH mode is accounted for by the space heating coil part.

The Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed object contains rated water heating capacity and capacity correction curves to simulate water heating capacity as a function of the outdoor air temperature and the water entering temperature at each speed level. The Coil:Heating:DX:VariableSpeed object calculates the total heating capacity added to the indoor air flow.

Loop object:

- Air side: share the same air side connections as the SH mode, i.e., AirLoopHVAC:UnitaryHeatPump:AirToAir.
- Water side: the same loop object as the DWH mode, i.e., WaterHeater:HeatPump:PumpedCondenser.

Load matching: Always match the space heating load by iterating the AirLoopHVAC object and the water heating amount in the water tank object is resultant.

2.2 Control and Mode Switch

At the beginning of each time step, a CoilSystem:IntegratedHeatPump:AirSource object surveys calls from all of its connected parent objects and nodes, e.g., AirLoopHVAC:UnitaryHeatPump:AirToAir, WaterHeater:HeatPump:PumpedCondenser. Upon analyzing the space conditioning and water heating calls, the ASIHP will operate in a selected mode for the following time-step, as shown below:

Case I:

If there is only a space cooling call – run SC mode.

Case II:

If there is only a space heating call – run SH mode.

Case III:

If there is only a water heating call, and if ambient temperature and indoor temperature are higher than the temperature settings above which indoor overcooling is allowed – run SCWH mode to match the water heating load above a minimum speed allowed.

Else – run DWH mode.

Case IV:

If there are simultaneous space cooling and water heating calls, and if the sum of heated water going through the ASIHP is less than a defined minimum volume, i.e. indicating a short water draw– run SCDWH mode by iterating the compressor speed to match the space cooling load above a minimum speed specified.

Else – run SCWH mode to match either the space cooling load or the water heating load, as specified, above a minimum speed allowed.

Case V:

If there are simultaneous space heating and water heating calls, and if the ambient temperature and indoor temperature are larger than temperature settings above which water heating has a higher priority and space heating call can be ignored – run DWH mode.

Otherwise, if the runtime of the water heating is less than a setting – run SHDWH mode to match the space heating load by iterating the compressor speed above a minimum speed specified, with the WH electric element in the water tank disabled.

Otherwise, if the runtime of the water heating is larger than the setting – run SHDWH mode to match the space heating load by iterating the compressor speed above a minimum speed allowed, with the WH electric element enabled.

3. ASIHP BUILDING ENERGY SIMULATIONS

3.1 Building and ASIHP Models

The most efficient operation mode of a commercial ASIHP is the combined space cooling and water heating mode (SCWH). This mode makes effective use of both the heating and cooling outputs of the heat pump by recovering the condenser waste heat during SC operation for water heating (WH). To illustrate the energy saving potential of an ASIHP product, we selected a quick-service (or fast-food) restaurant template building (built after 1980) from the EnergyPlus example buildings library, since it has the most frequent hot water draws and is able to facilitate extended SCWH running period. As illustrated in Figure 2, the fast-food restaurant building type has a much more demanding hot water use profile in comparison to a typical residential building, which mainly uses hot water in the morning or evening when the homeowners take showers. The small restaurant has noticeable hot water draws consistently from 7:00 AM to 22:00 PM, with peak loads occurring during the breakfast and dinner time periods.

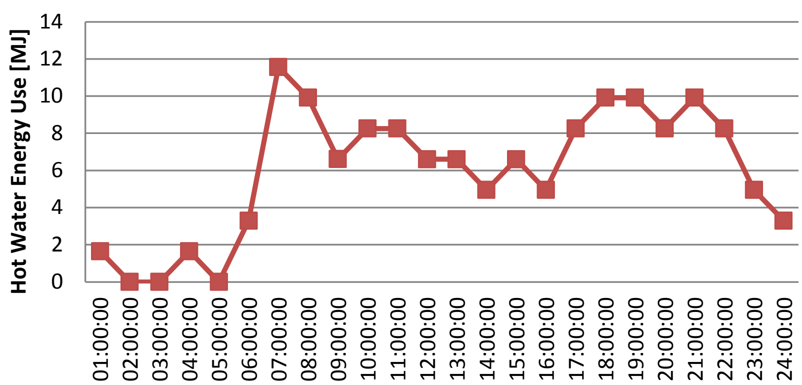

Figure 2. Hot water use profile for fast-food restaurant on a typical summer day in Atlanta, GA

The quick-service restaurant building is a single-story, two-zone building, having a floor area of 232 m^2 (2,500 ft^2). It has two HVAC systems, with one conditioning the kitchen area and the other conditioning the dining area. A 0.2 m^3 mixed water tank is used to store hot water. The tank's skin loss coefficient to surrounding temperature is 6.0 W/K. We modified the EnergyPlus input file, using an ASIHP to replace the HVAC system in the kitchen.

Performance curves and efficiency indices of the ASIHP were obtained from a heat pump modeling tool, i.e. ORNL Heat Pump Design Model (Shen and Rice, 2014) [13], which was calibrated with lab test data from a prototype ASIHP, as introduced by Rice et al. (2014) [12]. The ASIHP has an equivalent seasonal heating COP of 3.8, a seasonal cooling COP of 5.3, and a heat pump water heating energy factor of 3.3. The seasonal cooling and heating COPs are calculated according to AHRI 210/240 [1]. The performance curves and indices were input up to 9 speed levels for the variable-speed operation modes, with the DWH mode only having one speed level. The ASIHP was auto-sized at the top speed level in the SC mode to match the building peak cooling load in each city. Accordingly, the required rated cooling capacities range from 4.3 to 5.4 tons (15.1 to 19.0 kW) in the ten cities shown later in Figure 5. The corresponding space heating and water heating capacities were scaled with the unit rated cooling capacity. A baseline system consisting of a heat pump, having a seasonal cooling COP of 4.1 and seasonal heating COP of 2.3, and a conventional electric resistance storage water heater was used for comparison. The performance curves of the baseline system, cooling and heating as a function of the ambient and indoor temperatures, were actually obtained from the same ASIHP unit, but the rated cooling and heating COPs were adjusted to give the typical seasonal cooling and heating COPs. For the electric resistance water heating, it is assumed the electric use efficiency is 100%.

Figures 3 and 4 present the combined COPs of the SCWH mode, i.e. the added energy deliveries of space cooling and water heating divided by the total equipment energy consumption, as a function of the indoor wet bulb temperature and return hot water temperature, at the lowest and top compressor speeds. It can be seen that the combined COP gets higher when increasing the wet bulb temperature and reducing the return water temperature. The lower compressor speed led to higher combined COPs because of the reduced heat load in the heat exchangers. The SCWH was the most efficient operation mode. Even at very high water temperature, i.e. 50°C and low indoor humidity, the combined COPs were still around 5.0 to 6.0.

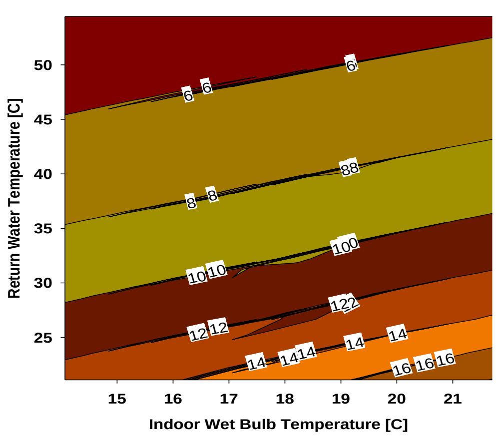

Figure 3. Combined SCWH COPs at the lowest compressor speed

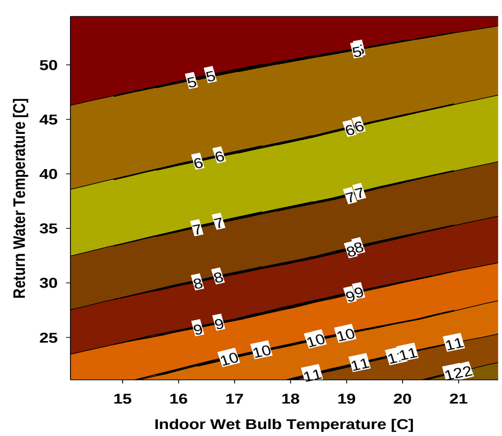

Figure 4. Combined SCWH COPs at the top compressor speed

For the annual energy simulations, in the cooling season, the kitchen space thermostat was set at 79°F (26°C) during occupied hours (5:00 AM to 1:00 AM, the second day), and 86°F (30°C) during unoccupied hours (1:00 AM to 5:00 AM). In the heating season, the thermostat was set at 66°F (19°C) during occupied hours and 60°F (15.6°C) during unoccupied hours. In the hot water tank, an electric element controlled the tank temperature at 125.6°F (52°C), and the heat pump controlled it at 131°F

(55°C), both having a 3.6 R (2 K) dead band below the set point. When running the baseline simulation, the electric element set point was unchanged. It means that the heat pump was targeted to deliver 5.4 R (3 K) higher water temperature than the electric resistance water heating. To simplify the comparison, the ASIHP and baseline heat pump only handled the indoor load. Loads induced by outdoor air ventilation were assumed to be handled by a separate dedicated outdoor air system.

For the ASIHP control, when the indoor air temperature was above 21°C and the ambient temperature was above 25°C, the indoor overcooling was allowed in the SCWH mode. During the SCWH mode, the compressor speed was altered to meet the water heating load first. In the heating season, the water heating request had a higher priority and the indoor heating calls were ignored when indoor air temperature was above 19°C and the ambient temperature was higher than 16°C. During the SHDWH mode, the auxiliary electric heater was turned on instantly if the water temperature hits the electric water heater set point, because generally the ASIHP can't provide sufficient water heating capacity in the SHDWH mode.

We ran EnergyPlus simulations in 10 US cities, including Miami, FL, Houston, TX, Phoenix, AZ Atlanta, GA, Las Vegas, NV, Baltimore, MD, Chicago, IL, Los Angeles, CA, Seattle, WA, and San Francisco, CA. Figure 5 illustrates indoor load distributions in the 10 US cities. It can be seen that the commercial kitchen's indoor loads (percentage to the sum of space cooling, space heating and water heating loads) are mostly dominated by cooling (SC) and water heating (WH). Except for cities in hot climate locations, WH loads constitute more than 50% of the total load (>90% in the west coast locations).

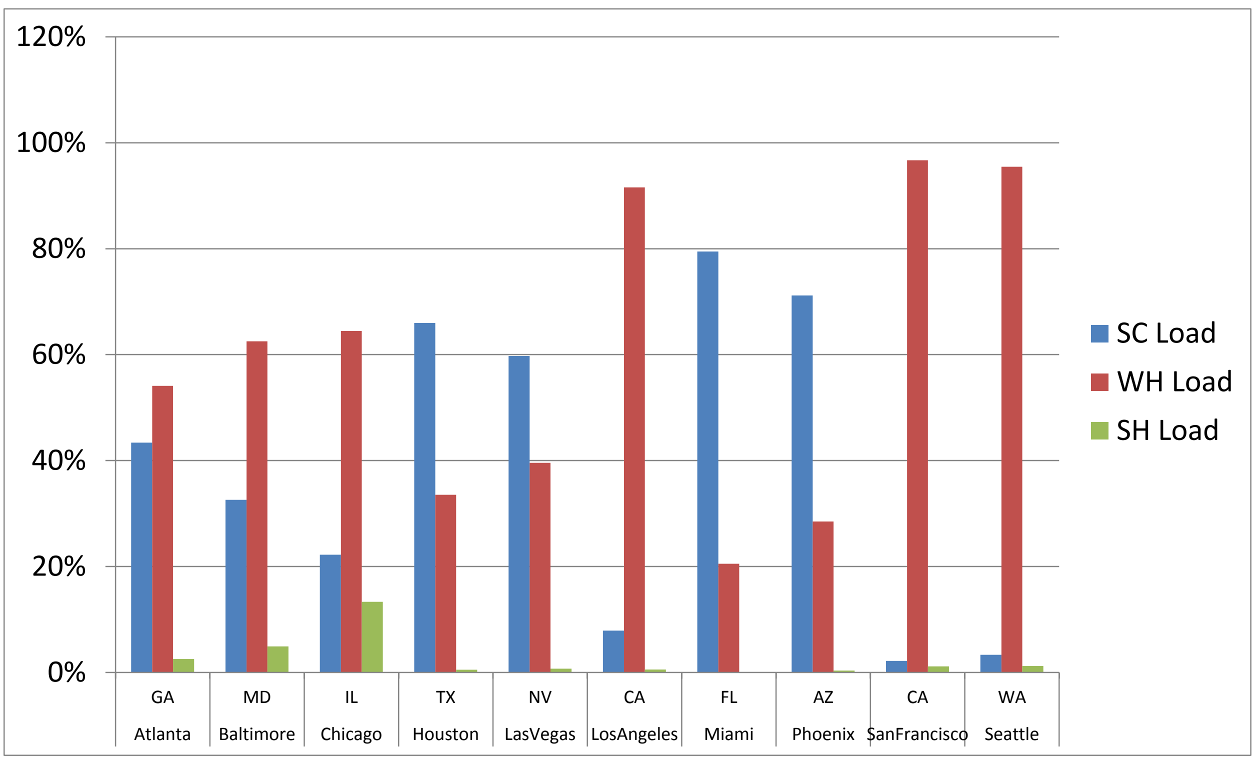

Figure 5. Internal Load Distributions in 10 US Cities

3.2 Predicted Energy Savings, Compared to a Baseline Heat Pump with Electric Water Heater

Figure 6 shows energy saving percentages of the ASIHP versus the baseline heat pump with electric water heating. Table 1 contains the detailed statistics. It can be seen that all the cities, except Chicago, IL and Miami, FL, have annual energy savings over 50%. Los Angeles, CA, San Francisco, CA and Seattle, WA have energy savings over 60%, because restaurants in these three cities are WH load dominated.

Table 1: Building Energy Simulation Results of ASIHP versus a Baseline Heat Pump with Electric Water Heating

City		Atlanta	Baltimore	Chicago	Houston	Las Vegas	Los Angeles	Miami	Phoenix	San Francisco	Seattle
State		GA	MD	IL	TX	NV	CA	FL	AZ	CA	WA
Baseline	Total SC Delivery [kWh]	12617	9020	6438	27007	21111	1318	45187	31339	385	633
	Total WH Delivery [kWh]	15737	17311	18692	13735	13980	15349	11658	12541	17062	18129
	Total SH Delivery [kWh]	737	1356	3865	197	251	93	11	158	197	230
	Total Delivery [kWh]	29091	27687	28995	40939	35342	16761	56857	44038	17644	18993
	Total Energy Consumption [kWh]	18936	20176	23060	19461	20477	15678	20739	21796	17223	18393
	Total Electric COP [W/W]	1.5	1.4	1.3	2.1	1.7	1.1	2.7	2.0	1.0	1.0
ASIHP	Total SC Delivery [kWh]	11807	8482	6305	24143	19452	2694	40666	28096	766	1236
	Total WH Delivery [kWh]	15957	17473	18843	13900	14144	15516	11822	12704	17230	18301
	Total SH Delivery [kWh]	741	1362	3877	197	250	92	11	153	195	230
	Total Delivery [kWh]	28505	27318	29025	38241	33846	18302	52499	40953	18191	19768
	Total Energy Consumption [kWh]	7864	9000	12116	8817	9565	5648	10551	10739	6397	7148
	Total Electric COP [W/W]	3.6	3.0	2.4	4.3	3.5	3.2	5.0	3.8	2.8	2.8
Total Energy Saving Percentage (ASIHP vs. baseline)		58%	55%	47%	55%	53%	64%	49%	51%	63%	61%

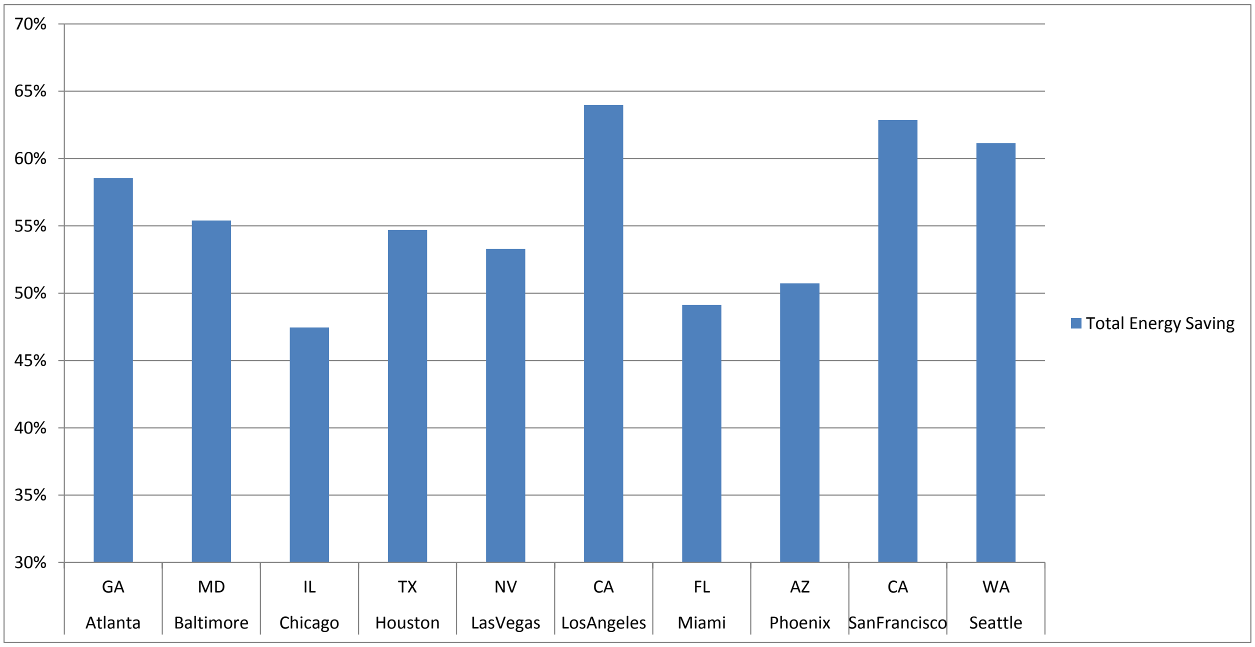

Figure 6. Total Energy Saving Percentages in 10 US Cities

3.2 Compare ASIHP Water Heating with Gas and Electric Water Heating

ASIHPs can provide somewhat higher source energy efficiency than gas water heating in mild and hot climate zones, where there are more simultaneous space cooling and water heating hours and higher efficiency for dedicated heat pump water heating (DWH) mode.

Based on the EnergyPlus annual simulations, we calculated water heating source energy COPs, i.e. converting the electric COPs to source energy COPs by multiplying a factor of 0.32 (to account for generation and transport losses assuming natural gas is used to generate electricity). To define the SCWH water heating COP, we need to split the power between the SC and WH operations. We first calculated the annual average COP of the SC mode, and assumed the power consumption share for space cooling during the SCWH mode is the total cooling capacity in SCWH mode divided by the SC annual COP. The remaining power consumption of the SCWH mode was attributed to water heating. For gas water heating, the source COP is assumed as 1.0. For electric resistance water heating, the source COP is assumed as 0.32.

Figure 7 illustrates annual DWH source energy COPs, SCWH source COPs and integrated WH source COPs, i.e. sum of water heating capacities divided by sum of energy consumptions in DWH and SCWH modes. It can be seen that SCWH WH source COPs are much higher than the DWH COPs which is because the condenser waste heat is recovered. The climate zones having integrated WH source COPs higher than 1.0, generally regions with the largest cooling loads, are considered promising for the use of ASIHPs to replace gas water heating, in terms of source energy efficiency. These are Houston, TX, Las

Vegas, NV, Miami, FL, Phoenix, AZ. All climate zones show integrated WH source COPs 3 to 4 times higher than electric resistance water heating.

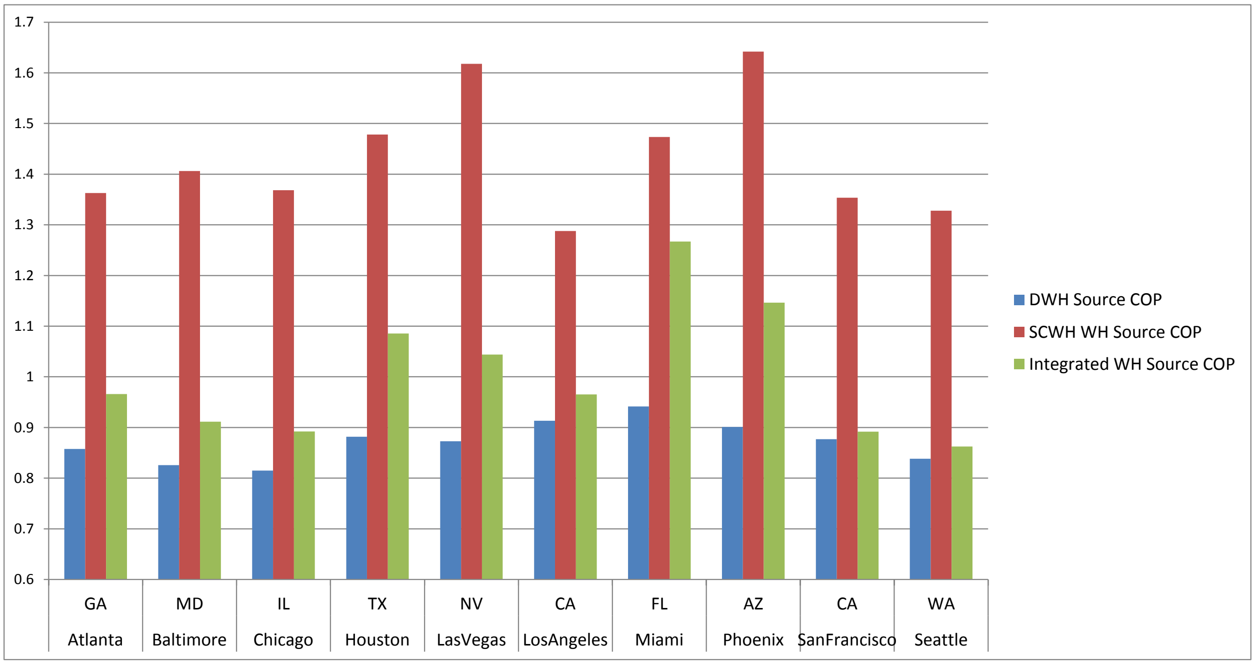

Figure 7. Water Heating Source Energy COPs in 10 US Cities

3.3 Simulation of Grid Integration Strategy

Electric rates differ between peak and off-peak hours because of varied power generation and transport efficiencies. The profiles of hourly electricity rates in summer and other seasons published by Comed [2], a utility company headquartered in Chicago with more than 3.8 million customers, are shown in Figure 8. We used EnergyPlus to simulate grid integrations of the air-source integrated heat pump (ASIHP). The profiles in Figure 8 were adopted in the EnergyPlus simulations, assumed to represent national trends. The hourly rates of individual cities are scaled by one multiplier to produce the annual average values given by EIA [5], as illustrated in Figure 9.

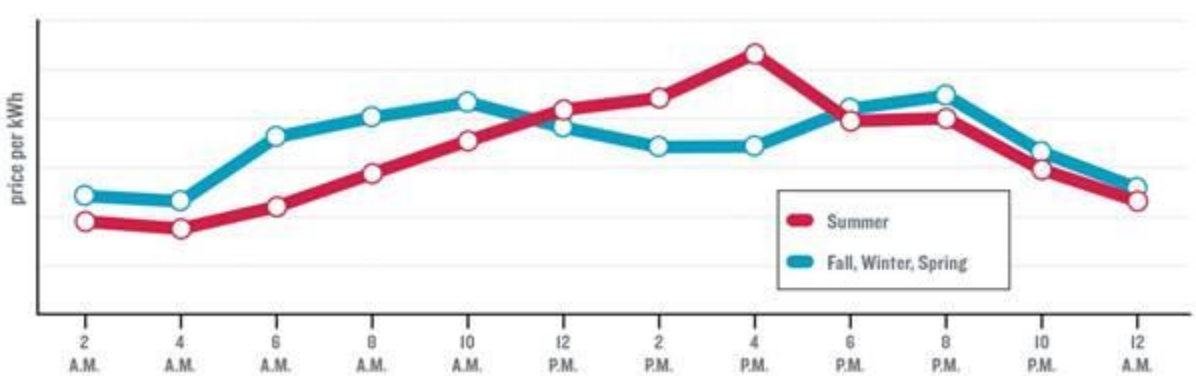

Figure 8. Profiles of hourly electricity rates (¢/kWh) published by the Comed Company.

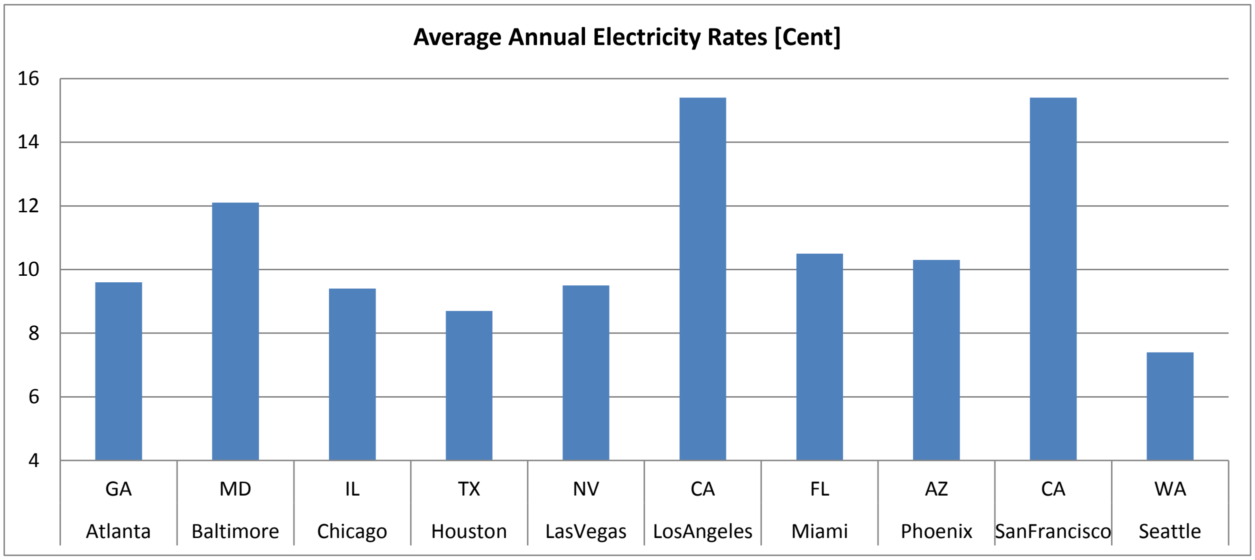

Figure 9. Annual average electricity rates in ten cities (¢/kWh).

To utilize the off-peak electricity rates and implement a power integration strategy, we increased the heat pump water heating set point to 60°C (140°F) from 1:00 AM to 5:00 AM, and kept the original 55°C (131°F) set point at all other times. Figure 10 compares energy savings relative to total ASIHP annual energy consumption for a setback schedule and no setback schedule for three different sizes of water tanks, i.e., 0.2 m^3 (53 gallons), 0.5 m^3 (132 gallons), and 1.0 m^3 (264 gallons). Increasing the water heating set point during the off-peak hours extended the water heating hours and had two effects, one was to promote more combined space cooling and water heating mode operation, which enhanced the overall energy efficiency; the other was that higher condensing pressures occurred which impaired the efficiency. With the two largest water tanks, the water heating setback schedule resulted in noticeable energy savings in Los Angeles, San Francisco, and Seattle (where the WH load heavily dominates the total building load) but greater energy consumption in Houston, Las Vegas, Miami and Phoenix (where SC loads dominate). For the cities having energy savings, the higher water set point extended the SCWH mode during the unoccupied hours from 1:00 AM to 5:00 AM, when it allowed overcooling below the 86°F (30°C) cooling set point. It resulted in higher SCWH efficiency at the higher source air temperature, reduced WH operation at the lower indoor set point, and saved cooling energy during occupied hours by pre-cooling the kitchen. With the smallest water tank, the setback schedule resulted in very slight energy penalties or gains in all cities. The low energy storage capacity of the small tank effectively limited the operating time in SCWH mode during overnight hours.

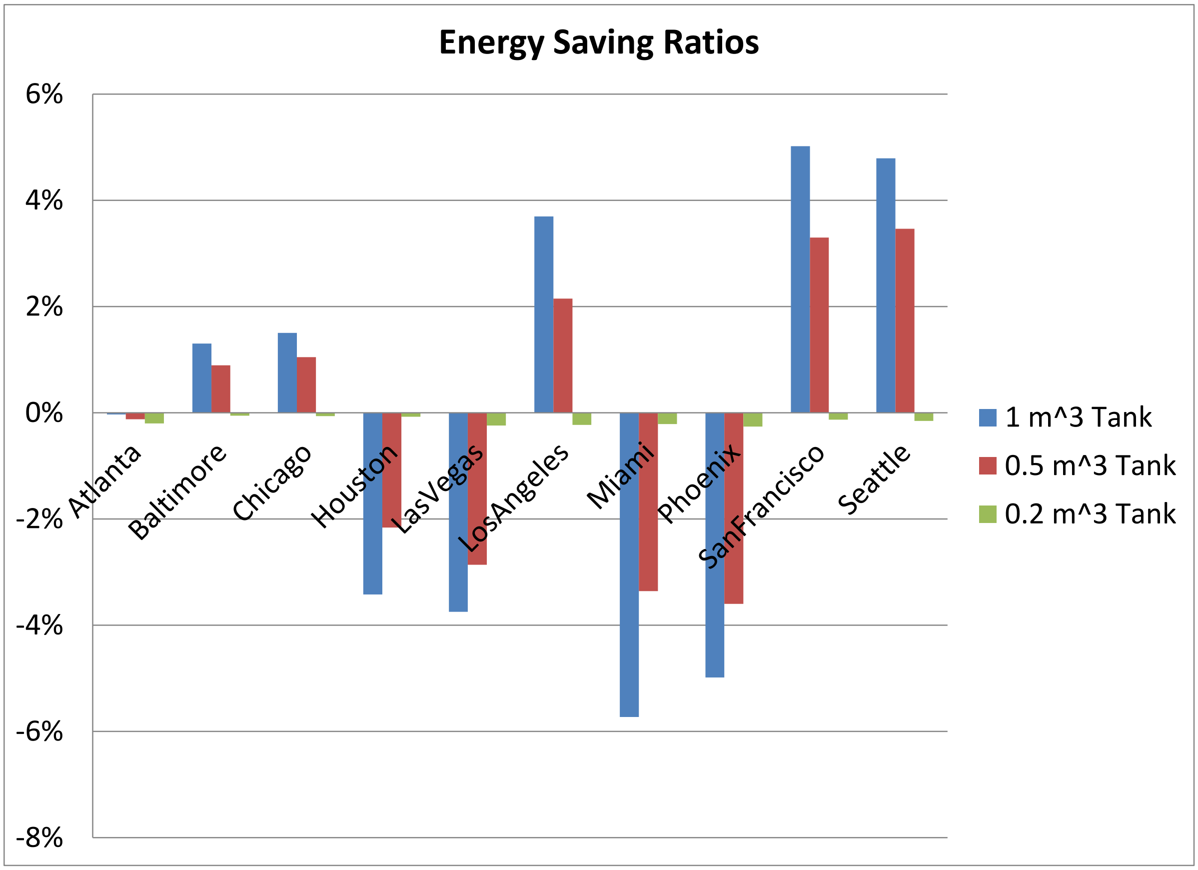

Figure 10. Annual energy savings of ASIHP with water heating temperature setback schedule in comparison to ASIHP without setback schedule.

Figure 11 shows annual electricity cost reductions, relative to the annual ASIHP utility costs without the grid integration in the ten cities. Using the two larger water tank sizes, the grid integration strategy reduced the electricity costs in most of the cities, except Houston, Las Vegas, Miami, and Phoenix which are the locations with the warmest ground water temperatures and SC loads. The grid integration, coupled with the 1 m^3 (264 gal) tank led to the largest additional cost reduction of 9 to 10% in Los Angeles and San Francisco, CA and Seattle, WA. The limited energy storage capacity with the smallest water tank led to minimal energy cost impacts for the setback strategy in all cities.

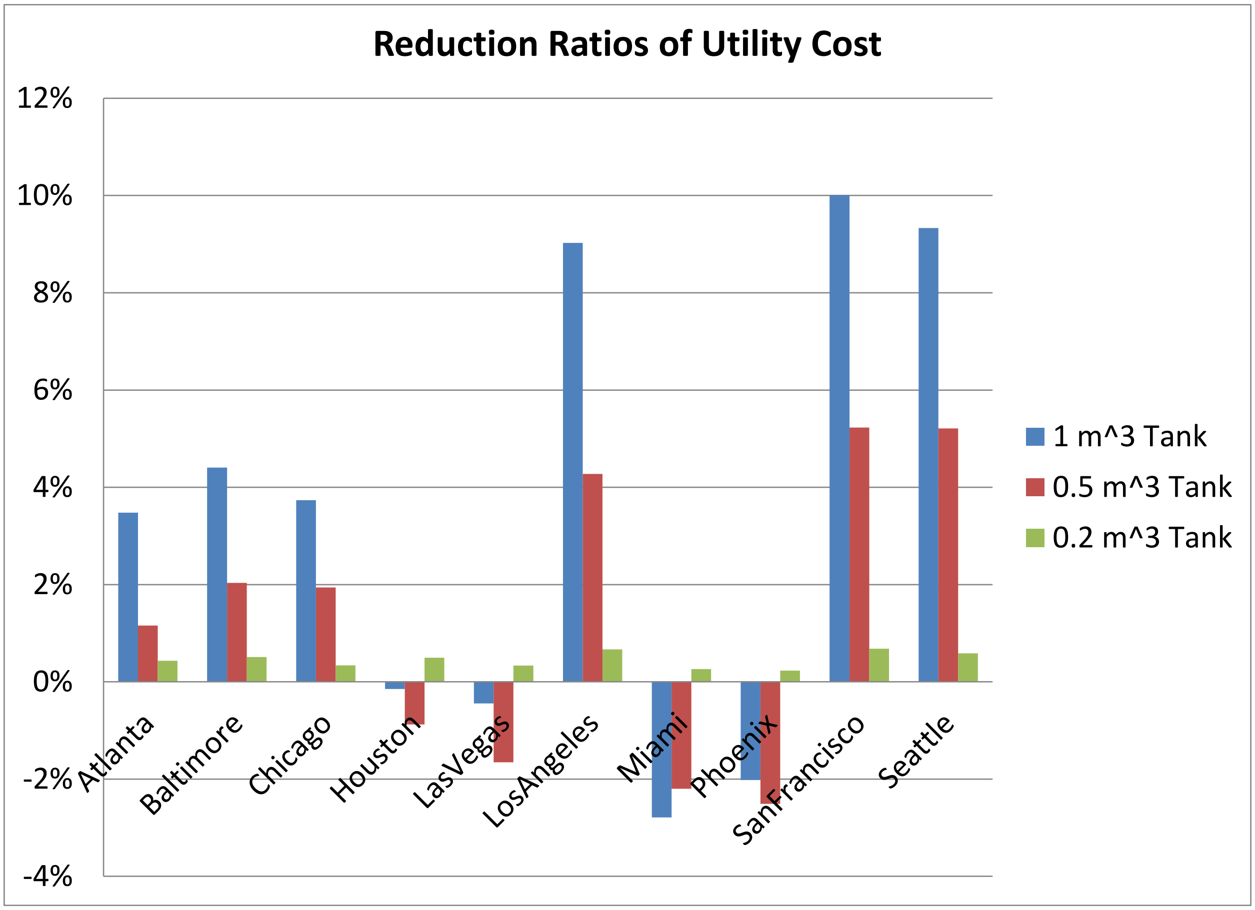

Figure 11. Annual cost reductions of ASIHP with water heating temperature setback schedule in comparison to ASIHP without setback schedule.

Summary

We developed a new ASIHP model in EnergyPlus, selected a quick-service restaurant template building, and conducted energy simulations over 10 US cities for comparison with baseline equipment. The performance curves and indices were obtained from a prototype ASIHP. In comparison to a baseline heat pump with electric water heating, the ASIHP is able to achieve annual energy savings ranging from 47% to 64%, averaging 56% over all 10 U.S. cities. We also compared the ASIHP water heating with gas and electric water heating in terms of source energy efficiency and showed that the ASIHP water heating is more efficient than gas in Houston, TX, Las Vegas, NV, Miami, FL, and Phoenix, AZ, i.e., regions with the largest cooling requirements All climate zones had integrated WH source COPs of 3 to 4 times higher than electric resistance water heating.

The building energy simulations were also used to investigate a grid integration strategy which increased the tank water setting temperature during off-peak hours, coupled with three tank sizes. Using the two largest tank sizes, the grid integration strategy led to further energy cost reductions and energy savings in six cities. However, it resulted in greater energy consumption and operating costs in the other four cities. For the cities having energy savings, the higher water set point extended the SCWH mode during the unoccupied hours, which resulted in higher SCWH efficiency at the higher source air temperature, reduced WH operation at the lower indoor set point, and saved cooling energy during occupied hours by pre-cooling the kitchen. The cities having energy penalties were SC load dominated where the energy gain of running extended SCWH mode during the unoccupied hours can't cover the penalties due to heating the water at the elevated set point with lower efficiency and the higher set point reducing the run time of SCWH operation during daytime. The limited energy storage capacity with the smallest water tank minimized the energy use and cost impacts of the setback strategy in all cities.

The future study will extend the building energy simulations and comparisons to other commercial building types, where are also heavy hot water uses, e.g. hotels, hospitals, and commercial laundry rooms, etc. The market potential and economics nationwide will be estimated.

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