FEASIBILITY OF COMBINED SOLAR/HEAT PUMP SYSTEMS FOR REDUCED RESIDENTIAL CONDITIONING ENERGY CONSUMPTION

Greg Marsicek, Sanford Klein, and Greg Nellis
University of Wisconsin – Madison: Solar Energy Laboratory
Madison, Wisconsin

ABSTRACT

This paper investigates the impact of using an air-source heat pump system in a thermally efficient house for two locations: Chicago, IL and Dallas, TX. In addition to an air-source heat pump, a geothermal heat pump system is implemented in the Chicago location. The source energy savings over a conventional system is reported as well as the life cycle costs for each of these cases. The conventional system is a natural gas furnace and air conditioner. In addition, to improve the performance of the air-source heat pump system, photovoltaics and solar thermal systems are implemented to analyze the effects on the energy savings and life cycle costs.

INTRODUCTION

Building research efforts have focused on reducing energy consumption by residential buildings. The Department of Energy reported that in 2009 the residential housing sector consumed 22% of primary energy (U.S. DOE, 2011). Of this 22%, nearly 50% went towards conditioning the home. With the current population growth rate, it is expected that the housing sector energy demand will grow in a similar fashion. The ability to reduce or offset the energy consumption of the housing sector would greatly reduce the dependence on non-renewable energy sources. The primary goal of this research is to reduce the energy required for conditioning the home, which is a large fraction of the building's energy consumption.

One opportunity to reduce energy consumption for conditioning a home is to use a heat pump. Heat pump efficiency is represented by the coefficient of performance (COP) which is the ratio of heating or cooling energy provided to the electrical energy required for operation. A heat pump can operate with a COP of 4 or higher, or in other words, providing 4 kJ of energy for conditioning for 1 kJ of energy consumed for operation. The heat pump operates on electricity which, unlike natural gas, can be easily offset by renewable energy. This research will investigate air-source heat pump systems in Dallas and Chicago. A geothermal heat pump system will also be implemented in the cold climate Chicago location. In addition, renewable options such as solar thermal and photovoltiacs will be investigated to determine the extent to which these systems help improve the performance of the air-source heat pump, especially in cold climate situations.

BUILDING MODEL

BEopt

To begin the simulation process, it was determined that a thermally efficient home must be used to achieve net-zero operation. BEopt, a building simulation program distributed by the National Renewable Energy Laboratory (NREL), was utilized to find the optimal home construction to reduce energy consumption (BEoptE+, 2012). BEopt allows a user to easily specify a building geometry and select various construction parameters including window and insulation type, water usage, building temperature set points, furnaces, heat pumps and much more. In addition, the user is also free to change the location (i.e., climate) and economic parameters. BEopt can also run parametric simulations in which multiple construction parameters can be selected and evaluated. For this research, a parametric study was done by using various insulation and window types, as well as other options in order to determine how a high efficiency house should be constructed. The thermally efficient house was chosen to have the construction parameters that are summarized in Table 1 on the following page. In addition, the house will utilize temperature set backs and internal shading in the cooling months.

The windows that are used in the high efficiency house depend on location. In a heating dominated climate, a low solar heat gain coefficient (SHGC) is less important as the cooling load is much smaller. However, in a cooling dominated climate, the SHGC becomes an important factor in window selection. Two different climates were considered in this work corresponding to Chicago and Dallas. For the Chicago home a double glazed window with a U-value of 0.91 W/m^2-K and a SHGC of 0.61 was used. For the Dallas home, a double glazed window with a U-value of 2.79 W/m^2-K and a SHGC coefficient of 0.379 was used. These values are in line with the recommendations made by the Efficient Windows Collaborative (Efficient Windows Collaborative, 2012).

Table 1: The construction parameters for the thermally efficient home.

Overview	
Finished Floor Area	2200 ft^2
Beds	3
Baths	2
Walls	
Double Stud	R45 batts, 2x4 Centered, 24"o.c
Exterior Finish	Grey Vinyl Siding
Interzonal Walls	R-19 Batts, 2x6, 24"o.c.
Ceilings/Roofs	
Unfinished Attic	R38 Fiberglass + 3.5" Rigid Ins
Finished Roof	R19 Fiberglass
Roofing Material	Asphalt Shingles, Dark
Foundation/Floors	
Slab (Garage)	Uninsulated
Finished Basement	4ft R5 Rigid
Unfin. Basement	Wall 4ft R5 Rigid
Interzonal Floor	R13 Fiberglass
Exposed Floor	20% Exposed
Thermal Mass	
Ext Wall Mass	2 x 5/8" Drywall
Partition Wall Mass	2 x 5/8" Drywall
Ceiling Mass	2 x 5/8" Ceiling Drywall
Windows & Shading	
Window Areas	15.0% F20 B40 L20 R20
Window Type	Varies by location
Interior Shading	Summer = 0.5, Winter = 0.95
Eaves	2 ft
Airflow	
Infiltration	Tight (0.5 Air Changes/hr)

Transient Energy System Simulation Tool

The Transient Energy System Simulation Tool, also known as TRNSYS, is the primary simulation tool used for this research (TRNSYS, 2010). TRNSYS is a robust program that allows for many different energy savings systems to be integrated with the thermally efficient building. One of the models in TRNSYS that will be used for this research is the Type 56 multi-zone building. The multi-zone building model allows for a user to create a thermal model of a building, divided into various thermal zones. For this research, each room in the home was modeled as an individual thermal zone.

The Type 56 model has two options for simulation: energy rate control (ERC) and temperature level control (TLC). In an ERC simulation, the Type 56 model determines the load required to meet the building temperature set point. This methodology prevents the building temperature from floating and is considered a "simplified" simulation as compared to a TLC simulation. TLC simulations closely mimic the operation of a real building. With TLC, the building temperature is allowed to float as experienced in a real house. In these simulations, a control strategy must monitor the house temperature and determine when conditioning is required. One major drawback to the TLC is that the simulation time is greatly increased over the ERC simulation. Small time steps must be used to accurately model the workings of a residential heating, ventilation and air conditioning (HVAC) system. In this research, since many simulations are required, it was decided that using the energy rate control would be sufficient to determine which combinations of conditioning systems would yield the most energy savings.

Currently, a Google SketchUp plug-in is available for use with the Type 56 building model, which allows a user to model the house in Google SketchUp and then import the model into TRNBuild, the interface for the Type 56 multi-zone building model (Google SketchUp 8, 2011). Figure 1 shows a front and back view of the thermally efficient home in Google SketchUp.

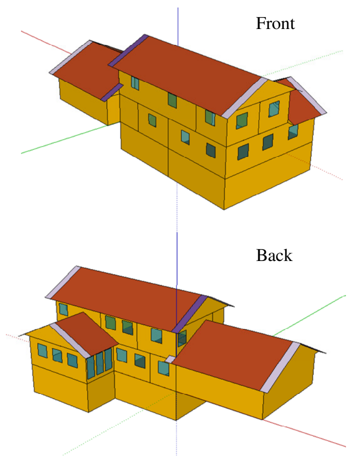

Figure 1: The front and back view of the home.

The parametric simulations in BEopt allowed for the construction parameters of a thermally efficient home to be determined. The properties of these materials (density, conductivity, heat capacity, emissivity, etc) were subsequently applied in TRNBuild in order to create a Type 56 building model in TRNSYS. In addition to the physical building parameters, occupancy related parameters must be specified.

The heating and cooling set points for the building vary depending on the day of the week and the time of day. Weekends do not experience any setbacks except for during sleeping hours in the heating season. Weekday set points are summarized in Table 2.

Table 2: This table summarizes the weekday heating and cooling set points for the building. Weekend setbacks occur at night during the heating season only.

Hour [hr]	**Cooling Set point [°C]**	**Heating Set point [°C]**
0	22.78	18.33
7	22.78	18.33
7	24.44	16.67
16	24.44	16.67
16	22.78	20
22	22.78	20
22	22.78	18.33
24	22.78	18.33

Since this building is simulating a residential home, internal gains from daily functions of a family must be included. The occupants of this home are assumed to be a family of four. A schedule was devised to include gains from showers, sinks, miscellaneous electronics (i.e., TV, computer), lights, and occupants who may be active or relaxed. Other gains included the stove, refrigerator, dishwasher and clothes washer and dryer.

With the clearly defined thermally efficient building, the next step was to calculate the building load at each time step. Table 3 shows the monthly energy requirements for conditioning. This building load could also represent a larger, more efficient home. For example if the infiltration were reduced (tighter construction) or wall insulation increased, this building load could represent a 2,500 ft^2 home.

The building load at each time step (15 minutes) is written to a text file that can be read into future simulations of HVAC equipment. Under energy rate control, the building conditioning equipment must run to meet the prescribed building load at each time step. If this condition is met, the building will maintain the set point. This method allows the simulation of the building to be carried out only once for each location.

Table 3: Heating and cooling load for Chicago and Dallas. Cooling loads are designated in blue and by the letter "C". Heating loads are red and noted with "H".

Month	**Monthly Building Load [GJ] Chicago, IL**	**Monthly Building Load [GJ] Dallas, TX**
Jan	8.77 (H)	3.61 (H)
Feb	7.07 (H)	2.66 (H)
Mar	4.99 (H)	0.34 (C)
Apr	2.95 (H)	0.82 (C)
May	0.65 (H)	2.49 (C)
Jun	1.90 (C)	4.44 (C)
Jul	3.64 (C)	6.47 (C)
Aug	2.18 (C)	6.37 (C)
Sep	0.89 (C)	4.48 (C)
Oct	0.82 (H)	1.30 (C)
Nov	4.02 (H)	0.73 (H)
Dec	8.23 (H)	3.18 (H)

HEAT PUMP SYSTEM

Air-Source Model Overview

TRNSYS contains several heat pump models but the one that will be used for this research is the Type 922 Air Source Heat Pump. This heat pump model uses a compilation of manufacturer's data to model the performance of the heat pump over a range of simulation conditions. These conditions include indoor and outdoor dry bulb temperature, indoor wet bulb temperature and air flow rate. However, two changes to the Type 922 heat pump model were required for this work.

First, it was found that the default heat pump model data file did not include a wide enough range of operating temperatures. If the operating conditions lie outside of the included data set, the Type 922 will not extrapolate. To address this problem, data sets for various heat pumps from two manufacturers (Carrier and Goodman) were analyzed to increase the range of operating temperatures. However, for each heat pump, the minimum operating temperature is taken to be -14°C. Below this temperature, the heat pump will shut off in order to avoid potential mechanical problems due to cold conditions.

The second change required was to adjust the source code so the Type 922 heat pump model could be used with an energy rate control simulation. The Type 922 heat pump initially has inputs and outputs of temperature and flow rate. This was modified so the input would be the building load for each time step and the output is the required power.

An assumption made for this heat pump was that the auxiliary heaters (electrical strip heating) have infinite capacity. When the heat pump is unable to meet the building load in the heating months, auxiliary heaters are assumed to be always capable of meeting the remaining load. This implies that the ability to meet the cooling load will determine the minimum allowable heat pump capacity for the building from a comfort standpoint (i.e., disregarding economics).

Geothermal Model Overview

The geothermal model uses a Type 919 liquid source heat pump, modified and verified in the same manner as the air-source heat pump model. For this research, an EER 20 liquid source heat pump is simulated, verified with data from ClimateMaster. Type 557 vertical bore heat exchangers are used to model the heat exchange process with the ground. BEopt is used as a reference for bore pricing (50.85 \$/m) and length (per ton of heat pump capacity: 106.7 m/ton). The soil conductivity is 4.68 kJ/hr-m-K and the heat capacity is 2016 kJ/m^3-K.

In order to determine the relative performance of the heat pump systems it is necessary to simulate a conventional conditioning system, which will create a basis for comparison. The conventional system consists of a natural gas furnace (92.5% annual fuel utilization efficiency) and a SEER 16 air conditioner. This higher efficiency conventional system is appropriate for a house that has been constructed with thermal efficiency in mind.

Chicago Results

A range of air-source heat pump capacities from 0.5 to 5 ton and efficiencies including SEER ratings 13, 14, 16 and 18 were simulated. The SEER 16 and 18 rated heat pumps take advantage of a two speed compressor, where the heat pump has the ability to provide two different capacities at any operating condition, depending on whether the compressor is in the low stage (slow speed) or high stage (high speed). The liquid source heat pump capacities simulated were 1.5, 2 and 2.5 ton, with an EER rating of 20.

For each case, a life cycle analysis was preformed, based on a simple model that assumes cash purchases, and no salvage values or incentives. The fuel inflation rate was varied but the results shown assume 15% with a market discount rate of 8%. The life of a heat pump system and thus the life time for the economic analysis is assumed to be 16 years. For the conventional system, two different natural gas costs are investigated, one is a representative value for recent costs at 0.88 \$/therm, while the second is a more expensive value, 1.53\$/therm, which is representative of prices several years ago (or, perhaps, several years in the future). Electricity is assumed to be 0.14 \$/kW-hr.

Since natural gas and electricity are compared in this analysis, source energy figures are used. Source energy allows multiple fuel types to be compared on the same basis. For example, 1 kW-hr of electricity is actually 3.34 kW-hr of source energy when the site to source ratio of 3.34 is applied, which factors in the inefficiencies involved in generating and distributing the electricity. For natural gas, only capturing and distribution is involved, which explains the site to source ratio of 1.047 (EnergyStar, 2011).

For the Chicago location, the minimum capacity heat pump system that was capable of meeting the simulated building cooling load at every time step was 1.5 ton. By increasing the capacity to 2.5 ton, the heat pump system reduces its source energy consumption. When a geothermal system is used, source energy savings are achieved, but at a higher life cycle cost. These results are seen in Figure 2. Data points to the left of the conventional system (green dots) consume more source energy.

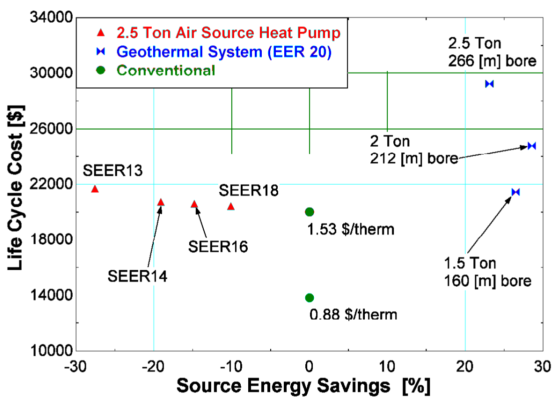

Figure 2: Heat pump systems vs. the conventional system (at two different natural gas rates) in the Chicago location. The fuel inflation rate in this analysis is 15%.

At around 1.50 \$/therm the air-source heat pump system appears to be economically competitive with the conventional system even though it actually consumes more source energy. When a 1.5 ton geothermal heat pump system is compared to the conventional system, it saves 25% more source energy but costs \$1500 more over the 16 year period. Current natural gas prices are in the 0.80$/therm range in the Chicago area and this cost has been decreasing recently.

Dallas Results

The Dallas simulation had the same economic parameters as the Chicago simulation. For this location, it was found that the minimum heat pump capacity that would fully meet the cooling load was 2 ton.

As seen in Figure 3, the heat pump in the Dallas location offers some source energy savings, particularly at higher SEER values, and lower life cycle costs over the conventional system. This is expected as current trends show heat pumps to be most common in cooling dominated climates.

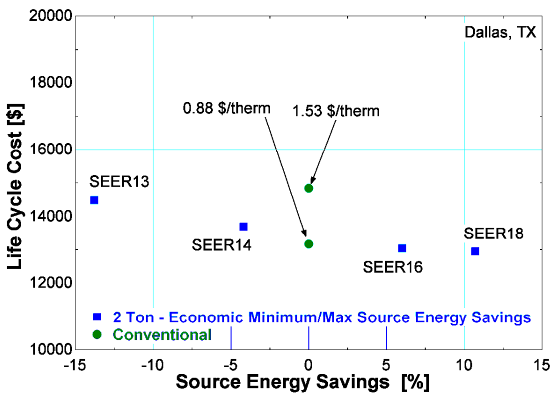

Figure 3: Heat pump system vs. the conventional system (at two different natural gas rates) in the Dallas location. The triangles represent the most source energy savings. The fuel inflation rate in this analysis is 15%.

Coefficient of Performance Results

Another metric of interest is the Coefficient of Performance (*COP*) of the heat pump. This index of performance is defined in equation (1) as the ratio of the provided heating or cooling load to the input power:

$$COP = \frac{Q}{W} \quad (1)$$

where Q is either the provided heating or cooling load and W is the power consumption. The monthly *COP* is calculated by the same ratio, where Q is total load provided throughout the month and W is the total power consumed over the month.

Figure 4 allows for a comparison between the performance of the air-source heat pump systems and ground source heat pump systems. It is clear that cold conditions and required use of the strip heaters in the Chicago location drastically reduce the *COP* during the heating season. The high monthly *COP* for the geothermal system explains the source energy savings over the conventional system.

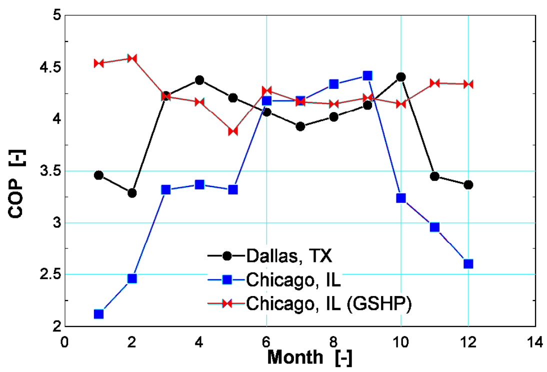

Figure 4: The monthly COP of the Dallas and Chicago heat pumps systems.

PHOTOVOLTAIC SYSTEM

Model Overview

Photovoltaic (PV) panels were added to the building in order to increase the source energy savings over the conventional system. For this house, it was assumed that the PV system would be grid connected and would sell back excess electricity to the utility, at the purchase rate of 0.14 $/kW-hr. The Solar Advisor Model (SAM) was used to simulate the monthly electricity output (SAM, 2011). The panels were mounted on the south facing roof and had a de-rating factor (efficiency penalty) of 80.1% for Chicago and 85.4% for Dallas. For pricing, three different levels were used; 4, 6 and 8 $/W_P$. This price range covers various incentive plans and installation rates.

Chicago Results

Figure 5 presents the photovoltaic results for the Chicago home. By moving to the right (i.e. increasing the source energy savings) of the “SEER18 w/ No PV” data point a PV array is added and used with the SEER 18 heat pump. Increasing the source energy savings increases the PV array size. The dashed vertical lines reference two different array sizes, 1.42 kW and 2.84 kW. Any point on the solid lines represents a different PV array size at a specified installed cost (4, 6, or 8

$/W$_P$). Reading between the cost lines is possible, for example, a 2.13 kW would have a source energy savings of around 49% and have a life cycle cost of $26,500 if installed at a cost of 7 $/W$_P$.

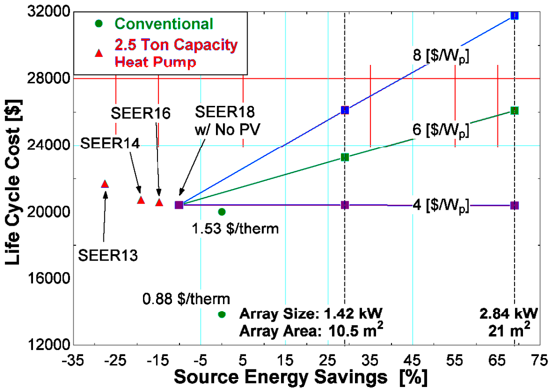

Figure 5: Heat pump system with PV vs. the conventional system in the Chicago location. The fuel inflation rate in this analysis is 15%.

By adding a PV system, the source energy savings increases greatly, however, the life cycle costs also increase unless the inexpensive 4 $/W$_P$ value is assumed. With the current natural gas costs, the conventional system has much lower life cycle costs. If the sell back rate becomes much cheaper than the purchase rate, the economic outcome becomes much worse with higher life cycle costs. As previously mentioned, this research assumes the buy and sell rate to be 0.14 $/kW-hr. Furthermore, if PV sell back becomes too popular, the utility may be unable to offer, or may limit, the buy back program because they will be unable to use all of the electricity produced by their consumer's PV panels.

Dallas Results

The same simulations were run for the Dallas location to determine the effect of adding PV to the heat pump system that already saved more source energy and was economically cheaper than the conventional system.

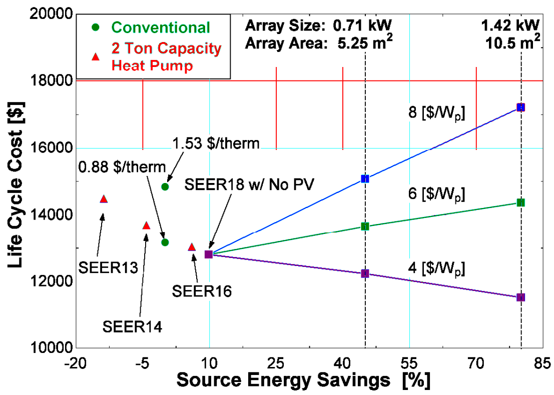

Figure 6: Heat pump system with PV vs. the conventional system in the Dallas location. The fuel inflation rate in this analysis is 15%.

By adding PV in the Dallas location, the source energy savings over the conventional system are substantial. At 6 $/kW-hr, a 1.42 kW array could be installed for a few thousand dollars more over a 16 year period. This addition increases source energy savings over the conventional system from 10% (for a SEER 18 heat pump system without PV) to 80% (with PV).

SOLAR THERMAL SYSTEM

Model Overview

The solar thermal system consists of a collector, storage tank and heat exchanger to transfer thermal energy from the tank to the air in the house, as shown in Figure 7.

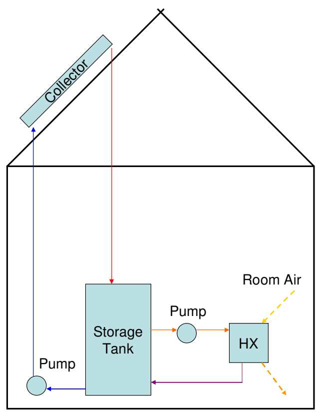

Figure 7: Solar thermal system model used for house heating. Water is the working fluid and a drain back system is used to prevent freezing.

As the collector size increases, the flow rate and storage capacity are scaled by factors of 0.015 kg/m^2-s and 75 L/m^2, respectively (Duffie and Beckman, 2006). Three costs are used (500, 1000 and 1500 $\$/m^2$) in order to cover a range of possible incentives and installation costs.

The TRNSYS Type 1 flat plate collector is used to model the thermal collector. The construction and optical properties are provided in Table 4.

Table 4: Summary of the Alternate Technologies AE-50 collector.

Specification	**Value**
Aperture Area	4.40 [m2]
Fluid Capacity	6.4 [L]
Absorber Material	Tube: Copper Plate: Copper Fin
Absorber Coating	Selective
Insulation (Side/Back)	Polyisocyanurate
$F_R(\tau\alpha)_n$	0.691
F_RU_L	3.396 [W/m2-C]
b_0, b_1	0.194, 0.006

The storage tank was modeled using the Type 4 stratified tank. This tank has the ability to be fully mixed, in which the tank would have warmer outlet temperatures that will decrease collector efficiency and useful energy gain. For a stratified tank, which occurs naturally due to water's temperature dependent density, both the collector efficiency and useful energy gain will increase as the tank will have cooler outlet temperatures. A stratification analysis was performed and it was observed that beyond 24 tank nodes there were no significant increases in efficiency or useful energy gain. For all simulations, 24 nodes were used. For heating months, tank losses are assumed to reduce the heating load. With the energy rate control simulation, a variable speed fan was used to allow the system to deliver the exact amount of thermal energy required to meet the building temperature set point.

The control strategy used to operate the room heat exchanger loop requires that the temperature of the water delivered to the heat exchanger be higher than 30°C in order to insure that comfortable heat transfer occurs. In addition, the building must require thermal energy in order for the system to run. The collector side control strategy provides flow through the collector during any time that the tank temperature can be increased.

At this time, the system is only used to reduce the heating load and does not have a control strategy to reduce the domestic hot water load. Thus, only the heating dominated location of Chicago is simulated.

Chicago Results

Three different collector sizes were simulated for the Chicago location; 8.8, 22 and 44 m^2. The collectors were assumed to be rack mounted at a 60° collector angle in order to increase the useful energy gain in the winter months. Figure 8 shows the results of the solar thermal simulations.

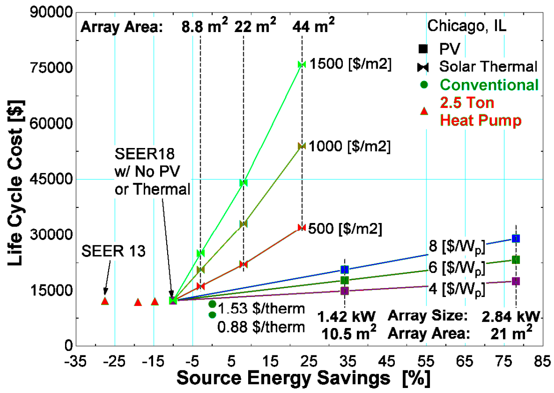

Figure 8: Solar thermal and PV results for the Chicago location. The fuel inflation rate for this simulation was 5%.

The solar thermal system in this case did not out-perform the PV system on a life-cycle cost basis. It should be noted that the PV system can operate year round, which gives it an advantage. However, even if the thermal system were used to heat domestic hot water during the summer months it still would not be as cost effective as the PV system.

Other results from this simulation were the fraction of the heating load met by the thermal system and collector efficiency, shown in Figures 9 and 10, respectively.

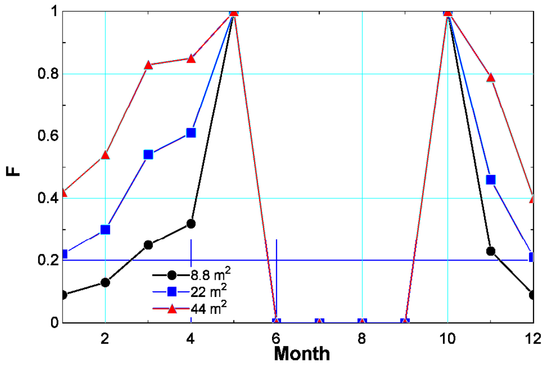

Figure 9: Fraction of the heating load met by the solar thermal system for each month.

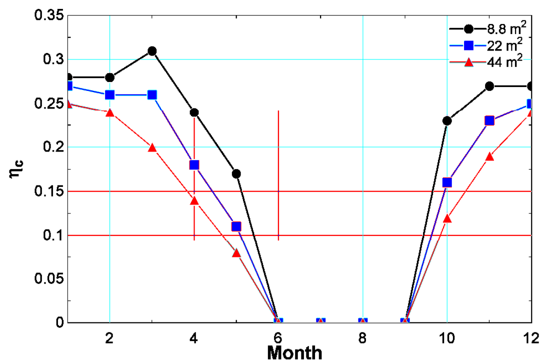

Figure 10: Collector efficiency for each month.

The fraction of the load met and efficiency results are intuitive. As the building load decreases in the spring months, the available solar radiation is also increasing allowing for the thermal system to maintain a hotter tank temperature and meet more of the building load. However, as the tank temperature increases in the spring months, the collector efficiency decreases due to increased thermal losses. In the summer months, the system is not used and the fraction of load met and collector efficiency are reported as zero.

CONCLUSION

Currently, this research has not found a clear economically viable way (with current natural gas prices) to use a heat pump in cold climate situations. Photovoltaics have proven to be the most cost effective decision when using solar energy with an air-source heat pump. But even with the addition of PV, the system is still more expensive on a life cycle costs basis than the conventional natural gas furnace and air conditioner system.

When a geothermal heat pump system is implemented, source energy savings occur, but at a higher life cycle cost. Natural gas prices above 1.50 \$/therm create a situation where the geothermal system becomes economically competitive with the conventional system. A downfall to the geothermal system is that it requires large amounts of space for the bore field, and may not be realistic option in city residences.

However, for warm climates, this research has found that heat pumps alone offer cost savings and source energy savings compared to the conventional system. When PV is added, the energy savings increase greatly while the life cycle cost increases by a smaller amount.

ACKNOWLEDGMENT

Financial support for this research was provided by the National Institute of Standards and Technology (NIST).

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