ASSESSMENT OF USING HEAT PUMPS FOR HEATING IN MOBILE HOMES: A CASE STUDY FROM NORTH CAROLINA

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ABSTRACT

This paper presents the results of "Upgrade and Save", a program to upgrade the standard electric furnaces and air-conditioning units in Mobile Homes for energy-efficient heat pumps. This program is implemented in North Carolina, USA and pays about $700 through a rebate provided by the North Carolina State Energy Office to the Mobile Homes' owners. The goal of this project is to subsidize low-income families by lowering their heating cost in the winter as well as improving their homes' indoor thermal comfort. More than 300 mobile homes have participated in this program. Field measurements, meter readings of the actual electrical consumption, and annual building energy simulation were used to measure the dollar saving and the indoor thermal comfort improvement in the mobile homes after the heating system upgrade. This research proved that the dollar saving of using the heat pump for heating in mobile homes ranges from $51 to $128 annually.

KEY WORDS

energy consumption, heat pumps, mobile homes, low-income families

INTRODUCTION

More than 15.9 million households in the United States are in fuel poverty (Rudge, 2000), and millions more are close to it (Henwood, 1997). Fuel poverty is defined as the need to spend over 10% of household income on energy to maintain an adequate standard of warmth. Fuel poverty in the United States is closely linked to low household incomes and associated factors such as age, housing tenure and geographical location. In 2005, 36% of fuel poor households had incomes higher than the Federal Poverty Guideline; 5% were ineligible for the federal Low-Income Home Energy Assistance Program (LIHEAP). However, the 2005 median income of the energy poor was $6100; only 5% had incomes higher than $21,000. There is a considerable amount of variation in energy expenditure; the fuel poor had a median annual energy expenditure of $1,330, but 25% spent more than $1,862. Just 15% were receiving any combination of income support or non-cash assistance, such as housing subsidies, food stamps, or assistance for the disabled. 39% of fuel-poor householders were 65 years old or older. The average income for this group in 2004 was $9,100; half of them lived alone. The average annual residential energy use of the fuel poor is 13% higher than the average for all U.S. residential energy use. Households under fuel poverty energy usage is more intensive by far; their homes use 30% more Btu per heated sq. ft (Rudge, 2000).

Fuel poverty is, fundamentally, a problem of housing cost and quality. It is statistically far more closely associated with poor energy efficiency standards than with other characteristics. Housing affordability is a major challenge for many Americans. Only 14% of all renters live in a metro area where one third of the average wage will be sufficient to rent a two-bedroom apartment. Nearly half of those in fuel poverty own their homes, but a startling 39% of the homeowners own mobile homes. These facts certainly raise the question: Why not retrofit these units? For example, The Weatherization Assistance program has reduced usage of the main fuels by an average 20% a year, and of base load electricity by 10%. However, its record on mobile homes is less than that of other low-income homes. Furthermore, many households which would not generally be considered low-income also face circumstances which make it difficult for them to pay their energy bills.

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Cold damp houses are a main health risk source, especially for elderly people. For many people aged over 60, central heating is an essential requirement. For such a major public health problem, there has been little methodologically sound research into the links between cold damp housing and ill health, although the available medical evidence has been well reviewed. Few controlled interventional studies have been done despite the opportunities afforded by major housing regeneration programmers. Cold, damp houses are associated with premature mortality, physical and mental illness, and impaired quality of life. They aggravate a wide range of medical conditions, increase suffering, and make it harder to care for vulnerable people at home, thus adding to the burdens on the National Health Services. The effects are widespread across the population, though elderly people, those with chronic disabling conditions or asthma, and families with small children are the groups most immediately and obviously affected. Among the major preventable medical problems partially caused, or aggravated, by cold damp houses are the 25,000–45,000 excess winter deaths, far more than in colder countries such as Norway. When the temperature falls, resistance to respiratory disease falls and vascular complications are increased, leading, for example, to increases in the incidence of myocardial infraction.

Traditionally, mobile homes are one of the most common homes for low income families in the United States. These houses are built in factories and shipped to the site. The sizes of these houses range between 100 and 220 m^2 (1070 and 2400 sqft). Most of these houses are heated by electric resistant furnaces which basically provide a little less than 1 kWh of heat of each 1 kWh of electricity consumed. Although the initial cost of this system is low compared with other heating systems such as heat pumps, the running cost of the electric resistance heater is much higher than heat pumps. After the latest increase in fuel prices, air source heat pumps have become a more popular heating system, especially in Southern United States. Most low-income apartment buildings in this region use heat pumps as a heating source. Utility companies programs have strongly leaned on heat pumps to reduce winter peak coincident demands. Reductions in peak demand over the use of resistance heaters is a major reason for electric companies to advocate and support using heat pumps (Southern Company, 2009). With the increase in the heat pumps' efficiency, the United States adapted President Barack Obama's American Recovery and Reinvestment Act (ARRA) of 2009. This act assigns several tax incentives to use new models of heat pumps for heating in all the US regions.

Heat pumps were introduced to the home heating market in the 1950's, evolving originally from central air conditioners which featured a reversing valve and a few other factory components allowing the heat pumps to provide heat under mild weather conditions. Early models were plagued with reliability problems related to failed reversing valves, improperly operating compressors or frost build up on the evaporators. Performance under colder conditions was often poor due to reduced heating capacity at low outdoor temperatures. Comfort was another complaint with early systems due to "cold blow" where the air temperature delivered by the heat pump was much lower (typically 38–41°C) compared with the 52–54°C typically delivered by natural gas furnace systems (Bouchelle, 2000). Modern heat pump systems are much more reliable and have become exceedingly common in moderate climates. By far the most common type of heating systems is air-to-air heat pumps which use outdoor air as the heat exchange medium. The problems with inadequate capacity and "cold blow" have been reduced by the addition of auxiliary resistance strip heat systems with a two-stage thermostat. As the indoor temperature drops, the first stage activates the heat pump; the second stage below it activates auxiliary strip heat. Under this regime, both the heat pump and the resistance heat operate together until the thermostat is satisfied.

The efficiency of the heat pump has two measures: its ability to extract heat from its heat source, usually the outside air, and to expel it into the home called its "Heating System Performance Factor (HSPF)", and its ability to extract heat from the home and to expel it into the outside air called its "Seasonal Energy Efficiency Ratio (SEER). A residential heat pump takes low-temperature heat from an outdoor medium (such as air, ground, groundwater or surface water) and mechanically concentrates it to produce high temperature heat suitable for heating the interior of homes. Because most of the heat is moved (pumped) from the outdoor source to the indoor source, the amount of electricity required to deliver it is theoretically much less than using electric resistance heat directly.

The theoretical Carnot efficiency of heat pumps is greater than 2000%. Thus, the COP, or coefficient of performance, would indicate 20 times as much heat delivered is used. However, the practical efficiency of the best air-to-air heat pumps produces COPs of 4.0 or less. Because COP varies with the outdoor temperature, a heating season performance factor (HSPF) is determined which takes into account operation under varying outdoor temperatures as well as part load impacts (effects of running short cycles under mild conditions, coil defrost, etc.). HSPF is rendered as Btu/Watt so that typical values are on the order of 6.8–10 Btu/W. Older systems may have HSPFs of 5–8 Btu/Wh (ARI, 2003). Fairey and Parker studied the Climate Impacts on HSPF and Seasonal Energy efficiency Ratio (SEER) for Air Source Heat Pumps in the USA. The study showed that the actual HSPF is 33% higher than the rated HSPF in hot climates such as Miami, Florida. The HSPF is 55% less than the rated HSPF in Minneapolis (Fairey, 2004).

DATA USED AND ANALYSIS

Approximately one-third of the new homes sited annually in North Carolina are manufactured homes (formally referred to as mobile homes). This percentage is considerably higher in rural areas of the state. Since manufactured homes are built in factories and then delivered to permanent home sites, US federal regulations (HUD) requires the installation of heating systems while the home is being constructed. Almost all manufacturers install forced air electric furnaces in the homes that they build. Rationale for this installation choice is based on lower initial cost and simplified installation. The duct system and associated connections is designed and installed to accept either an air conditioning and/or a heat pump unit without undue modifications or expense to the home owner. Both air conditioning units and heat pumps are installed after the home is permanently sited.

The field study is part of a research project at East Carolina University (ECU), USA, called " Upgrade and Save" funded by the North Carolina State Energy Office. It is known that the optimal heating-system-retrofit strategy for existing buildings differ due to the variations in energy prices, building and installation features, and climate conditions etc. For some of theses reasons, heat pumps are suggested by this project. Several home manufacturers such as GUSTAFSSON and BJIC found that the optimal heating-system retrofits in residential buildings is using heat pumps alone as heating systems.

Although heat pumps are generally more expensive to purchase and install than electric resistance heaters, the popularity of heat pumps is increasing. In moderate climates such as North Carolina, heat pumps are highly competitive because they can meet the entire cooling and heating needs of residential buildings.

In order to test the effect of upgrading the heating system on mobile homes' performance, field monitoring and computer simulations were conducted on 35 mobile homes. The energy savings from the retrofit were calculated based on actual temperature measurements and the actual energy consumption collected from 35 manufactured homes. In addition, an analytical model was created to simulate the energy consumption and the heating costs for one of the manufactured homes. The model is validated with the temperature measurements. To measure the actual mobile home performance before and after the retrofit, in-depth study of the actual thermal performance of three identical mobile homes was conducted.

Data acquisition systems were installed in each of these homes. A desktop computer with LabVIEW software, data acquisition card, and four thermocouples were installed in each house for three weeks before the retrofit and after the retrofit. Four thermocouples were connected to the computer through the data acquisition card and extended to four different locations in each house to measure outdoor temperature, supply air temperature, indoor temperature (room temperature), and indoor surface temperature. The temperature readings were measured and recorded every 5 minutes. Since December, January, February and March represent more than 80% of the annual degree-days heating days in North Carolina (ASHRAE, 2000), the data acquisition systems were installed in the mobile homes during these months.

NUMERICAL MODEL

In order to predict the annual performance of mobile homes, a typical mobile home which is identical to that of the field monitored homes was simulated. First, the home was graphically built using Revit© Computer modeling. Then, EnergyPlus© software was used to simulate the annual building energy performance. EnergyPlus© was selected for its capability of simulating heat transfer through the building envelope, solar radiation heat gain, natural ventilation, building heat load, active heating and cooling, predictive mean radiant temperature, moisture transfer, and comfort parameters. EnergyPlus© is the Department of Energy (DOE) official energy simulation software, and has its roots in DOE2 and BLAST energy simulation tools (EnergyPlus©, 2001). EnergyPlus is also supported by other simulation software such as WINDOW and Climate Consultant.

RESULTS AND DISCUSSION

The monthly electrical energy consumption for a sample of 14 mobile homes during February is shown in Figure 1. Heating makes up approximately 10.1% of the total energy consumption in a typical house in North Carolina (Figure 3). To determine the actual amount of electric used for heating in mobile homes, the duty cycle of the heat pump was monitored by installing a thermocouple in the supply air diffuser. The filed data showed that the heat pump operates when the indoor set point temperature was 18°C and the outside temperature was 3.5°C (Figure 5). We can safely assume that 3.5°C would be the heating balance point temperature. A typical balance point for a house can range between 3°C and 13°C. Although the balance point in the monitored mobile homes suggests that these houses are very energy efficient, mobile homes are relatively small in size and the internal heat gain contributes significantly to the reduction of the balance point temperature. We also noticed during our field visit that many mobile homes have high electric demand appliances such as large screen TV, incandescent lighting, washers and dryers which contribute to the internal heat gain.

The analysis of IWEC file for the Greenville area showed that the total number of hours where the average temperature is 3°C or less is 640 hours. These hours are distributed on the months of December, January, and February (ASHRAE, 2007). Thus the operating hours of the heat pump in three months would be 640 hours. The Electric consumption of the heat pump as installed is 2.6 kWh. The annual energy consumption of the heat pump will be 1560 kWh or $144 (Figure 1). The total annual number of hours where the average temperature is 4°C or less is 940 and the electric consumption will be 2340 kWh or $210.6. Thus, in average, the electric consumption for heating in the mobile homes will be 1950 kWh or $175.5.

METER READINGS

The previous results of the field monitoring are also supported by the meter readings of the Mobile homes. The meter readings showed that the average increase in electrical consumption during the heating season in 14 mobile homes was 2314 kWh or $208 (Table 1). In addition to the electric con-

FIGURE 1. Electric usage for 14 homes after the upgrade.

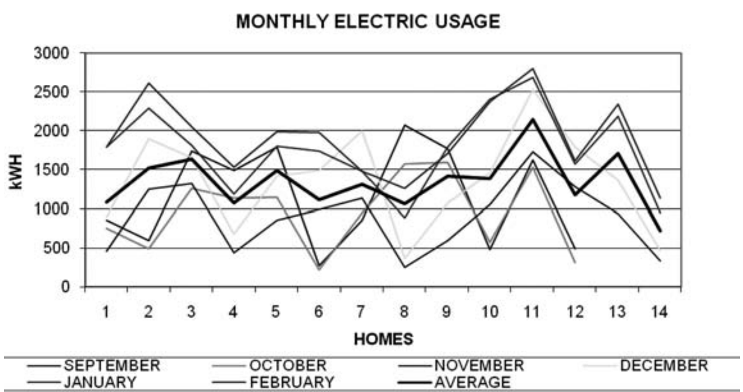


TABLE 1. Electricity consumption of 14 mobile homes which uses heat pump for heating.

Account Details							
	ELECTRIC CONSUMPTION Kwh						
Acct. #	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	AVERAGE
1	855	747	458	890	1792	1787	1088.17
2	601	485	1251	1889	2292	2612	1521.67
3	1738	1257	1332	1657	1808	2052	1640.67
4	1490	1135	438	673	1183	1530	1074.83
5	1786	1146	855	1409	1798	1984	1496.33
6	276	218	990	1484.01	1741	1971	1113.34
7	854	944	1140	2000	1477	1471	1314.33
8	2069	1568	254	363	884	1261	1066.50
9	1770	1591	594	1070	1792	1706	1420.50
10	484	576	1052	1453	2406	2369	1390.00
11	1625	1531	1733	2526	2682	2797	2149.00
12	494	308	1283	1784	1567	1614	1175.00
13			946	1364	2187	2339	1709.00
14			337	470	942	1132	720.25
Average	1170.166667	958.83333	904.5	1359.42929	1753.643	1901.78571	1348.54

sumption by the heat pump, extra electric consumption for hot water and the increase in using artificial lighting due to longer nights during the winter contribute to the increase in the electrical consumption. Figure 2 shows the average electricity consumption of the US household.

To calculate the dollar savings achieved when using heat pumps instead of electric resistance, the actual heat pump Heating Seasonal Performance Factor (HSPF) must be determined. The typical heat pump's HSPF is approximately 2.6 when the outside temperature is 3.5°C (Figure 3). However, a field survey conducted on 140 homes on HUD homes in Florida showed that the net HSPF of heat pump heating systems was 1.29–2.0 (Fairey, 2004). Therefore, the anticipated annual electric savings when using heat pumps will be 718 kWh–11950 kWh or $65.20–$175.50. These results matched the findings of the Florida Power Corporation (FPC) (Fairey, 2004).

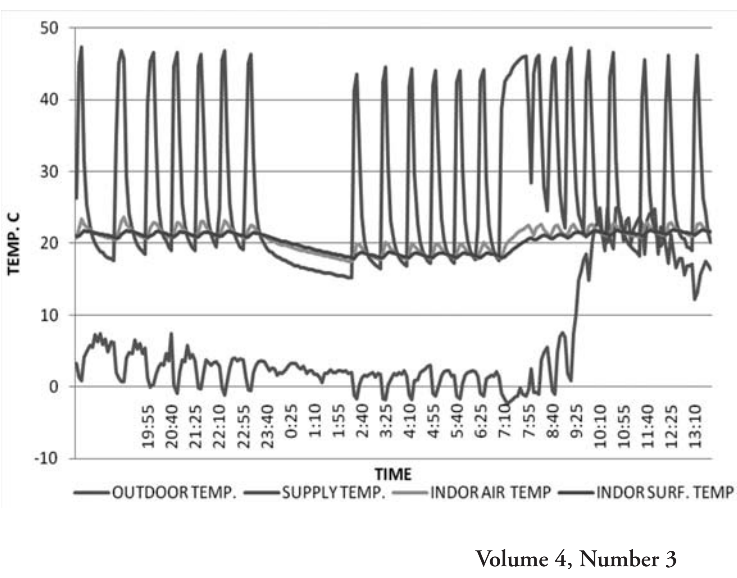
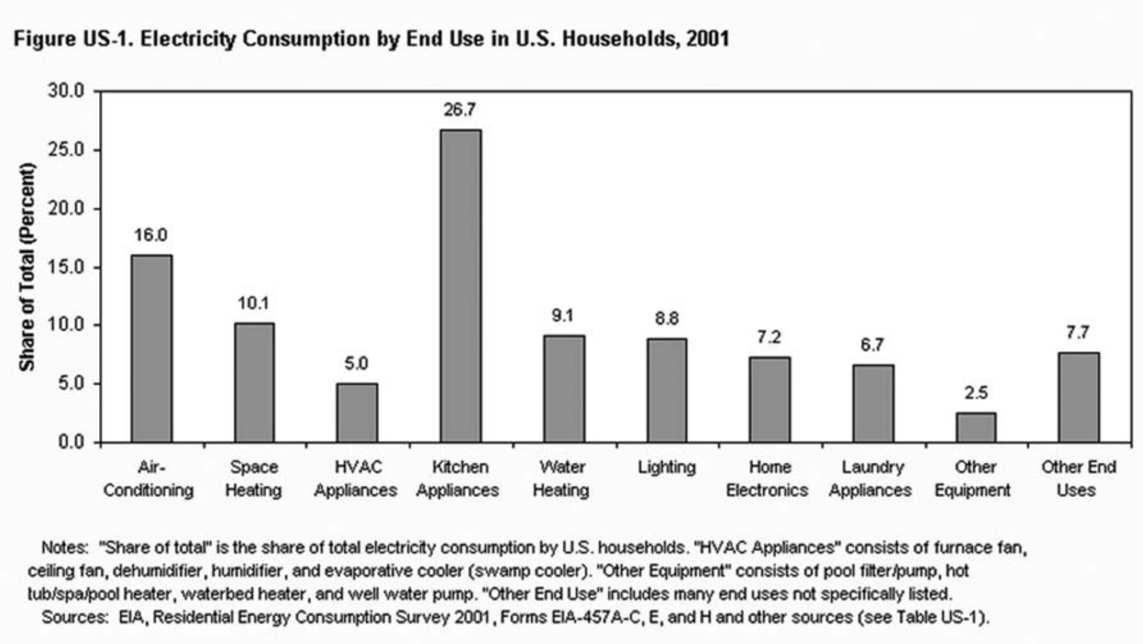


FIGURE 2. Electric consumption of Household in US.

FIGURE 3. Typical Heat pump efficiency (Fairey, 2004)



FIELD DATA

The field data was also used to predict the actual savings. Data collected from the monitored homes showed that during the heating times of December, the heat pumps run for 19% of the times when the outdoor temperature was 18.33°C or less (Figure 5). From the IWEC weather data file, the total number of hours where the temperature reached below 18.33°C (equivalent to 65°F of the heating degree day balance point) was 2880 hours. Therefore, the heat pumps will run for 547 hours and will consume 1422 kWh annually or $128. Thus, the annual dollar saving based on HSPF of 1.4–2 will be $51 to $128.

ENERGY SIMULATION MODEL

A simulation model was created to predict the annual savings generated by replacing the factory installed electric resistance heaters with heat pumps in manufactured homes. The simulation model was also used to verify the indoor comfort level when heat pump is used for heating. A simulation model for a typical manufactured home was created with Energy Plus. The manufactured home consists of 120 m^2 (2540 sft). The walls consists of #2-grade 2" × 4" (50.8mm × 101.6mm) lumber outer walls and maintain insulation values (R-11 thermal insulation)

Actual yearly weather data was used in the simulation. Field data was used to calibrate the simulation model. To predict the annual electric saving of replacing the factory installed electric resistance heaters with heat pumps, the manufactured home was first simulated with an electric heater as a sole heating source. Second, the house was simulated with the heat pump as the main heating source, and electric resistance was used as an auxiliary heater.

The simulation results showed that when using a heat pump as a main heating source, the manufactured home maintained an indoor air temperature above 74F° for 97% of the time during the heating season compared to 98% when electric resistance was used as a main heating source (Figure 4) These results showed that in moderate climates, heat pumps under continuous operation are as effective as conventional electric resistance heaters in achieving comfortable temperatures in manufactured homes. When comparing the annual simulated electric consumption of the HVAC heating system

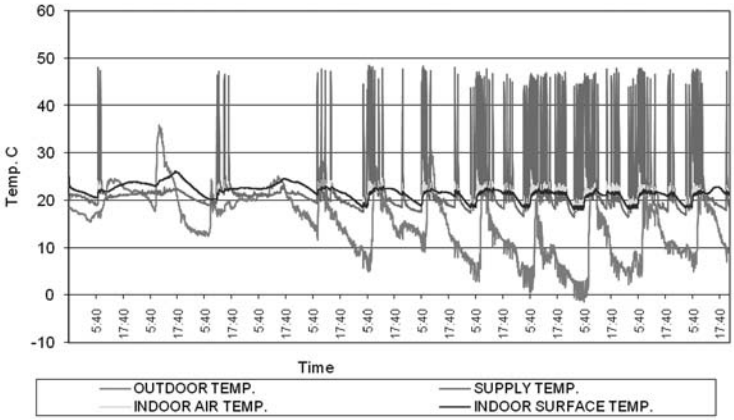


FIGURE 4. Field monitoring of a mobile home during heating and cooling periods on December.

in the manufactured home, results showed that the annual HVAC system electrical consumption of the manufactured home when the heat pump was used as a main heating source was 875 kWh compared to1720 kWh when the electrical resistance was used as an alternative heating source. Thus, the annual electrical consumption of the heat pump was 51% of the same manufactured home when an electric resistance was used as a heating source.

CONCLUSIONS

This research investigated the actual energy savings of using heat pumps in low-income houses in a moderate climate. The research findings were based on

FIGURE 5. Field date of mobile home's performance during January.

field measurements, electrical meter readings, and annual building energy simulation. The research conclusions can be summarized as follows;

- Heat pumps are considered one of the main heating energy saving alternatives in moderate climates. Heat pumps with HSPF of 10 are assumed to be 3.1 times or 310% more energy efficient than electrical resistance heating systems. However, this research showed that the actual energy saving is 51%.
- In moderate climates, heat pumps can maintain thermal comfort and accommodate the heating load when operated on continuous mode. However, the actual heat pumps' efficiency is significantly decreased when the system is setback to save energy.
- Although the tested mobile homes did not include high energy efficiency features compared to typical energy efficient designs, mobiles homes are relatively small in size, and the internal heat gain reduces the balance point temperature. Heat pumps run in short cycles, thus reducing the heat pumps' efficiency.
- The annual dollar saving in a mobile home was \$51 to \$128. The extra cost between resistance heaters and heat pumps is \$700. The simple pay back period for upgrading resistance heaters to heat pumps in mobile homes will be 6–13 years.

ACKNOWLEDGEMENT

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