GEOTHERMAL HEAT PUMP SYSTEM FOR U.S. RESIDENTIAL HOUSES:BARRIERS OF IMPLEMENTATION AND ITS ENVIRONMENTAL AND ECONOMIC BENEFITS

by

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ABSTRACT

Residential buildings account for 22 percent of the primary energy consumption in the U.S. Over half of this home energy requirement comes from heating and cooling demands. The geothermal heat pump (GHP) system can provide significant energy savings and greenhouse gas (GHG) abatement in homes with its high efficiency. However, despite its long history in the market, less than 0.5 percent of U.S. homes are utilizing GHP systems as of 2009.

In this study, a model is developed to analyze the energy savings, GHG abatement, and energy bill savings potentials of the GHP in U.S. single-family detached houses and to identify major barriers for nation-wide implementation of the GHP system. Particularly, this study systematically pairs two national housing surveys to identify the house lot size, a key parameter that is not adequately addressed in other studies.

This study estimates 1.26 quads of national energy savings, which is equivalent to 66 percent of energy savings from house heating and cooling, and 76 million tonCO2eq of GHG abatement every year. Moreover, this project identifies the major barriers as:(1) high cost premiums to homeowners, and (2) lack of available lots for ground loop. This study finds that about 21 percent of the sample houses cannot install the GHP system due to their small lots and about 61 percent of the sample houses will not fully recover the cost premium of the GHP system. The GHP system costs 9,855 dollars more than the equivalent conventional systems. An annual energy bill savings of 265 dollars with the GHP is not enough to financially justify the high cost premium for many homes. The average payback period is around 22 years under a 5 percent interest rate. A 30 percent federal tax credit reduces the percentage of houses that find the GHP system financially unattractive and sets the average payback period to 13.5 years. However, this payback period is still too long, meaning more aggressive policy is needed for a large scale GHP implementation.

ACKNOWLDEGEMENTS

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1. INTRODUCTION

1.1 U.S. Residential House Characteristics

The number of housing units in the U.S. has seen a greater growth rate than the population increase in the U.S. in recent decades. Among different housing types, single-family detached houses provide living space for one household or family and have been the most popular form of housing in the U.S. Although the percentage of single-family detached houses dropped from 64 percent in 1940 to 60 percent in 2000, they still remain as a dominant form of housing unit in the U.S (Census 2014e) and this trend is not expected to change dramatically in the near future.

However, the single family-houses have shown unsustainable growth for the last few decades. The average square footage of single family-houses has increased from 1,500 square feet in 1970 to 2,200 square feet in 2012, which is a 155 percent increase from 1950 (CSS 2013) while the average number of occupants decreased from 3.14 persons to 2.55 persons, a 24 percent decrease for the same period (CSS 2013).

Given these trends it is important to improve the sustainability of the single-family detached houses; and renewable technologies that save energy can contribute toward this goal.

1.2 U.S. Residential Energy Consumption

The residential buildings account for 22 percent of the U.S. primary energy consumed (EIA, 2012) and 17 % of greenhouse gas (GHG) emissions in 2011 (Buildings Energy Data Book 2014a, EIA 2012c). The growth of residential energy use has declined since 2007 largely due to the recent economic recession (DOS 2010), but trends indicate that energy use and emissions footprint of buildings has grown relatively larger than that of transportation and industry sectors (Hughes 2008).

As of 2005, single-family detached homes consumed 81 percent of total delivered energy to all U.S. housing units (Buildings Energy Data Book 2014c). New homes are more efficient on per square foot basis, due to energy efficiency standards and technological innovations, but increasing home sizes have offset these improvements (Buildings Energy Data Book 2014b). Over half the primary energy in residential sector is used for heating and cooling purposes (Annual Energy Outlook 2013) as shown in Figure 1.

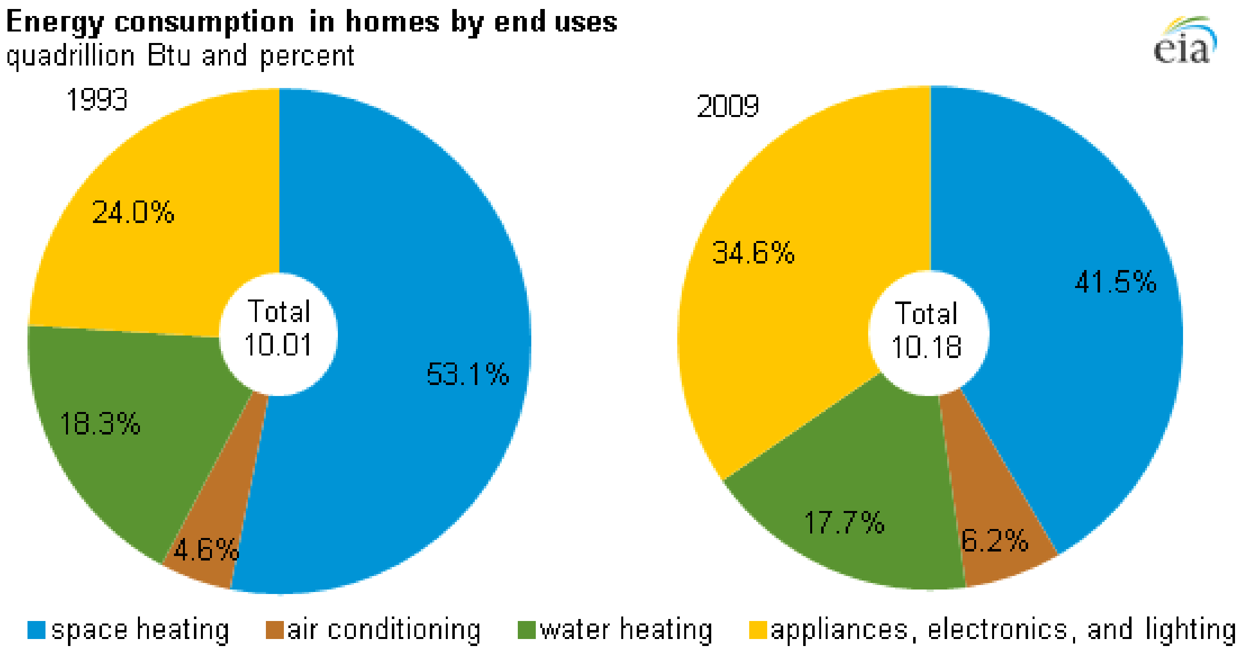

Figure 1. Average primary energy use at U.S. homes. While overall energy use for space heating and cooling is decreasing, they still remain a major form of energy consumption.

The residential sector has a unique opportunity to reduce energy and GHG emissions. The efficiency of the heating and cooling system is one of the primary factors that determine the energy use pattern in homes. Therefore better heating and cooling equipment can significantly lower home energy use and GHG emissions. Policy makers can influence the behavior of the homeowners by providing a right incentive to use more sustainable equipment. Therefore unlike other sectors such as industrial, the residential sector provides a unique opportunity for concerned individuals to take action to mitigate GHG emissions. The geothermal heat pump

(GHP) system can play an important role in reducing energy use and GHG emissions at homes as GHP is three to four times more efficient than conventional heating and cooling systems.

1.3 Geothermal Heat Pump Technology

1.3.1 History and Current Trend

The history of GHP dates back to as early as the 19th century when Lord Kelvin developed the concept in 1852 (Lund 2004). After gaining commercial popularity in the 1960s (Lund 2004), GHP has become one of the fastest growing renewable energy applications in the world (Curtis 2005).

The GHP global market review in 2005 indicated that the U.S. had the largest installed GHP capacity but other countries surpass the U.S. on a per capita basis (Hughes 2008, Curtis 2005). It is estimated that about 92,000 GHP units were shipped to European residential homes in 2004 whereas about 34,000 and 32,000 units were delivered to U.S. residential homes in 2006 and 2007 respectively (Hughes 2008). About 75 percent of residential application is thought to be new construction and 25 percent to be a retrofit of existing homes (Hughes 2008).

1.3.2 GHP Technology

The basics of the GHP technology changed little over the decades (Hughes2008). Geothermal Heat Pump (GHP) technology, or Ground-Source Heat Pump system, utilizes relatively constant ground or groundwater temperature ranging from 4 to 30 degrees Celsius to provide space heating, cooling and domestic water heating for buildings. GHP technology is distinguished from other types of geothermal technologies that use extreme subsurface heat to generate electricity in utility-scale which can be implemented in limited geographical locations.

GHP is essentially an air-conditioner that operates in two directions. Instead of burning fuel to generate thermal energy as in most other heating equipment, GHP moves thermal energy from warmer underground to cooler indoor in the winter. In the summer, GHP moves thermal energy in the other direction from hotter indoor to cooler underground like an air-conditioner.

However, GHP is distinguished from air-source heat pump systems which use ambient air as a heat transfer medium. GHP can operate with much higher efficiency than air-source heat pump as it utilizes better heat capacity and more stable temperature of various ground sources including earth, surface water, and subsurface aquifers (Liu 2010).

A GHP system is comprised of two main components: a water-source heat pump and a ground loop, which is described in Figure 2.

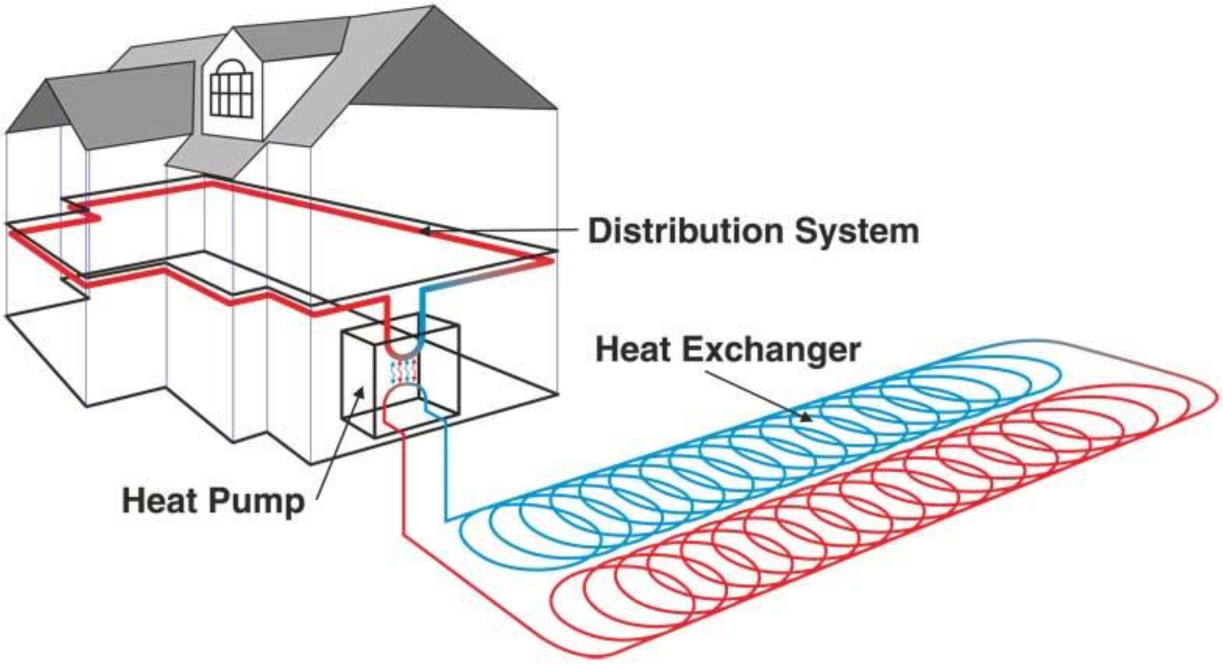

Figure 2. The diagram of the GHP system at residential houses. This shows the closed loop system which is the main type of GHP system of interest in this study. The ground loop is described as a heat exchanger in this diagram. The image is adopted from http://mbtechnicalservices.webs.com

The ground loop, or heat exchanger in Figure 2, is setup underground to make a direct contact with the earth via grouting materials which helps increase the thermal conductivity and thus enhance the overall system efficiency. The ground loop is filled with antifreeze and forms a closed loop and is connected to the heat pump unit which is usually installed inside the house. The heat pump unit is also connected with the distribution system at home such as a duct system or radiant floor. Here, the ground loop and the distribution system make a thermal contact via heat exchanger. Using a small amount of electricity, a heat pump moves thermal energy from relatively warm underground to inside the house in the winter and moves thermal energy from relatively warm indoors to underground in the summer.

1.3.3 Status of GHP in the U.S.

At least 16 GHP manufactures in the U.S. serve residential and commercial markets. In the U.S., the GHP market began to develop in the late 1970s (Hughes 2009) and the GHP installation experienced a steady increase over past decade with an annual growth rate of around 12 percent, mostly in the mid-western and eastern states (Lund 2004). The recent trend of the GHP shipment is shown in Figure 3 below:

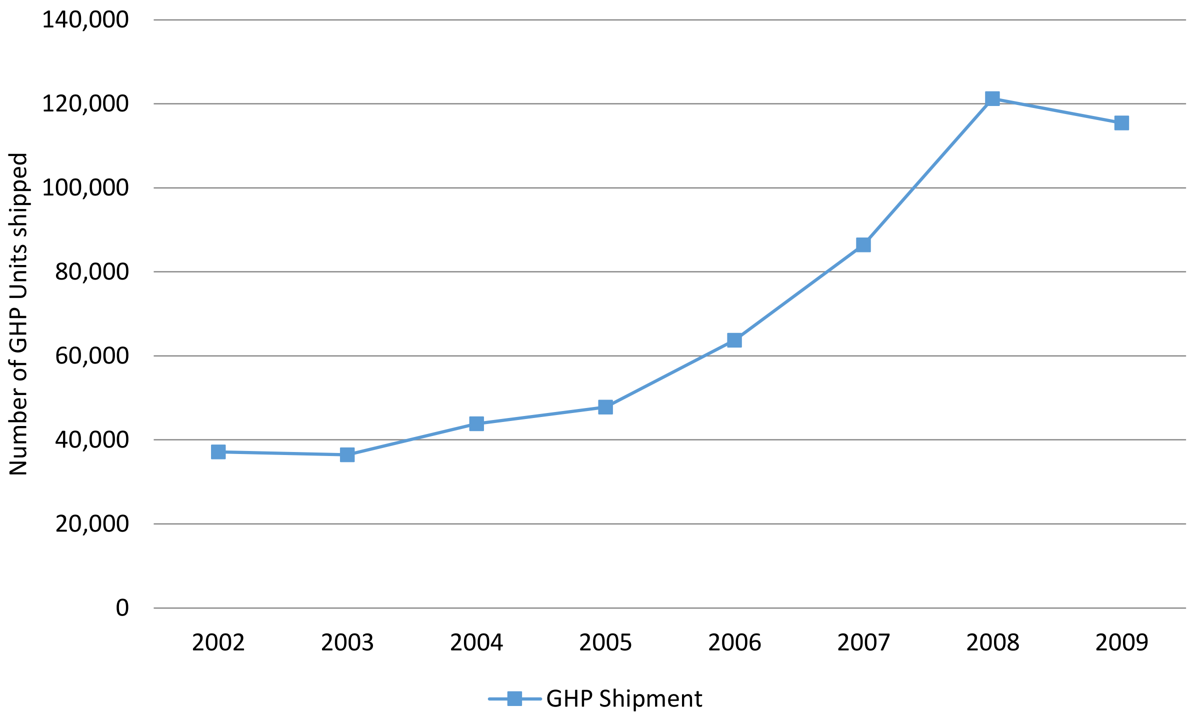

Figure 3. Historical GHP shipments from 2000 to 2009. Source: U.S. Energy Information Administration (EIA), " Geothermal heat pump shipments by model type, 2000 –2009 "

In general, just over half of these units were shipped for residential application each year (Hughes 2008, EIA 2014a) and the application on new construction exceeded the retrofits by a factor of 3 to 1 (Hughes 2008).

1.4 Research Objectives and Scope

This study analyzes the performance of the GHP system in terms of its impact on home energy use, climate change, and economics compared to conventional heating and cooling systems. The scope of study includes residential households in the contiguous U.S., which comprises 112.9 million housing units. This study focuses further on single-family detached units that are owner-occupied, have their own independent heating and cooling system, and have a forced-air distribution system.

The GHP system of interest includes water-to-air heat pump unit and either vertical or horizontal ground loop; and the conventional heating and cooling systems include forced-air furnaces, air-source heat pumps, and central and window/wall air conditioners. This study identifies major barriers to the nation-wide implementation of the GHP system and determines if the current policy is adequate to promote GHP installation at homes.

2. METHODOLOGY

To identify candidates of U.S. houses that can install the GHP system, two independent national surveys of the existing U.S. housing stocks are utilized to model the residential sector. Based on the physical characteristics of the houses, entries in both surveys are paired to combine disaggregated data. Appropriate GHP system and conventional alternatives are assigned to each entry based on the existing heating and cooling equipment being used and other physical settings at the houses. The GHP database of existing stocks in the market is used to find the appropriately sized units for houses, and the heating and cooling systems are sized based on the heating and cooling load calculations. The equipment efficiency is calculated based on the historical shipment data and new energy efficiency standards set by the Department of Energy (DOE). Upon identifying the appropriate GHP system and conventional alternative, relative benefits of the GHP system in terms of its energy savings, GHG abatement and cost savings is assessed. These processes are presented step by step in this chapter.

2.1 Modeling of U.S. Residential Units

2.1.1 Data

Residential Energy Consumption Survey

The Residential Energy Consumption Survey (RECS) 2009 is utilized to model U.S. residential houses. First conducted by Energy Information Administration (EIA) in 1978, RECS is a national survey of energy characteristics of U.S. residential homes. The 2009 RECS is the thirteenth survey and contains 12,083 housing units that represent 113.6 million households in the U.S. as a primary residence in 2009(EIA 2014b). The RECS dataset is chosen as the main microdata for this study since it contains information essential for energy and economic analysis, such as house square footage that is heated or cooled, heating and cooling equipment type and age, heating fuel, annual energy use, and annual energy bill.

American Housing Survey

The American Housing Survey (AHS) 2011 is used to supplement RECS 2009 dataset with its data on lot size. Initiated in 1973 by the United States Department of Housing and Urban Development (HUD), AHS is a national survey on a wide range of housing subjects, including national housing inventory, physical condition of houses, characteristics of occupants, and housing costs. The AHS 2011 contains 186,448 entries that represent 132.4 million housing units in the U.S. in 2011(Census 2014a).

2.1.2 Sample Selection

2.1.2.1 Housing Characteristics and Energy Use Pattern

Both RECS and AHS datasets contain various options for housing types and heating and cooling systems that are commonly found in U.S. residential houses. However, some of the options that do not have significant market penetration are not considered in the survey. The GHP system is one of those omitted options in both surveys. In fact, GHP systems existed in 2005 RECS data as one of the options for heating and cooling, but did not have a single entry. As a result, GHP is deleted from the equipment option in 2009 survey. Given that less than 0.5 percent of the U.S. housing units installed GHP, this is not surprising (Liu 2010).

GHP technology is not applicable to all houses. There exist a number of requirements for residential homes to be considered as potential candidates for GHP retrofit. Table 1 shows the criteria used in the RECS and AHS datasets to filter out these potential candidates.

Table 1. Key house variables used to select entries of interest from the RECS and AHS dataset. Variable, variable description adopted from RECS 2009 Variable and Response Codebook.

Variables		**Variable Description**	**Selected Characteristics**
RECS	**AHS**		
TYPEHUQ	TYPE, NUNIT2	Type of housing unit	Single-family detached
CONDCOOP	CONDO	Housing unit is part of a condominium or cooperative	Not Applicable
KOWNRENT	TENURE	Ownership of the housing unit	Owned by someone in the household
Equip_NoUse	-	Heating or cooling equipment is not being used	No
HEATOTH	-	Main space heating equipment heats other units	No or Not Applicable
ACOTHERS	-	Central air conditioner cools other units	No or Not Applicable
WHEATOTH	-	Main water heater is used by more than one housing unit	No or Not Applicable
-	STATUS	Interview status	Occupants interviewed

Houses with a large empty lot are usually good candidates for GHP retrofit. However, this is not always the case since the lot might not belong to the homeowner or there could be other restrictions that are not favorable to the GHP retrofit. For example, if the unit is being rented to the tenant, the homeowner has a little motivation to invest in a better heating and cooling system as the owner would not directly benefit from it. GHP installation is also a challenge in a condominium or a housing cooperative because an individual homeowner or a tenant does not have exclusive authority on changing infrastructure on the property. Therefore houses which are not occupied by the homeowner, or are part of condominium, or housing cooperative are screened out. Single family attached houses are ruled out for the same reason. Mobile homes are also excluded as the installation of GHP would require long-term residence of the homeowner on site with a significant investment in the infrastructure. Therefore, only single-family detached houses are chosen for possible candidates for GHP installation.

Also, due to the high capital cost of the technology, GHP is not reasonable for households that do not have much heating and cooling demand. Therefore, households in RECS whose heating and cooling energy demand in 2009 was zero are excluded from the analysis. The RECS households whose heating or cooling equipment also serves other neighboring units are also ruled out. Lastly, AHS households that did not have an interview with a surveyor are excluded to ensure the quality of the data.

After this screening process 6,691out of 12,083 RECS entries and 69,716 out of 186,448 AHS entries are selected.

2.1.2.2 Heating and Cooling Equipment

Both RECS 2009 and AHS 2011 datasets report heating and cooling equipment type being used at homes. A number of criteria are implemented to select equipment for the analysis based on data availability. Table 2 demonstrates these criteria:

Table 2. Key variables for heating and cooling system in RECS 2009 dataset. Variable, variable description adopted from RECS 2009 Variable and Response Codebook.

RECS Variable	Variable Description	Selected Characteristics
EQUIPM	Type of main space heating equipment used	Central Warm-Air Furnace, Heat Pump
FUELHEAT	Main space heating fuel	Natural Gas, Propane/LPG, Fuel Oil, Electricity, Kerosene
EQUIPAUX	Secondary space heating equipment used	Ignored
EQMAMT	Portion of space heating provided by main space heating equipment (for homes with main and secondary heating only)	Ignored

Since AHS 2011 dataset does not contain any detailed information on heating and cooling systems in homes other than equipment type, most screening is performed using the RECS 2009 dataset. RECS contains twelve heating systems which can use one or more different types of fuel out of nine reported heating fuels. However, their popularity shows a wide range, from cooking stove (0.15%) to central warm-air furnace (62%) for equipment type, and from solar (0.01%) to natural gas (49%) for heating fuel. Due to the data availability for this study, only two equipment types (central warm-air furnace and heat pump) and five most popular heating fuels (natural gas, electricity, fuel oil, propane/Liquefied Petroleum Gas (LPG), and kerosene) are selected as valid entries. Also, about 38 percent of RECS entries reported use of secondary heating equipment other than main equipment. However, most heating energy (all or three quarters) is provided by the main equipment and for simplicity of the analysis, secondary heating equipment is not considered in this study. Lastly, GHP systems are also capable of providing hot water to homes if a desuperheater is implemented. This will improve the performance of the GHP system but performance of the water heater is not considered in this analysis.

Appendix B contains a summary of these key equipment variables and also the key house variables in RECS and AHS datasets.

2.1.3 Creation of Virtual Cohorts for State-level Analysis

The 19,542 virtual cohorts of U.S. residential houses are constructed from 12,083 RECS 2009 entries to perform state-level analysis. The methodology is adapted from Logue (2013). Each RECS entry reports its geographical location in Census region, division and reportable domain which is a group of states. The RECS also indicate in which climate region each sample belongs as defined by the Building America Climate Region (DOE 2010b). This information, along with the weight, is used to build a virtual cohort of 19,542 houses that represent the U.S. housing units.

Reportable domain contains a number of states ranging from one to as many as five, and it also includes up to three climate regions. RECS 2009 dataset also has a weight which represents the total number of houses represented by each RECS sample in the reportable domain. Given the reportable domain, the RECS entries are first grouped in terms of the climate regions and then their weights are subdivided into the different states according to the number of housing units located in the counties in terms of the states and the climate regions. The housing unit estimates by state and county data are taken from the Census (Census 2014d) and climate region by county data is imported from Building America Climate Region (DOE 2010b). For data consistency, six counties in North Carolina that have cold climate are merged with counties with mixed-humid climate.

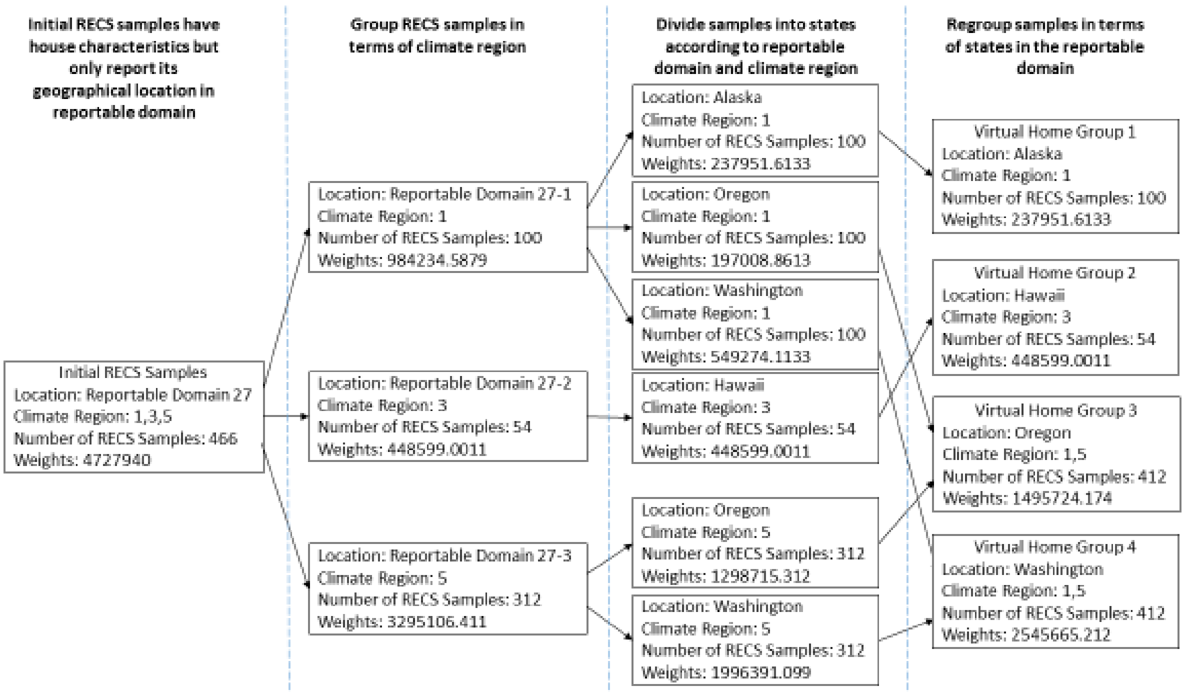

Figure 4. Assignment of RECS entries to states according to climate zone within the reportable domain. *This figure shows an example of how RECS entries that belongs to reportable domain 27 are assigned to different states. Upon grouping entries in terms of climate region, the weight of the each sample is divided into different states to create new virtual entries according to the number of homes located within the states. This figure is an adaptation from Logue (2013).*

Figure 4 shows this process with an example of entries in reportable domain 27. Reportable domain 27 contains four states (Alaska, Hawaii, Oregon, and Washington) and three climate regions (Very Cold/Cold, Hot-Dry/Mixed-Dry, and Marine or 1, 3, 5 respectively). Out of 466 RECS entries in reportable domain 27, 100 entries belong to Very Cold/Cold, 54 entries to Hot-Dry/Mixed-Dry, and 312 entries to Marine region. All entries with Hot-Dry/Mixed-Dry climate belong to Hawaii and the rest are further subdivided into different states. The number of housing units in each state is used in this step to divide the weight of the sample. As a result, 978 virtual homes are created from 466 RECS entries in reportable domain 27. Figure 5 demonstrates the final result. The total number of houses shows a good match with the Census 2009 housing unit estimates across the U.S. The discrepancy in the state of New York is due to the smaller total weight in the region inherent in the RECS 2009 dataset.

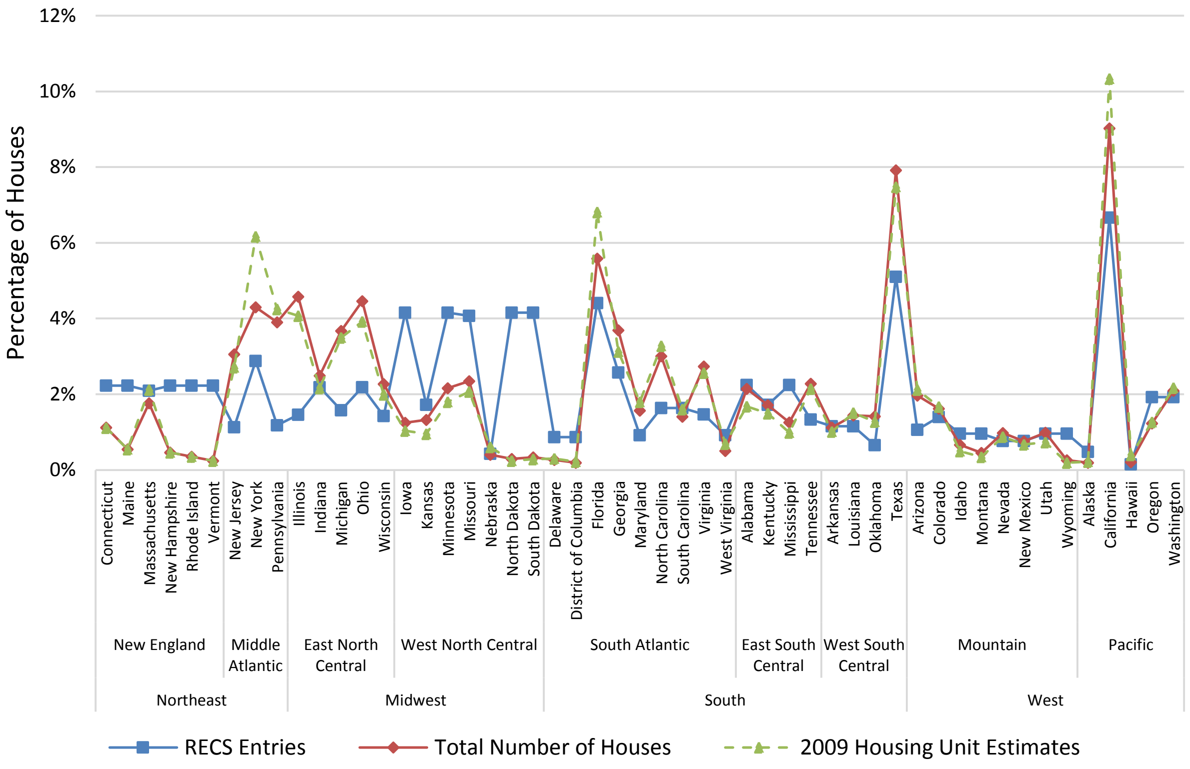

***Figure 5. Geographical Distribution of the RECS 2009 Virtual Cohorts in terms of Census Region, Division, and States**. This figure shows the distribution of each virtual cohort entries (RECS Entries) as well as the sum of weights (Total Number of Houses). Not all RECS entries have same the leverage of weights which can be seen in New England Census Division (lower weight per entry) and in Middle Atlantic Census Division (higher weight per entry). The data of 2009 housing unit estimates is also provided for a reference (Census 2014b).*

2.2 Modeling Residential Heating and Cooling System

2.2.1 Equipment Vintage Year and Efficiency Calculation

The RECS 2009 data reports the age of heating and cooling equipment at residential homes. However, instead of reporting the actual age of the equipment, RECS report it in terms of five age groups: less than 2 years old, 2 to 4 years old, 5 to 9 years old, 10 to 14 years old, 15 to 19 years old and more than 20 years old. For this study, equipment that is more than 20 years old is assumed to be less than 30 years old. RECS 2009 also reports the vintage year of the house, which could be used to identify whether the system was upgraded after the construction. There were 891 RECS entries, whose reported vintage year of the house was older than the age group of the equipment. In this case, equipment vintage year is assumed to be the same as the house construction year. Knowing the age of the heating and cooling equipment is important in estimating efficiency level of conventional HVAC systems which can directly affect the calculation of the relative GHP performance.

Department of Energy has conducted research on energy efficiency of the conventional heating and cooling equipment to update new energy efficiency standards. The DOE classified equipment in terms of technology, fuel type, and output capacity for a detailed analysis. The data on annual shipments and efficiency level for each equipment types were adopted from the Technical Support Documents (TSD) (DOE 2010a, 2011a, 2011b). Historic shipment data are used to assign efficiency to the heating and cooling equipment of the RECS entries according to their vintage year, which is the manufacturing year of the equipment. The process is as follows:

1. Prepare historical equipment shipment data to be applicable to the RECS entries
2. Assign vintage year of the heating and cooling equipment to RECS entries according to the relative equipment stock at each year
3. Prepare shipment-weighted efficiency (SWEF) of each equipment type to fit RECS entries and assign average efficiencies for heating and cooling equipment to RECS entries according to SWEF

2.2.1.1 Preparation of the Historical Equipment Shipment Data

First, the historic annual shipment data of the heating and cooling equipment from the TSD (DOE 2010a, 2011a, 2011b) are prepared to be used with the RECS entries. The TSD for residential central air conditioners, heat pumps, and furnaces reported shipment information of new equipment from 1972 to 2009. The TSD also estimated the percentage of equipment survived or retired by its age based on survival/retirement functions devised for each equipment type. Then the number of equipment still being used at houses is calculated by multiplying new equipment shipments each year with survival rates with corresponding equipment age. The results are as shown in Figure 6 and Figure 7 and the data can be found in Appendix C.

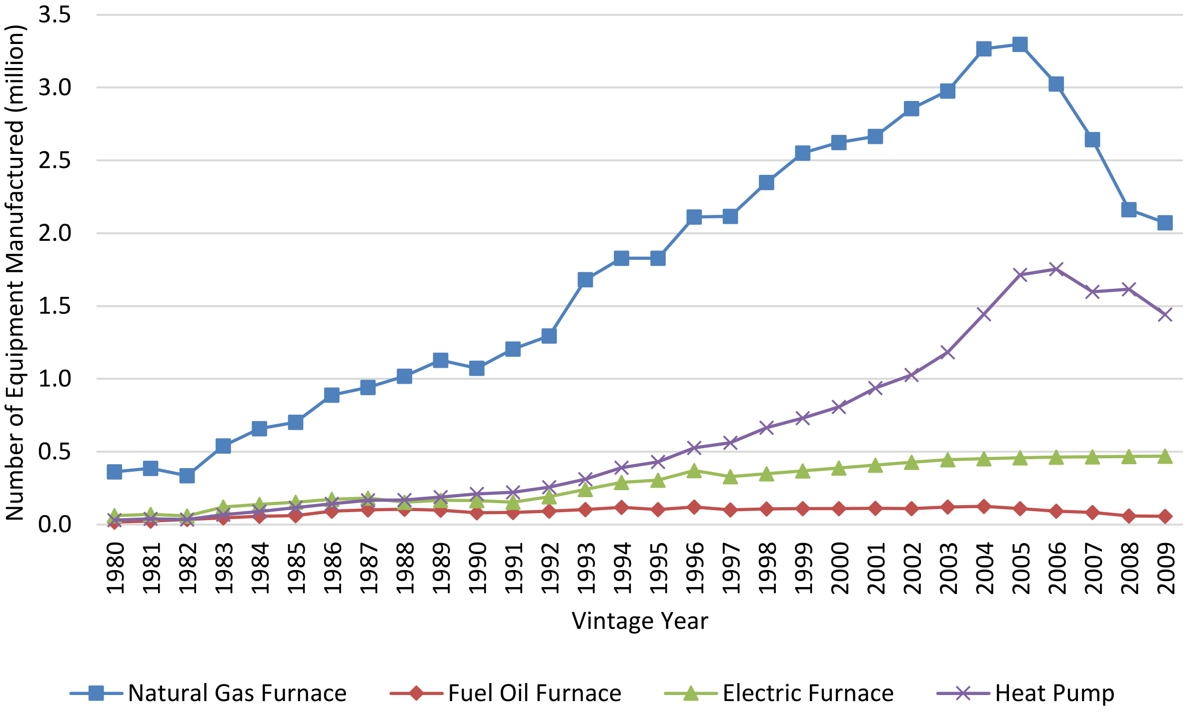

Figure 6. The number of heating equipment manufactured by vintage year that is being used at households in 2009.

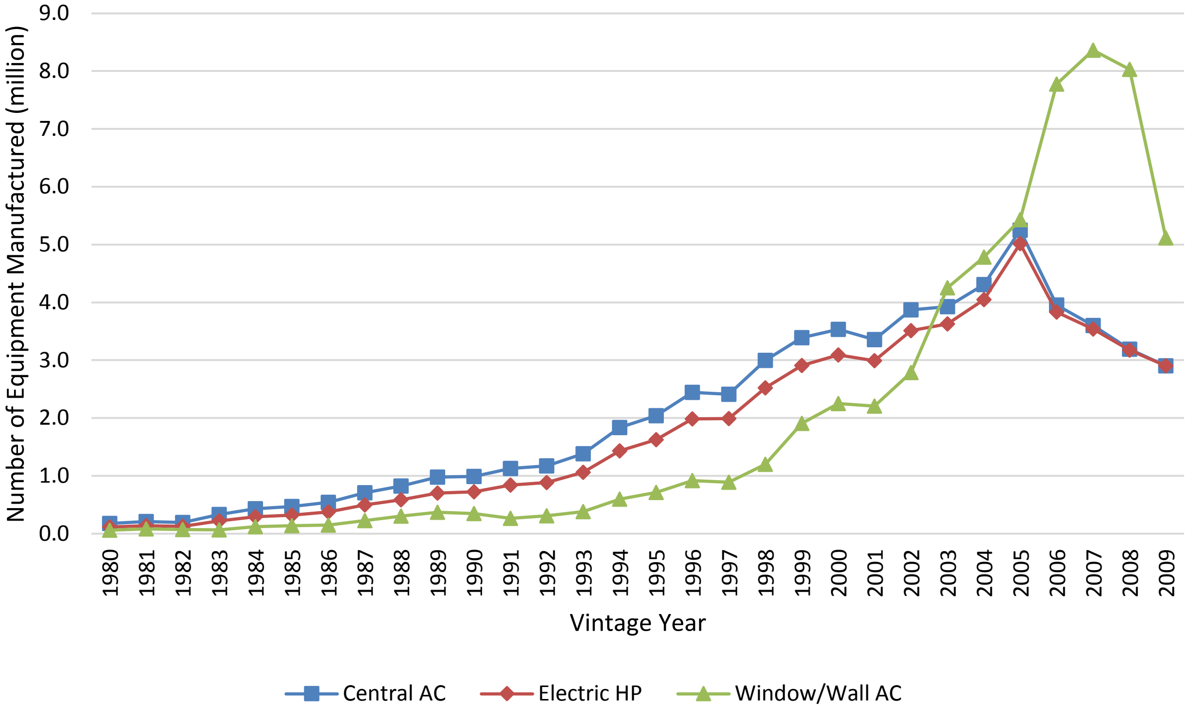

Figure 7. The number of cooling equipment manufactured by vintage year that is being used at households in 2009.

2.2.1.2 Assignment of equipment vintage year to RECS entries

These more detailed data on equipment vintage year can be applied to the RECS dataset to enable year-by-year equipment efficiency analysis. Random numbers are generated for each RECS entry to proportionally assign equipment vintage year according to the relative number of equipment manufactured in that vintage year within the age group. The results are as shown in Figure 8.

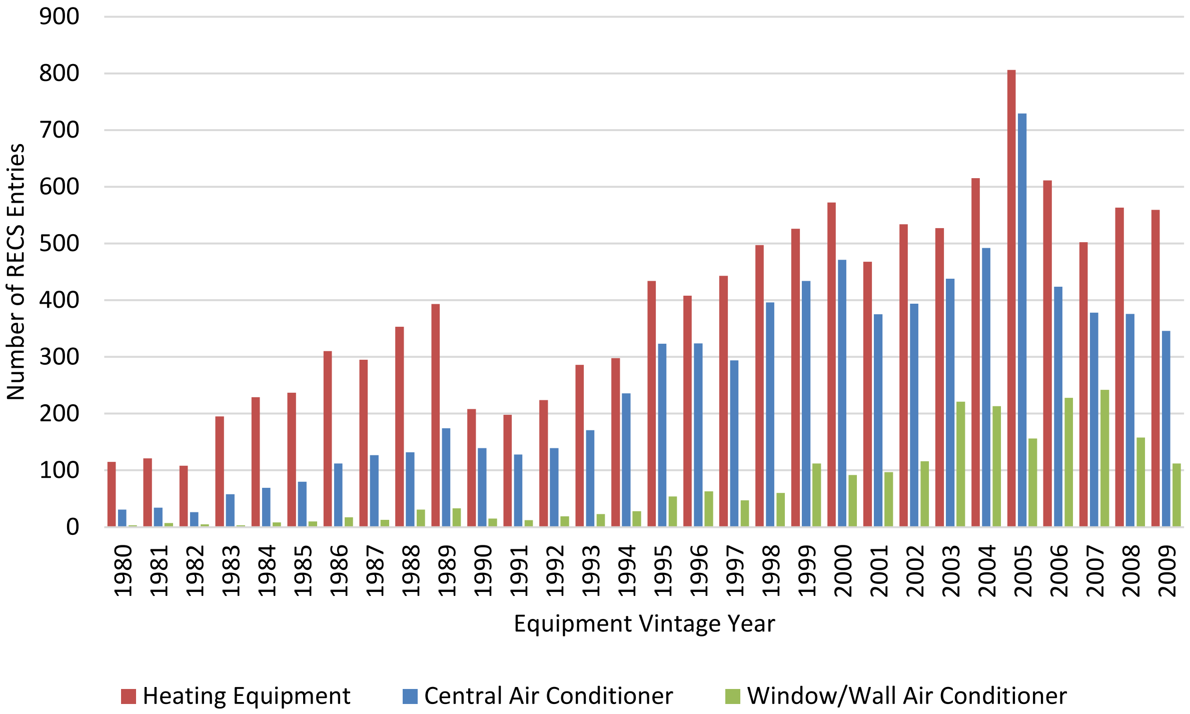

Figure 8. Vintage Year of Heating and Cooling Equipment of RECS Entries. *This figure shows the result of the vintage year assignment to each RECS sample. Heating equipment and central AC shows similar shipment trends while the shipment of window/wall AC are more concentrated in recent years.*

2.2.1.3 Preparation of the SWEF Data and Assignment of Equipment Efficiency by Vintage Year

The average efficiency of the equipment in terms of its vintage year was calculated with SWEF. The SWEF is a national average of equipment efficiency proportional to its annual shipment. The SWEF data of heating and cooling equipment were reported in Home Energy Saver (HES) engineering documentation (Mills 2005) and the TSD (DOE 2010a, 2011a, 2011b) of equipment efficiency standards organized by DOE. The efficiencies of the heating and cooling equipment are defined as Annual Fuel Utilization Efficiency (AFUE) and Coefficient of Performance (COP), respectively.

Data from the HES and TSD were organized in terms of system types and fuels. These data were aggregated to be imported into the RECS dataset. The SWEF data from 1980 to 2003 were imported from HES whereas data from 2004 to 2009 were imported from TSD. However, the RECS 2009 dataset had more diverse heating and cooling systems in terms of system types and heating fuels than HES or TSD data. For example, data for propane or electric boilers, floor or wall pipeless furnaces that run with materials other than natural gas and built-in room heaters did not exist in the HES and TSD dataset. In this case, SWEF for this equipment was derived from that of the same system type by weighing the efficiency level with a relative performance of another system type with the same fuel. For instance, SWEF of the propane boiler was derived from the SWEF of the gas boiler and weighted by the relative performance of the propane furnace to that of the gas furnace. For all electric heaters, their SWEF was fixed to 98% as in HES. TSDs were prepared to set up a new energy efficiency standard but they were not prepared for every equipment type that RECS 2009 has listed. If equipment TSD data did not exist, SWEF data beyond 2003 were extended from the last year like in HES. If equipment types had a TSD data entry, TSD SWEF data were merged with HES data from 2004 to 2009. TSD entries were scaled to match HES data and to take into account minor rounding errors between the two datasets. For floor or wall pipeless furnaces, room heaters and window/wall air conditioners, TSD provided more detailed SWEF data in terms of system size and system types. These SWEF data were aggregated to fit the RECS 2009 equipment classification using historic shipment and SWEF data. The results can be seen in Figure 9 and Figure 10. The detailed data can be found in Appendix C.

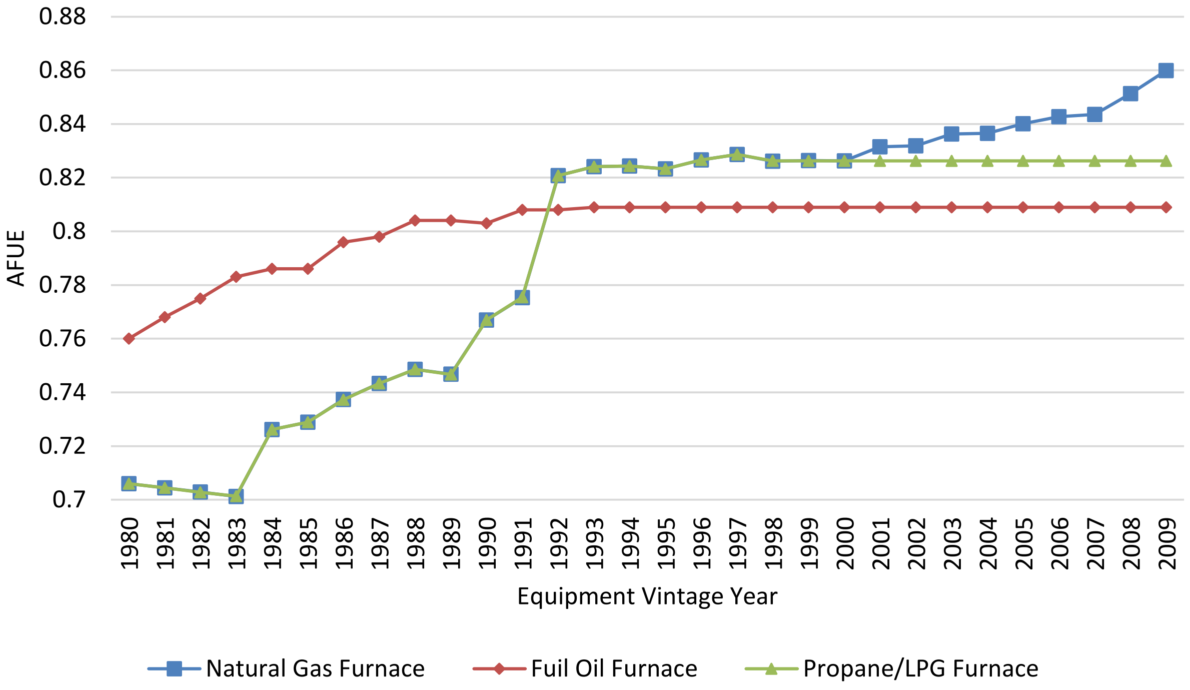

Figure 9. The historical shipment-weighted efficiency of the heating equipment by vintage year. When no data were available, efficiency was assumed to be the same as the previous year as could be seen in propane/LPG furnace since 1999.

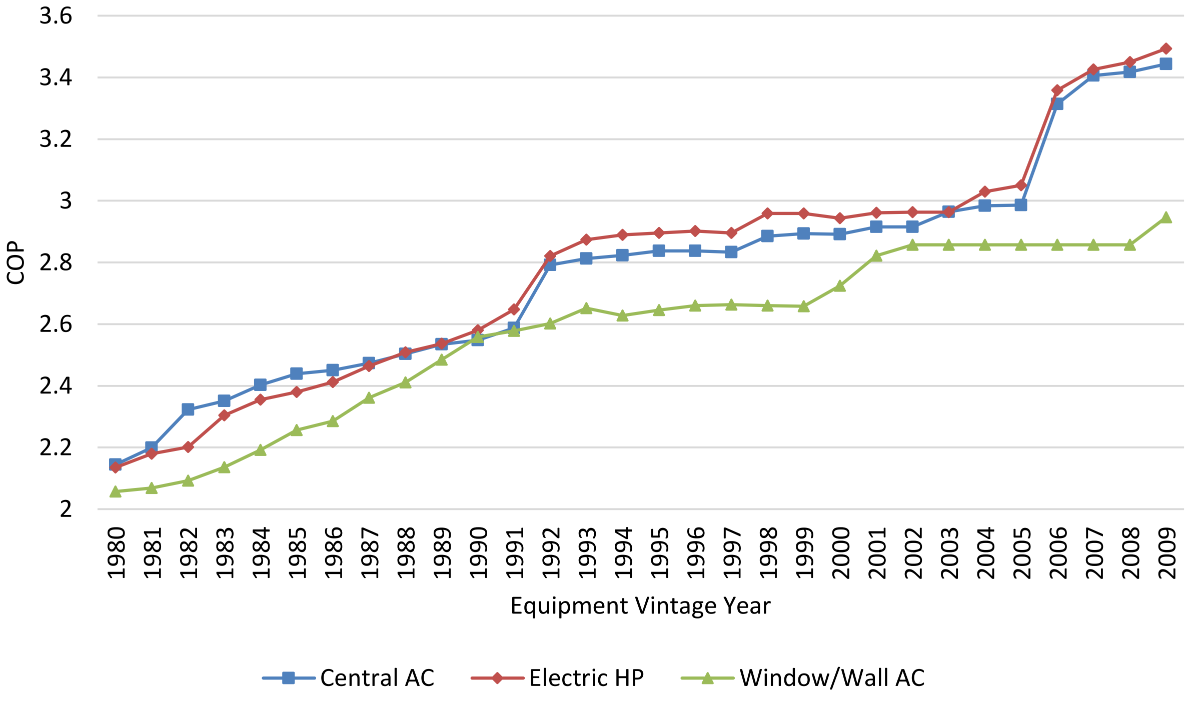

Figure 10. The historical shipment-weighted efficiency of the cooling equipment by vintage year.

Upon the construction of the SWEF data for all equipment types in terms of vintage year, they are assigned to each RECS entry according to their vintage year.

2.2.2 New Energy Efficiency Standards

The efficiency standards periodically updated by the DOE are the main driver that encourages manufacturers to produce more energy efficient products. These new efficiency standards are set based on available technology, technological limitation, and economics to foster energy conservation and economic benefit. Manufacturers are required to meet this minimum energy standard and therefore, they provide important information on the efficiency status of the heating and cooling equipment now and in the near future.

The new energy efficiency standards for heating and cooling system are imported from energy standards data organized by the Office of Energy Efficiency and Renewable Energy (EERE 2014a, 2014b, 2014c, 2014d). New standards that are going to be effective after 2009 are organized in terms of three distinctive climate regions as defined in the TSD prepared to set up new standards. Appendix A contains the definition of the TSD climate region and the list of states belonging to each region. The standards are compiled to represent heating and cooling equipment being used at the RECS 2009 entries. These data are summarized in Table 3 as follows:

Table 3. Energy efficiency standards for heating and cooling systems in the RECS 2009 dataset. These standards are going to be effective after 2009 and can be used to predict energy efficiency trends in the near future. The region-specific standards are listed separately from the national standard under the corresponding TSD climate region. When there is no regional specific standard other than national standard, these regional standards are left as '-'.

Heating Equipment				
RECS 2009 Equipment Classification	**DOE Equipment Classification**	**National Standards (AFUE)**	**Northern Standards (AFUE)**	**Effective Date**
Central Warm-air Furnaces (AFUE)	Non-weatherized gas furnace	80	90	Non-weatherized furnace manufactured on or after May 1, 2013. Weatherized furnace manufactured on or after Jan 1, 2015
	Non-weatherized oil-fired furnace	83	83	
	Electric furnace	78	78	

Floor/Wall Pipeless Furnace	Gas wall fan type up to 42,000 Btu/h	75	-	Manufactured on or after April 16, 2013
	Gas wall fan type over 42,000 Btu/h	76	-	
	Gas wall gravity type up to 27,000 Btu/h	65	-	
	Gas wall gravity type over 27,000 Btu/h up to 46,000 Btu/h	66	-	
	Gas wall gravity type over 46,000 Btu/h	67	-	
	Gas floor up to 37,000 Btu/h	57	-	
	Gas floor over 37,000 Btu/h	58	-	
Built-in Room Heater	Gas room up to 20,000 Btu/h	61	-	Manufactured on or after April 16, 2013
	Gas room over 20,000 Btu/h up to 27,000 Btu/h	66	-	
	Gas room over 27,000 Btu/h up to 46,000 Btu/h	67	-	
	Gas room over 46,000 Btu/h	68	-	

Cooling Equipment and Heat Pump

RECS 2009 Equipment Classification	**DOE Equipment Classification**	**National Standards (EER)**	**Southeastern Standards**	**Southwestern Standards**	**Effective Date**
Heat Pump	Split system heat pumps	SEER = 14 & HSPF = 8.2	-	-	Manufactured on or after Jan 1, 2015
	Single package heat pumps	SEER = 14 & HSPF = 8.0	-	-	
Central Air Conditioner	Split system air conditioners	SEER = 13	SEER = 14	SEER = 14 & EER = 12.2 if capacity < 45 kBtu/h. EER = 11.7 if capacity > 45 kBtu/h	Manufactured on or after Jan 1, 2015
	Single package air conditioners	SEER = 14	SEER = 14	SEER = 14 & EER = 11.0	
Window/Wall Air Conditioner	Without reverse cycle, with louvered sides < 6000Btu/h	11	-	-	Manufactured on or after Jun 1, 2014
	Without reverse cycle, with louvered sides. 8,000 to 13,999 Btu/h	10.9	-	-	
	Without reverse cycle, with louvered sides. 20,000 to 24,999 Btu/h	9.4	-	-	
	Without reverse cycle, with louvered sides. > 25,000 Btu/h	9	-	-	
	Without reverse cycle, without louvered sides. 8,000 to 10,999 Btu/h	9.6	-	-	
	Without reverse cycle, without louvered sides. 11,000 to 13,999 Btu/h	9.5	-	-	

2.2.3 Heating and Cooling Load Calculation

The RECS 2009 dataset reports annual energy consumption of the houses but does not report heating and cooling energy load. Load calculation is an essential part of estimating the size of the heating and cooling equipment required for houses which could affect overall price of the system. More accurate analysis of the load calculation requires detailed information of physical properties of houses including the insulation level, number of windows, and shade of the trees, none of which are available in the RECS dataset.

For this analysis, an online equipment sizing calculator is adopted as a rule of thumb (HVAC Equipment Size Finder 2014). The heating and cooling load is calculated as a function of house square footage and location of a house. Figure 11shows the map of the climate region and the list of states belonging to each region.

Region 1	Region 2	Region 3	Region 4	Region 5
Maine	California	Arizona	Alabama	Florida
Michigan	Colorado	Arkansas	Georgia	
Minnesota	Connecticut	Missouri	Louisiana	
Montana	Delaware	New Mexico	Mississippi	
New Hampshire	District of Columbia	North Carolina	South Carolina	
North Dakota	Idaho	Oklahoma	Texas	
Vermont	Illinois	Tennessee		
Washington	Indiana			
Wisconsin	Iowa			
Wyoming	Kansas			
	Kentucky			
	Maryland			
	Massachusetts			
	Nebraska			

	Nevada New Jersey New York Ohio Oregon Pennsylvania Rhode Island South Dakota Utah Virginia West Virginia			

Figure 11. Climate region for heating and cooling load calculation. As shown in the map, the regions are classified in terms of average degree days. When more than one climate regions exist within the state, the climate region with the largest coverage is selected as a representative region.

The contiguous U.S. is divided into five different climate regions based on average degree days. The boundary of the regions does not match with the state boundaries and most of the states have more than one climate region within its boundary. In this case, the climate region with the largest coverage within the state boundary is selected as a representative region.

Both the climate region and the square footage of the house that is cooled or heated are used to calculate energy demand at homes as shown in the following calculations:

$$HeatingEnergyDemand = SQFT * (48 - 4 * ClimateRegion)$$

$$CoolingEnergyDemand = \frac{SQFT}{650 - 50 * ClimateRegion}$$

$HeatingEnergyDemand$ = heating load at a house (Btu/hr)
$CoolingEnergyDemand$ = cooling load at a house (ton)
$SQFT$ = house square footage that is cooled or heated
$ClimateRegion$ = climate region as defined in Figure 11

This results in the following load distribution across the U.S. when applied to the RECS 2009 dataset.

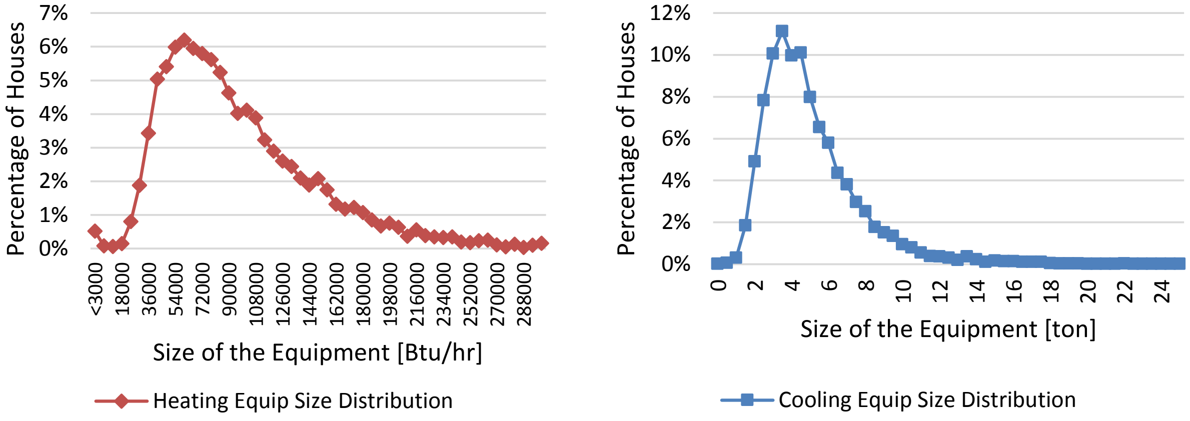

Figure 12. Heating and cooling energy load distribution at single-family detached houses in the U.S. They resemble a skewed normal distribution and peaks around 70,000 Btu/hr and 4 ton for heating and cooling loads, respectively.

2.3 Microdata Pairing

Conventional heating and cooling systems do not require much space outside the housing unit for the equipment. Some space is required for the placement of an outdoor unit for air-source heat pumps or central air conditioners but this does not require significant space. However, GHP systems necessitate the installation of a ground loop heat exchanger and require lot space available for the loop installation. The ground loop may be installed below the foundation of the house in case of new construction, although this is not an option for most of the retrofit projects. Therefore, it is important to understand the available lot size to determine if the house can install a GHP system and to determine the type of ground loop available for the house.

The RECS 2009 dataset contains important data on energy use patterns of houses as well as house characteristics such as the area of the home that is heated and cooled. However, RECS 2009 does not provide any information on the lot size of the house. Instead, the information on the lot size can be found in the AHS 2011 dataset. The AHS does not, however, contain any data on home energy consumption. Therefore, the lot data is imported to RECS 2009 from AHS 2011 by merging AHS entries of the same or similar housing characteristics with the RECS entries using linear regression. The procedure of this pairing process is as follows:

1. Derive comparable housing variables from given housing characteristics in RECS and AHS for direct comparison
2. Marry RECS and AHS entries with minimum impact on lot size using linear regression
3. Import lot size data from matched AHS pair to the RECS entry

2.3.1 Derivation of Housing Variables

Both RECS 2009 and AHS 2011 dataset contain basic information on house characteristics, which can be used to find the matching pairs from the RECS and AHS data. Many available house characteristics can be used for direct comparison between the two microdata, but not all house characteristics are defined or organized in the same manner. In this case, new housing variables are derived from the available data for direct comparison. Table 4 demonstrates the list of housing characteristics used and how they are redefined for microdata pairing when direct comparison was not possible.

Table 4. List of house characteristic variables used to pair RECS and AHS dataset. Description includes how each variable is redefined to result in common values as shown in the second column.

House Characteristics	Values	Variable Description	
		RECS 2009	AHS 2011
Census Region		Used original	Used original
Census Division		South Atlantic &East South Central divisions; and Mountain &Pacific divisions are combined.	Used original
Built Year	1920-2009	Used original	Used original
Urban/Rural	Urban/Rural	Used original	Urban = All urban area inside and outside Metropolitan Statistical Area (MSA) and unspecified area inside MSA Rural = All rural area
Size of the Garage	0-3 cars	Detached &attached garages are reorganized by size. Detached garage is assumed to be same size as attached garage. 39% of carports are allocated to one-car garage and 61% to two-car garage.	The size of the garage is derived from the number of vehicles households have: One-car Garage = 0-1 vehicles Two-car Garage = 2-3 vehicles Three-or-more-car Garage = more than 4 vehicles
House Square Footage	RECS: 100-16122 AHS: 99-20159	Attached garage is subtracted from house square footage. 250, 400 and 650 square feet is used for one-car, two-cars, and three-or-more-cars garage, respectively.	Used original

Cellar	Yes/No	Same as the original	Yes = House has full- or partial-sized basement No = Others
Number of Floors	1-4	Entries with split level are removed	Full-sized basement is excluded from the floor count Houses with more than 4 stories are aggregated into 4 stories and more category
Number of Occupants	1-10, 11+	Variable range reorganized into 1-10 and 11 or more	Variable range reorganized into 1-10 and 11 or more
Number of Bedrooms	1-7, 8+	Variable range reorganized into 1-7 and 8 or more	Used original
Number of Full-Bathrooms	0-7, 8+	Used original	Variable range reorganized into 0-7 and 8 or more
Number of Half-Bathrooms	0-2, 3+	Used original	Variable range reorganized into 0-2 and 3 or more

The house characteristics in Table 4 are selected on the assumption that they could have a meaningful impact on the lot size of the house. House characteristics such as heating and cooling system are important for energy analysis but they are excluded on the assumption that they are not a significant factor that determines the size of the lot.

Urban/Rural

RECS 2009 data contains separate categories that distinguish whether RECS entries are located in urban or rural areas and also whether they are located at Census Metropolitan Statistical Areas or Micropolitan Statistical Areas (MSA). AHS 2011 data also report the geographical locations of its entries in terms of the central city and suburban status. However, RECS and AHS do not show a good match with their original classification as shown in Figure 13, due to the different definition of the Metropolitan and Micropolitan area. The AHS codebook indicates that various definitions of central city and urban areas are used depending on date of entry of the sample to the dataset, and for some entries their locations are masked due to a disclosure rule (Econometrica, 2013). Details of those various definitions are not disclosed for the AHS public use file and thus this location data cannot be used without further information.

Therefore, the locations of the AHS entries are reclassified into general urban and rural areas to be matched with RECS classification. The AHS entries within all urban areas, which include both inside and outside MSA, and unspecified areas within MSA, are assigned to the urban area whereas the rest are assigned to the rural area. This results in a good match between the RECS and AHS dataset as shown in Figure 14.

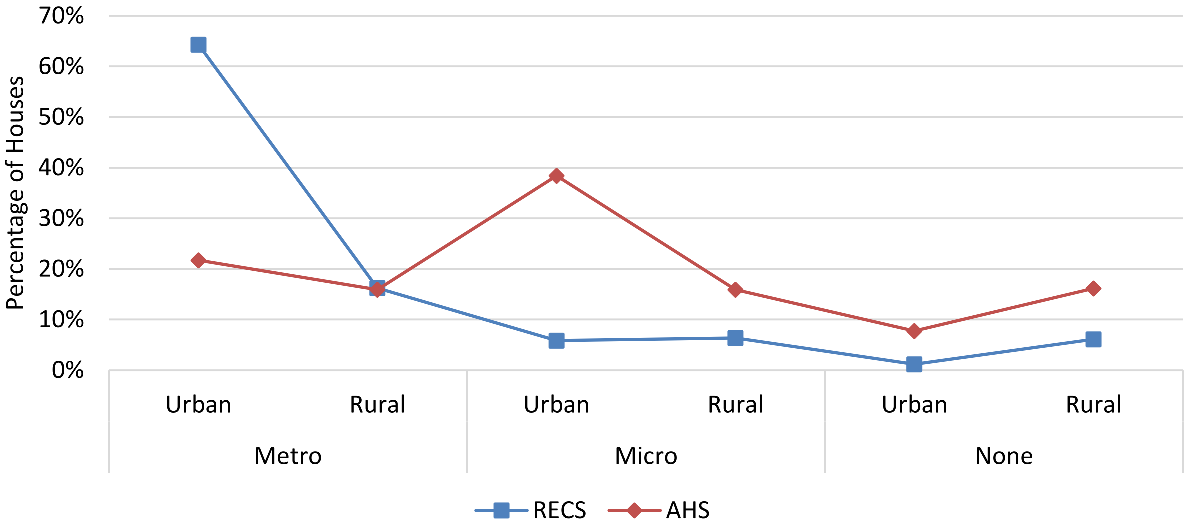

Figure 13. Distribution of the RECS 2009 and AHS 2011 Entries According to the Original Urban and Rural Definition.

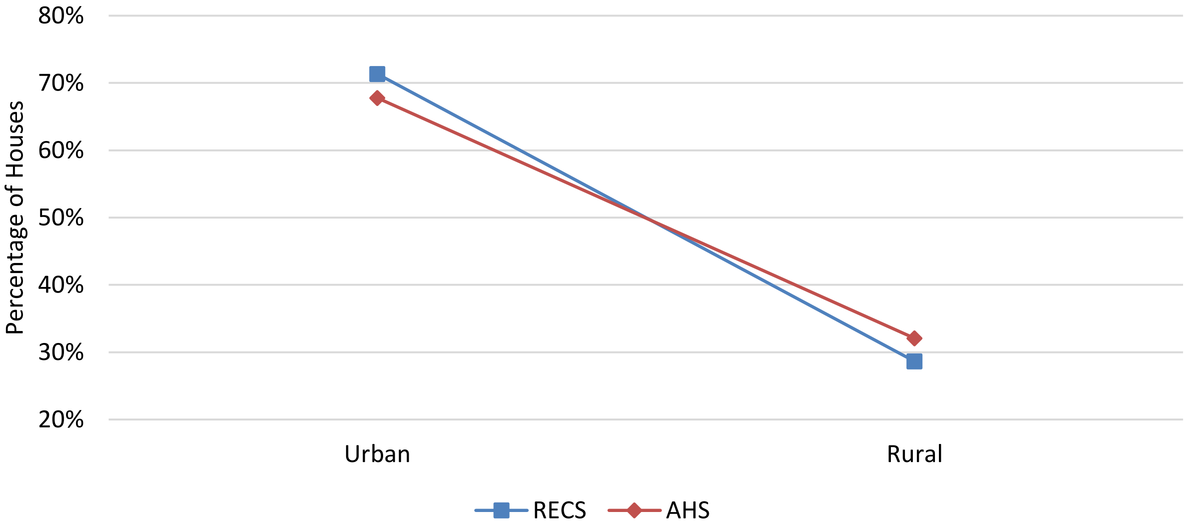

Figure 14. Distribution of the RECS 2009 and AHS 2011 Entries According to the New Urban and Rural Definition.

Garage

Both the RECS and AHS datasets indicate the existence and the size of home garages but in a different manner. The RECS 2009 has more detailed information in terms of the type of garage (attached or detached) and its size. The AHS 2011 dataset only states whether the house has a garage or not, but also includes additional information on how many vehicles (cars and trucks reported separately) occupants possess.

In RECS 2009, attached garages (59 percent of houses) and detached garages (24 percent of houses) are reported separately. They are grouped together and classified in terms of size to be matched with AHS data. However, 5 percent of detached garages are reported as carports whose size is unknown. Here, the size of the carport is assumed to be smaller than three-car garage and RECS entries with carports are proportionally distributed into one-car and two-car garage in terms of their relative popularity. As a result, 38.8 % of carports are allocated into one-car garages while the rest are assigned to two-car garages.

In AHS 2011, the number of vehicles (cars and trucks combined) is used to estimate the size of the garage. The size of the garage is categorized in terms of RECS 2009 classification and the number of vehicles is grouped as following: one-car garage for 0-1 vehicles, two-car garage for 2-3 vehicles, and three-or-more-car garage for more than 3 vehicles. The results show a good match between the RECS and AHS data as shown in Figure 15.

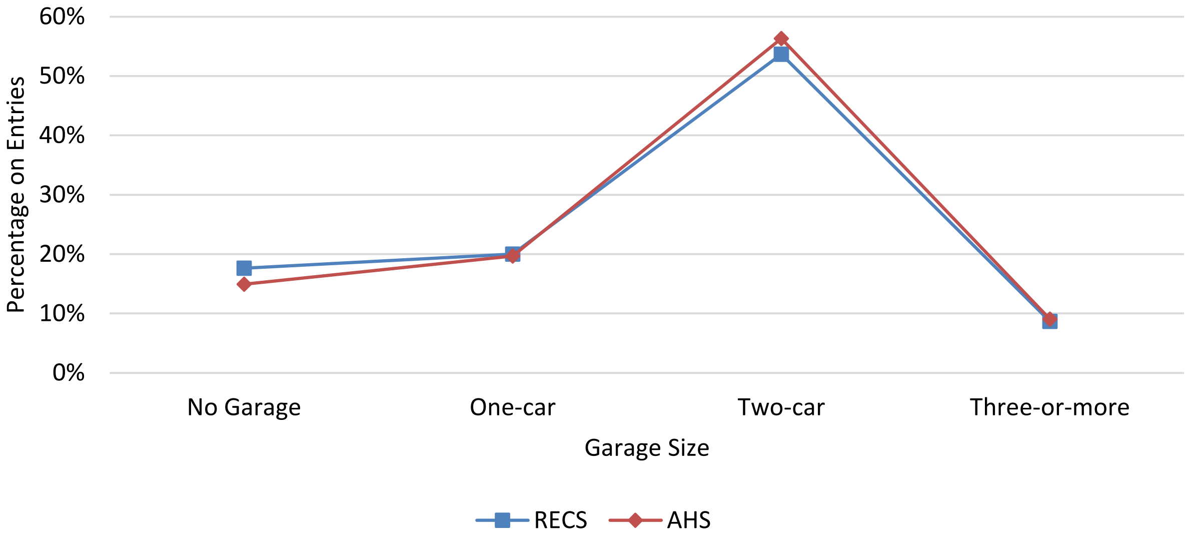

Figure 15. Comparison of RECS and AHS microdata for the common variable: Size of the Garage. RECS and AHS data show good match.

Cellar

The AHS 2011 data informs whether each AHS entry has a basement, along with information on its size (full or partial basement),but the RECS 2009 dataset indicates only the existence of the basement and does not provide further details. The AHS data show that 34 percent and 12 percent of its entries have reported to have a full-sized and partial-sized basement, respectively. Since the RECS data report 58 percent of its entries have a basement, AHS basement is redefined to include all sizes to match with the RECS data.

Number of Floors

The RECS 2009 dataset only counted floors above ground but not basements when counting the number of floors at a house. However, the AHS 2011 dataset does not inform whether or not the basement is counted. Comparison of the original RECS and AHS data on the number of floors does not show a good match as shown in Figure 16 and suggests that the basement might have been counted in AHS contrary to RECS dataset.

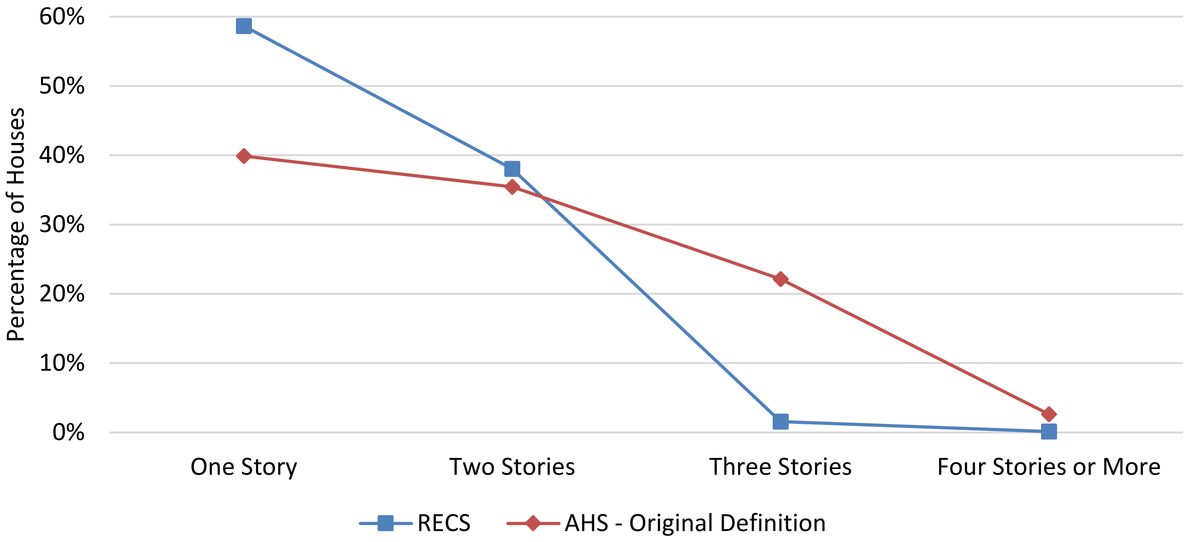

Figure 16. Comparison of the RECS 2009 and AHS 2011 entries on the number of stories as defined in the datasets.

The AHS classification does not include a category for 'split-level' unlike in the RECS. The AHS codebook also does not provide any information on how split-levels are classified, but a hint is provided in the Census survey on new single-family houses completed (Census 2014b). Here, split-levels are treated as a normal floor and the greatest number of stories counted is used for data entries. In RECS 2009, "split-level" entries account for about 1.7 percent of all houses. While RECS 2009 does not disclose how they are defined, the Census reveals that the definition of split-level varies across different areas (Census 2014c). Since no reliable statistics of split levels are found during this analysis, these entries are removed for the quality of the analysis.

In the AHS data, basements are removed from the floor count for the comparison with the RECS data. Here, two different definitions of basements are compared: (1) A basement under the entire house (2) A basement under all or part of the house. The Census new single-family houses survey (Census 2014b) also contains information on the number of stories in new construction by year and this is used as a reference to compare two different definitions. Figure 17 and Figure 18 show the comparison in the case of single-family houses with one story, and more than one story, respectively. Both definitions of basement show good match with the Census reference while the case including basements of all sizes shows a slightly better fit on average. Here, RECS 2009 data is also provided as a reference. Another comparison of AHS and RECS data also show that the AHS data show a better match with the RECS if the latter definition is used as well, as seen in Figure 19. Therefore, basement of all sizes are removed from the floor counting in the AHS to be matched with the RECS data.

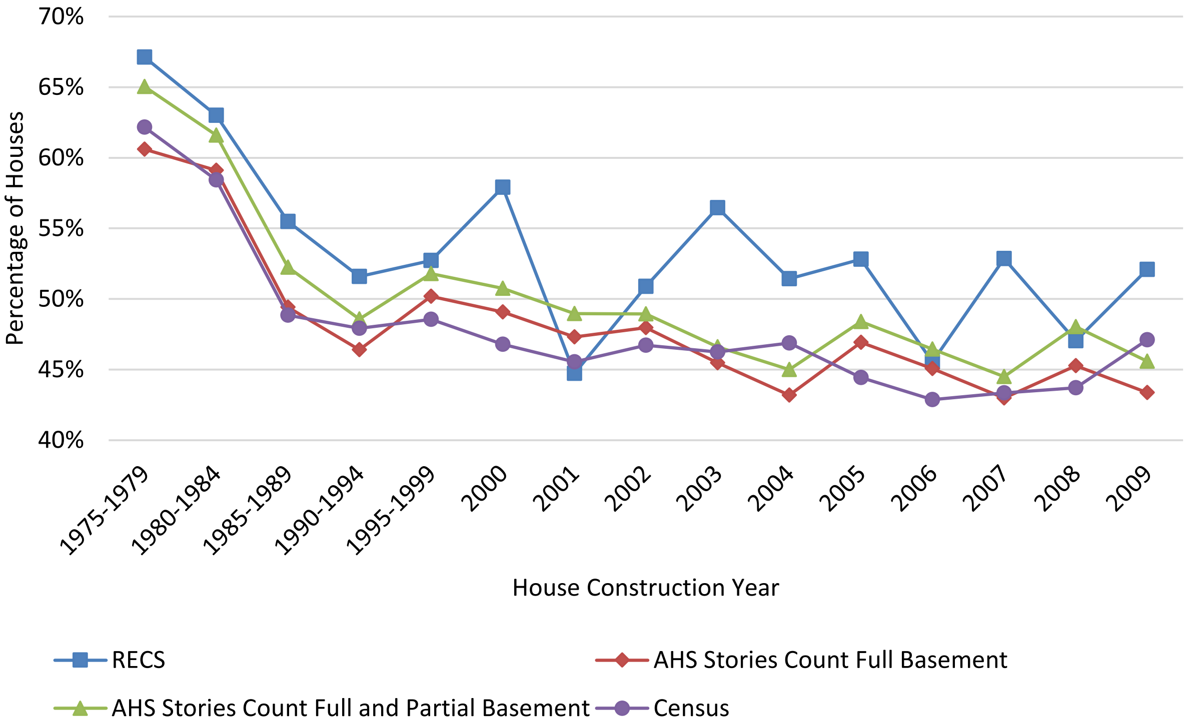

Figure 17.Comparison of single-family houses with one floor with Census new single-family house construction data, RECS 2009, and AHS 2011 dataset with two different definitions on basement

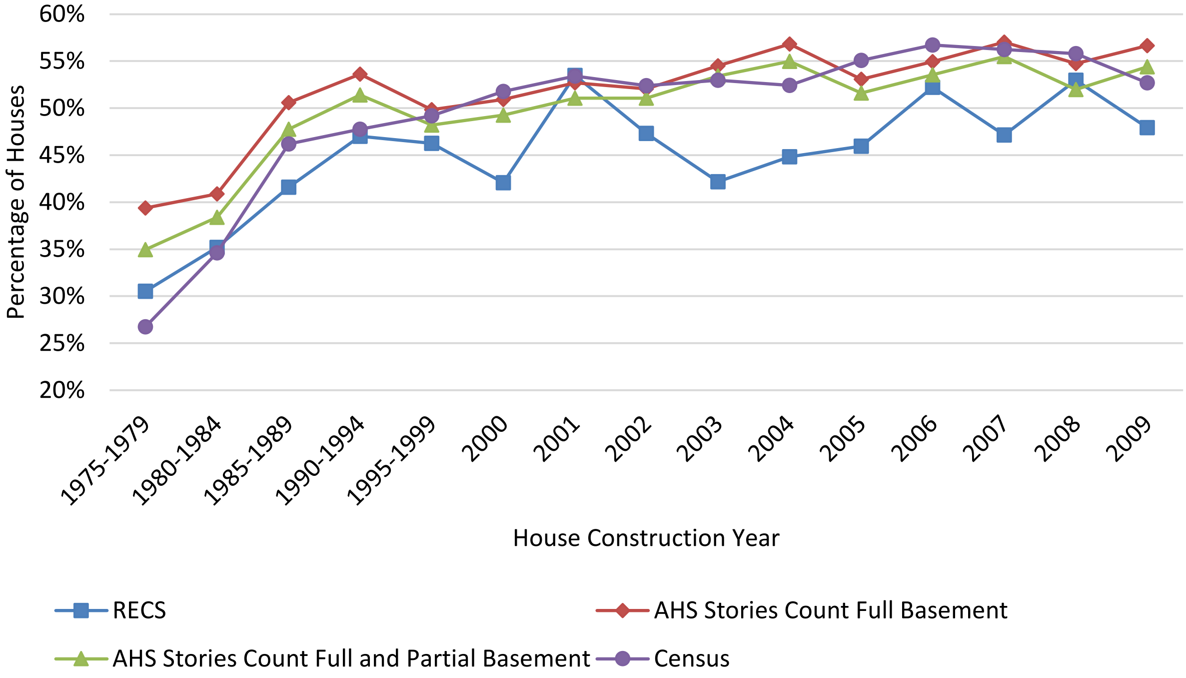

Figure 18.Comparison of single-family houses with more than one floor with Census new single-family house construction data, RECS 2009, and AHS 2011 dataset with two different definitions on basement.

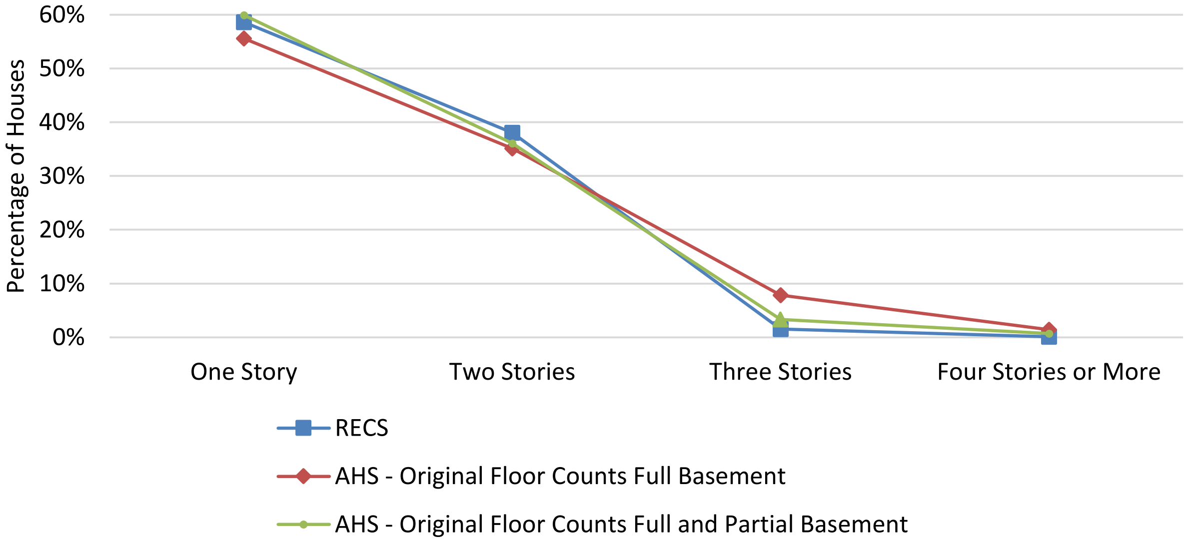

Figure 19. Comparison of the RECS 2009 and AHS 2011 entries with a new definition of floors in AHS 2011.

House Square Footage

The RECS and AHS datasets apply different definitions when measuring total square footage of houses. RECS 2009 includes attached garages and all basements. Attics are also counted in the measurement if they are finished or heated or cooled (EIA 2012b). On the other hand, AHS

2011 includes only finished attics in square footage and excludes unfinished attics, carports, and attached garages (EIA 2012b). For a direct comparison between the RECS and AHS dataset, attached garages are excluded from the house square footage calculation in RECS to match AHS definition of house square footage. No additional adjustment for attics is made due to the lack of information in both the RECS and AHS dataset.

The RECS 2009 data do not indicate the square footage of the garage directly. The size of the attached garage is not measured during the survey. Rather, it is classified in terms of the number of cars a garage can accommodate and a fixed value is assigned for each category. This number can be derived by comparing RECS variables TOTSQFT and TOTSQFT_EN for houses which do not heat or cool their garages. The variable TOTSQFT includes the square footage of all attached garages when calculating total house square footage, whereas the variable TOTSQFT_EN only counts attached garages when it is heated or cooled. Therefore, the difference between these variables reveals the values that EIA assigned to each size of the garage category. The analysis shows that 250, 400, and 650 square feet are assigned to one-car, two-cars, and three-or-more-cars attached garages, respectively. These values are subtracted from total house square footage when a house has an attached garage in RECS 2009 for direct comparison with the AHS 2011 data. As shown in Figure 20, subtraction of attached garage from RECS improves the matching with AHS.

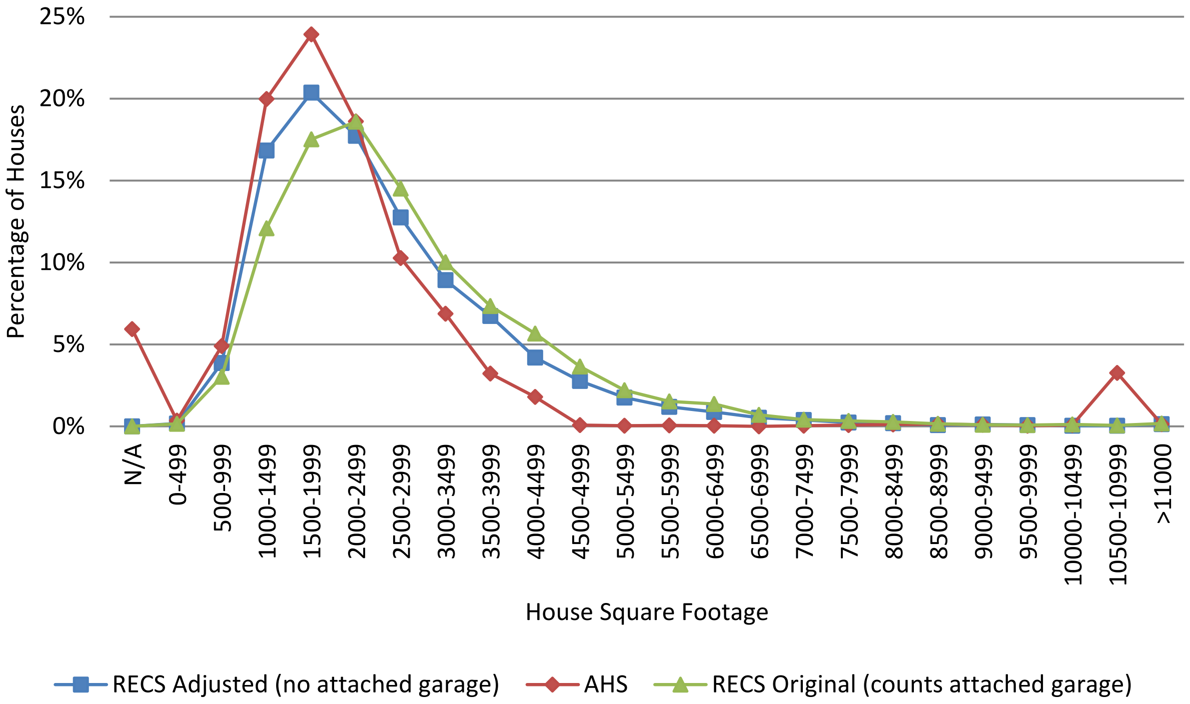

Figure 20. Comparison of the RECS 2009 and AHS 2011 dataset on house square footage. The RECS show better match with the AHS with the adjustment where attached garage is no longer counted in the house square footage measurement.

Variables with Range Adjustment

Housing variables such as the number of occupants in a house, number of bedrooms, full-size and half-size bathroom are provided in both the RECS 2009 and AHS 2011 dataset with a good data match. Because the data range of these variables differ slightly in RECS and AHS, these ranges are adjusted to the shorter range between the RECS and AHS dataset for direct comparison. Figure 21 shows the comparison of these variables after range adjustment, with good matches between the RECS and AHS data.

Upon completing the adjustment processes for direct comparison, above variables are used as key variables to merge RECS and AHS entries.

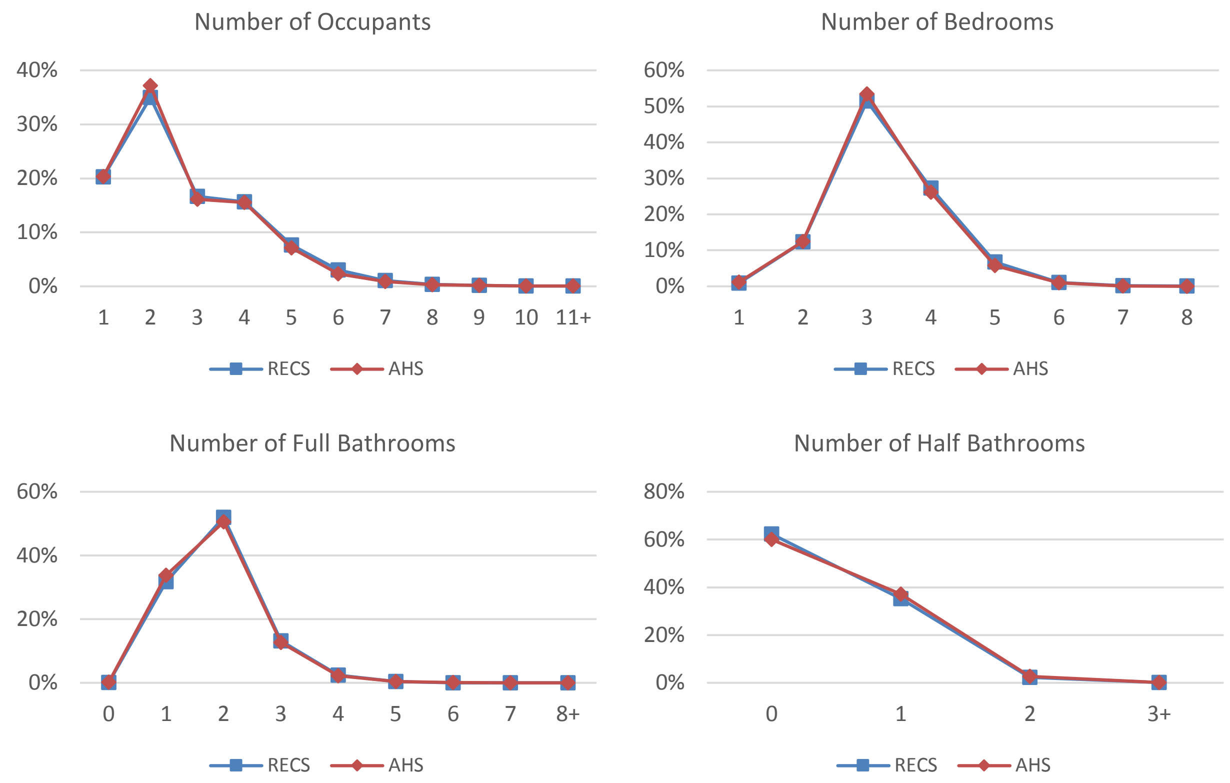

Figure 21. Comparison of the number of occupants, bedrooms, full and half bathrooms between the RECS 2009 and AHS 2011 dataset.

Calculating Average Lot Size of AHS Entries with the Same Variables

Ideally, one entry from AHS dataset would be matched with a RECS entry with the same key variables. However, an analysis of the AHS entries shows that while most of the AHS entries contain a unique combination of key variables (62 percent), 38 percent of AHS entries find other AHS entries with the same key variables. The number of AHS entries with the same key variables among the AHS dataset range from two to forty five, and over half of those variables find one or two more other AHS variables which share the same key variables. In these cases, lot size information is averaged among the AHS entries with the same key variables since we need only one lot size to be imported to the RECS entries.

2.3.2 Linear Regression and Pairing

Since the RECS 2009 and AHS 2011 are independent surveys which do not share the same sample in their entries, we cannot expect to find AHS entries with the exact same key variables for all RECS entries. In this case, alternative AHS entries which share most of the key variables with the RECS entry are selected for the pairing. Log-linear regression is used to find this alternative AHS entry by identifying the key variable that can be altered and the amount of change which would cause minimum impact on the lot data. The relationship is shown below:

$$\ln(\text{Lot}) = \alpha + \beta_1 * UrbanRural + \beta_2 * Cellar + \beta_3 * FullBath + \beta_4 * Garage + \beta_5 * Floors + \beta_6 * HalfBath + \beta_7 * Occupants + \beta_8 * Bedrooms + \beta_9 * HouseSQFT + \beta_{10} * BuiltYear + \epsilon$$

The result of the regression is shown in Table 5, which shows all key variables that are statistically significant at 95 percent significance level.

Table 5. Results of the log-linear regression of logarithm of lot size and other key variables.

Regression Statistics	
Multiple R	0.4059
R Square	0.1648
Adjusted R Square	0.1646
Standard Error	1.2024
Observations	64434

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.041524	0.416893	4.897003	9.75E-07	1.224414	2.858634
HouseSQFT	7.07E-05	2.73E-06	25.909	3.00E-147	6.53E-05	7.60E-05
Garage	0.086958	0.00642	13.5439	9.82E-42	0.074374	0.099542
Floors	-0.07465	0.007937	-9.40515	5.36E-21	-0.09021	-0.05909
Cellar	0.319955	0.010426	30.68796	2.50E-205	0.29952	0.34039
UrbanRural	1.341006	0.01444	92.86929	0	1.312704	1.369308
NumBedrooms	-0.02252	0.007355	-3.06117	0.002206	-0.03693	-0.0081
NumOccupants	-0.04258	0.003613	-11.7867	4.93E-32	-0.04966	-0.0355
NumFullBath	0.109037	0.008318	13.10854	3.30E-39	0.092733	0.12534
NumHalfBath	0.064199	0.009586	6.697125	2.14E-11	0.04541	0.082987
BuiltYear	0.002909	0.000214	13.56389	7.49E-42	0.002489	0.00333

The coefficients of each variable indicate the amount of impact on the lot size upon the change of the variable by one unit. For example, if the AHS entry with one less full bathroom is paired with the RECS entry, the expected value of the lot decreases by $e^{0.109}$, which is about a 12 percent decrease from the original value. Therefore, the impact on the expected value of the lot can be minimized by minimizing the total change of the multiple changes in variables and its coefficient. This method ensures finding the best AHS entry that can be paired with the RECS entries given key variables with minimum impact on its lot size. The AHS entries with the same key variables will be paired with the RECS entries if they exist. In case they do not exist, alternative AHS entries will be paired together with minimum impact on the lot size.

The analysis shows that 48 percent or 9372 RECS entries are paired with the AHS entries with the same key variables (zero impact on lot size), and 95 percent or 18555 RECS entries are paired with the AHS entries with equal to or less than 0.01 percent impact on lot size. The range of the impact on the lot size was 2.28 percent with a maximum impact of 1.77 percent. So most of the RECS entries are paired with less than 0.01 percent impact on the lot size. Even in the worst case scenario, the impact was less than 2 percent. The information of lot size is directly imported from the AHS entries to the RECS entries upon the pairing. As a result, about 85 percent of the RECS entries are paired with one AHS entry with the same key variables, while 9 percent and 3 percent of the RECS entries are paired with two and three such AHS entries, respectively, in which case average lot size is imported.

The correlation test shows that there is no significant amount of correlation among the variables. In addition, a fairly large sample size means that the amount of correlation found is tolerable. The correlation table can be found in Appendix D.

Figure 22 shows the results of the pairing with a general increase in lot size with increasing house square footage. Since the percentage of houses whose square footage is greater than 5000 square feet is less than two percent, the average square footage of lots shows more fluctuation due to a smaller sample size.

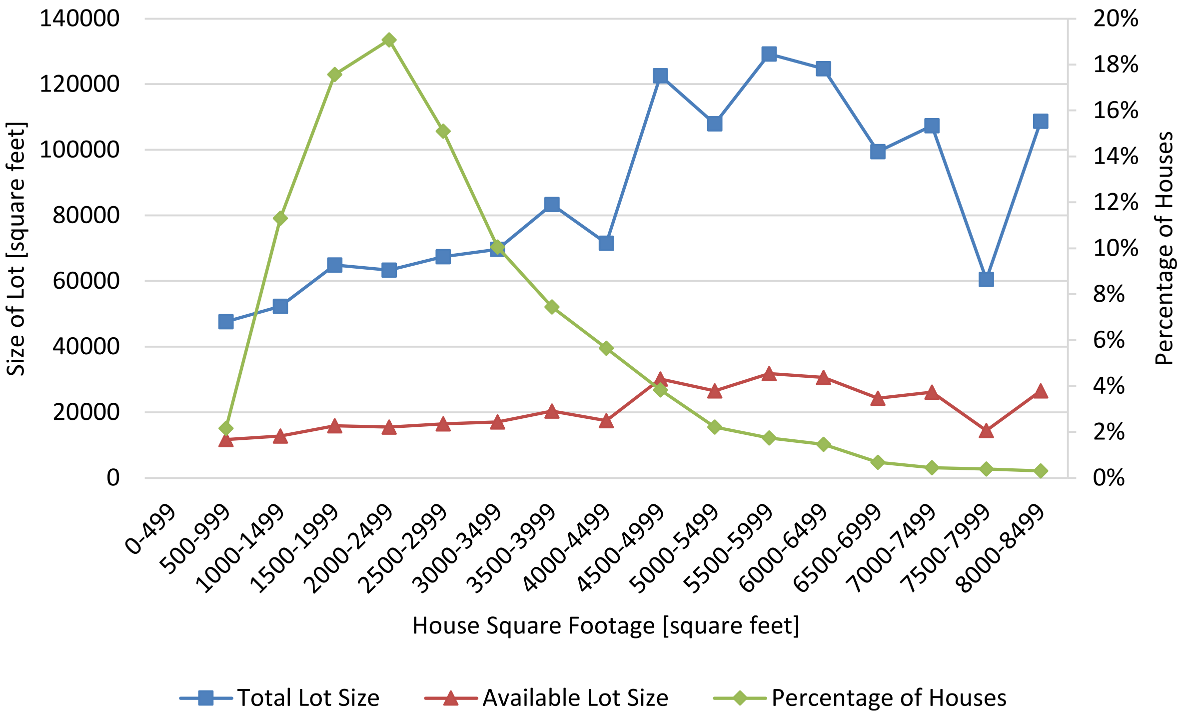

Figure 22. The average size of the lots allocated to the RECS entries by pairing with the AHS entries. This shows the general increase in lot size with increasing square footage of the house.

2.3.3 House Footprint Calculation

House footprint is the area of the total lot that is covered by the house and garages. House footprint is an important parameter for the GHP system as a GHP retrofit requires an empty lot for ground loop installation.

The RECS 2009 dataset reports physical characteristics of the houses that can be used to calculate house footprint. Figure 23 shows how total house square footage is calculated in the RECS 2009 dataset and **Error! Reference source not found.** summarizes these RECS variables and their response codes and labels.

Figure 23. Graphical description of how house square footage is calculated in the RECS 2009 dataset. See **Error! Reference source not found.** *for total square footage of a house. The square footage of the house is measured by the interviewers during the survey. EIA performed in-person measurements as many alternative sources such as property tax records, real estate listings, and respondent estimates use varying definitions which underestimated house square footage for the purpose of energy analysis*[1].

Table 6. House characteristics of the RECS 2009 entries used to calculate house footprint. N/A denotes not available and total square footage of house is reported in natural number.

House Characteristics	RECS 2009 Variable	RECS 2009 Response Codes and Labels
Attic	ATTIC ATTICFIN ATTCHEAT ATTCCOOL	Attic in housing unit: Yes, No, N/A Finished attic: Yes, No, N/A Heating used in attic: Yes, No, N/A Cooling used in attic: Yes, No, N/A
Basement	CELLAR	Basement in housing unit: Yes, No, N/A
Attached Garage	PRKGPLC1 SIZEOFGARAGE	Attached garage: Yes, No, N/A One-car garage, Two-car garage, Three-or-more-car garage, N/A

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[1] http://www.eia.gov/consumption/residential/reports/2009/methodology-square-footage.cfm

Detached Garage	PRKGPLC2 SIZEOFDETACH	Detached garage or carport: Yes, No, N/A One-car garage, Two-car garage, Three-or-more-car garage, Carport, N/A
Number of Stories	STORIES	Number of stories in a single-family home: One, Two, Three, Four or more stories, Split-level, Other type, N/A
Total Square Footage of House	TOTSQFT	Total square footage including all attached garages, all basements, and finished/heated/cooled attics
Total Square Footage of House that is weathered	TOTSQFT_EN	Total square footage including heated/cooled garages, all basements, and finished/heated/cooled attics

As described in Table 6, the total house square footage includes all attached garages, all basements, and finished/heated or cooled attic space. To calculate house footprint, it is necessary to accurately estimate how much square footage is assigned to the garage, basement, attic and regular floors. The calculations for this square footage assignment to different house areas are as follows:

Attic

Calculating square footage of the attic is not as straight forward as calculating square footage in regular floors. A number of rules exist in calculating attic square footage since most attics have a sloped ceiling. Usually, the part of the attic that has height less than the standard height for a living space is not counted in the measurement. Therefore, the square footage of the attic is usually smaller than that of the regular floors. Since there exist no further data that allows detailed analysis, only half of the square footage found in the regular floor is considered as the square footage of the attic when it is either finished, heated, or cooled. When there is no attic or if it is not finished, heated, or cooled, no square footage is assigned to attic space.

Basement

The basement is always included in the square footage measurement but its dimension is not reported. The AHS 2011 database reveals that not all houses have basements that are the same size as regular floors. About 75 percent of houses with a basement have a basement with the same floor space as regular floors while the rest of the houses have smaller basements than their regular floor space. But since the RECS 2009 dataset does not report other house variables to estimate the actual size of the basement, basements are assumed to have the same square footage as regular floors when they exist in a house.

Attached and Detached Garage

Two types of garages are reported in the RECS 2009 dataset: attached garage, and detached garage or carport. The attached garage is the garage that is physically connected to the housing unit whereas a detached garage or a carport exists as a separate structure outside the house. The detached garage and carport are distinguished by the existence of an outer wall that separates the garage space from outside; if it has a wall it is a detached garage and it is carport otherwise. Both attached and detached garages are classified by size: One-car, Two-car, Three-or-more-car garage. Comparing TOTSQFT and TOTSQFT_EN of a house which has a garage that is not conditioned(not heated or cooled) reveals that RECS assigns a fixed value for garage space: 250, 400, 650 square footage for One-car, Two-car, Three-or-more-car garage, respectively. However, there are no comparable variables in RECS to calculate square footage assigned for detached garages. But since the only difference between attached and detached garages is its location at home, the square footage assigned to the detached garage is assumed to be the same as the attached garage with the same size. Also, no variables exist in RECS to estimate the size of the carport. As defined in section 2.3.1, 38.8 % of carports are assigned as a one-car garage and the other 61.2 % are assigned as a two-car garage, and the same square footage that applied to attached and detached garages is also used for carports depending on what size garage they are assigned to.

Number of Stories

The number of stories reported at RECS does not include the basement and thus can be treated separately from the basement. The number of stories includes split level and ‘other type,’ both of which are not well defined in RECS and comprise less than 2 percent of the entire households. Therefore, entries with split level or other type as its STORIES are not included in this analysis. For all the other entries, each floor is assumed to have the same square footage which is equal to house footprint.

Total Square Footage of House

In RECS, the total square footage of a house is defined as a summation of square footage of all floors, the basement, the attached garage, and any finished/heated/cooled attic. The equation to calculate total square footage of house is as follows:

$$SQFT = n * X + Attic + Basement + AttachedGarage$$

Where:
$SQFT$ = total square footage of the house
n = number of stories in the house. Entries with 'split level' or 'other type' are excluded.
X = housing unit footprint
$Attic$ = if the attic is finished/heated/cooled: $Attic = X/2$,
otherwise: $Attic = 0$,
$Basement$ = if the house has a basement: $Basement = X$
otherwise: $Basement = 0$,
$AttachedGarage$ = if the house has an attached garage and if its size is
One-car garage: $AttachedGarage = 250$,
Two-car garage: $AttachedGarage = 400$,
Three-or-more-car garage: $AttachedGarage = 650$,
otherwise: $AttachedGarage = 0$.

Solving this equation in terms of results in the housing unit footprint (X)results in the square footage of the housing unit. Then total house square footage can be calculated by adding the square footage of the detached garage or carport to this housing unit square footage. Figure 24 shows the result.

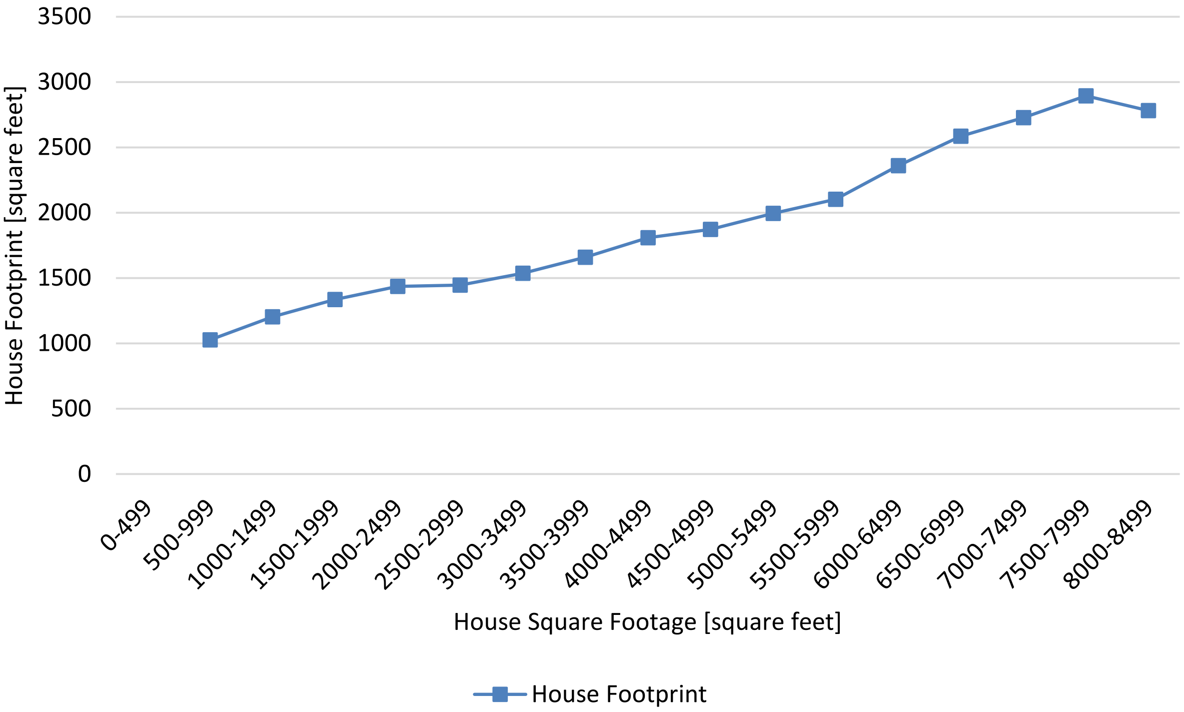

Figure 24. The average house square footage in terms of house footprint. This shows that the house footprint and house square footage are positively correlated as expected.

2.4 GHP System Modeling

The GHP system consists of two major components: a heat pump unit and a ground loop. The ground loop is buried underground to make a thermal conduction with the earth. Different types of ground loops can be used to transport thermal energy in and out of the house depending on lot availability, access to ground water or a body of water near the house, and other physical settings such as the location of bedrocks. For this analysis, horizontal loops and vertical loops are considered as ground loop candidates on account of their popularity.

Heat pump units are connected with the ground loop and heat distribution system at home through a heat exchanger and can transport thermal energy between home and underground. The common types of home distribution systems include forced-air, gravity and radiant systems. The GHP can be fitted to work with most of these distribution systems commonly found in the U.S. homes. Most of the GHP equipment can be used with forced-air systems (water-to-air heat pump) and mini-split GHP systems can be used in homes with gravity systems which do not have a duct work. Radiant systems, which utilize conventional boilers, can be further sub-divided according to their distribution type: hot water system, steam system and radiant floor. Most of the heat pump units are designed to heat water (water-to-water heat pump) to around 150 degree Fahrenheit which is enough to be used with a radiant floor. However, only a fraction of U.S. homes utilize radiant floors for heating and the majority of homes with a boiler system use hot water or a steam system which requires higher water temperature. There exist specially designed heat pump units to provide higher heat to be used with hot water systems; however, this does not represent most heat pump units on the market. Due to the lack of data, gravity and radiant systems are excluded from the analysis and only the forced-air system is considered for GHP installation.

2.4.1 GHP Database and System Setup

A database of geothermal heat pump units available on the market is included in the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) directory of certified product performance (AHRI 2012). The AHRI directory reports three major types of heat pump units for geothermal application: direct geoexchange (DGX) heat pump, water-to-air (WTA) heat pump, and water-to-water (WTW) heat pump. Here, WTA heat pump is selected for this study as it is the most widely used heat pump that can be used with air distribution systems found in homes.

The AHRI directory contains a database of 5,675 WTA heat pump products currently available in the U.S. market. This dataset includes ratings for the efficiency and capacity for heating and cooling of each product when matched with different types of ground loops: water loops, ground water loops and ground loops. From these options, ground loops are selected for this study including horizontal and vertical loops. Water loops and ground water loops are not included in this study as they require a body of water or ground water nearby the house of which information was not available at the time of this analysis.

Many of the heat pumps represented in the AHRI database also report partial load efficiency along with full load efficiency. Efficiency is higher at partial loads but this does not provide a realistic representation of heat pump operation at homes. Therefore, only full load efficiency is used for the analysis.

2.4.2 Lot Requirement for Ground Loop

The ground loop is an essential part of the GHP system and requires a certain amount of land available for its installation. For new construction, the loop can be installed below the foundation which solves the issue of lot availability and also lowers the installation costs. But for a retrofit, the ground loop needs to be installed in an empty lot.

The size of the empty lot available for horizontal and vertical loops is dependent on a number of site-specific factors. The location of underground pipe or other physical barriers can reduce the size of available lot. The geometry of the house and detached garage might make its backyard inaccessible to the drilling vehicles. These site specific details are not available in the RECS and AHS dataset. Therefore, only half of the empty lot is assumed to be available for the ground loop to take this limitation into account. So, the available lot size for the ground loop is defined as follows:

$$Available\ Lot = (Total\ Lot - House\ Footprint) * {}^{1}/_{2}$$

Where *Total Lot* is the lot size of the house imported from AHS dataset and *House Footprint* is defined as in section 2.3.3.

For both horizontal and vertical loop, a fixed amount of land per tonnage of the system is used to estimate required lot size. Literature review and interviews of the local installers revealed that this requirement is also site-specific and varies among practitioners. For example, if the house contains soil with a higher conductivity, a smaller loop suffices to provide the required heating and cooling to the house, but would not suffice if the same house contained a less conductive soil. Better grouting material can also lower the loop size required to deliver the same amount of heating and cooling.

Interviews with local installers yielded a range of minimum lot requirements for the loop. The minimum lot requirement for the vertical system varied between 100-255 square feet per ton while it ranged from 1,500 to 14,520 square feet per ton for the horizontal loop. The minimum amount of 255 square feet per ton for vertical loop and 14,520 square feet per ton for horizontal loop is used as a default which results in conservative estimate of the number of houses that have enough available lot for such systems.

2.4.3 Finding the Appropriate GHP System for RECS Entries

2.4.3.1 Ground Loop

A large portion of the total cost of ground loop comes from the drilling process. This requires drilling vehicles and labor which could be more costly than the loop itself. For this reason, vertical loop is more expensive than horizontal loop as it requires more drilling. Interviews with local installers revealed that horizontal loop is approximately 40 percent cheaper than vertical loop for installation. Since there are no differences in terms of performance between vertical and horizontal loop, horizontal loop is assumed to be used whenever the house has enough lot.

Using the default minimum lot requirement for horizontal and vertical loops, about 6 percent of the houses of interest are found to have enough lot to utilize horizontal loop. Most of those houses are located in rural areas (66.5percent). The urban area defined in RECS dataset not only contains central cities but also regions outside the central cities within Metropolitan Statistical Regions. Most of the houses which have lot sizes big enough for horizontal loop in urban areas are expected to be located in these regions outside central cities. The percentage of houses with lots big enough to install horizontal loops is shown in Figure 25. More rural homes have lots big enough for horizontal loop than urban homes. Overall, 15 percent of rural homes and 3 percent of urban homes can utilize horizontal loop, which is 6 percent of U.S. homes of interest. Most of the U.S. homes cannot use horizontal loop due to their small lot size. The overall percentage of houses capable of having horizontal loop decreases with increased house square footage, as required lot size increases with the increased demand for heating and cooling.

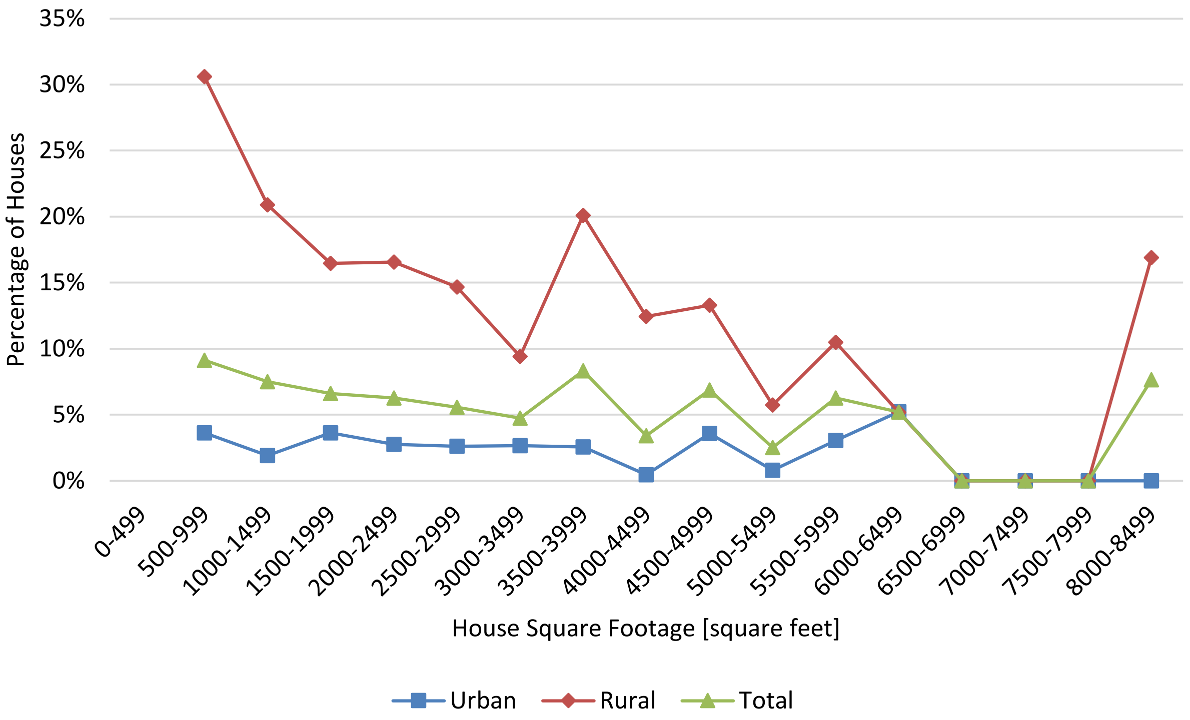

Figure 25.Percentage of houses which have lots big enough to install a horizontal loop. More rural homes have lot sizes big enough for horizontal loop than urban homes. Regardless of house square footage, the percentage of urban homes that can install horizontal loop remains smaller than rural homes.

Lot sizes that can accommodate vertical loops are much more available for both rural and urban homes as shown in Figure 26.About 93 percent of rural homes and 74 percent of urban homes have lot big enough to install vertical loop, which is 79 percent of U.S. homes of interest. As is the trend with horizontal loops, large houses tend to require bigger ground loop systems for their heating and cooling demand which increases their lot requirement. This results in a decrease in the number of houses that can use vertical loop.

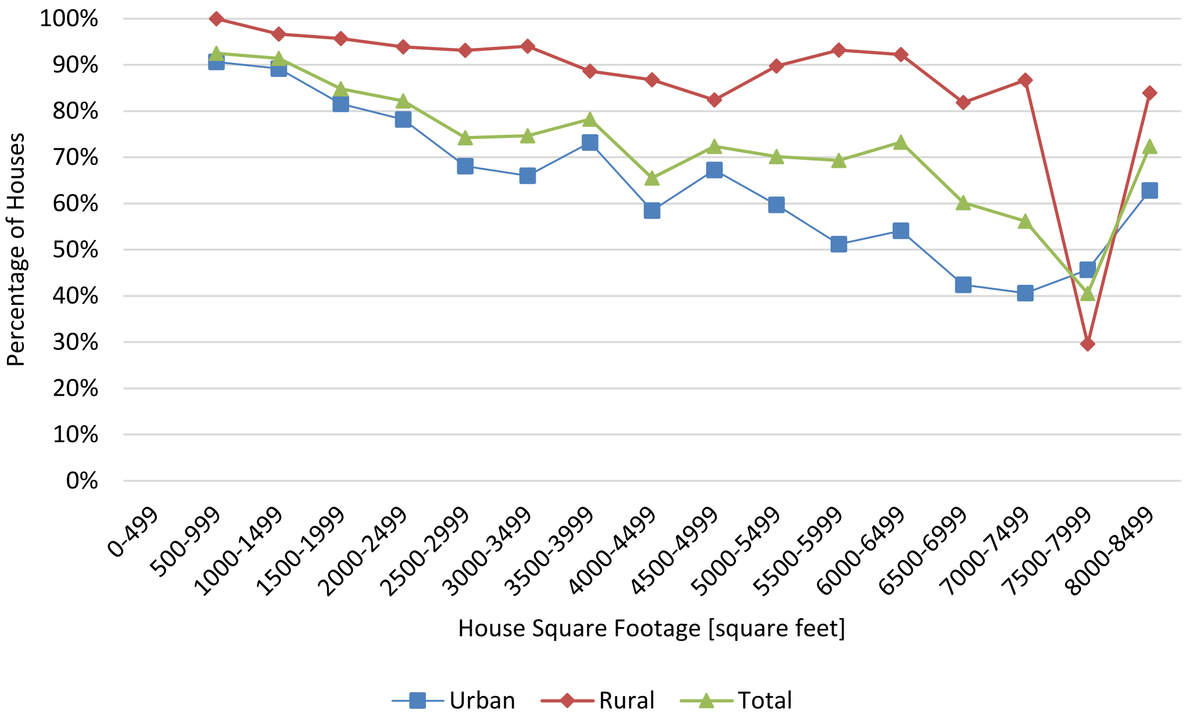

Figure 26. Percentage of houses that can install vertical loops on the lot. More rural homes have lot big enough for vertical loop than urban homes.

If a house has a lot big enough to accommodate a horizontal loop, it can also install a vertical loop. This means that about 21 percent of U.S. homes of interest cannot utilize the GHP system due to their small lot. Most of these homes are located in urban areas. Figure 27 compares the number of houses that can use horizontal and vertical loop.

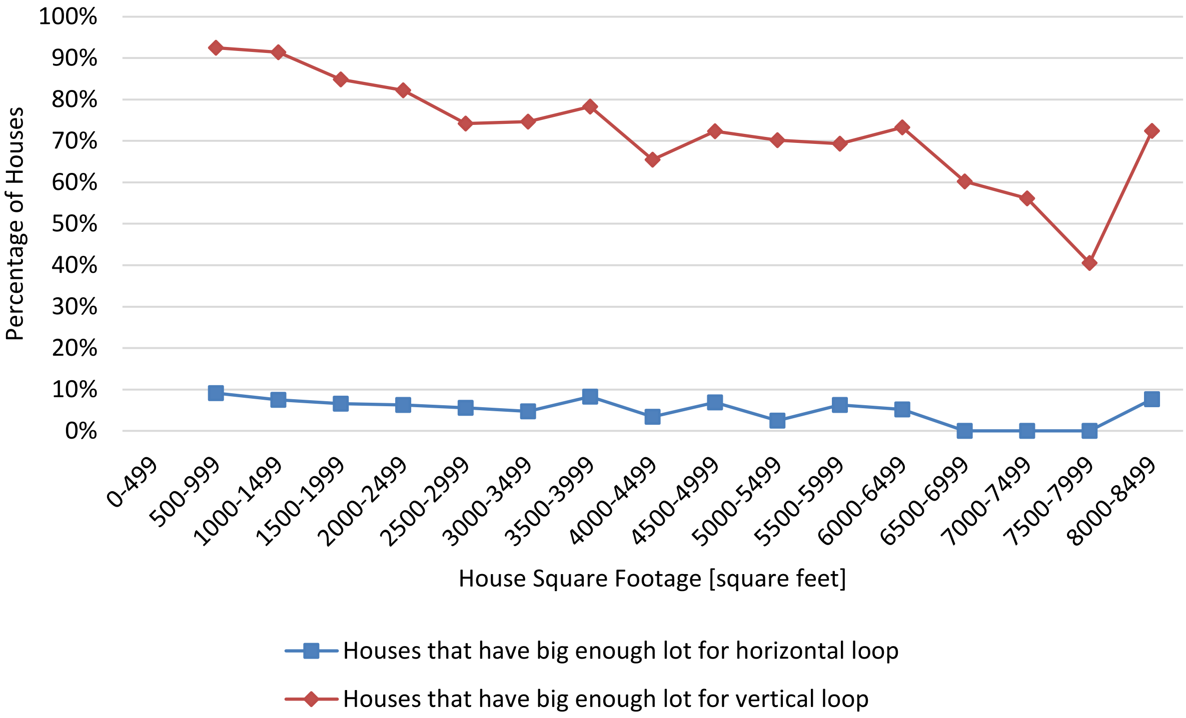

Figure 27. Comparison of the percentage of houses that can use horizontal and vertical loop. Only about 6 percent of U.S. homes of interest can install horizontal loop in their lot whereas 80 percent of them can install vertical loop.

2.4.3.2 Heat Pump Unit

Finding the appropriate size of heat pump is an important part of GHP implementation as undersized or oversized systems can result in less efficiency, which affects the overall performance of the system. Lund (2004) suggests that most units are sized for the peak cooling load and are oversized for heating in the U.S. except in the northern states. Personal interviews with local installers (Cribley Drilling Company 2014, Michigan Energy Services Inc. 2014) and International Geothermal Heat Pump Association revealed that there is no universal rule in sizing heat pump units and local installers often use their own rule in finding the appropriate size. Thus, different sizing methods are tested based on the interviews with the installers and literature review. For instance, heat pump units can be sized to meet cooling demand in the summer and thus are oversized for heating (Curtis 2005), or heat pumps could be sized to meet the dominant energy demand (heating or cooling).

The heat pump database provided by the AHRI directory reveals that heat pump units have different heating and cooling capacities in most cases. Even at the same efficiency level, some heat pumps might have a higher heating capacity than cooling capacity, while the others have a higher cooling capacity than heating capacity. Most houses also have a different energy load for heating and cooling which could make finding the appropriate sized heat pump a challenge.

A set of selection criteria is implemented to systematically select heat pump units that can be used for each RECS entry. When selecting a heat pump unit from the database that can be installed in a house, units must meet either: 1) cooling demand, 2) dominant energy demand between cooling and heating, or 3) both cooling and heating demand for a house. This results in a smaller set of heat pump units with the same cooling or heating capacity depending on the criteria. But often these heat pump units have different efficiency levels and a different cooling or heating demand that is not used for selection criteria. In this case, the average efficiency of the units in a subgroup is taken as representative unit efficiency.

Upon finding a group of heat pump units depending on the selection criteria, different sizing methods are analyzed to systematically find the appropriate size of the unit in homes. In this analysis, heat pump units are sized to meet either: 1) higher energy demand between cooling and heating at home, or 2) higher energy demand at the climate region where a house is located. The first method compares the cooling and heating energy demand at home and the size of the heat pump for the relatively higher energy demand. The second method determines higher energy demand by climate region as defined by the RECS 2009 dataset which is based on Building America Climate Region (DOE 2010b). The heat pump unit is sized to meet house heating demand if the house is located in a very cold/cold climate region whereas the heat pump unit is sized to meet house cooling demand if the house is located in the other climate regions, which include hot-humid, hot-dry/mixed-dry, mixed-humid and marine climate region. Figure 28 and Figure 29 show the results depending on heat pump selection and sizing criteria.

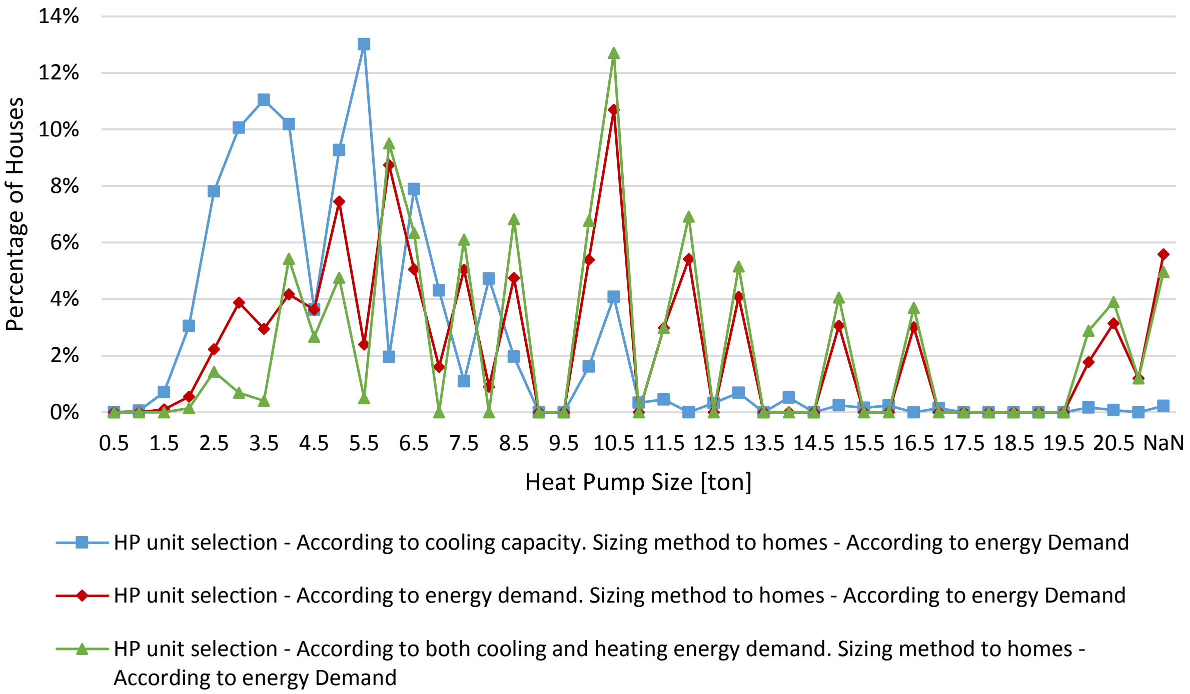

Figure 28. Appropriate heat pump for homes with different heat pump selection criteria when the sizing method is to find heat pumps that meet higher energy demand between cooling and heating at home.

Figure 28 shows the difference among heat pump unit selection criteria when a sizing method is fixed as a higher home energy demand. Smaller heat pumps are selected when the units are selected to meet house cooling demand only. Bigger heat pumps are selected when the units are selected to meet either heating and cooling demand, or higher energy demand between heating and cooling. In the database, the heat pump unit with the largest cooling capacity has a 129,000 btu/hr or 10.75 ton of cooling power. When houses require more cooling or heating energy than a single heat pump unit can provide, two or more units are installed to meet the energy demand. For this analysis, up to two heat pump units with equal capacity are found to be installed at the houses to meet their heating and cooling demands. The houses that require three or more heat pump units are classified as *NaN*. Since larger heat pumps are selected when the units are selected to meet dominant or both energy demands between heating and cooling, more houses are classified as *NaN* in these cases.

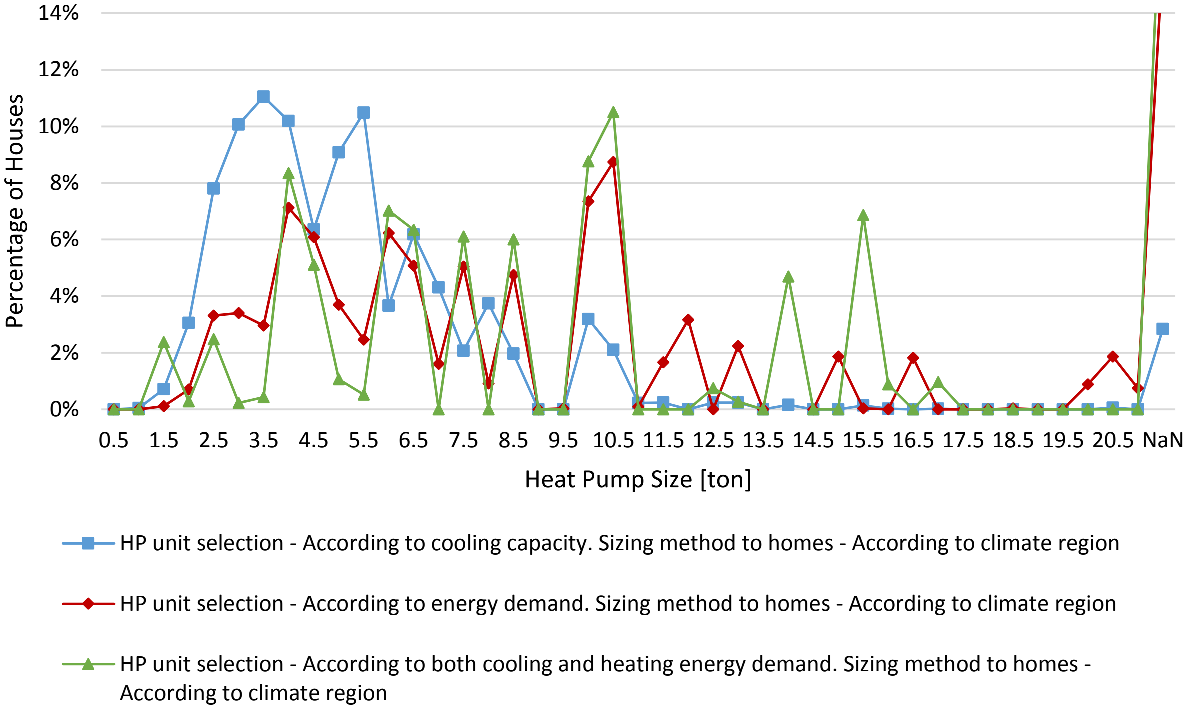

Figure 29. Appropriate heat pump for homes with different heat pump selection criteria when the sizing method is to find heat pumps that meet higher energy demand according to the climate region.

Figure 29 shows the result when the sizing method used climate region to determine dominant energy use at home. Compared to the results in Figure 28, larger heat pump units are selected when climate region is used to determine dominant energy use instead of the actual energy use pattern at home. As a result, about 16 and 20 percent of homes need more than two heat pumps when heat pump units are selected according to the dominant or both cooling and heating energy demand, respectively.

The interviews with the installer (Cribley Drilling Company 2014, Michigan Energy Services Inc. 2014) revealed that the typical heat pump units being installed at homes are around 4 tons. This is best simulated when heat pump units are selected based on house cooling demand and are sized for dominant energy demand between cooling and heating. Therefore, this criterion is selected as a default for the analysis. Once the size of the heat pump units is determined according to the selection criteria, average efficiency of the heat pump unit of that size is assigned to each RECS entry.

About 20 percent of the RECS entries that passed the filtering process using housing characteristics, and heating and cooling equipment as defined in Section 2.1.2 are left with no GHP system after finding the appropriate heat pump unit and ground loop for RECS entries as defined in previous sections. Mostly, this was due to their small lot size. These entries are screened out from the further analysis.

2.5 Switching Scenarios

There are a number of factors that influence how households would switch from the conventional system to the GHP system, some of which include the initial price of the system, and the payback period. To evaluate the performance of the GHP system compared to conventional equipment, a few criteria are assumed for this analysis: 1) Households have to install new heating and cooling equipment in 2015. 2) Households can either install new conventional equipment that meets minimum energy efficiency or install a GHP system. 3) New conventional equipment will have the same equipment size as the old heating and cooling equipment. 4) For the GHP system, three different methods for finding heat pump size and how to size the system are considered for the analysis as defined in section 2.4.3.2:

1. Cooling Demand: Find the heat pump unit according to cooling capacity. Size the system according to dominant energy demand.
2. Dominant Demand: Find the heat pump unit and size the system according to the dominant energy demand at home.
3. Both Demands: Find the heat pump unit according to both cooling and heating demand. Size the system according to the dominant energy demand.

The first option assigns the smallest heat pump system out of the three options and results in a typical heat pump size around 4 tons. The second option can be expected to result in a more ideal sizing as homes are assigned the system that meets its dominant energy demand. The third option results in assigning the biggest heat pump system to the home to meet both heating and cooling demand. These three options can provide a range of results which would help accurately predict GHP performance. For the rest of the sections in methodology, the first option for the GHP system is assumed. Comparison of these three options is presented in the Sensitivity Analysis of section 3.

2.6 Energy Analysis

2.6.1 Weather Normalization of Home Energy Use with Conventional System

The RECS dataset reports the heating and cooling energy use of U.S. households in the year 2009. The RECS 2009 dataset reports annual energy use at home on space heating and cooling in 2009, which is denoted as Unit Energy Consumption (UEC). These data are based on actual meter readings of electricity, natural gas, fuel oil, LPG and kerosene, which EIA acquired from energy suppliers for most of the houses in the RECS dataset. Thus this provides accurate information on energy use at the houses. However, these data only indicate the total amount of energy used in homes throughout 2009. Therefore, EIA developed an end-use model based on statistics to disaggregate this annual fuel consumption into end uses such as space heating, air conditioning, water heating, refrigeration, and other uses (EIA 2013a), as illustrated in Figure 30.

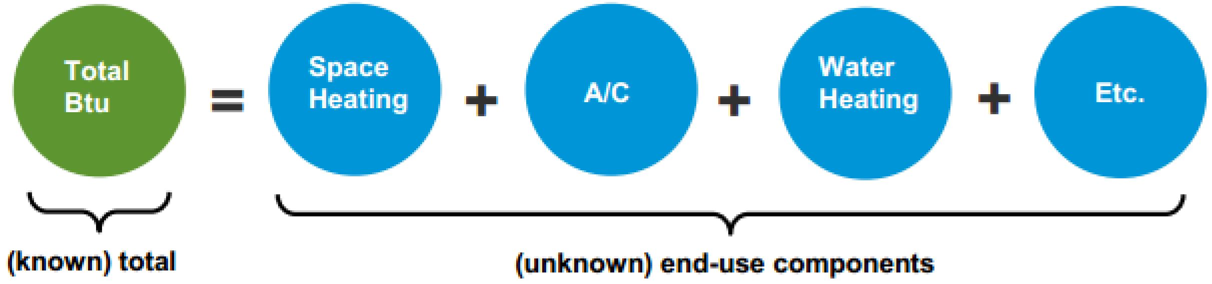

Figure 30. End-use model which EIA used to disaggregate energy use at home into different end uses. This figure is adapted from Residential energy Consumption Survey (RECS) End-Use Models FAQs.

This enables an accurate energy trend analysis by fuel types and by end demands. The end-use model is also used to estimate detailed energy use pattern at homes whose data on energy use and energy bill were not available.

Since 2009 may not represent a typical climate in the region, the reported annual energy use is normalized with weather. The RECS 2009 reports regional degree days data for 2009; also 30-

year averaged degree day data from 1980 to 2010 could be used to normalize UEC by weather. The following equations summarize the calculation:

$$UEC\_C_{CONV\_adj} = UEC\_C_{CONV} * \frac{CDD_{30yr\_avg}}{CDD_{2009}}$$

$$UEC\_H_{CONV\_adj} = UEC\_H_{CONV} * \frac{HDD_{30yr\_avg}}{HDD_{2009}}$$

Where:

$UEC\_C_{CONV\_adj}, UEC\_H_{CONV\_adj}$ = annual unit energy consumption after weather-normalization for cooling and heating, respectively;

UEC_C_{CONV} , UEC_H_{CONV} = annual unit energy consumption as reported in the RECS 2009 dataset for cooling and heating, respectively;

CDD_{30yr_avg} , HDD_{30yr_avg} = 30 year averaged (1981-2010) cooling degree days (CDD) and heating degree days (HDD) at the region where housing unit is located with base temperature of 65°F;

CDD_{2009} , HDD_{2009} = CDD and HDD in 2009 at the region where housing unit is located with base temperature of 65°F.

2.6.2 Home Energy Use with GHP System

The annual energy use at homes reported in the RECS 2009 dataset is with conventional heating and cooling systems since no homes in the survey had the GHP system. To calculate heating and cooling energy use with the GHP system, the weather-normalized energy use is first multiplied by the conventional equipment efficiency as found in section 2.2.1.3 to yield heating and cooling energy required at home. This represents the amount of heating and cooling energy demand at home that has to be met by heating and cooling equipment. Then this unit energy requirement is divided by GHP efficiency found in section 2.4.3.2 to result in the amount of heating and cooling energy consumption expected for the GHP system to provide the same amount of heating and cooling energy that is supplied by the conventional systems. The following equations summarize this calculation of energy use with the GHP system:

$$UEC\_C_{GHP\_adj} = UEC\_C_{CONV\_adj} * \frac{Eff\_C_{CONV}}{Eff\_C_{GHP}}$$

$$UEC\_H_{GHP\_adj} = UEC\_H_{CONV\_adj} * \frac{Eff\_H_{CONV}}{Eff\_H_{GHP}}$$

Where:

$UEC\_C_{GHP\_adj}$, $UEC\_H_{GHP\_adj}$ = annual unit energy consumption after weather-normalization for cooling and heating with GHP system, respectively;
$UEC\_C_{CONV\_adj}$, $UEC\_H_{CONV\_adj}$ = annual unit energy consumption after weather-normalization for cooling and heating with conventional system, respectively;
Eff_C_{CONV}, Eff_H_{CONV} = energy efficiency of the conventional for cooling and heating system, respectively;
Eff_C_{GHP}, Eff_H_{GHP} = energy efficiency of the GHP for cooling and heating, respectively.

Comparing unit energy consumption using GHP at home with unit energy consumption using the conventional system shows the potential energy saving with the GHP system as illustrated in Figure 31 and Figure 32. The graphs show more fluctuation with houses whose square footage is bigger than 5,000 square feet due to smaller sample size.

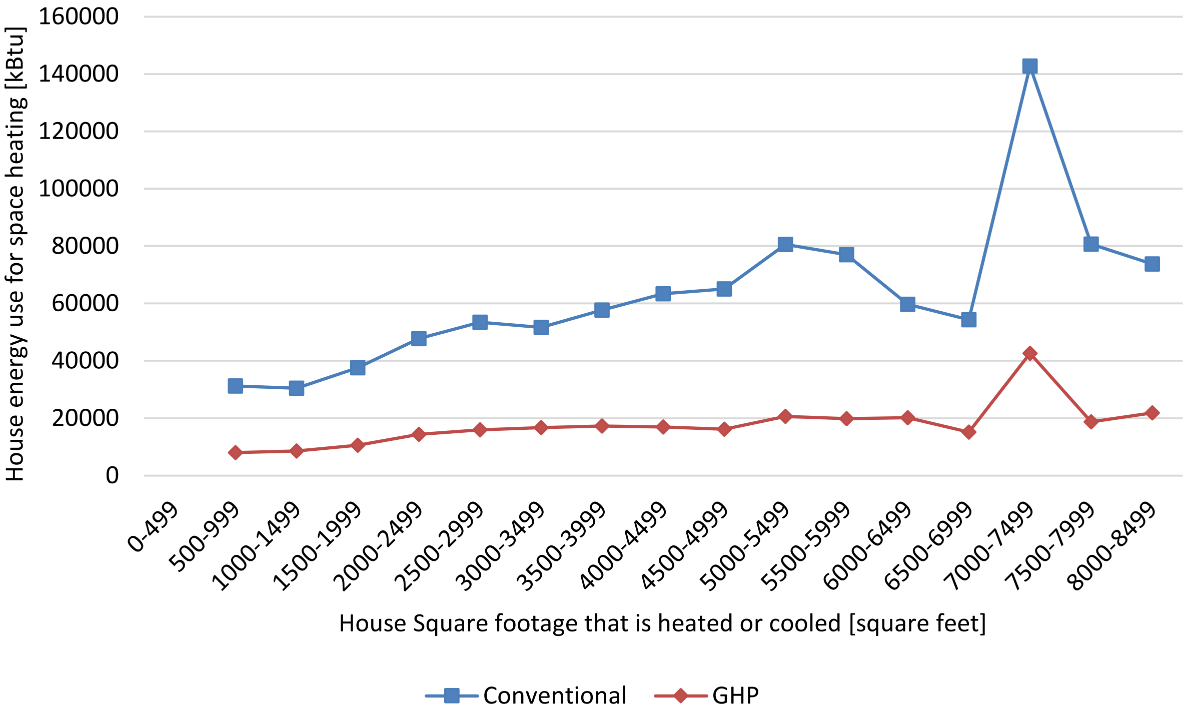

Figure 31. Heating energy use at homes with the conventional and GHP systems. Each data point represents average heating energy use for the RECS entries that belong to the house size bin.

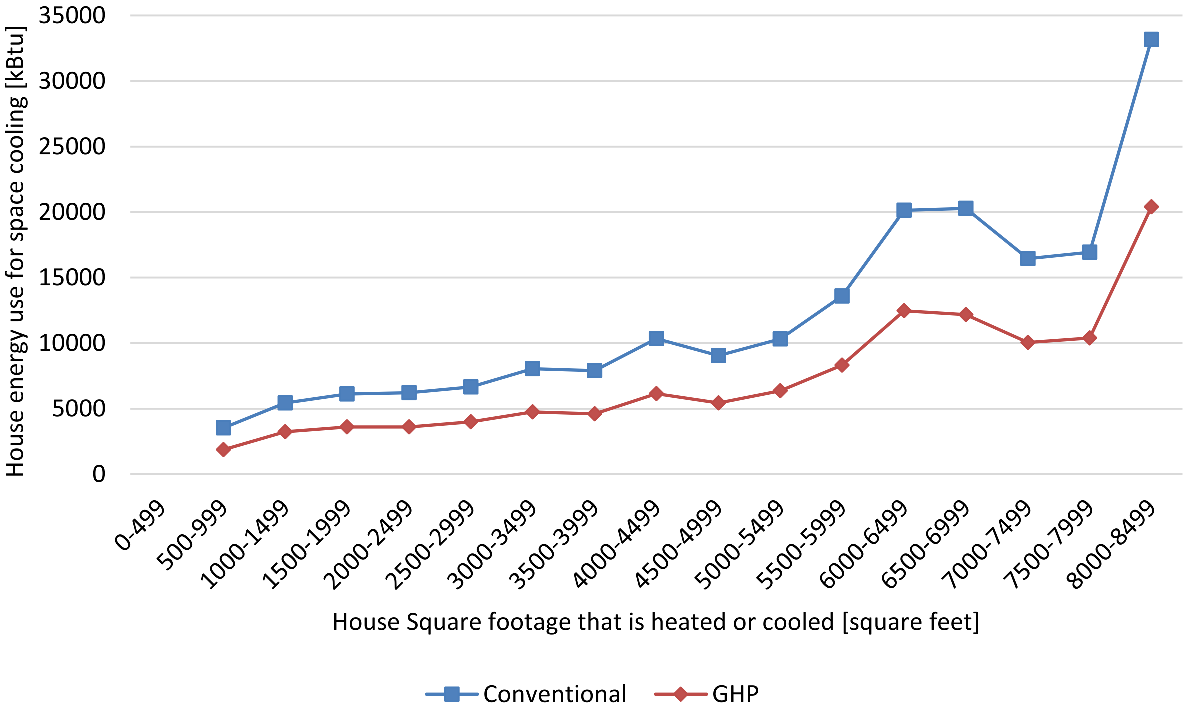

Figure 32. Cooling energy use at homes with conventional and GHP systems. Each data point represents the average cooling energy use for the RECS entries that belong to the house size bin.

Due to its higher efficiency level, GHP consumes less energy for both heating and cooling compared to conventional equipment. The difference between the energy use of conventional and GHP systems denotes the energy savings. Note the energy saving from heating is bigger than that from cooling which is consistent with the findings of Stein (1997).

Figure 31 and Figure 32 also show that larger homes use more energy for space heating and cooling. This increase in energy demand for larger homes mostly come from larger space to heat and cool as equipment efficiency of both conventional and GHP system is relatively constant throughout the equipment size as shown in Figure 33.

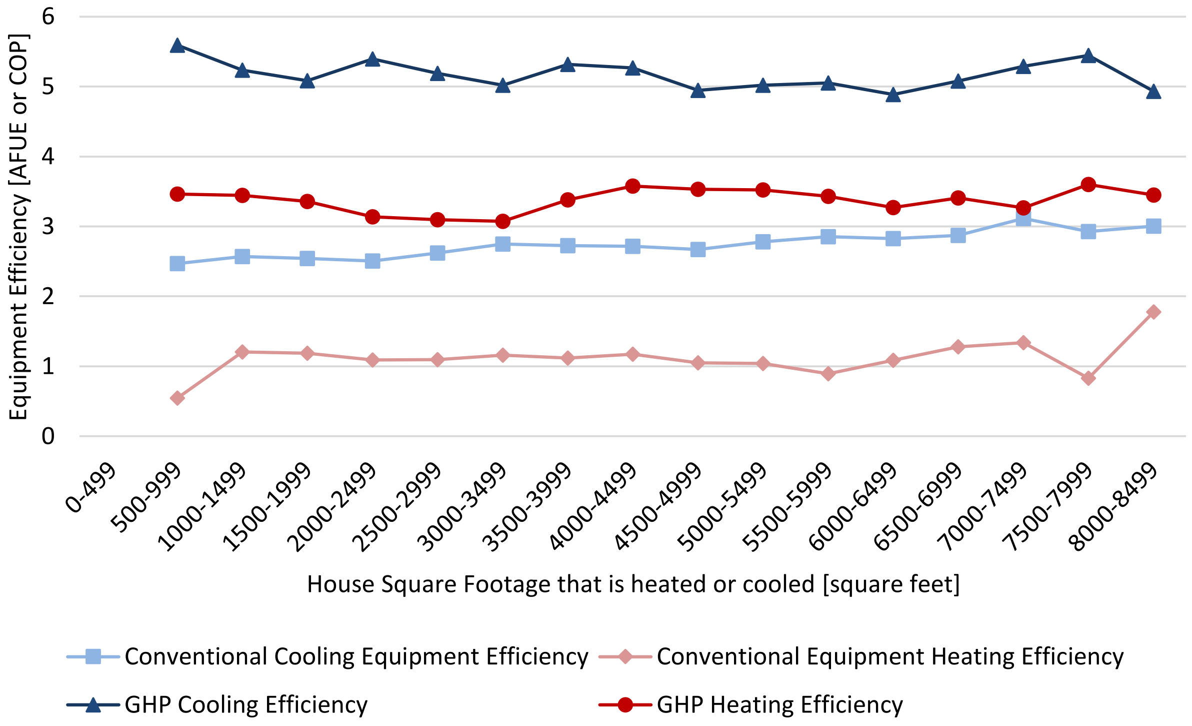

Figure 33. Average heating and cooling efficiency of the conventional and GHP equipment. Fluctuation at the lower and higher end of the house size is due to smaller sample size. Efficiency of heating equipment is measured in AFUE whereas that of cooling equipment is measured in COP. The default selection method from section 2.5 of finding heat pump unit according to cooling capacity and sizing the system according to dominant energy demand is used.

Also, regional analysis shows that most of the energy savings occur in cold regions (e.g., TSD climate region north) where heating is the dominant form of home energy use. This is shown in Figure 34.

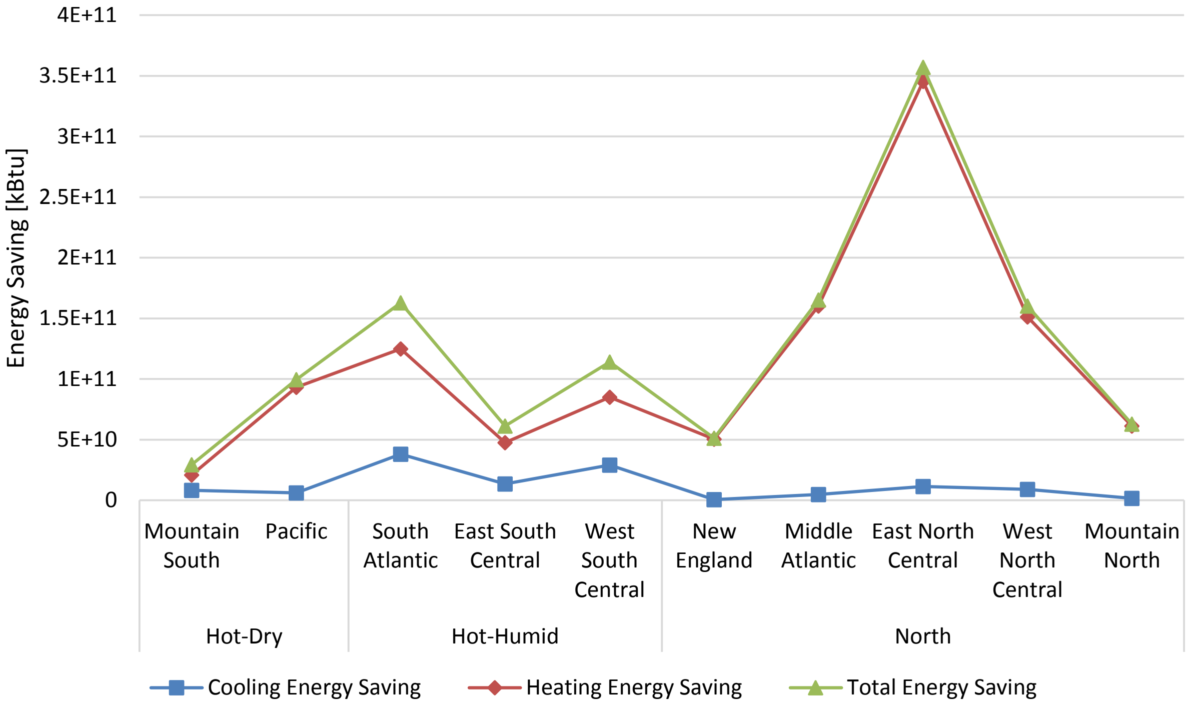

Figure 34. Energy savings with GHP system for space heating and cooling by census division and TSD climate region.

Overall, these results suggest that if all houses which can replace their conventional heating and cooling equipment with the GHP systems switched to GHP, a national energy saving would be around 1.26 quad every year. On average, this translates to 33,204 kBtu of energy savings per house over one year. This is equivalent to 31 percent of total home energy use or 66 percent of energy spent on space heating and cooling at residential houses of study. As can be observed at Figure 31 and Figure 32, 90 percent of this savings comes from heating energy savings.

2.7 Life-cycle Greenhouse Gas Emissions Analysis

2.7.1 GHG Emissions from Electricity Generation

Not all GHG emissions associated with space heating and cooling occur at the house. The GHG can be emitted from a remote power plant where electricity is generated and also from gas plants where natural gas is extracted. These upstream emissions that are associated with electricity and heating fuel generation and delivery are included to capture life-cycle GHG emission of space heating and cooling. The GHG emissions associated with the production and delivery of heating and cooling equipment are not included in this analysis.

To calculate the life-cycle GHG emission factors associated with the electricity generation, the Emissions & Generation Resource Integrated Database (eGRID) from the U.S. EPA (EPA 2012) and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model from Argonne National Laboratory (Wang 2010) are utilized. The eGRID contains comprehensive data on environmental characteristics of most of the power plants in the U.S. in terms of generator, plant and state level along with grid loss factor. To perform state-level emission analysis, GHG emission data from electricity generation are obtained from the eGRID2012 version 1.0 state file which contains the 2009 GHG emission data by plant type along with the transmission loss factor by regions. These emission data are divided by the percentage of electricity actually delivered to the houses to calculate the total emission factor from electricity generation at the power plants.

The GREET model is designed to evaluate energy and emission impacts of vehicle and transportation technologies and consists of two main components: GREET 1 model for a fuel-cycle and GREET 2 model for vehicle-cycle. The upstream emissions data of the power plants that burn coal, natural gas, oil, and biomass along with nuclear and hydroelectric plants are adapted from the GREET 1 model. These upstream emissions factors are multiplied by the percentage of electricity generation by each plant type (coal, natural gas, oil, biomass, nuclear, and hydroelectric) and divided by the percentage of electricity actually delivered to the houses to calculate GHG emission factor of the upstream. The total amount of GHG emissions from electricity generation due to unit energy consumption at homes can be calculated by adding emission resulted from upstream and electricity generation. The following equations summarize the GHG calculations:

$$GHG_{Electricity} = GHG_{Generation\_Adj} + GHG_{Upstream\_Adj}$$

$$GHG_{Generation\_Adj} = \frac{GHG_{Generation\_state}}{1 - GridLossFactor}$$

$$GHG_{Upstream\_Adj} = \frac{GHG_{Upstream\_state}}{1 - GridLossFactor}$$

$$GHG_{Upstream\_state} = \sum \rho * GHG_{Upstream\_plattype}$$

Where:

$GHG_{Electricity}$ = total GHG emissions per unit electricity use (gCO$_2$eq/kWh) at home from the state where the sample house is located;

$GHG_{Generation\_Adj}$ = GHG emissions per unit electricity use at home by power plant operation from the state where the sample house is located;

$GHG_{Upstream\_Adj}$ = GHG emissions per unit electricity use at home by fuel extraction and delivery to the power plant from the state where the sample house is located;

$GHG_{Generation\_state}$ = GHG emissions per unit electricity use at home by power plant operation before grid loss correction from the state where the sample house is located;

$GHG_{Upstream\_state}$ = GHG emissions per unit electricity use at home by fuel extraction and delivery to the power plant before grid loss correction from the state where the sample house is located;

$GridLossFactor$ = percentage of electricity lost during transmission due to electrical resistance and heating of conductors;

ρ = percentage of electricity generation by specific fuels (coal, oil, natural gas, nuclear, hydro) and by state;

$GHG_{Upstream\_plattype}$ = GHG emissions per unit electricity use at home by fuel extraction and delivery to the power plant by fuel type (coal, oil, natural gas, nuclear, hydro) before grid loss correction from the state where the sample house is located.

Data used for the calculation can be found in Appendix E and Table 7 summarizes the life-cycle GHG emissions factors for electricity per state.

Table 7 Life-cycle GHG emissions factor of electricity grid in the states.

State	Life-cycle GHG Emission Factor [gCO$_2$eq/kWh]
Alabama	561.7
Alaska	647.2
Arizona	591.3
Arkansas	611.1
California	361.5
Colorado	937.4
Connecticut	338.0
Delaware	949.8
District of Columbia	1341.5
Florida	674.7
Georgia	680.2
Hawaii	873.1
Idaho	78.2
Illinois	567.5
Indiana	1041.8
Iowa	831.9
Kansas	859.7
Kentucky	1047.1
Louisiana	633.6
Maine	326.6
Maryland	639.6
Massachusetts	634.3
Michigan	791.6
Minnesota	721.8
Mississippi	619.3
Missouri	927.5
Montana	751.5
Nebraska	816.4
Nevada	618.6
New Hampshire	347.7
New Jersey	325.8
New Mexico	952.8
New York	347.7
North Carolina	617.8
North Dakota	1044.9
Ohio	916.8
Oklahoma	812.4
Oregon	225.0
Pennsylvania	603.5
Rhode Island	568.7
South Carolina	440.9
South Dakota	466.4
Tennessee	554.4
Texas	705.7
Utah	989.2
Vermont	16.5
Virginia	536.2
Washington	164.9
West Virginia	1027.7
Wisconsin	786.5
Wyoming	1105.2
U.S. Average	656.0

Regional GHG emissions factors of electricity grids ranges from 16.5 (Vermont) to 1341.5 (District of Columbia) gCO$_2$eq/kWh with a national average of 656 gCO$_2$eq/kWh. Fuel mix of the electricity grid is the major cause of this variability. This GHG emissions factor can be used to calculate the life-cycle GHG emissions at homes which use electric heaters, heat pumps, central and window/wall air conditioners, and the GHP system.

2.7.2 GHG Emissions from On-Site Combustion

A dataset from a source energy and emission report (Deru 2007) prepared by the National Renewable Energy Laboratory (NREL) is used to calculate GHG emissions associated with the conventional heating equipment that burns fuels on-site. This includes forced-air furnace systems that burn natural gas, fuel oil, and LPG. This dataset contains national averaged data that can be used to calculate GHG emissions associated with the extraction, processing, and delivery of the fuel to homes as well as emissions from the combustion process that provides heating.

The GHG emissions associated with the delivery of fuel to homes (pre-combustion) and combustion of the fuel with the heating equipment are taken from the report. The summation of pre-combustion and combustion emissions needs to be weighted by the source energy factor and the reciprocal of higher heating value to account for upstream GHG emission. This results in the GHG emissions factor for on-site fuel combustion at homes which is illustrated in the following equation:

$$GHG_{OnSite} = \frac{SourceEnergyFactor}{HigherHeatingValue} * (GHG_{Precombustion} + GHG_{Combustion})$$

Where:

GHG_{OnSite} = total GHG emissions per unit energy use (gCO_2eq/Btu) at home that occur at the house during the use of the equipment;
$SourceEnergyFactor$ = factor that represent the energy required to extract, process and deliver the fuel to homes per unit of energy embodied in the fuel;
$HigherHeatingValue$ = embodied energy in the fuel per unit mass or volume of the fuel;
$GHG_{Precombustion}$ = GHG emissions associated with the delivery of the fuel to homes per unit mass of volume of the fuel;
$GHG_{Combustion}$ = GHG emissions associated with the combustion of the fuel at the house for heating per unit mass or volume of the fuel.

The dataset only includes the GHG emissions data for residential furnaces that burn natural gas. The emissions factors for furnace systems that burn LPG or fuel oil are derived from residential boilers. The relative emissions factors of boiler systems that burn natural gas, LPG, or fuel oil are assumed to be similar to that of furnace system and thus the emissions factors of furnace systems that burn LPG or fuel oil are scaled with that relative emissions factor. Table 8 shows the values used in this analysis.

Table 8. Factors used to calculate the GHG emissions factor for residential furnaces by heating fuels. Values are based on NREL report on Source Energy and Emission Factors for Energy Use in Buildings.

Heating Fuel	Source Energy Factor	Higher Heating Value [Btu/(ft3 or gal)]	Pre-combustion Factor [lbCO2eq/(ft3 or gal)]	Combustion Factor for Residential Furnace [lbCO2eq/(ft3 or gal)]
Natural Gas	1.092	1010	0.0278	0.121
Propane / LPG	1.151	91000	2.56	13.280
Fuel Oil	1.191	149500	4.47	25.183

Calculations using Table 8 data show that the on-site GHG emissions rate with furnace systems that burn natural gas, propane, and fuel oil are 249, 310, and 366 gCO2eq/kWh, respectively. Natural gas results in the lowest emissions rate among these fuels and these emission rates are generally lower than those from electricity used at home as found in Table 7.

2.7.3 GHG Analysis - Results

Applying these calculations to RECS entries yields life-cycle GHG emissions at home due to space heating and cooling. The results show the relationship between GHG emissions and house size, and geographical region.

GHG Emission and House Size

Figure 35 shows the overall correlation of GHG emissions and house size. As expected, these trends are very similar to those found in Figure 31 and Figure 32, which shows heating and cooling energy use at home by house square footage. More GHG emissions occurred from space heating and cooling at larger houses for both conventional and GHP systems. And Figure 33 confirms that this increase in energy use in larger homes is not due to lower GHP efficiency in these houses. This means the energy increase for heating and cooling is mostly attributable to increase in space, which agrees with the findings from the energy analysis.

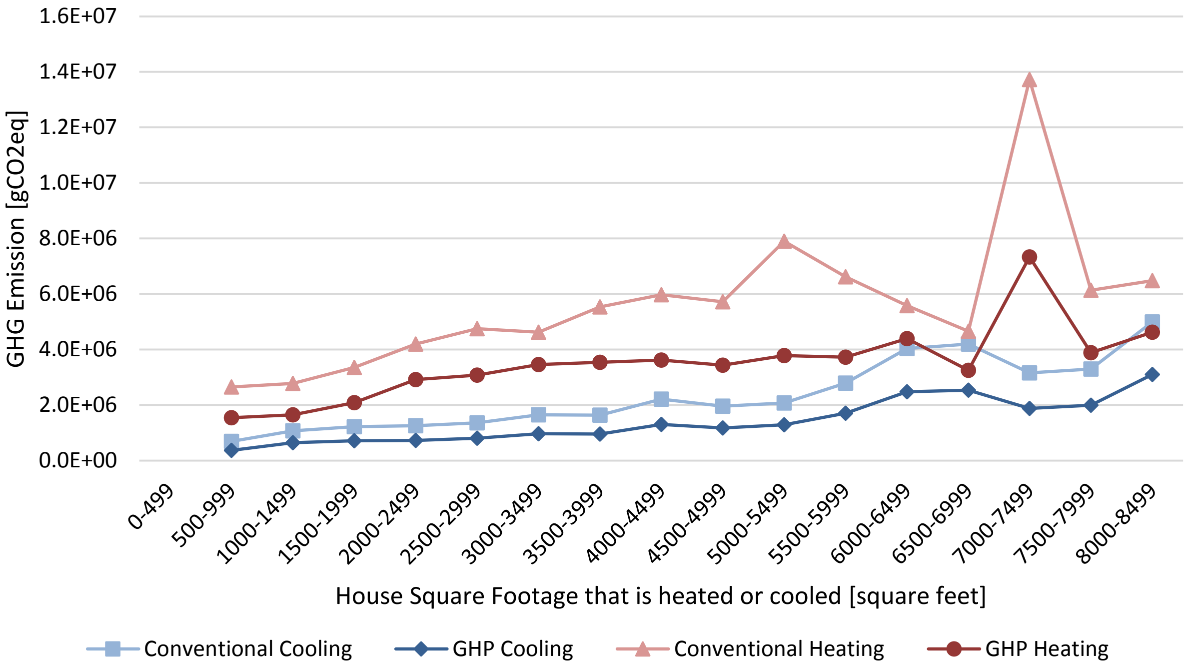

Figure 35. Average GHG emissions from space heating and cooling. Life-cycle GHG emission from conventional system and GHP system for heating and cooling are plotted for direct comparison of emission level.

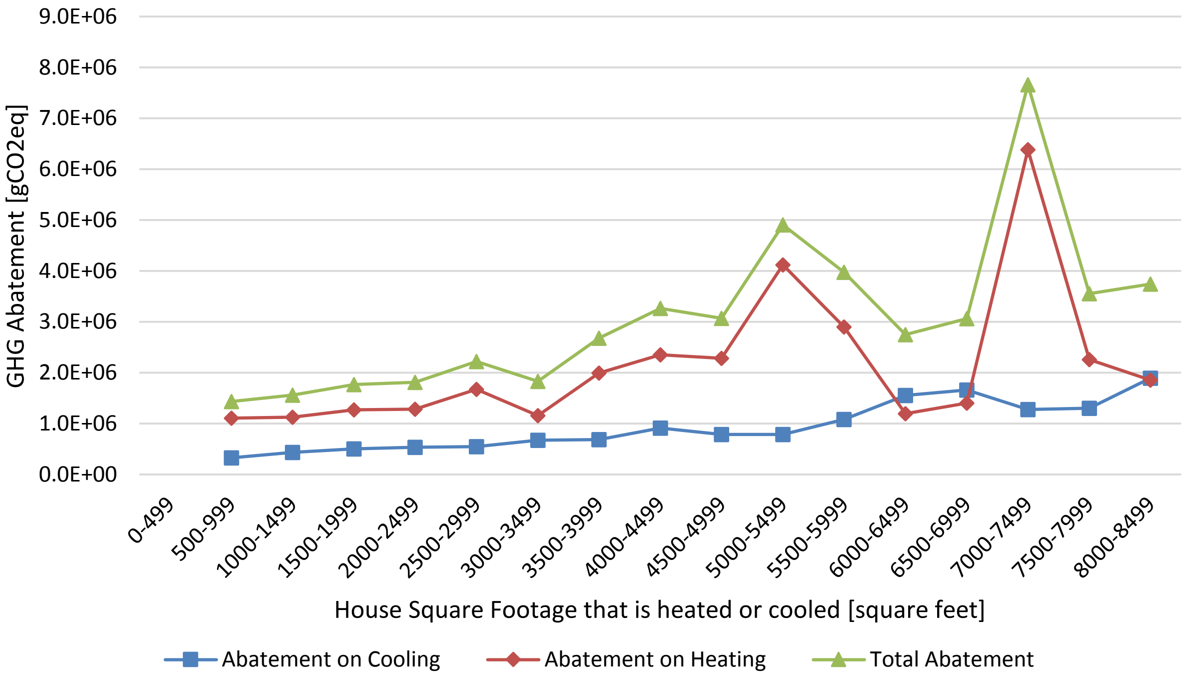

Figure 36. GHG abatement from heating and cooling energy use when conventional equipment is switched with GHP system.

Figure 36 illustrates GHG abatement by switching to the GHP system. This can be also inferred by calculating the gap between GHG emissions from conventional and GHP systems in Figure 35. Since more energy is used in larger homes, more GHG can be abated with the GHP system in these homes.

Overall, if all houses with GHP potential switch to GHP systems, 76 million tonCO2eq of GHG would be abated nationwide every year. On average, this translates into about 1.99 tonCO2eq of GHG abatement per home. About 68 percent of this abatement would come from energy savings from heating while the rest comes from the energy savings from cooling.

GHG Emissions by Geographical Region

The GHG emissions data can be organized in terms of geographical region to identify key regions where the GHP system would bring about the most benefits, and to figure out appropriate strategies for effective GHG abatement. For this analysis, the GHG emissions results are organized in terms of TSD climate region and census division as defined in the RECS 2009 dataset. The total amount of GHG emissions from conventional heating and cooling equipment and the total amount of GHG abatement with the GHP system are shown in Figure 37 and Figure 38:

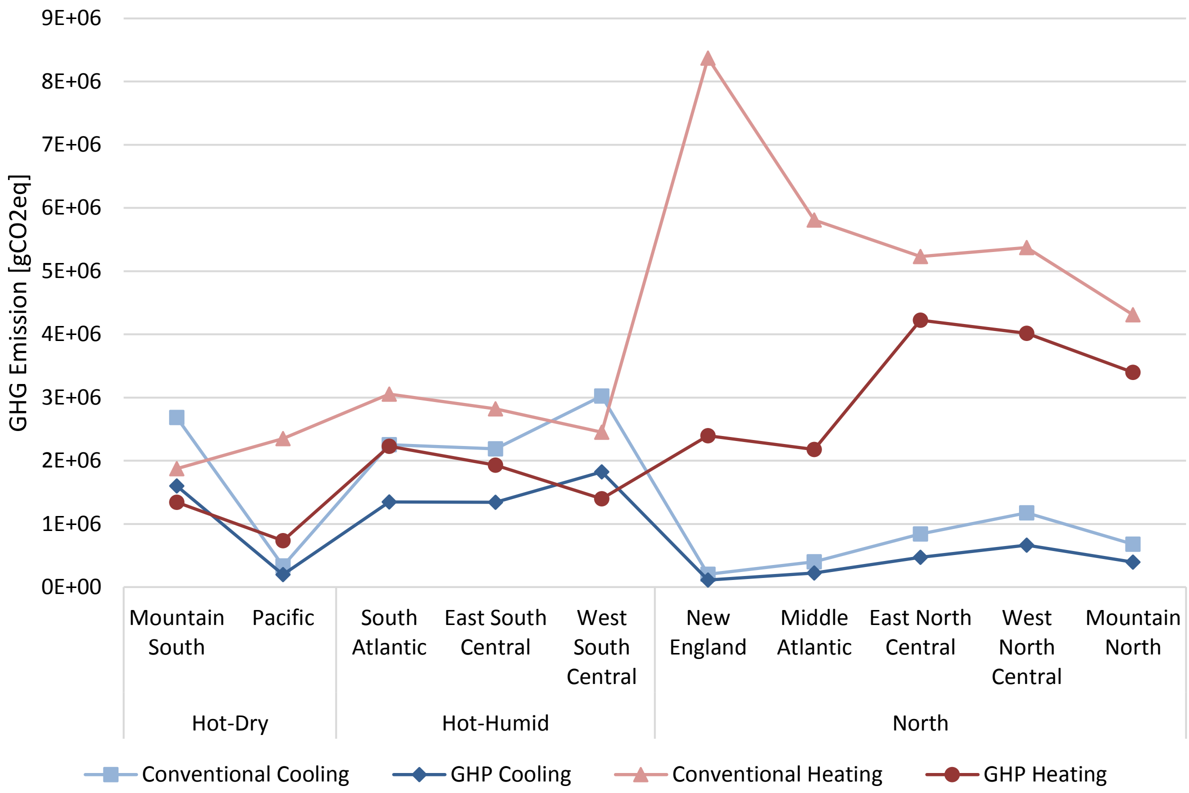

Figure 37. Average GHG emissions from space heating and cooling at homes by geographical region. Census division and TSD climate region are utilized for region reference.

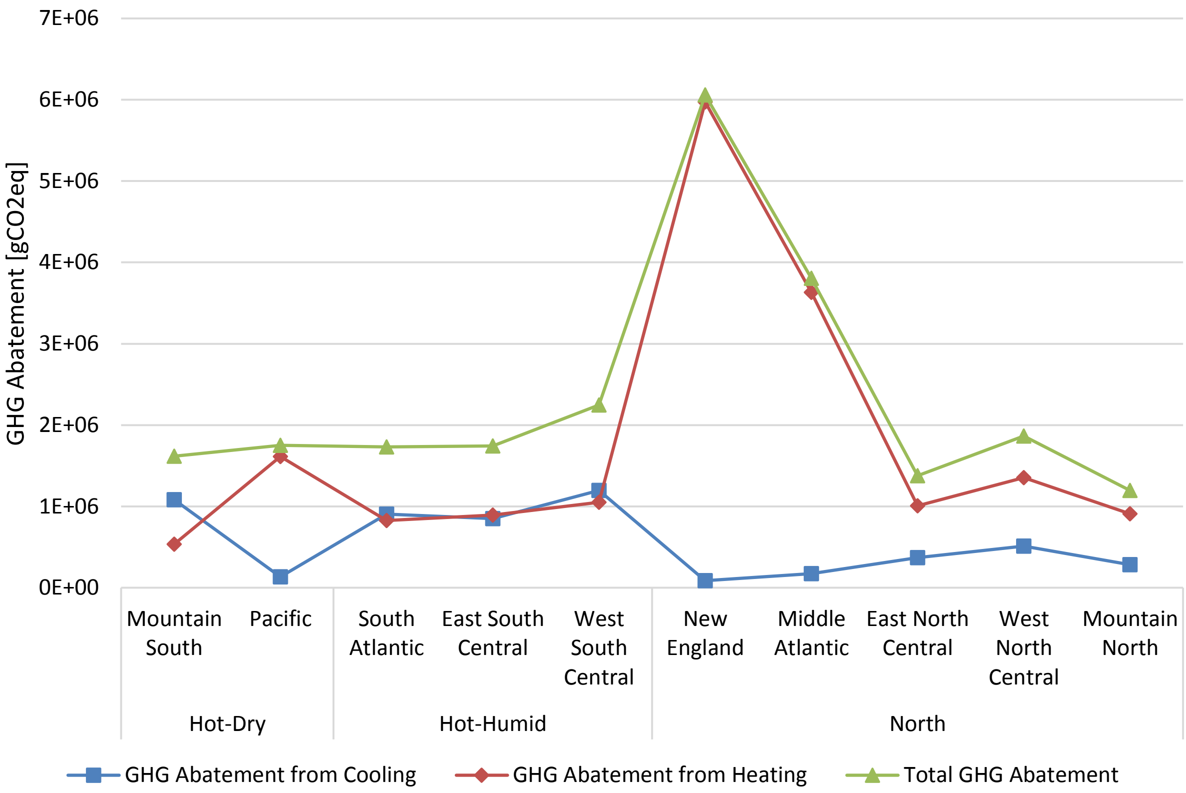

Figure 38. GHG abatement by switching from conventional equipment to the GHP system by census division and TSD climate region.

Comparing regional analysis of energy savings and GHG abatement shows that the region with the most energy savings does not necessarily coincide with the region with the most GHG abatement (Figure 34 and Figure 38). Both energy savings and GHG abatement occurred the most in TSD climate region North where heating is the dominant home energy use, followed by TSD climate region Hot-Humid where both heating and cooling are needed.

However, a comparison of census division level shows a discrepancy between the energy saving trend and that of GHG abatement. For example, census division East North Central shows the largest heating energy saving among census divisions, but the GHG abatement in this region is below average. On the other hand, the New England division shows the largest GHG abatement despite below-average energy savings. To explain this discrepancy, the GHG emissions factor of electricity grid and other heating fuels is analyzed.

Impact of GHG Emissions Factor on the Grid and Other Heating Fuels

To systematically compare energy savings and GHG abatement at each geographical region, the percentage of energy savings and GHG abatement at each region are calculated among census division, and the difference between percentage of energy savings and GHG abatement is also calculated. This provides a metric to compare the GHG abatement with the energy savings in the region. To identify and analyze major factors that contribute to this behavior, the GHG emissions rate of the electric grid and the contribution of GHG emissions by major heating fuels are investigated as shown in Table 9 below:

Table 9. Comparison of relationship between energy savings and GHG reduction by switching to the GHP system. Data highlighted with orange indicate less GHG reduction compared to energy saving and data highlighted with light green and green indicate more GHG reduction compared to energy saving. This relative GHG reduction performance compared to energy saving is dictated by the grid intensity in the regions highlighted with light green, and percentage of GHG emitted by the grid in the regions highlighted with green This difference in performance stems from fuel used for space heating and space cooling, especially the composition of electricity and natural gas use at homes.

TSD Climate Region	Census Division (RECS 2009)	% GHG Abatement - % Energy Saving			Average Grid Intensity [gCO2eq/kWh]	Relative Deviation of Grid Intensity	% GHG Emission by Heating Fuel				
		Heating	Cooling	Heating and Cooling			Electricity	Natural Gas	Propane / LPG	Fuel Oil	Kerosene
Hot-Dry	Mountain South	-0.2%	-0.3%	0.9%	672.5	2.5%	23%	68%	6%	4%	0%
	Pacific	4.9%	-2.2%	1.8%	307.5	-53.1%	8%	84%	5%	4%	0%
Hot-Humid	South Atlantic	2.5%	-1.2%	5.8%	655.7	0.0%	45%	42%	5%	8%	0%
	East South Central	1.0%	0.1%	2.2%	689.3	5.1%	48%	44%	8%	0%	0%
	West South Central	1.8%	1.3%	5.2%	699.3	6.6%	35%	58%	6%	0%	0%
North	New England	3.8%	-0.1%	1.7%	428.3	-34.7%	1%	24%	0%	75%	0%
	Middle Atlantic	7.3%	-1.4%	2.2%	479.9	-26.8%	3%	65%	8%	25%	0%
	East North Central	-13.7%	1.7%	-13.3%	795.7	21.3%	8%	80%	9%	3%	0%
	West North Central	-4.7%	1.9%	-3.9%	856.4	30.5%	17%	61%	20%	3%	0%
	Mountain North	-2.7%	0.2%	-2.6%	902.7	37.6%	6%	90%	4%	0%	0%

The '% GHG Abatement - % Energy Saving' can be used to analyze the trend of energy savings and GHG abatement; a positive value indicates more GHG abatement compared to energy savings, whereas a negative value indicates less GHG abatement compared to energy savings.

As shown in Table 9, the overall trend is dictated by heating as it dominates both energy savings and GHG abatement as found in previous sections.

The ‘Average Grid Intensity’ is the life-cycle GHG emissions factor of the electric grid as found in Table 7, aggregated into census division level. To systematically assess its regional variability, another metric of ‘Relative Deviation of Grid Intensity’ is derived. This metric is found by calculating its deviation from the average in each census division, and dividing it by national average grid intensity. A positive value indicates a higher GHG emissions rate than the national average whereas a negative value means fewer emissions than average. As indicated with orange and green highlights, these relative deviations of grid intensity are strongly associated with % GHG Abatement - % Energy Saving trend in Hot-Dry and North TSD climate regions. This is due to the fact that the GHG emissions factor for furnaces that burn fuels other than electricity do not vary across regions unlike that for the electric grid. Therefore, the performance of the electric grid (Relative Deviation of Grid Intensity) dictates the performance of GHG abatement (% GHG Abatement - % Energy Saving). The regions highlighted with light green best exemplify this pattern. When switching to the GHP system, the scale of GHG abatement would be relatively less than that of energy savings if the electric grid is dirty (higher Relative Deviation of Grid Intensity). On the other hand, if the electric grid is clean (lower Relative Deviation of Grid Intensity), the scale of GHG abatement would be comparable to that of energy savings with the GHP system.

On the other hand, performance in Hot-Humid TSD region (green highlight) is more closely associated with the percentage of GHG emitted from electricity use for heating. Since Relative Deviation of Grid Intensity in this region does not deviate much from the average (less than 7 percent), this does not deteriorate GHP performance in GHG abatement as it did in the North TSD region. In addition, GHG emitted from electricity used for heating is higher than other regions, which means switching to GHP system will replace more of these “dirty” heating systems and enhance GHG abatement performance of the GHP system.

In the Mountain South census division, all of these factors play out equally to average out GHP performance in this region. Relatively low Relative Deviation of Grid Intensity enhances GHP performance, whereas its relatively high percentage of GHG emissions from electricity used for heating lowers the GHP performance, averaging out GHP performance in GHG abatement.

Therefore, GHG abatement per energy savings can be maximized if policy encourages GHP system implementation in regions highlighted with dark green and green in Table 9 first. However, GHG abatement per house can be maximized if policy encourages GHP system implementation in the TSD North region first, as most of the energy savings and GHG abatement comes from space heating.

2.8 Economic Analysis

2.8.1 Capital Cost

Capital cost is an initial cost of the system that includes price of the equipment along with labor and installation. Neither the RECS 2009 nor AHS 2011 dataset provide information on the cost of the system, so capital cost of the conventional system and GHP system is calculated based on literature review and interviews with local installers.

2.8.1.1 GHP System Cost

Few published papers analyze the economics of the GHP system itself. Kavanaugh (1995) reports the price breakdown of the GHP system based on cost survey to various companies and individuals associated with the technology. Based on this cost survey, the paper provides a detailed component-by-component price analysis for a 3-ton system with horizontal, vertical and slinky loop. A more recent paper from Oak Ridge National Laboratory (Liu, 2010) finds that this result still represents the system price of GHP well if the price of the heat pump is updated to the current level. Using data from Kavanaugh (1995) and Liu (2010), the price breakdown of GHP is shown in Table 10.

Table 10. Price breakdown of 3-ton GHP system with vertical ground loop as adapted by Kavanaugh 1995 and Liu 2010.

Price for 3-ton GHP System with Vertical Loop		Kavanaugh 1995	Liu 2010	
		1995 $	2010 $	2010 $ Updated Heat Pump
Ground Loop	Labor	$ 2,465	$ 3,469	$ 3,469
	Loop	$ 612	$ 861	$ 861
Heat Pump		$ 2,717	$ 3,823	$ 6,911
Interior Installation		$ 1,898	$ 2,671	$ 2,671
Ductwork		$ 1,305	$ 1,836	$ 1,836
New Construction Price		$ 8,997	$ 12,660	$ 15,748
Retrofit Price		$ 5,794	$ 8,153	$ 11,241

Kavanaugh (1995) shows that ground loop is the most expensive major component of the GHP system (34 %). Most of this ground loop price comes from drilling for the borehole, which is classified as labor (80 % of ground loop price). Interior installation cost includes thermostats, auxiliary heat, wiring, unit connections, non-loop related labor, overhead and profit, while ductwork includes price associated with the installation of the duct system at houses (Kavanaugh 1995). These costs for interior installation and ductwork do not occur in retrofits because homes with forced-air systems already have these features. Thus only the price for heat pump and ground loop systems are included in the total price for the GHP retrofit.

Liu (2010) adopted this price breakdown of the GHP system from Kavanaugh (1995) for his analysis. In adopting data, Liu used a higher end of the price range provided at Kavanaugh (1995) and used a 2.47 annual inflation factor between 1995 and 2010 for price correction. This resulted in $ 12,660 for new construction for the 3-ton GHP system in 2010, which Liu (2010) found comparable to other literature. However, Liu (2010) further updated the price of heat pump to better characterize state-of-the-art GHP systems which have an energy efficiency ratio (EER) of 18.2 and a COP of 4 at full capacity. This represents heat pumps with a higher efficiency from the AHRI directory. As this efficiency level is well within the efficiency range of the heat pump from the AHRI directory, this updated heat pump price is adopted in this study. The price breakdown of the 3-ton GHP system in 2010 with updated heat pump price is as shown in

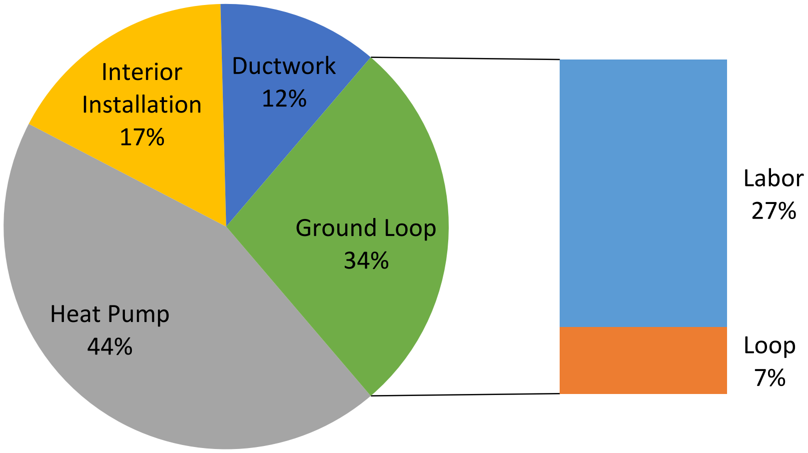

Figure 39.

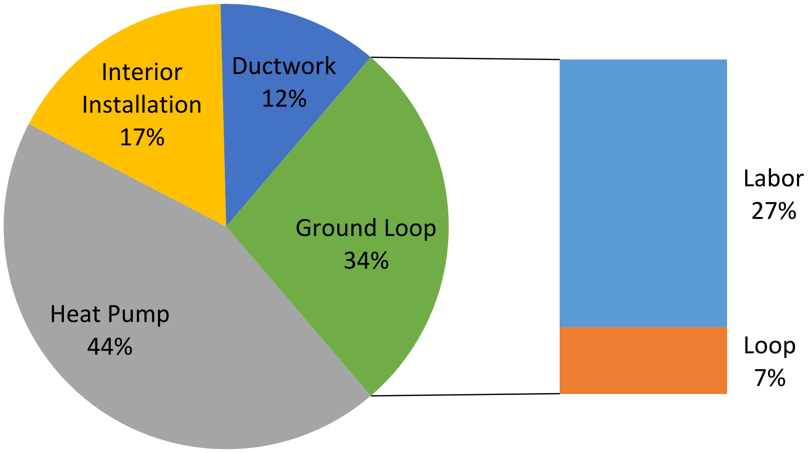

Figure 39. Price breakdown of the 3-ton GHP system adopted from Liu (2010). The price of all components except the heat pump is adopted from Kavanaugh (1995). For the retrofit of existing house stocks, costs for interior installation and ductwork are excluded.

This results in an increase in the cost of GHP retrofit to $11,241 for the 3-ton system with a vertical loop, which is comparable to other literature. Cummings (2008) indicates that in Indiana, the average cost of a retrofit with a 3-ton GHP system is $ 13,894 with 1.3 percent of the cumulative inflation rate between 2008 and 2010. More recent analysis on GHP installation at Department of Defense facilities (SOD 2007) finds that the average cost of GHP systems is $4,600 per ton in 2006 or $13,800 for a 3-ton system. This is equal to $14,926 for the 3-ton in 2010 with a cumulative inflation rate of 8.16 percent. Lastly, a study of economics of GHP system by Bloomquist (2001) finds that average capital cost of the GHP system with vertical loop is $117.9/m^2. This results in $16,175 for the 3-ton system when the average square footage of houses that require the 3-ton system is 1,477 square feet. Bloomquist (2001) suggests that most of the projects under the analysis are new constructions which require more capital cost due to interior installation and duct work. Given this setup, the resultant capital cost is reasonably comparable with the $15,748 capital cost of the new construction. These data indicate that the calculation of GHP capital cost in this study is comparable to the findings of the other studies. Based on these findings, a markup of 1.2 is applied to the GHP retrofit price which increased the cost of GHP retrofit for the 3-ton system to $13,489. This is equivalent to $4,496 per ton, which is taken as a baseline cost of the GHP retrofit with a vertical loop.

Bloomquist (2001) also compares the price difference between the vertical and horizontal loop based on 58 case studies and finds that the average capital cost of horizontal loop is about 47 percent of the average capital cost of vertical loop. An interview with a local installer (Michigan Energy Services Inc. 2014) indicates that the capital cost of the horizontal system is about 57 percent of that of the vertical loop. Based on these reviews, half of the capital cost of vertical loop is set as a baseline capital cost for horizontal loop.

2.8.1.2 Conventional System Cost

The DOE performed detailed analysis on equipment prices of conventional heating and cooling systems during the setup of new efficiency standards (DOE 2010a, 2010b, 2011a, 2011b). This includes the system cost of non-weatherized gas and oil furnaces, electric furnaces, central air conditioners and heat pumps, and room air conditioners. This data and methodology are adopted from the Engineering Analysis (chapter 5), Markups for Product Price Determination (chapter 6), and Life-cycle Cost and Payback Period Analysis (chapter 8) of the TSD to calculate capital cost of conventional equipment for this study. Throughout the calculation, data for replacement are used for this analysis.

In the TSD Engineering Analysis, detailed product types were identified in the Market and Technology Assessment (chapter 3) and each product type was further classified into different equipment efficiency levels based on the most commonly shipped equipment efficiency. This includes baseline efficiency, which just meets but does not exceed current federal energy conservation standards; intermediate efficiency level, which represents the most common efficiency levels available on the market; and max-tech efficiency level, which represents the highest efficiency on the market (DOE 2011). Then the TSD utilized a teardown analysis and a cost model to estimate the manufacturing cost of a product including cost for materials, labor, depreciation and overhead (DOE 2011). This manufacturer production cost was multiplied by a markup factor and added to a shipping cost to result in the manufacturer selling price.

2.8.1.2.1 Equipment Price and Transportation Price

The DOE reported shipments-weighted prices of the equipment and installation by efficiency levels and by TSD climate region. However, these results aggregated equipment with different capacity and cannot be used to show different total system cost by system size. Therefore, the equipment and installation costs are recalculated to capture price difference according to equipment capacity as well as efficiency level and house location using the data reported in the TSD.

The DOE identified three equipment capacity levels for CAC and HP systems (2, 3, and 5 ton) and four capacity levels for window/wall AC (less than 6, 8-11, 20-25, and greater than 25 Btu/hr). The DOE also identified four capacity levels for gas furnaces (60, 80, 100 and 120 kBtu/hr) and one equipment size is analyzed for oil furnaces (105 kBtu/hr). Equipment price was determined at the baseline efficiency model and incremental price increase at higher efficiency levels. The DOE also identified shipping costs in terms of equipment size.

The DOE also categorized each product with detailed specification. However the RECS 2009 dataset does not have enough information to fully utilize this detailed data so they are aggregated using historical shipment data reported by Government Regulatory Impact Model (GRIM) (Navigant Consulting, Inc. 2011a, 2011b). For split AC system, coil-only and blower-coil product were assumed to represent 90 % and 10 % of the shipped products respectively. Unlike split system, DOE identified only one product size for package system (3 ton). For consistency, the price of package system was derived by scaling the product price at 3 ton with the relative price of the split system at 2 ton and 5 ton compared with 3 ton. The product price of split system and package system are combined using a historical shipment to result in shipment-weighted price of CAC and CHP at 2, 3, and 5 ton system capacity. For furnace system, products with permanent split capacitor (PSC) blower motors and electronically commutated motors (ECM) were assumed to represent 71 % and 29 % of the shipped product in 2009.

However, the range of product size recognized by DOE is not enough to represent heating and cooling equipment needed for the RECS entries. Therefore, a linear regression is used for each product type to approximate the price of the system that is not represented at the DOE analysis. For oil furnace, the linear equation derived from gas furnace is scaled to match the price at the 105 kBtu/hr to result in an equation.

Based on these, the capital cost of the conventional system can be calculated by the equipment type, efficiency level, capacity and house location, given the required size of the equipment which is determined by the load calculation in section 2.2.3. Table 11 shows the result of these linear regressions for the new minimum required efficiency levels from 2014.

Table 11. The price of the conventional equipment by type and region. The calculation is for the new minimum efficiency level that takes effect after 2014.

	Equipment Type	Climate Region	Baseline Price [2009 $]	Incremental Price Increase [2009 $]
Heating Equipment	Oil Furnace	Nationwide	0.00357*EquipSize + 854.7	N/A
	Gas Furnace	North	0.000873*EquipSize + 227	0.00037*EquipSize + 84.2
		H-D or H-H	0.000873*EquipSize + 227	N/A
	Central AC	Nationwide	140.3*EquipSize + 441.7	22.15*EquipSize + 74.4

Cooling Equipment	Central Heat Pump	Nationwide	119.49*EquipSize + 710.2	30.49*EquipSize + 118.6
	Window/Wall AC	Nationwide	0.0289*EquipSize + 231.7	N/A

The investigation of the AHRI directory of furnace, which contains a database of existing furnace systems in the market, reveals that furnaces for central heating systems have minimum capacity. Based on this database, the minimum furnace capacity was set to 30 kBtu/hr and this was applied to all RECS entries that have heating capacity less than or equal to 30 kBtu/hr. On the other hand, cooling equipment capacity is usually rated in half ton increments. Therefore, if the cooling load of the RECS entry was not at this half ton increment, a higher capacity with a half-ton increment just bigger than the actual load was selected to represent required cooling equipment size.

2.8.1.2.2 Markup Factor

The markup factors are multipliers that convert the manufacturer production cost into manufacturer selling price. DOE identified key distribution channels for the products in Markups for Product Price Determination chapter which includes manufacturer, wholesaler, and mechanical contractor for retrofit installations. These markups cover business costs and profit margins at each step in the distribution channel. For wholesaler and contractors, DOE estimated markups for baseline equipment and incremental markups for equipment with higher efficiency. These results are adopted from the TSD documents and are as shown in Table 12. The markup at each step in the distribution channel was multiplied with each other to result in an overall markup throughout the channel.

Table 12. Overall markups to convert manufacturer production cost to manufacturer selling price for central AC and heat pump and furnace. The markups are for retrofit installations and include markup of manufacturer, wholesaler, and contractor. The TSD climate region is as defined in energy efficiency programs for consumer goods by DOE. The list of states belonging to each region can be found in Appendix A.

TSD Climate Region	Central Air Conditioner and Heat Pump		Furnace	
	Baseline Markup	Incremental Markup	Baseline Markup	Incremental Markup
Hot-Dry (H-D)	2.180	1.398	2.038	1.320
Hot-Humid (H-H)	1.951	1.252	2.009	1.302
North	2.024	1.297	2.027	1.280

2.8.1.2.3 Installation Price

The TSD calculated installation cost by equipment type, efficiency level and by location. For heating equipment, installation cost was derived in terms of TSD climate region and in terms of equipment efficiency levels. For cooling equipment, TSD provided installation costs in terms of states and equipment types. These detailed TSD data are aggregated using the same methodology from the previous section to be applied to the RECS entries. This aggregated data can be multiplied with the installation price index, a factor that describes relative price difference among the regions. The price index is derived in state level for cooling equipment whereas it is derived in terms of TSD climate region for heating equipment.

Table 13. Installation price for heating and cooling equipment at its new minimum efficiency level as set by DOE. The data and methodology is adapted from TSD. Cooling equipment has detailed information by state whereas heating equipment is calculated in terms of more aggregated TSD climate region.

State	Cooling Equipment [2009 $]		Heating Equipment [2009 $]	
	Central AC	Heat Pump	Gas Furnace (80% efficiency)	Gas Furnace (90% efficiency)
Alabama	301.8	322.3	642	1,202
Alaska	565.9	604.4	884	1,457
Arizona	397.1	424.2	642	1,202
Arkansas	292.6	312.5	642	1,202
California	661.2	706.2	642	1,202
Colorado	421.1	449.7	884	1,457
Connecticut	627.5	670.3	884	1,457
Delaware	643.9	687.7	642	1,202
District of Columbia	517.9	553.2	642	1,202
Florida	349.7	373.5	642	1,202
Georgia	382.3	408.4	642	1,202
Hawaii	595.4	636.0	642	1,202
Idaho	361.9	386.6	884	1,457
Illinois	726.4	775.9	884	1,457
Indiana	456.3	487.3	884	1,457
Iowa	383.4	409.5	884	1,457
Kansas	355.8	380.1	884	1,457
Kentucky	421.1	449.7	642	1,202
Louisiana	313.5	334.9	642	1,202
Maine	363.0	387.7	884	1,457
Maryland	487.9	521.1	642	1,202
Massachusetts	660.2	705.1	884	1,457
Michigan	577.1	616.4	884	1,457
Minnesota	648.9	693.1	884	1,457
Mississippi	324.2	346.3	642	1,202
Missouri	542.4	579.3	884	1,457

Montana	382.8	408.9	884	1,457
Nebraska	419.0	447.6	884	1,457
Nevada	565.9	604.4	642	1,202
New Hampshire	478.7	511.3	884	1,457
New Jersey	711.7	760.1	884	1,457
New Mexico	393.5	420.3	642	1,202
New York	866.6	925.6	884	1,457
North Carolina	214.1	228.7	642	1,202
North Dakota	302.8	323.4	884	1,457
Ohio	503.7	538.0	884	1,457
Oklahoma	302.3	322.9	642	1,202
Oregon	536.8	573.3	884	1,457
Pennsylvania	668.8	714.4	884	1,457
Rhode Island	620.4	662.6	884	1,457
South Carolina	213.1	227.6	642	1,202
South Dakota	245.7	262.4	884	1,457
Tennessee	394.1	420.9	642	1,202
Texas	331.4	353.9	642	1,202
Utah	379.8	405.6	884	1,457
Vermont	364.5	389.3	884	1,457
Virginia	383.4	409.5	642	1,202
Washington	549.0	586.4	884	1,457
West Virginia	477.2	509.6	884	1,457
Wisconsin	531.2	567.4	884	1,457
Wyoming	313.5	334.9	884	1,457

2.8.1.2.4 Calculating Total System Price

The total system price of the conventional heating and cooling system can be calculated using the data derived in the previous sections. The calculation is as follows:

$$TotalPrice = EquipPrice + Installation\ Price * InstIndex$$

$$EquipPrice = BasePrice * BaseMarkUp + IncrementalPrice * IncreMarkUp$$

Where:

$TotalPrice$ = total price of the system;
$EquipPrice$ = equipment price;
$Installation\ Price$ = installation price;
$InstIndex$ = location dependent installation price index, 1.0 at a national average;
$BasePrice$ = manufacturer selling price of the equipment at baseline efficiency;
$BaseMarkUp$ = overall baseline markup factor for retrofit;
$IncrementalPrice$ = increase in equipment price at higher efficiency level;
$IncreMarkUp$ = overall incremental markup factor for retrofit.

All variables in the equations are derived and presented in the previous sections. Using these data and equations, the capital cost of conventional heating and cooling systems are calculated for all RECS entries.

Table 14 shows the results of this calculation as an example using a heating system with 70 kBtu/hr and cooling system with 4 ton capacity, as these represent typical energy demand in the RECS entries as identified in the energy load calculation section.

Table 14. Result of the conventional equipment price calculation for 70 kBtu/hr heating and 4 ton cooling demand. Total price is a summation of equipment price and installation price. Price for the equipment and installation is combined for Window/Wall AC. The results are presented in terms of TSD climate region.

Equipment Type		Equipment Price [2009 $]			Installation Price [2009 $]			Total Price [2009 $]		
		Hot-Dry	Hot-Humid	North	Hot-Dry	Hot-Humid	North	Hot-Dry	Hot-Humid	North
Heating Equipment	NG Furnace	587	579	725	642	642	1,457	1,229	1,221	2,182
	Oil Furnace	2,244	2,214	2,233	909	909	909	3,153	3,123	3,142
	Heat Pump	3,078	2,710	2,858	643	367	641	3,721	3,077	3,499
Cooling Equipment	Central AC	2,582	2,273	2,398	602	344	600	3,185	2,617	2,998
	Heat Pump	3,078	2,710	2,858	643	367	641	3,721	3,077	3,499
	WWAC							232	232	232

The results show the price differences in terms of equipment types and location. The minimum efficiency levels at 2014 are assumed. Window/Wall AC units show the lowest price as expected and natural gas furnaces exhibit lower prices than other heating equipment.

This equation can be directly applied to all RECS entries to calculate capital cost of the new conventional systems. Figure 40 shows the price distribution of the capital cost for both heating and cooling equipment.

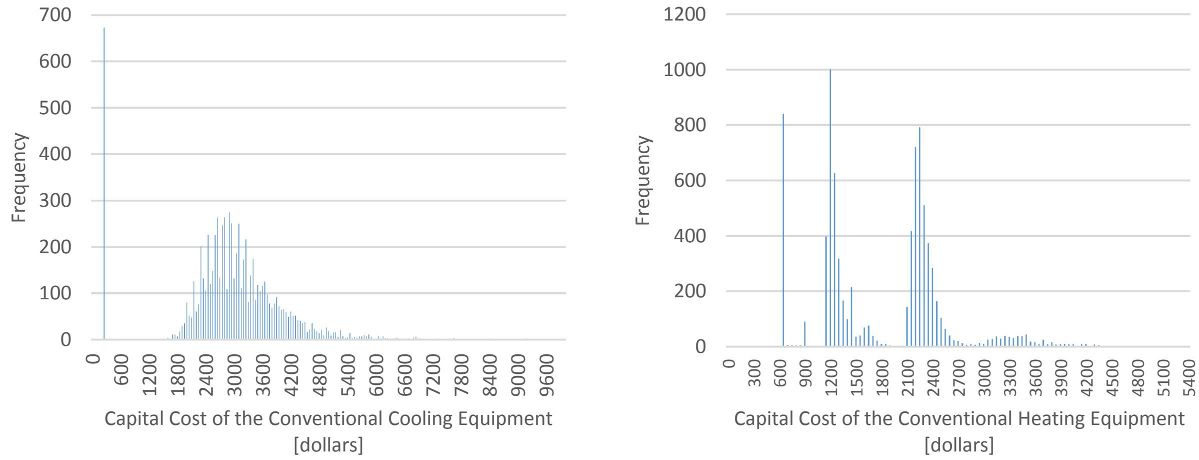

Figure 40. Frequency distribution of the capital cost of the conventional heating and cooling equipment.

As shown in Figure 40, the capital cost distribution of the cooling equipment shows a price gap between window/wall unit (around $200) and central cooling system (rather continuous distribution with the median value of $2900). The household-weighted average capital cost of the cooling system is calculated as $2,582. The capital cost distribution of the heating equipment also shows a price gap between natural gas furnace, oil furnace and heat pump. The average capital cost of the heat pump, natural gas furnace and oil furnace are found as 784, 1,919, and 3,473 dollars respectively. The household-weighted average capital cost of the heating system is $1,666.

However, comparison to another database reveals that this might be an underestimate of the real price. A database at homeadvisor.com (Home Advisor 2014) contains price information of over a thousand actual projects of furnace, heat pump and AC unit installation across the U.S. The distribution of the projects show variability in location and the database does not provide detailed information for further analysis, however, it reports national and regional average project costs which can be used as a reference. The database reports $4,360 for furnace systems, $5,576 for heat pump systems, and $5,399 for AC systems for national average capital cost from over 16,000 projects. Since this price range differs from that derived from TSD methodology, a set of multipliers are introduced to scale the calculated capital cost of the conventional equipment to the price range comparable to the Home Advisor reference.
The comparison with the Home Advisor reference reveals that the real heating and cooling equipment price is about 2.57 times, and 2.03 times as high as values calculated with TSD methodology on average, respectively. Therefore, a multiplier of 2.5 and 2 are used as a default multiplier to scale capital cost of conventional heating and cooling equipment for this study. Figure 41 shows the capital cost of conventional heating and cooling equipment using these default multipliers.

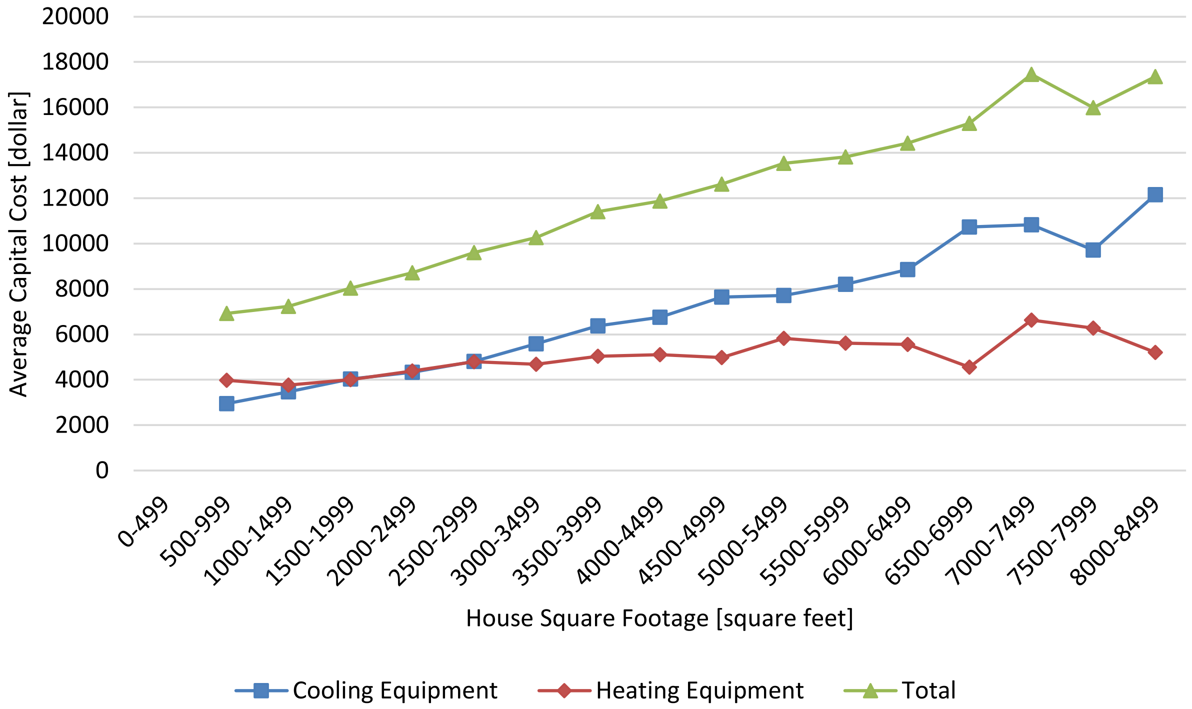

Figure 41. Average capital cost of conventional heating and cooling equipment with default multipliers (2.5 for heating and 2 for cooling equipment). Capital costs show general increasing trend with bigger house size.

2.8.2 Operational Cost

The annual operational cost of the equipment is the annual energy bill directly occurred from space heating and cooling over a year. This includes fuel cost but doesn't include maintenance cost.

The RECS 2009 dataset reports annual operational cost of heating and cooling equipment in 2009. EIA acquired these home energy bills in 2009 from the energy suppliers for most of the houses in the RECS dataset. These data are based on actual meter readings of electricity, natural gas, fuel oil, LPG and kerosene, and thus provide accurate information on the cost incurred from space heating and cooling at the houses.

As discussed in section 2.6.1 Weather Normalization, EIA disaggregated energy use at homes into different end uses utilizing end-use model. This end-use model is also used to disaggregate energy bills by different end uses, such as space heating and cooling. Since RECS 2009 dataset does not have any households with GHP systems, energy bills reported in RECS effectively informs energy bills of the conventional heating and cooling systems.

The unit energy consumption with GHP which was calculated in section 2.6.2 can be used to compute annual energy bill with GHP system. The unit energy consumption with GHP shows how much electricity a house need to meet its heating and cooling demand for a year and this can be multiplied with average electricity price to calculate annual energy bill with GHP system. The following equation summarizes the calculation:

$$EnergyBill_{GHP} = UER_{GHP} * \frac{1000}{3412} * ElectricityPrice$$

Where:

$EnergyBill_{GHP}$ =	annual operational cost to meet heating and cooling demand at home with GHP system;
UER_{GHP} =	annual energy requirement at home for space heating and cooling with GHP system;
$ElectricityPrice$ =	regional average electricity price.

A constant serves to switch units from 1,000 Btu to KWh and the electricity price by states in 2009 is obtained from Electric Power Annual published by EIA (EIA 2013b). Comparing this operational cost of GHP with a reported energy bill in RECS, which is the operational cost of a conventional system, provides information on annual energy bill savings at homes as shown in Figure 42.

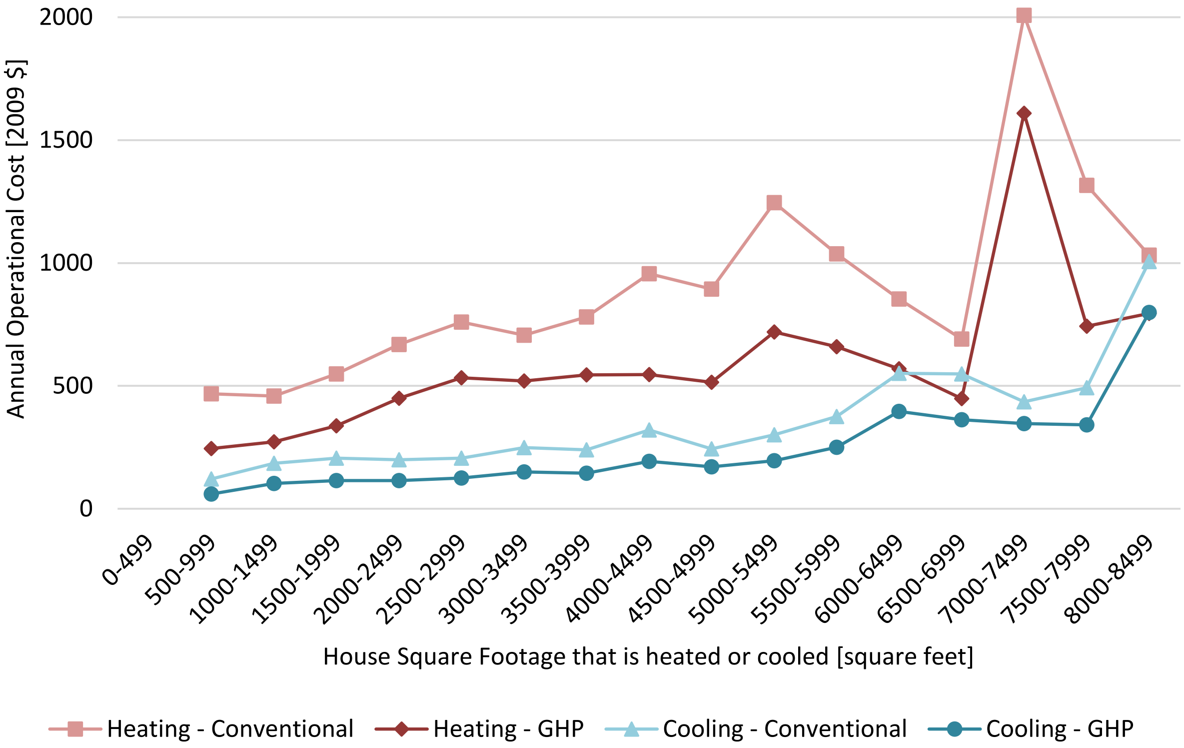

Figure 42. Comparison of annual operational cost of the conventional and GHP system. The difference of operational cost of conventional and GHP system is the cost saving with GHP system. For both heating and cooling, GHP shows lower operational cost than conventional equipment both in heating and cooling.

On average, GHP systems consume less energy than the conventional heating and cooling equipment and can save energy bills for houses with all sizes. This result suggests that that if all houses that can utilize GHP systems switched from conventional systems to GHP, we expect a national energy bill saving of 11.9 billion dollars every year. On average, this translates into 265 dollars of annual energy bill savings per home which is about 35 percent of the average annual energy bill occurred from space heating and cooling. About 65 percent of the saving comes from heating while the rest comes from cooling. This suggests that GHP systems would be more competitive in cold climate where heating is dominant form of energy use.

2.8.3 Payback Period Analysis

To evaluate the overall economic performance of the GHP system, both capital cost and operational cost of the GHP over its product lifespan need to be assessed. A simple payback period, which is the length of time required to recover initial investment, is calculated to assess economic feasibility of the GHP system.

2.8.3.1 Payback Period Calculation

Since the GHP system typically costs less to operate compared to conventional equipment, the initial capital cost that was spent to install a GHP system can be recovered little by little every year. The following equation shows the calculation:

$$PBP = \log_{1+r} \frac{a}{a - r * C}$$

Where:

PBP = simple payback period in year;
r = interest rate;
a = annual energy bill saved by the GHP system compared to conventional system;
C = cost premium of capital cost of the GHP system compared to conventional system.

The annual energy bill saved by the GHP system (a) is calculated by subtracting the reported energy bill for space heating and cooling in 2009 from the expected annual energy bill with GHP system calculated in section 2.8.2. This value is typically positive as energy bills expected for the GHP systems are lower than that with conventional systems. The cost premium of capital cost of GHP system (C) is calculated by subtracting capital cost of conventional system from that of GHP system. This value is also typically positive as GHP systems are usually more expensive than conventional heating and cooling equipment. Interest rate (r) works as a discount rate which discounts financial cost of benefit in the future in terms of current value. For this study, interest of 3, 5, and 7 percent are used for the analysis.

In this equation, payback period cannot be calculated when log value is negative or equal to zero. This can occur when the denominator of the log value becomes negative, which can happen when either cost premium of the GHP system is too high to be offset with annual energy bill saving or annual energy bill with GHP is actually higher than that with conventional system. In this case, homeowners need to pay more for heating and cooling with the GHP system and payback period is not defined. Figure 43 shows the percentage of RECS entries whose payback period is not defined for this reason.

Figure 43. Percentage of RECS entries where GHP system is more expensive than conventional system. Note that interest rates play an important role in evaluating the economic performance of the GHP system.

Overall, 40, 61, and 71 percent of the RECS entries across the contiguous U.S. found that GHP system is more expensive using 3, 5, 7 percent interest rate, respectively. Clearly, the choice of interest rate can greatly influence the economic performance of the GHP system. Higher interest rates discount more of the future benefits that occur from higher efficiency of the GHP and thus place relatively more weight on the cost premium of the GHP. This can be easily observed in Figure 43.

After separating out these entries, average payback period is calculated for each census division, which is displayed in Figure 44.

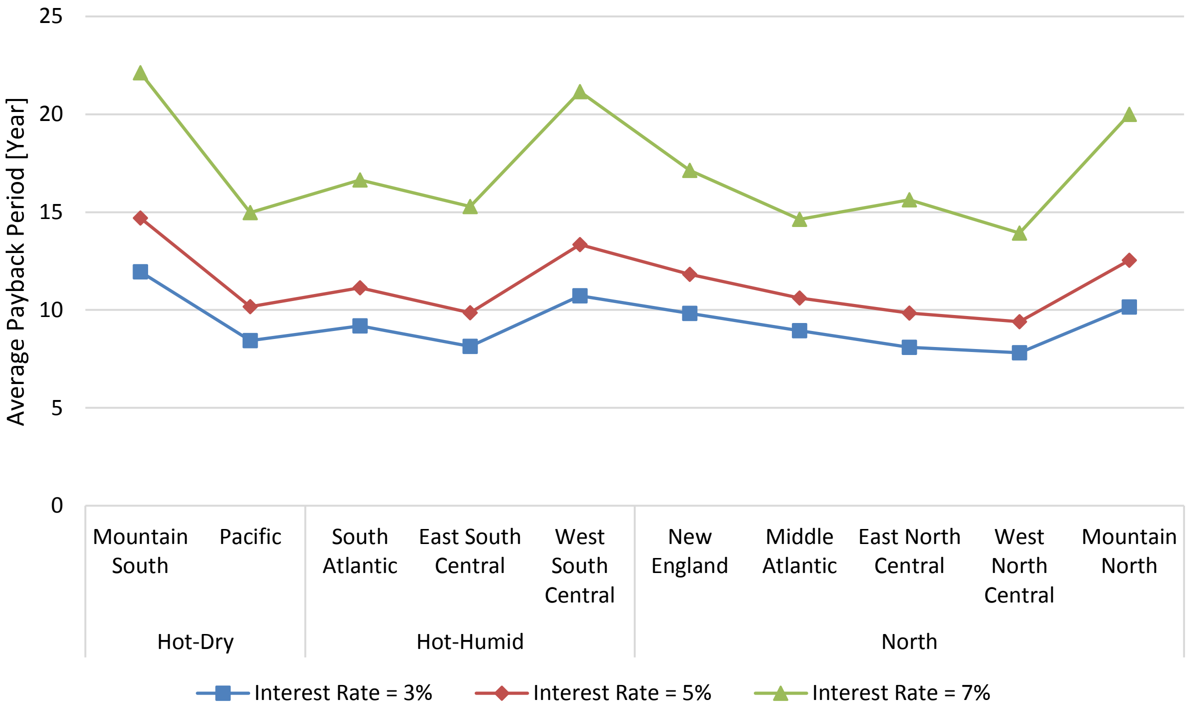

Figure 44. Average simple payback period of the GHP system by census division and TSD region. Since the number of RECS entries that has defined payback period differ among different interest rates, only the entries which have a defined payback period at 7 percent interest rate are used for fair comparison.

Here, only a subset of the RECS entries that has defined payback period at interest rate of 3 and 5 percent are selected to ensure fair comparison among interest rates, and thus average payback period of 3 and 5 percent here is not a true representation of real average payback period at these interest rates. Using these RECS entries, the national average payback periods are calculated as 8.7, 10.6, and 16 years with 3, 5, and 7 percent interest rate, respectively. Here, interest rates also play an important role. Since higher interest rates discount more of future benefits, it results in longer payback period which can be seen in Figure 44.

More accurate prediction of average payback period can be made if all RECS entries that have a defined payback period at each interest rate are considered for the analysis. This results in 33.2, 22.3, and 16 years of payback period at interest rate of 3, 5, and 7 percent, respectively. In this case, higher interest rates result in lower payback periods since many of the RECS entries are excluded from the analysis at higher interest rate as their payback period becomes undefined with lowered future benefits. In this example, 79, 64, and 53 percent of the total RECS entries are used to calculate average payback period with 3, 5, and 7 percent of interest rate, respectively.

2.8.3.2 Payback Period with Financial Incentive

To promote implementation of efficient equipment, federal, state and local governments as well as utilities provide various financial incentives to the users. There exist 384 programs (DSIRE 2014a) across the nation to promote the use of GHP system. These incentives take the form of tax rebates (personal, sales, and property tax), utility rebate program, grant, loan or other financing options such as Property Assessed Clean Energy (PACE) financing, which is an alternative to a loan that is designed specifically to help property owners to overcome high upfront cost (DSIRE 2014b).

However, the availability of these incentives also shows big geographical variability. The service areas of the utilities usually do not coincide with state boundary or county boundary. Some of the incentives are only available for houses located in specific counties as it is offered by local government. Since the RECS 2009 dataset does not possess this detailed geographical information of each entry even after the creation of virtual cohorts in section 2.1.3, the benefits of most of these incentives are not analyzed in this study to assure integrity. Instead, the effectiveness of the federal tax credit is analyzed as this applies to all households regardless of its location. Residential Renewable Energy Tax Credit provides 30 percent of expenditures that occur from GHP implementation as a personal tax credit. This means homeowners only need to pay 70 percent of the implementation cost of the GHP system and this policy is expected to promote installation of the GHP. Figure 45 shows the percentage of RECS entries whose payback period is not defined after applying this federal tax credit program.

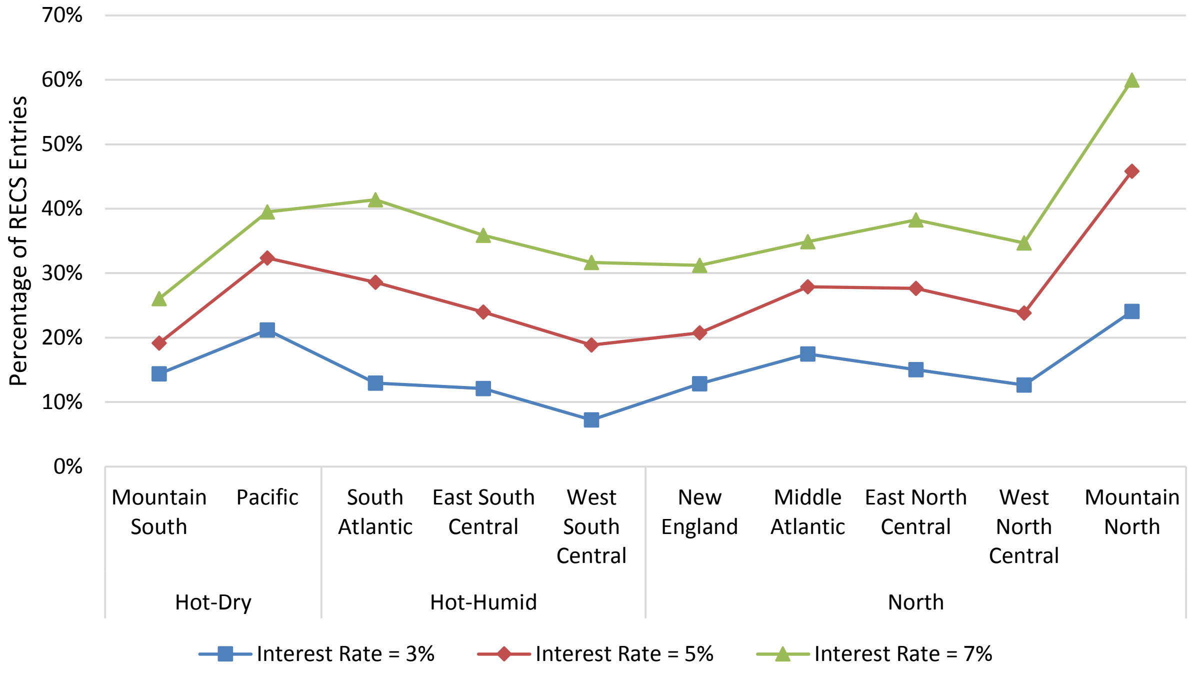

Figure 45. Percentage of RECS entries where GHP system is more expensive than conventional system after applying a 30 percent federal tax credit.

Comparison of Figure 43 and Figure 45 show that this federal tax incentive greatly enhances the economic performance of the GHP system. For 3, 5, and 7 percent interest rates, only 14, 27, and 37 percent of RECS entries across the contiguous U.S. has undefined payback period, respectively. This is a drastic decline from 40, 61, and 71 percent as found in the previous section.

The federal tax rebate program also reduced average payback period as shown in Figure 46.

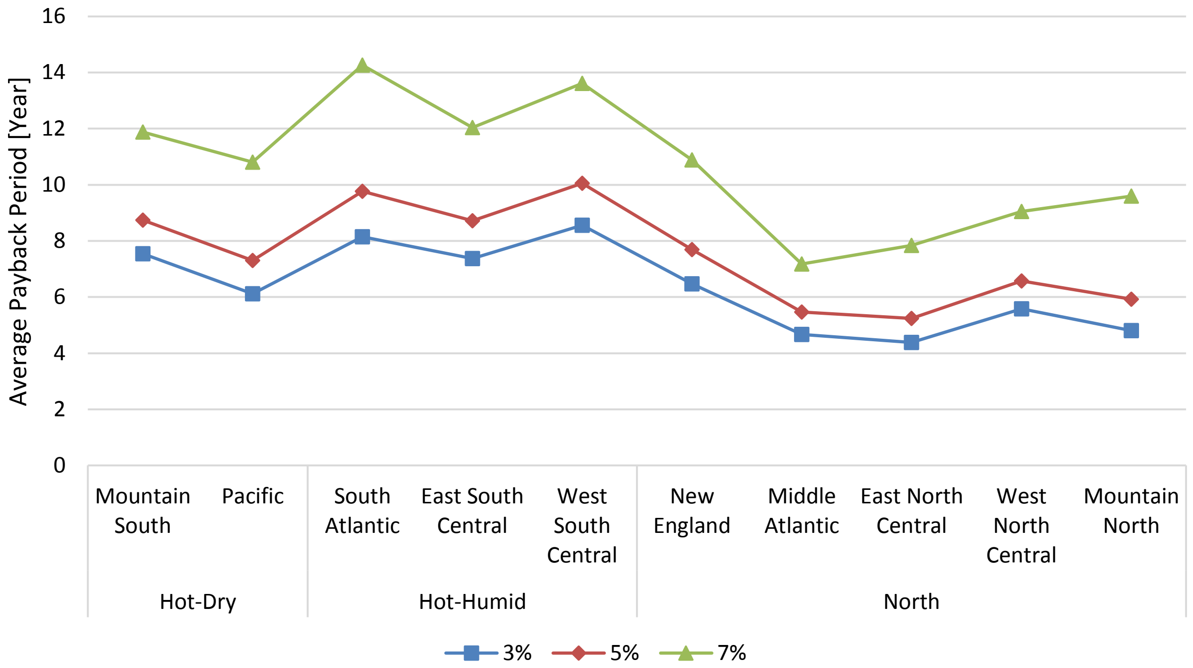

Figure 46. Average simple payback period of the GHP system by census division and TSD region. Since the number of RECS entries that have defined a payback period differ among different interest rates, only the entries which have a defined payback period at 7 percent interest rate are used for fair comparison among different interest rates.

As in the previous section, only a subset of RECS entries that have a defined payback period at 7 percent interest rate are used for fair comparison. With a 30 percent federal tax rebate, the average payback period for 3, 5, and 7 percent interest rates are calculated as 6.4, 7.6, and 10.8 years. This is not a true representation of the average payback period but the impact of interest rate can be observed here as well.

Using all RECS entries which have a defined payback period at each interest rate results in more accurate average payback periods, which are calculated as 17.2, 13.5, and 10.8 years for 3, 5, and 7 percent interest rates, respectively. This is a great improvement from 19.5, 13.8, and 9.1 years as found in the previous section before financial incentives. This result is within a range of findings in other literature. For instance, Lienau (1995) found the range of simple payback period of residential GHP system from 1.4 to 24.1 years with the mean of 7 years in his 27 case studies.

When this is further incentivized by local programs supported by state, local government and utilities, the payback period of the GHP system would become even less and the system would become a more attractive option for homeowners.

However, these local incentives are often not as strong as the federal incentive and they are not likely to bring down payback period significantly. Past projects show that customers are very reluctant to participate in the projects even when the payback period is as low as 4.7 years (Kilpatrick 1993) which is less than half the payback period with 7 percent of interest rate. Therefore, much more aggressive policy measures are needed for nation-wide implementation of the GHP.

3. SENSITIVITY ANALYSIS

Not all required information was available at the time of this analysis, in which case certain assumptions were made based on literatures or interviews with the installers. The final results of energy savings, GHG abatement and economic performance of the GHP system are dependent on these assumptions and therefore understanding the impact of these assumptions are critical. In this section, these uncertainties are addressed with sensitivity analysis of the final results on the assumptions on calculating available lot size at home for ground loop, geothermal heat pump selection method, and lot requirement for ground loop.

3.1 Available Lot for Ground Loop

The size of the empty lot available for ground loop installation was calculated in section 2.4.2. Using data available from the RECS 2009 and AHS 2011 dataset, total square footage of empty lot was calculated but no further data were available to calculate empty lot available for loop installation. Therefore only half the total empty lot was assumed to be available for loop installation in section 2.4.2. However, other values could be used instead of half which will affect the result. Here, a factor of 1/2, 1/3, and 1/4 are analyzed to address its impact on available lot for ground loop as shown in Table 15.

Table 15. Impact of the choice of lot availability factors on loop assignment, energy saving, GHG abatement, and economic performance of the GHP. Note that the number of RECS entries used to calculate average payback period differs slightly by lot availability factors, interest rates, and the presence of financial incentives as they influence the number of RECS entries where GHP is more expensive than conventional system. The first column of the lot availability factor (1/2) denotes the default value.

			Lot Availability Factor		
			1/2	1/3	1/4
Ground Loop Assignment		Horizontal	6%	4%	3%
		Vertical	73%	63%	55%
		Not Enough Lot Available	21%	33%	42%
Energy Saving [kBtu]		Average	36108	35671	35314
		Total	1.26E+12	1.05E+12	8.99E+11
GHG Abatement [tonCO2eq]		Average	2.099	2.090	2.085
		Total	7.57E+07	6.38E+07	5.48E+07
Average Capital Cost		GHP Capital Cost	$19,477	$19,405	$19,529
		GHP Capital Cost with Tax Rebate	$13,634	$13,584	$13,670
		GHP Cost Premium	$9,855	$9,833	$9,953
		GHP Cost Premium with Tax Rebate	$4,012	$4,011	$4,095
Percentage of RECS entries where GHP is more expensive	Without Incentive	Interest Rate = 3%	40%	40%	40%
		Interest Rate = 5%	61%	60%	60%
		Interest Rate = 7%	71%	71%	71%
	With Federal Tax Rebate	Interest Rate = 3%	14%	14%	15%
		Interest Rate = 5%	27%	26%	27%
		Interest Rate = 7%	37%	37%	37%
Average Payback Period [Year]	Without Incentive	Interest Rate = 3%	33.2	32.8	32.2
		Interest Rate = 5%	22.3	22.4	22.8
		Interest Rate = 7%	16.0	16.5	17.1
	With Federal Tax Rebate	Interest Rate = 3%	17.2	17.0	17.1
		Interest Rate = 5%	13.5	13.2	13.1
		Interest Rate = 7%	10.8	10.5	10.4

As summarized in Table 15, the choice of lot availability factor affects the type of ground loop that can be installed at homes. The number of homes that have a sufficiently large available lot for the loop installation decreases with smaller factors; and the impact is bigger in vertical loop since there are more homes with vertical setups. Since the type of loop does not impact the efficiency of the GHP system, average value of energy savings and GHG abatement per house is not affected by the choice of the factor, but total energy savings and GHG abatement decreases with smaller factors as fewer homes can install ground loop. The average capital cost of the GHP system is relatively unaffected by the lot availability factor since the relative ratio between vertical and horizontal loop is little changed. Since there is little impact in capital cost and operational cost of the GHP system from the choice of lot availability factor, there is no significant impact on payback period of the GHP. Therefore, the lot availability factor does little impact on the performance of the GHP system at individual homes. But it can dictate the total number of homes which can implement GHP so influence the scale of national benefit from GHP.

3.2 Geothermal Heat Pump Selection

As introduced in section 2.5, three heat pump selection methods are compared side by side in this section. Heat pump units were selected from the AHRI database of geothermal heat pump based on one of these requirements: heat pump units meet 1) cooling demand, 2) dominant demand between heating and cooling, 3) both heating and cooling demand at homes. Once the heat pump units are selected, the GHP system is sized to meet dominant energy demand. Table 16 summarizes the results as following:

Table 16. Impact of the choice of heat pump selection method on heat pump size needed, energy saving, GHG abatement and economic performance of the GHP. Note that the number of RECS entries used to calculate average payback period differs significantly by heat pump selection methods, interest rates, and the presence of financial incentives as they influence the number of RECS entries where GHP is more expensive than conventional system. The first column of the heat pump selection methods (cooling demand) denotes the default method.

		Heat Pump Selection Methods		
		Cooling Demand	Dominant Demand	Both Demands
Size of the Heat Pump Needed [ton]	Average	5.3	8.5	9.5
Energy Saving [kBtu]	Average	36108	32638	33150
	Total	1.26E+12	8.70E+11	8.29E+11
GHG Abatement [tonCO2eq]	Average	2.099	2.146	2.143
	Total	7.57E+07	5.91E+07	5.54E+07
Average Capital Cost	GHP Capital Cost	$19,477	$28,454	$31,428
	GHP Capital Cost with Tax Rebate	$13,634	$19,918	$22,000
	GHP Cost Premium	$9,855	$19,270	$22,234
	GHP Cost Premium with Tax Rebate	$4,012	$10,734	$12,806
	Interest Rate = 3%	40%	63%	74%

Percentage of RECS entries where GHP is more expensive	Without Incentive	Interest Rate = 5%	61%	83%	91%
		Interest Rate = 7%	71%	90%	95%
	With Federal Tax Rebate	Interest Rate = 3%	14%	42%	50%
		Interest Rate = 5%	27%	57%	69%
		Interest Rate = 7%	37%	67%	80%
Average Payback Period [Year]	Without Incentive	Interest Rate = 3%	33.2	40.2	46.9
		Interest Rate = 5%	22.3	26.0	28.7
		Interest Rate = 7%	16.0	18.5	18.6
	With Federal Tax Rebate	Interest Rate = 3%	17.2	25.3	33.5
		Interest Rate = 5%	13.5	18.5	23.8
		Interest Rate = 7%	10.8	15.0	19.0

The choice of heat pump selection method directly influences the size of the heat pump unit that would be installed at homes. When selection priority is given only to cooling, the average heat pump size was the smallest. This average heat pump size is increased as the unit is selected to meet dominant demand between heating and cooling, and then when selected to meet both demands.

This impact on the average heat pump size directly influenced economic performance of the GHP system. Operational cost is little affected as efficiency level of the heat pump unit is not a function of the size of heat pump unit. However, since a bigger unit is more expensive to purchase, this directly affects the capital cost and payback period of the system. Especially when heat pump units are selected to meet both demands, most homes find the GHP system is too expensive and payback period is over 15 years for all interest rates tested when there are no financial incentives.

However, the impact of heat pump selection method is not as obvious in energy savings and GHG abatement. Since the average energy efficiency of geothermal heat pump units is not significantly affected by the size of the unit, average energy savings and GHG abatement are little affected by heat pump unit selections. But fewer homes find the GHP system financially favorable when a bigger heat pump unit is selected which resulted in decreased in total energy savings and GHG abatement.

3.3 Minimum Lot Requirements for Ground Loops

In section 2.4.2, a range of minimum lot requirements for ground loop are identified based on the interviews with local installers: 100, 144, and 255 sqft/ton for vertical, and 1,500, 7,260, and 14,520 sqft/ton for horizontal loop. The sensitivity of the results on the choice of these minimum lot requirements is analyzed in this section, which is summarized in Table 17.

Table 17. Impact of the choice of minimum lot requirement for ground loops on loop assignments, energy savings, GHG abatement and economic performance of the GHP. Note that the number of RECS entries used to calculate average payback period differs by minimum lot requirements, interest rates, and the presence of financial incentives as they influence the number of RECS entries where GHP is more expensive than conventional system. The third column of the minimum lot requirements (14,520 sqft for horizontal and 255 sqft for vertical loop) denotes the default method.

			Minimum Lot Requirements for Ground Loops		
			H: 1,500 sqft/ton V: 100 sqft/ton	H: 7,260 sqft/ton V: 144 sqft/ton	H: 14,520 sqft/ton V: 255 sqft/ton
Ground Loop Assignment		Vertical	62%	80%	73%
		Horizontal	32%	11%	6%
		Not Enough Lot Available	6%	9%	21%
Energy Saving [kBtu]		Average	37033	36738	36108
		Total	1.53E+12	1.47E+12	1.26E+12
GHG Abatement [tonCO2eq]		Average	2.13	2.12	2.10
		Total	9.12E+07	8.72E+07	75718068.4
Average Capital Cost		GHP Capital Cost	$17,257	$19,346	$19,477
		GHP Capital Cost with Tax Rebate	$12,080	$13,542	$13,634
		GHP Cost Premium	$7,554	$9,675	$9,855
		GHP Cost Premium with Tax Rebate	$2,377	$3,871	$4,012
Percentage of RECS entries where GHP is more expensive	Without Incentive	Interest Rate = 3%	32%	40%	40%
		Interest Rate = 5%	48%	60%	61%
		Interest Rate = 7%	56%	70%	71%
	With Federal Tax Rebate	Interest Rate = 3%	11%	14%	14%
		Interest Rate = 5%	21%	27%	27%
		Interest Rate = 7%	30%	38%	37%
Average Payback Period [Year]	Without Incentive	Interest Rate = 3%	22.4	32.1	33.2
		Interest Rate = 5%	12.5	20.5	22.3
		Interest Rate = 7%	7.3	13.7	16.0
	With Federal Tax Rebate	Interest Rate = 3%	12.6	16.9	17.2
		Interest Rate = 5%	9.6	13.3	13.5
		Interest Rate = 7%	7.1	10.5	10.8

The choice of minimum lot requirement is grouped to represent from loose to stringent requirements while the stringent requirement is used as a default. It mostly affects the ratio of horizontal and vertical loop to be installed at homes and the total number of houses which can install the GHP system. As the requirement becomes looser, more homes switch to horizontal loops they are cheaper than the vertical loops while overall percentage of homes which can install GHP increases. Therefore, total energy savings and GHG abatement across the nation increases with looser minimum requirements due to increased number of homes with the GHP system. Since the choice of loop type does not affect the system efficiency, average energy savings and GHG abatement per home is relatively unaffected by this change.

The change in the ratio between horizontal and vertical loop and the change in total number of homes with GHP directly affect economic performance of the GHP. The average capital cost and payback period of GHP decreases as more homes find horizontal loop feasible and switch from vertical loop at looser requirements.

4. CONCLUSIONS

4.1 Findings of this study

The GHP system has a potential of saving a significant amount of energy being used at homes and reducing GHG emissions that are responsible for climate change. This study finds that nation-wide implementation of the GHP system at the eligible single-family detached houses (39 percent of total residential housing stock) can save 1.26 quad of energy and reduce 76 million tons of GHG emissions every year. This is equivalent to 66 percent of home energy savings on heating and cooling at the eligible single-family detached houses and can greatly reduce the environmental foot print from the residential sector.

However, the size of the available lot at homes and high capital cost of the GHP system remain major barriers for the nation-wide implementation of the system. About 21 percent of the U.S. single-family detached houses of interest cannot install the GHP system due to their small lot size and most of the other houses that can install GHP system need to use more expensive vertical loop due to their lot size constraint.

The high cost premium of the GHP system over a conventional heating and cooling system is another obstacle. On average, the GHP system is 9,855 dollars more expensive than the conventional system and 265 dollars of annual energy bill savings of the GHP is often not enough to cover this high initial cost. Using 5 percent interest rate, around 61 percent of the RECS entries of interest will not fully recover this cost premium and the average payback period is around 22 years. The 30 percent federal tax credit can bring this numbers down to 27 percent and 13.5 years, respectively, and there are other incentives that are provided by utilities or local governments to further lower these numbers. However, often these incentives are not as strong as the federal incentive and given the fact that customers were even reluctant to participate in the projects with the payback period as low as 4.7 years, more aggressive policies are necessary to boost GHP implementation. Hughes (2008) makes a compelling argument that "GHP infrastructure," or the portion of the GHP system that is outside the house such as the ground loop may not be paid by the homeowners. Since the GHP infrastructure will outlive the building and many generations of heat pump units, more than one family would benefit from it and it could be thought of as utility infrastructure (Hughes 2008). The GHP infrastructure takes up significant portion in the total GHP system price, and if it is excluded from the consumer price, it would make the GHP system much more competitive to its conventional alternatives.

The sensitivity analysis of some of the key variables revealed that the choice of factors and methods can impact the scale of energy saving and GHG abatement as well as economic performance of the GHP system. As identified in section 3.1 and 3.3, the types of ground loop that can be installed at homes are sensitive to the choice of lot availability factor and minimum lot requirements for ground loops. Depending on the choice of these factors, the percentage of homes that can install GHP system can be anywhere between 58 and 94 percent. This directly influences the scale of total energy savings and GHG abatement but since the choice of ground loop and does not influence the efficiency of the GHP system, this does little impact on average every savings and GHG abatement per houses.

Also, section 3.2 shows that the choice of heat pump selection methods can impact the scale of national energy savings and GHG abatement by influencing the size of the system at homes but since the average efficiency of the heat pump unit is stable across different sizes, average energy saving and GHG abatement at homes are little affected by this selection methods.
This study also shows that the benefits the GHP systems show geographical variation. Heating is the dominant form of energy use at home and the advantage of the GHP system in terms of efficiency is bigger in heating than in cooling. Therefore, the GHP system shows better performance and results in cold region (e.g., North TSD region) where heating is the dominant form of energy use at home. This regional difference is consistent with the findings of Stein (1997) and is shown in Figure 34 and Figure 46. However, the capital cost is still too high compared to the conventional system even after accounting 30 percent of federal tax rebate. Even though the GHP system is more efficient and thus saves energy bills each year, this turns out to be not enough to cover the cost premium of the GHP system which homeowners need to pay. Even though there are additional financial incentives provided by utilities or local government which was not considered this study, this does not make GHP available to the most of the homes. More radical measures such as making utilities pay for the GHP infrastructure (ground loop), not the homeowners as proposed by Hughes (2008) is needed to make GHP more financially compatible.

Lastly, it is important to note that the GHP installation that is studied in this paper is for retrofits of existing homes. It is well understood that retrofits are more expensive than installing the GHP during the construction of the house. Thus policies that incentivize the GHP system for new constructions can help promote the implementation of the GHP system.

4.2 Limitations of this study and future works

This model can be improved by incorporating better data and by use of better methodology. The energy load calculation can be improved by utilizing energy modeling software such as EnergyPlus by the DOE and weather data such as Typical Meteorological Year 3 (TMY3). This will enable more detailed modeling of heating and cooling energy load and better calculate the size of the system required at homes. The GHP system modeling can be improved by including factors like soil type (e.g., dry soil, damp soil), grouting materials used at ground loop and also incorporating other ground loop types such as water loop. Underground temperature can also be included in the modeling to better calculate efficiency of the system. When the data becomes available, houses of different types or houses that use different heating equipment such as boiler could be also incorporated to assess the performance of the GHP system. The efficiency of the GHP would increase if the water heater is incorporated in the analysis as many GHP systems are equipped with desuperheaters which can provide hot water. Lastly, the financial performance of the GHP system can be better assess if local financial incentives provided by utilities and state government are included.

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APPENDICES

Appendix A

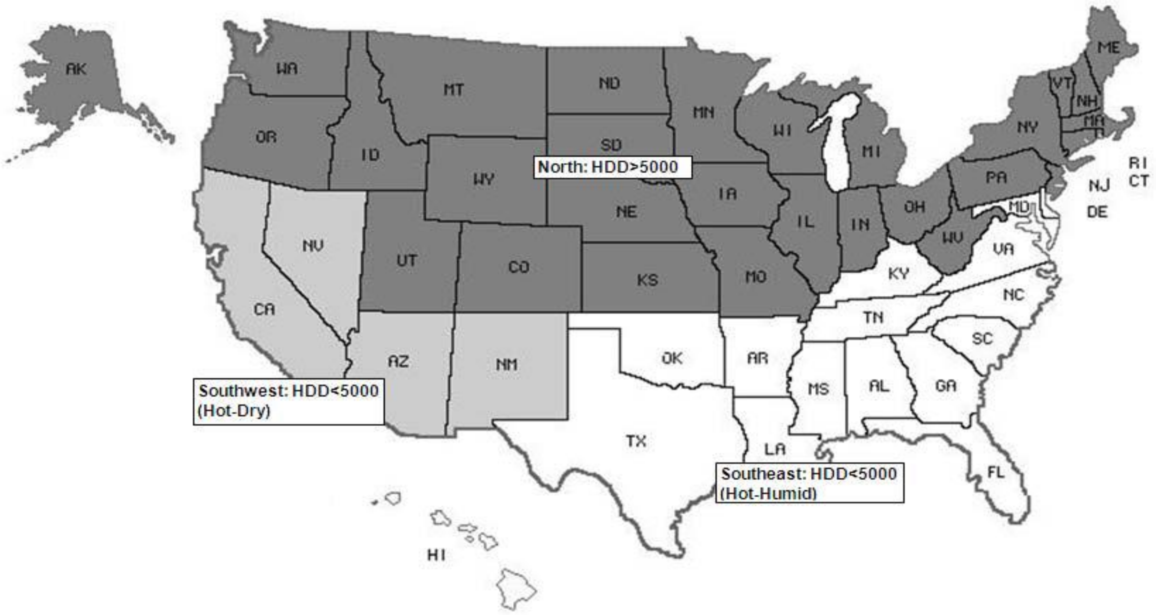

Figure A 1. Climate region as defined in the Technical Support Document for energy efficiency by Department of Energy. The U.S. is classified into three climate regions based on heating degree days and cooling degree days.

Northern Region States (North)		Southeastern Region States (Hot-Humid)	Southwestern Region States (Hot-Dry)
Alaska	New York	Alabama	Arizona
Colorado	North Dakota	Arkansas	California
Connecticut	Ohio	Delaware	Nevada
Idaho	Oregon	District of Columbia	New Mexico
Illinois	Pennsylvania	Florida	
Indiana	Rhode Island	Georgia	
Iowa	South Dakota	Hawaii	
Kansas	Utah	Kentucky	
Maine	Vermont	Louisiana	
Massachusetts	Washington	Maryland	
Michigan	West Virginia	Mississippi	
Minnesota	Wisconsin	North Carolina	
Missouri	Wyoming	Oklahoma	
Montana		South Carolina	
Nebraska		Tennessee	
New Hampshire		Texas	
New Jersey		Virginia	

Appendix B

Table B 1. Percentage of U.S. households that belongs to each response for housing characteristics and energy use pattern before and after screening as found in section 2.1.2.1. Column 'Original,' and 'Post Screening' show the percentage of households in each response in original RECS 2009 dataset and after screening process, respectively. Note that only one response is selected for each characteristics.

Housing Characteristics and Energy Use Pattern - RECS 2009 and AHS 2011						
	RECS 2009			AHS 2011		
Characteristics	Response	Original	Post Screening	Response	Original	Post Screening
Housing Type	Mobile home	6%	-	Mobile home	7%	-
	Single-Family Detached	63%	100%	Single-Family Detached	63%	100%
	Single-Family Attached	6%	-	Single-Family Attached	6%	-
	Apartment with 2-4 Units	8%	-	Apartment with 2+ Units	25%	-
	Apartment with 5+ Units	17%	-			
Condominium or Cooperative	Condominium	4%	-	Either Condo or Cooperative	8%	-
	Cooperative	1%	-	Neither one	92%	100%
	Neither one	94%	100%			
Ownership	Owned by someone in the household	67%	100%	Owned by someone in the household	58%	100%
	Rented	31%	-	Rented	28%	-
	Occupied without payment of rent	1%	-	Occupied without payment of rent	1%	-
				Not applicable	13%	-
Equipment not used	Equipment is being used at home	99.8%	100%	Not Available		
	Equipment is not used at home	0.2%	-			
Interview Status	Not Available			Occupied interview	87%	100%
				Usual Residence Elsewhere interview	2%	-
				Vacant interview	11%	-
				Noninterview	0%	-

Table B 2. Percentage of U.S. households that belong to each response for heating and cooling equipment before and after screening as found in section 2.1.2.2. Column 'Original,' and 'Post Screening' show the percentage of households in each response in original RECS 2009 dataset and after screening process, respectively. Note that a few responses are selected for analysis for heating equipment and fuel.

Heating and Cooling Equipment - RECS 2009							
Characteristics	Response	Original	Post Screening	Characteristics	Response	Original	Post Screening
Heating Equipment	Not Applicable	3.1%	-	Heating Fuel	Not Applicable	3.1%	-
	Steam or Hot Water System	10.6%	-		Natural Gas	49.0%	59.7%
	Central Warm-Air Furnace	61.9%	86%		Propane/LPG	4.9%	6.0%
	Heat Pump	9.0%	14%		Fuel Oil	6.1%	4.1%
	Built-In Electric Units	5.0%	-		Kerosene	0.4%	0.0%
	Floor or Wall Pipeless Furnace	1.5%	-		Electricity	33.6%	30.2%

	Built-In Room Heater	2.9%	-
	Heating Stove	2.0%	-
	Fireplace	0.5%	-
	Portable Electric Heaters	2.4%	-
	Portable Kerosene Heaters	0.2%	-
	Cooking Stove	0.2%	-
	Other Equipment	0.6%	-
Cooling Equipment	Not Applicable	17%	10%
	Central system	60%	81%
	Window/wall units	21%	8%
	Both a central system and window/wall units	1%	2%

	Wood	2.5%	-
	Solar	0.2%	-
	District Steam	0.2%	-
	Other Fuel	0.0%	-
Primary and Secondary Equipment	No Secondary Equipment	62%	54%
	Almost all	27%	34%
	About three-fourths	6%	7%
	Closer to half	4%	4%

Appendix C

Table C 1. The number of heating and cooling equipment each year, from 1980 to 2009. The equipment age group as defined in the RECS 2009 dataset is also displayed on the left.

RECS Age Group	Vintage Year	Heating Equipment Stock (million)				Cooling Equipment Stock (million)		
		Natural Gas Furnace	Fuel Oil Furnace	Electric Furnace	Heat Pump	Central AC	Electric HP	Window/Wall AC
6	1980	0.361	0.017	0.062	0.030	0.178	0.115	0.058
	1981	0.385	0.024	0.070	0.040	0.209	0.137	0.080
	1982	0.336	0.034	0.058	0.035	0.192	0.127	0.071
	1983	0.539	0.045	0.121	0.067	0.329	0.219	0.063
	1984	0.658	0.057	0.137	0.090	0.431	0.291	0.121
	1985	0.702	0.062	0.154	0.116	0.468	0.319	0.137
	1986	0.889	0.091	0.173	0.142	0.544	0.375	0.146
	1987	0.940	0.100	0.182	0.165	0.707	0.495	0.224
	1988	1.018	0.106	0.152	0.168	0.825	0.585	0.306
	1989	1.127	0.099	0.165	0.187	0.977	0.703	0.372
5	1990	1.074	0.082	0.165	0.210	0.989	0.723	0.345
	1991	1.206	0.082	0.153	0.221	1.127	0.838	0.266
	1992	1.295	0.093	0.191	0.256	1.173	0.887	0.308
	1993	1.681	0.103	0.241	0.311	1.383	1.063	0.380
	1994	1.829	0.119	0.290	0.390	1.833	1.434	0.598
4	1995	1.829	0.102	0.304	0.430	2.039	1.623	0.710
	1996	2.111	0.120	0.371	0.526	2.446	1.984	0.919
	1997	2.115	0.101	0.329	0.561	2.410	1.991	0.889
	1998	2.349	0.108	0.349	0.666	2.996	2.521	1.200
	1999	2.552	0.109	0.369	0.730	3.390	2.908	1.907
3	2000	2.624	0.108	0.389	0.807	3.534	3.089	2.250
	2001	2.664	0.113	0.408	0.936	3.357	2.989	2.208
	2002	2.855	0.109	0.427	1.027	3.870	3.510	2.786
	2003	2.977	0.120	0.445	1.184	3.928	3.627	4.252

	2004	3.266	0.125	0.452	1.443	4.308	4.048	4.782
2	2005	3.297	0.109	0.458	1.715	5.250	5.015	5.433
	2006	3.026	0.091	0.462	1.753	3.953	3.835	7.775
	2007	2.644	0.083	0.465	1.597	3.599	3.539	8.362
1	2008	2.162	0.059	0.467	1.616	3.193	3.174	8.032
	2009	2.072	0.056	0.469	1.442	2.903	2.903	5.115

Table C 2. The shipment-weighted efficiency of the heating equipment.

Equipment Type	Furnace (AFUE)				Heat Pump (COP)	Floor or Wall Pipeless Furnace (AFUE)			
Fuel	Natural Gas	Fuel Oil	Propane/LPG	Electricity	Electricity	Natural Gas	Fuel Oil	Propane/LPG	Electricity
1970	0.600	0.700	0.600	0.980	1.612	0.500	0.583	0.500	0.980
1971									
1972	0.627	0.736	0.627	0.980	1.820	0.595	0.698	0.595	0.980
1973	0.627	0.736	0.627	0.980	1.820	0.595	0.698	0.595	0.980
1974	0.627	0.736	0.627	0.980	1.820	0.595	0.698	0.595	0.980
1975	0.658	0.736	0.658	0.980	1.820	0.595	0.665	0.595	0.980
1976	0.661	0.741	0.661	0.980	2.013	0.595	0.667	0.595	0.980
1977	0.664	0.745	0.664	0.980	2.019	0.595	0.667	0.595	0.980
1978	0.667	0.750	0.667	0.980	2.122	0.595	0.669	0.595	0.980
1979	0.687	0.755	0.687	0.980	2.151	0.595	0.654	0.595	0.980
1980	0.706	0.760	0.706	0.980	2.201	0.595	0.641	0.595	0.980
1981	0.704	0.768	0.704	0.980	2.257	0.631	0.688	0.631	0.980
1982	0.703	0.775	0.703	0.980	2.283	0.631	0.696	0.631	0.980
1983	0.701	0.783	0.701	0.980	2.412	0.631	0.705	0.631	0.980
1984	0.726	0.786	0.726	0.980	2.476	0.631	0.683	0.631	0.980
1985	0.729	0.786	0.729	0.980	2.509	0.631	0.680	0.631	0.980
1986	0.737	0.796	0.737	0.980	2.550	0.642	0.693	0.642	0.980
1987	0.743	0.798	0.743	0.980	2.617	0.642	0.689	0.642	0.980
1988	0.749	0.804	0.749	0.980	2.676	0.642	0.689	0.642	0.980
1989	0.747	0.804	0.747	0.980	2.714	0.656	0.706	0.656	0.980
1990	0.767	0.803	0.767	0.980	2.772	0.656	0.687	0.656	0.980
1991	0.775	0.808	0.775	0.980	2.863	0.656	0.684	0.656	0.980
1992	0.821	0.808	0.821	0.980	3.107	0.656	0.646	0.656	0.980
1993	0.824	0.809	0.824	0.980	3.183	0.656	0.644	0.656	0.980
1994	0.824	0.809	0.824	0.980	3.206	0.656	0.644	0.656	0.980
1995	0.823	0.809	0.823	0.980	3.215	0.656	0.645	0.656	0.980
1996	0.827	0.809	0.827	0.980	3.224	0.656	0.642	0.656	0.980
1997	0.829	0.809	0.829	0.980	3.215	0.656	0.640	0.656	0.980
1998	0.826	0.809	0.826	0.980	3.309	0.656	0.642	0.656	0.980
1999	0.826	0.809	0.826	0.980	3.309	0.656	0.642	0.656	0.980
2000	0.826	0.809	0.826	0.980	3.285	0.656	0.642	0.656	0.980
2001	0.832	0.809	0.826	0.980	3.312	0.656	0.638	0.652	0.980
2002	0.832	0.809	0.826	0.980	3.315	0.656	0.638	0.652	0.980
2003	0.836	0.809	0.826	0.980	3.315	0.656	0.635	0.648	0.980
2004	0.837	0.809	0.826	0.980	3.315	0.656	0.634	0.648	0.980
2005	0.840	0.809	0.826	0.980	3.315	0.656	0.634	0.648	0.980
2006	0.843	0.809	0.826	0.980	3.315	0.656	0.634	0.648	0.980
2007	0.844	0.809	0.826	0.980	3.315	0.685	0.634	0.648	0.980
2008	0.851	0.809	0.826	0.980	3.315	0.686	0.634	0.648	0.980
2009	0.860	0.809	0.826	0.980	3.315	0.686	0.634	0.648	0.980

Table C 3. The shipment-weighted efficiency of the heating and cooling equipment.

Equipment Type	Built-in Electric Heater (AFUE)	Built-in Room Heater (AFUE)				Central AC (COP)	Heat Pump (COP)	Window/Wall AC (COP)
Fuel	Electricity	Natural Gas	Fuel Oil	Propane /LPG	Electricity	Electricity	Electricity	Electricity
1970	0.980	0.500	0.583	0.500	0.980	1.886	1.628	1.699
1971	0.980							
1972	0.980	0.595	0.698	0.595	0.980	1.926	1.812	1.752
1973	0.980	0.595	0.698	0.595	0.980	1.949	1.812	1.758
1974	0.980	0.595	0.698	0.595	0.980	1.973	1.812	1.787
1975	0.980	0.595	0.665	0.595	0.980	2.003	1.812	1.817
1976	0.980	0.595	0.667	0.595	0.980	2.018	1.978	1.875
1977	0.980	0.595	0.667	0.595	0.980	2.042	1.983	1.919
1978	0.980	0.595	0.669	0.595	0.980	2.093	2.069	1.969
1979	0.980	0.595	0.654	0.595	0.980	2.125	2.093	2.013
1980	0.980	0.595	0.641	0.595	0.980	2.144	2.134	2.057
1981	0.980	0.631	0.688	0.631	0.980	2.199	2.180	2.069
1982	0.980	0.631	0.696	0.631	0.980	2.323	2.201	2.092
1983	0.980	0.631	0.705	0.631	0.980	2.351	2.304	2.136
1984	0.980	0.631	0.683	0.631	0.980	2.403	2.355	2.192
1985	0.980	0.631	0.680	0.631	0.980	2.439	2.380	2.256
1986	0.980	0.642	0.693	0.642	0.980	2.450	2.412	2.285
1987	0.980	0.642	0.689	0.642	0.980	2.473	2.464	2.362
1988	0.980	0.642	0.689	0.642	0.980	2.504	2.508	2.411
1989	0.980	0.656	0.706	0.656	0.980	2.535	2.537	2.485
1990	0.980	0.656	0.687	0.656	0.980	2.548	2.581	2.558
1991	0.980	0.656	0.684	0.656	0.980	2.587	2.647	2.578
1992	0.980	0.656	0.646	0.656	0.980	2.792	2.821	2.602
1993	0.980	0.656	0.644	0.656	0.980	2.813	2.873	2.652
1994	0.980	0.656	0.644	0.656	0.980	2.823	2.889	2.628
1995	0.980	0.656	0.645	0.656	0.980	2.837	2.895	2.646
1996	0.980	0.656	0.642	0.656	0.980	2.837	2.901	2.660
1997	0.980	0.656	0.640	0.656	0.980	2.833	2.895	2.663
1998	0.980	0.656	0.642	0.656	0.980	2.885	2.959	2.660
1999	0.980	0.656	0.642	0.656	0.980	2.893	2.959	2.657
2000	0.980	0.656	0.642	0.656	0.980	2.891	2.943	2.725
2001	0.980	0.656	0.638	0.652	0.980	2.915	2.961	2.822
2002	0.980	0.656	0.638	0.652	0.980	2.915	2.963	2.857
2003	0.980	0.656	0.635	0.648	0.980	2.964	2.963	2.857
2004	0.980	0.656	0.634	0.648	0.980	2.984	3.029	2.857
2005	0.980	0.656	0.634	0.648	0.980	2.986	3.050	2.857
2006	0.980	0.656	0.634	0.648	0.980	3.314	3.359	2.857
2007	0.980	0.663	0.634	0.648	0.980	3.406	3.426	2.857
2008	0.980	0.663	0.634	0.648	0.980	3.418	3.450	2.857
2009	0.980	0.663	0.634	0.648	0.980	3.443	3.494	2.946

Appendix D

Table D 1. The Result of the correlation test of the microdata pairing.

	Census Division	State	Lot Size	House Square Footage	Garage Size	Number of Floors	Cellar	Urban Rural	Number of Bedrooms	Number of Occupants	Number of Full Bathroom	Number of Half Bathroom	House Construction Year
Census Division	1												
State	-0.34	1											
Lot Size	-0.08	0.13	1										
House Square Footage	-0.01	0.00	0.07	1									
Garage Size	0.08	-0.08	0.02	0.15	1								
Number of Floors	-0.12	0.02	0.01	0.21	0.10	1							
Cellar	-0.45	0.16	0.08	0.11	0.01	0.30	1						
Urban Rural	-0.09	0.48	0.27	-0.01	-0.03	-0.03	0.05	1					
Number of Bedrooms	0.07	-0.06	-0.01	0.36	0.24	0.29	0.04	-0.05	1				
Number of Occupants	0.04	-0.04	-0.03	0.11	0.29	0.13	0.01	-0.04	0.33	1			
Number of Full Bathroom	0.17	-0.11	0.02	0.43	0.27	0.22	-0.05	-0.04	0.53	0.19	1		
Number of Half Bathroom	-0.10	0.01	0.01	0.25	0.15	0.32	0.20	-0.04	0.23	0.09	0.03	1	
House Construction Year	0.11	-0.01	0.01	0.17	0.23	-0.01	-0.19	0.03	0.24	0.14	0.42	0.15	1

Appendix E

Table E 1. Factors used to calculate GHG emission from the conventional heating equipment.

Heating Fuel	Source Energy Factor	Higher Heating Value [Btu/(ft3 or gal)]	Precombustion lbCO2eq/unit of fuel (ft3 or gal)	Combustion Factor for Residential Furnace [lbCO2eq/unit of fuel (ft3 or gal)]
Natural Gas	1.092	1010	0.0278	0.121
LPG	1.151	91000	2.56	13.28049
Fuel Oil	1.191	149500	4.47	25.18374
Kerosene	1.205	135000	3.83	-

Appendix F

Table F 1. The lifecycle GHG emission rates by states and the factors used for the calculation.

State	GHG Emission Rate [gCO2eq/kWh]			
	Generation	Upstream	Grid Loss Factor	Total
Alabama	512.1	97.4	5.84E-02	647.3
Alaska	474.5	54.4	5.82E-02	561.6
Arizona	507.3	53.6	5.82E-02	595.6
Arkansas	494.1	62.7	8.21E-02	606.6
California	253.3	78.5	8.21E-02	361.5
Colorado	791.5	69.0	8.21E-02	937.4
Connecticut	263.7	54.6	5.82E-02	338.0
Delaware	1,131.1	132.3	5.82E-02	1,341.5
District of Columbia	817.9	76.6	5.82E-02	949.8
Florida	543.1	92.3	5.82E-02	674.7
Georgia	586.4	54.3	5.82E-02	680.2
Hawaii	696.3	108.6	7.81E-02	873.1
Idaho	741.2	42.3	5.82E-02	831.9
Illinois	54.7	19.0	8.21E-02	80.2
Indiana	486.9	34.0	5.82E-02	553.1
Iowa	927.4	53.7	5.82E-02	1,041.8
Kansas	763.2	46.4	5.82E-02	859.7
Kentucky	933.0	53.1	5.82E-02	1,047.1
Louisiana	513.7	83.0	5.82E-02	633.6
Maine	508.3	89.1	5.82E-02	634.3
Maryland	562.2	40.2	5.82E-02	639.6
Massachusetts	231.3	76.3	5.82E-02	326.6
Michigan	695.3	50.2	5.82E-02	791.6
Minnesota	637.8	42.0	5.82E-02	721.8
Mississippi	824.3	49.2	5.82E-02	927.5
Missouri	502.2	81.1	5.82E-02	619.3
Montana	656.1	33.7	8.21E-02	751.5
Nebraska	527.5	39.5	5.82E-02	602.1
Nevada	938.2	45.9	5.82E-02	1,044.9
New Hampshire	728.6	40.3	5.82E-02	816.4
New Jersey	275.2	52.3	5.82E-02	347.7
New Mexico	250.3	56.5	5.82E-02	325.8
New York	830.2	67.2	8.21E-02	977.6
North Carolina	482.6	100.0	8.21E-02	634.7
North Dakota	265.5	53.7	5.82E-02	338.9
Ohio	812.1	51.3	5.82E-02	916.8
Oklahoma	680.9	84.2	5.82E-02	812.4
Oregon	165.6	41.0	8.21E-02	225.0
Pennsylvania	520.1	48.3	5.82E-02	603.5
Rhode Island	406.6	129.0	5.82E-02	568.7
South Carolina	376.1	39.2	5.82E-02	440.9
South Dakota	416.9	22.3	5.82E-02	466.4
Tennessee	488.7	33.4	5.82E-02	554.4
Texas	566.0	83.3	7.99E-02	705.7
Utah	845.6	62.5	8.21E-02	989.2
Vermont	453.8	51.2	5.82E-02	536.2
Virginia	2.5	13.1	5.82E-02	16.5
Washington	130.6	20.8	8.21E-02	164.9
West Virginia	690.5	50.2	5.82E-02	786.5
Wisconsin	916.9	51.0	5.82E-02	1,027.7
Wyoming	965.1	49.4	8.21E-02	1,105.2