September 2010

BACKGROUNDER

Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems

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Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems

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Abstract

This report first briefly reviews geothermal heat pump (GHP) technology and the current status of the GHP industry in the United States. Then it assesses the potential national benefits in terms of energy savings, reduced summer peak electrical demand, consumer energy cost savings, and reduced carbon dioxide emissions from retrofitting the space-heating, space-cooling, and water-heating systems in existing U.S. single-family homes with state-of-the-art GHP systems. The investment for retrofitting a typical U.S. single-family home with a state-of-the-art GHP system is also analyzed using the metrics of net present value and levelized cost.

This background paper is one in a series developed as part of the Resources for the Future and National Energy Policy Institute project entitled "Toward a New National Energy Policy: Assessing the Options." This project was made possible through the support of the George Kaiser Family Foundation.

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Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems

Xiaobing Liu[*]

Executive Summary

The geothermal heat pump (GHP) is a proven technology capable of significantly reducing energy use and summer peak electrical demand in buildings. However, only about 600,000 GHP units have been installed in the United States (Rybach 2005). Given the 127.8 million households in the United States, even if all 600,000 GHP units were installed in residential buildings, they would account for only slightly less than 0.5 percent of the entire U.S. housing stock. The barriers preventing rapid growth of GHP applications have been identified as a high initial cost to consumers, a lack of knowledge and/or trust in GHP system benefits, limited design and installation infrastructure for GHP systems, and a lack of new technologies and techniques (Hughes 2008).

This report assesses the potential national benefits of retrofitting U.S. single-family homes with state-of-the-art GHP systems at various penetration rates. The benefits considered include energy savings, reduced summer electrical peak demand, consumer utility bill savings, and reduced carbon dioxide (CO_2) emissions. The assessment relies heavily on energy consumption and other data obtained from the Residential Energy Consumption Survey conducted by the U.S. Department of Energy's Energy Information Administration. It also considers relative differences in energy consumption between a state-of-the-art GHP system and existing residential space-heating, space-cooling, and water-heating (SH–SC–WH) systems, which were determined with a well-established energy analysis program for residential SH–SC–WH systems. The impacts of various climate and geological conditions, as well as the efficiency and market share of existing residential SH–SC–WH systems, have been taken into account in the assessment.

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[*] Xiaobing Liu, Energy and Transportation Science Division, Oak Ridge National Laboratory. This work was sponsored by Resources for the Future (RFF). Special thanks to RFF Senior Fellow Margaret Walls for her support. The author also wishes to acknowledge Patrick Hughes, John Shonder, and Erica Atkin at Oak Ridge National Laboratory for their valuable input.

The analysis shows that replacing all SH–SC–WH systems in existing U.S. single-family homes with properly designed, installed, and operated state-of-the-art GHP systems would yield the following benefits annually:

- a savings of **4.2 quadrillion (quad) British thermal units (Btu) in primary energy**, a **45.1 percent** reduction in primary energy consumption associated with SH–SC–WH in existing U.S. single-family homes;
- a reduction of **271.9 million metric tons of** CO_2 **emissions**, a **45.3 percent** reduction in CO_2 emissions associated with SH–SC–WH in existing U.S. single-family homes;
- a savings of $**52.2 billion in energy expenditures**, a **48.2 percent** reduction in energy costs for SH–SC–WH in these homes; and
- a reduction of **215.9 gigawatts (GW) in summer peak electrical demand**, a **56.1 percent** reduction in summer peak electrical demand for SC in existing U.S. single-family homes.

Though it is not feasible to realize the above maximum benefits, the benefits of GHP retrofits are still very significant even at lower market penetration rates, as shown in Table E-1.

Table E-1. Potential Benefits of Retrofitting Existing U.S. Single-Family Homes with State-of-the-Art GHP Systems at Various Market Penetration Rates

Estimated national benefits	Market penetration rate of GHP retrofit				
	20%	40%	60%	80%	100%
Primary energy savings [quad BTU]	0.8	1.7	2.5	3.3	**4.2**
Percentage savings	9.0%	18.0%	27.1%	36.1%	**45.1%**
CO2 emissions reduction [MM ton]	54.3	108.7	163.0	217.3	**271.7**
Percentage savings	9.1%	18.1%	27.2%	36.2%	**45.3%**
Summer peak electrical demand reduction [GW]	43.2	86.4	129.5	172.7	**215.9**
Percentage savings	11.2%	22.4%	33.6%	44.9%	**56.1%**
Energy expenditures savings [Billion $]	10.4	20.9	31.3	41.7	**52.2**
Percentage savings	9.6%	19.3%	28.9%	38.5%	**48.1%**

Notes: (MM ton, million metric ton).

The investment for retrofitting a typical U.S. single-family home with state-of-the-art GHP system is evaluated using the metrics of net present value (NPV) and levelized cost. This assessment determined that state-of-the-art GHP systems will yield a positive NPV for installed systems over a 20-year period at current market prices, and without any financial incentives, when the discount rate is lower than 8 percent. The levelized-cost analysis shows that saving energy with the GHP retrofit is cheaper than generating and delivering electricity to residences when the discount rate is lower than 8 percent. The current federal tax credits for 30 percent of the installed cost of a GHP system (valid through 2016) were not considered in this analysis. Had they been, investments in state-of-the-art

GHP systems would be beneficial even at higher discount rates. Other factors not considered in this analysis include the value of the ground loop heat exchanger beyond the service life of the heat pump unit (ground loops can outlive the building and several generations of heat pump units), and significant values from reduced CO_2 emissions and reduced summer peak electrical demand.

1. Introduction

Buildings present one of the best opportunities for reducing energy consumption and limiting carbon dioxide (CO_2) emissions cost-effectively. The long-term goal of the U.S. Department of Energy's Building Technologies Program (DOE–BTP) is to maximize the cost-effective energy efficiency of buildings. DOE–BTP's vision for achieving the goal involves, among other things, reducing the energy used by residential energy service equipment (which provides space heating [SH], space cooling [SC], and water heating [WH]) by 50 percent compared with today's best common practice.

The geothermal heat pump (GHP) is a proven technology capable of significantly reducing energy use and peak electrical demand in buildings and could play an important role in reaching the goal. According to the latest Residential Energy Consumption Survey (RECS) by the Energy Information Administration (EIA), 67.4 percent of the 127.8 million U.S. households (U.S. Census Selected Housing Characteristics: 2006-2008) live in single-family homes, most of which have space conditioning and/or WH (DOE 2009). Many of these 86.1 million single-family homes are good candidates for GHP retrofits because:

- an average of about 73 percent of the delivered energy consumed in single-family homes is used for space conditioning and WH—about 43 percent for SH alone (DOE 2009);
- the conventional space conditioning and WH equipments used in existing single-family homes usually have 10-15 years of service life. This means homes built in the mid to late 1990s, or heating and cooling systems replaced at that time, are now most likely to be in need of servicing or retrofit; and
- Many U.S. single-family homes have front and/or back yards with more than enough space for installing the vertical or horizontal ground heat exchangers required for GHP systems.

However, only about 600,000 GHP units have been installed in the United States (Rybach 2005). Given the 127.8 million households in the United States, even if all 600,000 GHP units were installed in residential buildings, they would account for only slightly less than 0.5 percent of the entire U.S. housing stock. Obviously, the potential for growth in GHP installations in residential buildings is huge.

A study recently conducted by Oak Ridge National Laboratory (ORNL; Hughes 2008) concludes, from a survey of U.S. GHP industry experts, that high initial costs to consumers, a lack of knowledge and/or trust in GHP system benefits, limited design and installation infrastructures for GHP systems, and a lack of new technologies and techniques are the most significant barriers to the wide application of GHP. The study recommends a series of actions to overcome these barriers. One of the two highest-priority actions is to conduct an independent assessment of the national benefits (including energy savings, reduced energy demand, low operating cost, reduced CO_2 emissions, and increased jobs) achievable from implementing a maximum deployment strategy for GHP systems, including comparisons with other supply- and demand-side options in terms of when benefits could be achieved, the national investment required, and the probability of success.

This report gives a brief overview of GHP technology and the current status of the GHP industry in the United States (Section 2) and assesses the technical potential for total energy savings, reduced summer electrical peak demand, consumer utility bill savings, and reduced CO_2 emissions from retrofitting space-heating, space-cooling, and water-heating (SH–SC–WH) systems in existing U.S. single-family homes with state-of-the-art GHP systems. The study methodology is described in Section 3. An analysis of the economics of GHP retrofits is presented in Section 4.

2. Overview of GHP Technology and the GHP Industry in the United States

This section of the report presents the basics of GHP technology and an overview of the current status of the GHP industry in the United States. Key barriers preventing rapid growth of the GHP industry in the United States, identified by a recent survey of GHP industry experts, are summarized. Hughes (2008) provides a more detailed and comprehensive overview of GHP technology and the GHP industry.

2.1 Basics of GHP Technology

The biggest difference between GHP and conventional space conditioning and WH systems is that, instead of rejecting heat from buildings to the ambient air (in cooling mode) and extracting heat from fossil fuel combustion, electricity, or the ambient air (in SH and/or WH modes), a GHP rejects heat to (in cooling mode) or extracts heat from (in SH and/or WH modes) various ground resources, including the earth, surface water, recycled gray water, sewage treatment plant effluent, stormwater retention basins, harvested rainwater, and water from subsurface aquifers—either alone or in combination with conventional heat addition and rejection devices in a hybrid configuration.

Because the ground resources usually have a more favorable temperature than the ambient air for the heating and cooling operation of the vapor-compression refrigeration cycle, GHP systems can operate with much higher energy efficiency than conventional air-source heat pumps (ASHPs), especially for heating operation in cold climates. GHP systems harvest the free and renewable energy (solar, geothermal, and heat removed from the built environment) stored in various ground resources to provide SH and/or water WH. GHPs thus can significantly reduce energy consumption and greenhouse gas (GHG) emissions compared with heating systems using oil or electricity and a highly energy efficient GHP system can also outperform natural gas-fired furnace or boiler, especially when the electricity consumed by the GHP system is generated with cleaner energy than coal.

A study by the U.S. Environmental Protection Agency (EPA) comparing the major heating, ventilating, and air-conditioning (HVAC) options for residential applications determined that GHP was the most energy-efficient and environmentally benign option (EPA 1993). A report by the American Physical Society (2008, 56, 73) referred to GHP systems as being among the options that could help the U.S. building sector achieve the goal of using no more primary energy in 2030 than in 2008, rather than increasing energy use by 30 percent by 2030 as currently projected. Enhanced use of ground energy sources and heat sinks at the building or community level is highlighted as a promising option in the 2008 report designed to establish the federal research and development (R&D) agenda for buildings issued by National Science and Technology Council (2008).

A GHP system is made up of three major components: a water-source heat pump (WSHP) unit operable over an extended range of entering fluid temperatures (EFT; referred to as the GHP unit hereafter); a ground heat exchanger designed for available ground resources; and a circulation system to deliver cold or warm air or water to the built environment and circulate the liquid heat transfer medium (water or aqueous antifreeze solution) through the GHP unit and the ground heat exchanger.

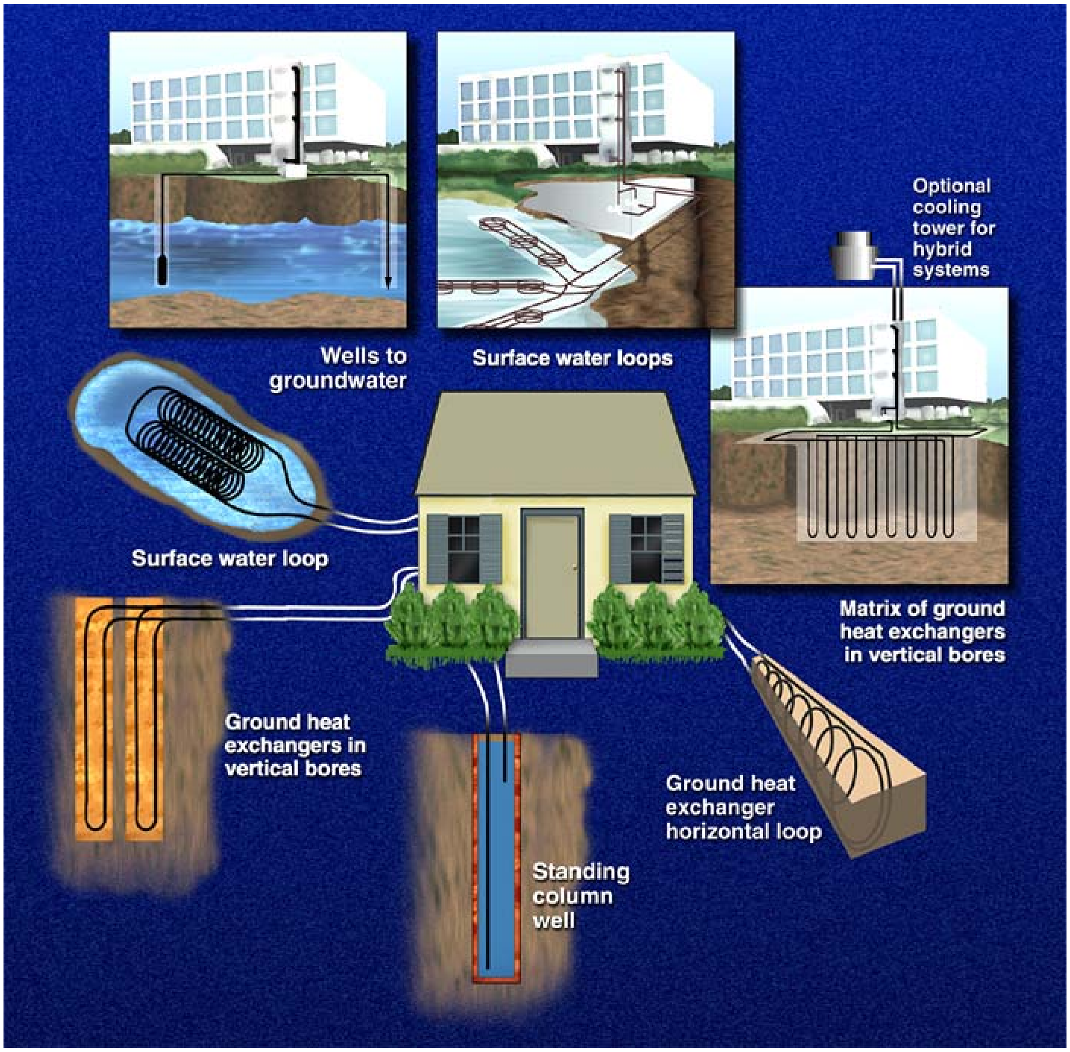
Small packaged or split water-to-air heat pump units are most popularly used in the GHP systems in the United States. An alternative configuration that may be more economical in some situations is a small or large water-to-water heat pump unit. Rather than directly delivering cold or hot air to spaces as the water-to-air heat pump does, a water-to-water heat pump delivers chilled or hot water to various types of zone terminals. Today’s GHP systems move three to five times more energy between the building and the ground sources than they consume in doing so. With sufficient motivation, the GHP industry could further increase this multiplier effect by integrating the most advanced commercially available components and technologies into their heat pumps, such as variable-speed compressors, variable refrigerant–flow systems, and special refrigerants.

Figure 1 illustrates a number of options for the ground heat exchanger. The vast majority of GHP systems in the United States are installed with closed-loop heat exchangers using high-density polyethylene (HDPE) pipe buried in the earth in either a vertical or horizontal configuration. The closed-loop technology permits GHPs to be applied effectively in many locations. The HDPE piping technology has been perfected by the natural gas industry for collecting underground natural gas in production fields and distributing it to customers.

The ground heat exchanger can be designed at the scale of a community or a single building and can serve new construction or retrofits of existing communities or buildings. In many areas, it may be possible to serve the modest heating, cooling, ventilation, WH, and refrigeration loads of highly efficient new homes and commercial buildings with efficient heat pumps coupled to ground loops placed in construction excavations, without any extra digging or drilling whatsoever.

GHP technology is not the same technology as geothermal power production, in which the extreme heat of subsurface geological processes is used to produce steam and ultimately to generate electricity. Nor is it the same as the direct use of geothermal heat, in which moderate-temperature geothermal sources such as hot springs are used directly to heat greenhouses, aquaculture ponds, and other agricultural facilities. GHP systems use the only renewable energy resource that (a) is available at most building's point of use, (b) is available on demand, (c) cannot normally be depleted (assuming proper design), and (d) are potentially affordable in all 50 states.

Figure. 1 Typical Options for Ground Heat Exchanger Used in GHP Systems



Technologies aimed at cost reduction and performance improvement of GHP systems are being pursued in the United States and even more aggressively in some European and Asian countries. Research topics include the following:

- integrated GHP units serving multiple purposes, including heating, cooling, WH, and dehumidification;
- design tools and models for ground heat exchangers installed in the excavations and/or foundations needed to construct buildings;
- design tools for surface-water heat pump systems;
- design guidelines and tools for hybrid GHPs;
- single-well groundwater supply and return systems;
- compact horizontal loops reloaded via heat exchange with exhaust air;
- devices to test borehole heat exchanger installation quality; and
- new-generation technology for in situ ground thermal property testing.

2.2 Current Status of GHP Industry in the United States

The U.S. GHP industry was started in the early 1970s by entrepreneurs including contractors and manufacturers. Currently, it is made up of manufacturers of WSHPs, HDPE piping and fittings, circulating pumps, and specialty components, as well as a design infrastructure, an installation infrastructure, and various trade allies, most notably electric utilities.

A small group of manufacturers—including ClimateMaster (a unit of LSB Industries), Florida Heat Pump (a unit of Bosch), WaterFurnace International, Inc., and Trane (a unit of Ingersoll Rand)—are believed to produce most GHP units, supplemented by McQuay International (a unit of Daikin), Mammoth, and several regional manufacturers. Most of these manufacturers produce WSHP units not only for the GHP market but also for water loop heat pump (WLHP) systems, which use more conventional cooling towers and boilers in place of ground heat exchangers. Other major brands, such as Carrier, participate in the WLHP and GHP markets by sourcing WSHP units from other manufacturers.

In addition to serving GHP applications, HDPE pipe is used in oil production fields and for natural gas collection and distribution, sewerage collection, potable water distribution, landfill gas collection, industrial applications, and irrigation. The manufacturing base is large and well-established. It is believed that Performance Pipe (a unit of Chevron–Philips), ISCO Industries, and Centennial Plastics are the largest suppliers of HDPE to the GHP market.

Circulating pumps, propylene glycol antifreeze, plate heat exchangers, fluid coolers, and many other products used in GHP systems are already mass-produced to serve markets much larger than the GHP market.

The specialty products unique to the GHP market—such as flow centers, flush carts, purge pumps, pump stations, headers, vaults, hose kits, thermally enhanced grouts, specialty installation equipment, and surface water immersion heat exchangers—are generally made by relatively small regional firms.

Despite the significant number of competent and experienced designers of residential and commercial GHP systems—especially those with vertical-bore ground heat exchangers—they still make up a small percentage of HVAC design engineers. Similarly, experienced and competitive installation infrastructures for ground heat exchangers are in short supply and exist only in portions of some states.

During the 30-year history of the U.S. GHP industry, many modest but successful GHP programs sponsored by the electric utilities have boosted the GHP industry in some localities. The contribution of GHP systems in reducing summer peak electrical demand and improving the load factor of the electricity supply is the main reason for electric utility support of the GHP industry. Until the 1990s, GHP technology received attention from policymakers in Washington, DC, and two notable federal GHP programs—the National Earth Comfort Program and the Federal Energy Management Program's GHP technology-specific program (Hughes and Pratsch 2002)—were initiated to demonstrate GHP technology, mobilize the GHP market, and provide financial and technical support for implementing GHP systems. These utility and federal GHP programs successfully increased public awareness of GHP technology, increased GHP unit shipments, and collected hard data proving the benefits of GHP systems in terms of reducing maintenance and energy costs.

Though the United States was the world leader in GHP technology and still has the largest installed base of GHP systems—approximately 600,000 units in 2005 (Rybach 2005)—the GHP market share in the United States is much smaller than in some European counties. A 2005 review of the global market status of GHP systems estimated that Sweden, Denmark, Switzerland, and some other countries ranked higher on a per capita basis (Rybach 2005) than the United States. Owing to supportive government policies, the GHP market is growing rapidly in Asia, especially in China and South Korea. It is believed that the European and Asian markets have currently exceeded U.S. markets in annual shipments of GHP units.

Although the GHP industry in the United States remains small, it is better positioned for rapid growth than at any time during the past 30 years in many respects. Federal and state governments in the United States are giving strong incentives to support the development and application of energy efficiency and renewable energy technologies, among which GHP has been given high priority. Tax credits for home and business owners investing in GHP systems were enacted in October 2008 through 2016. Since 2007, rural electric cooperatives have been able to obtain loans from the U.S. Department of Agriculture Rural Utilities Service with terms of up to 35 years, at the cost of government funds, to provide the outside-the-building portion of GHP systems to customers in exchange for a tariff on the utility bill. The tariff would be more than offset by the GHP system's energy cost savings. In December 2007, Congress directed the General Services Administration (GSA) to establish a program to accelerate the use of more cost-effective energy-saving technologies and practices in GSA facilities, starting with lighting and GHPs. A growing number of states offer tax credits or other incentives for GHP systems (listed on the Database of State Incentives for Renewable Energy website). In October 2009, DOE awarded a total of $63 million in American Recovery and Reinvestment Act funds to support the sustainable growth of the U.S. GHP industry though actions in three areas:

- demonstrating innovative business and financing strategies and/or technical approaches designed to overcome barriers to the commercialization of GHPs;
- gathering data, conducting analyses, and developing tools to assist consumers in determining project feasibility and achieving lowest-life-cycle-cost GHP applications; and
- creating a national certification standard for the GHP industry to increase consumer confidence in the technology, reduce the potential for improperly installed systems, and ensure product quality and performance.

GHP units have been improved significantly in energy efficiency, noise level, and lifespan. Most GHP unit manufacturers have well-established supply chains and paths to market. In addition, improvements in the design and energy analysis of GHP systems include (a) a design tool sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for hybrid GHP systems (Hackel et al. 2009) and (b) the integration of improved representations of vertical-bore ground heat exchangers and GHP systems in eQUEST, a DOE-2–based building energy analysis program that is credible but also relatively easy to use (Liu 2008).

The diverse segments of the GHP industry are better able to work with each other as a cohesive whole than ever before. The installed base of systems is much larger today and can serve to inform best practices. The most important trade allies of the GHP industry, electric utilities, are better able now to focus on peak load reduction and an improved load factor, two key GHP system benefits, than they were in 1993 when utility restructuring was looming.

The infrastructure of support organizations is also much stronger now than it was in 1993. The International Ground Source Heat Pump Association, which represents all segments of the industry, has matured. It provides the nation's only major conferences and exhibitions totally focused on GHP technology, and it has developed respected training programs for drillers and installers. The Geothermal Heat Pump Consortium (GHPC) has been reconstituted as an advocacy and government relations organization sponsored by the GHP industry. ASHRAE Technical Committee TC 6.8, Geothermal Energy Utilization, has made great strides in developing the technical foundation for the sound design of commercial GHP systems. The National Ground Water Association is more engaged than ever. National laboratory and university expertise persists, even though these institutions have never had reliable funding sources to sustain GHP programs.

2.3 Key Barriers Preventing Rapid Growth of the GHP Industry in the United States

ORNL recently conducted an informal survey of a group of GHP industry experts to identify the barriers to rapid growth of the U.S. GHP industry (Hughes 2008). The survey identified the following barriers in order of priority (1 being the most important):

Tier one

1. high initial cost of GHP systems to consumers

Tier two

2. lack of consumer knowledge of and/or trust in GHP system benefits
3. lack of policymaker and regulator knowledge of and/or trust in GHP system benefits
4. limitations in GHP design and business planning infrastructure
5. limitations in GHP installation infrastructure

Tier three

6. lack of new technologies and techniques to improve GHP system cost or performance

The multiple tiers are included to indicate that barriers two–five had essentially the same level of support among survey participants, whereas barrier one was perceived as being of greater importance and barrier six of lesser importance than two–five. Somewhat surprisingly, most of these barriers are the same as those identified in surveys conducted decades ago. As early as 1994, the National Earth Comfort Program (GHPC 1994) had identified initial cost, confidence or trust in the technology, and design and installation infrastructure as the primary barriers to the growth of the GHP industry.

How high is the initial cost of GHP systems to consumers? The U.S. Department of Defense (DOD)—perhaps the largest single customer for GHP retrofit projects—reports that, in 2006 dollars, housing and commercial retrofits cost $4,600 and $7,000 per ton, respectively, and simple paybacks in the two regions with the most installed capacity averaged 8.6 to 12 years (DOD 2007). Retrofits in the private sector would probably be similar in cost and payback. New construction has the potential to be more economical because part of the initial cost is offset by the avoided cost of the displaced conventional system, but simple paybacks exceeding five years are still common.

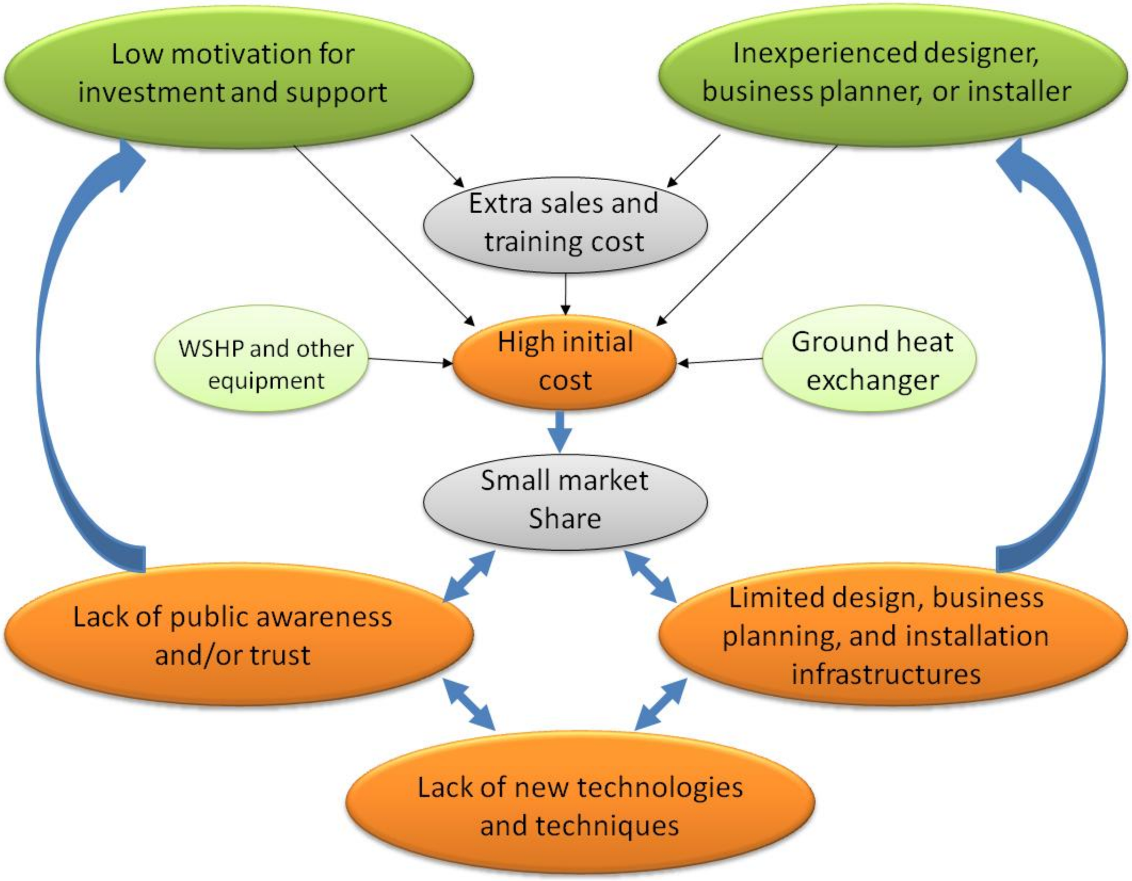
Initial cost and long payback periods clearly limit GHP system acceptance in many markets. Currently in commercial markets, GHPs are primarily limited to institutional customers (e.g., federal, state, and local governments and K–12 schools) that take the lifecycle view. In residential markets, GHPs are limited to a small subset of newly constructed homes that the builder plans to occupy—and thus wants to equip with the best available system—and to home retrofits in which the owner plans to occupy the premises long enough to justify the investment. In all of these cases, the building owner must have the financial wherewithal to use his or her own credit to finance the system.

What contributes to the high initial cost of GHP systems? The ground heat exchanger (especially the vertical-bore system, the one most often used) is the major reason for the high initial cost. The cost of the ground heat exchanger usually makes up more than half the total cost of a GHP system. The GHP unit also contributes to the high initial cost—currently 50–100 percent more expensive at retail than ASHP units of comparable capacity and component quality. Several other interacting factors, which are directly or indirectly related to the tier two and three barriers listed above, also contribute to the high initial cost. Figure 2 illustrates the factors that affect the initial cost of GHP systems and their relationships to the identified barriers.

As shown in Figure 2, all of the barriers result in a small market share for GHP systems in the United States. In turn, the small market share perpetuates the barriers because the GHP technology is almost invisible to the general public and thus unattractive to design, business planning, and installation professionals. The lack of public awareness and trust directly leads to low motivation to invest in and support the GHP industry. The limited design, business planning, and installation infrastructure implies that many HVAC professionals are not experienced with GHP applications. As a result, R&D for GHP technology has been limited, and few new technologies and techniques have been developed. Without a substantial contribution from R&D, significant cost reduction, performance enhancement, improvement in public awareness and trust, and improvement in design and installation infrastructure are unlikely.

Given the large proportion of unmotivated consumers and inexperienced design and installation professionals, the GHP supply chain (original equipment manufacturers, distributors, and dealers) must educate them and even provide extra technical assistance for the design and installation of GHP systems. These extra selling and training costs are included in the prices of GHP products. That partially explains why GHP units are currently 50–100 percent more expensive at retail than ASHP units of comparable capacity and component quality. Of course, the relatively small shipment volume and the low motivation for investment and support (i.e., R&D to reduce cost and improve performance) also contribute to the relatively high cost of GHP units.

Figure 2. Factors That Affect the Initial Cost of GHP Systems and Their Relationships



Inexperienced designers tend to oversize GHP systems and/or add excessive backup capacity to provide a larger safety margin, but doing so unnecessarily increases their cost. A lack of experience and competition in ground heat exchanger installation is another reason for the high initial cost of GHP systems.

Figure 2 shows that the GHP industry is trapped in a cycle of a high initial cost leading to a small market, which perpetuates the high initial cost. To escape this cycle, the high initial cost to consumers of GHP systems must be reduced to a level more competitive with that of other technologies.

3. Assessment of National Benefits from GHP Retrofit

The benefits achievable from retrofitting existing single-family homes with GHP systems depend on many factors, including the characteristics of the building itself (e.g., construction, orientation, insulation level, and air tightness), energy efficiency and fuel type of existing SH–SC–WH systems (e.g., natural gas, heating oil, propane or liquefied petroleum gas [LPG], and electricity), occupants' lifestyle, and many other location-sensitive parameters, such as:

- climate conditions;
- the cost of fuels used by the existing SH–SC–WH systems;
- primary energy (e.g., coal, natural gas, nuclear, and various types of renewable energy) consumption and CO_2 emissions associated with generating electricity and delivering it to building sites, which depend on the energy mix for electricity generation at a particular location; and
- primary energy consumption and CO_2 emissions associated with harvesting and delivering fossil fuels to building sites.

To accurately predict the magnitude of the national potential of benefits from retrofitting U.S. single-family homes with GHP systems, all of these factors need to be properly accounted for.

3.1 Energy Use of Typical SH–SC–WH Systems in Existing Single-Family Homes

EIA keeps track of the annual delivered energy[1] consumption of the entire U.S. residential sector through national area probability–sample surveys[2], and the results are published regularly by DOE in the *Buildings Energy Data Book*. Data for SH–SC–WH system types and associated annual energy use for existing U.S. single-family homes have been extracted from the Public Use Microdata Files of the latest RECS (EIA 2005). Table 1 summarizes the SH–SC–WH systems that are most popularly used in existing U.S. single-family homes and their energy efficiencies (EIA 2000; DOE 2005). The number of single-family homes that use a particular SH–SC–WH system in each U.S. census region and the corresponding annual consumption of delivered energy are presented in Table 2.

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[1] Energy delivered to a building without adjustment for the energy consumed to produce and deliver the energy.

[2] The survey collected data from 4,382 households sampled at random using a complex, multistage, area-probability design to represent 111.1 million U.S. households, the Census Bureau's statistical estimate for all occupied housing units in 2005. Data were obtained from residential energy suppliers for each unit in the sample to produce the consumption and expenditures data.

Table 1. Typical SH–SC–WH Systems Used in U.S. Single-Family Homes

Energy services	Existing systems and equipment	Rated efficiencies
Space heating	ASHP	3.2 COP
	Electric heater	100 EF
	Natural gas–fired furnace/boiler	80 AFUE
	Propane- or LPG-fired furnace/boiler	80 AFUE
	Heating oil–fired furnace/boiler	80 AFUE
Space cooling	CAC/ASHP	10 SEER
	RAC	7.7 SEER
	Combination of CAC and RAC	7.7–10 SEER
Water heating	Electric heater	88 EF
	Natural gas heater	58 EF
	Propane or LPG heater	58 EF
	Heating oil heater	58 EF

Notes: The AFUE, annual fuel utilization efficiency, is the ratio of the annual amount of heat actually delivered to the amount of fuel supplied to the furnace. The COP, coefficient of performance, is the ratio of heating energy provided to the space to the electric energy consumed. The COP of the ASHP listed in the above table is measured at standard, mild weather (47°F) rating conditions. The EF, energy factor, indicates a water heater’s overall energy efficiency based on the amount of hot water produced per unit of fuel consumed over a typical day. The SEER, seasonal energy efficiency ratio, is the average annual cooling efficiency of an air-conditioning or heat pump system determined with a standard methodology and assuming typical weather. CAC, central air conditioner; RAC, room air conditioner. Effective on January 23, 2006, manufacturers in the US will be allowed to produce only equipments that meet the new minimum rating of 13 SEER for CAC and ASHP (up to 5 ton capacity).

Table 2. Number of Single-Family Homes with SH–SC–WH in Each Census Region and Corresponding Annual Consumption of Delivered Energy (Based on Data from RECS Public Use Microdata Files)

SH-SC-WH system types	Number of existing single-family homes	Percentage of existing single-family homes in a region that use various systems for SH-SC-WH	Delivered energy consumed for SH-SC-WH by existing single-family homes in each census region (from RECS 2005)	Percentage of delivered energy consumption in a region by single-family homes with various systems for SH-SC-WH
	Millions	-	Billion Btu	-
Space heating	**13.0**	**100%**	**1,036,111.4**	**100%**
Electric heat pump	0.18	1.4%	1,869.5	0.2%
Electric heater	0.70	5.4%	15,518.5	1.5%
Natural gas furnace	7.19	55.5%	545,290.1	52.6%
Propane/LPG furnace	0.36	2.8%	26,577.9	2.6%
Fuel oil furnace	4.54	35.0%	446,855.4	43.1%
Space cooling	**11.1**	**100%**	**55,800.7**	**100%**
Central air conditioner	4.95	44.4%	35,651.9	63.9%
Room air conditioner	6.10	54.8%	18,571.6	33.3%
Both central and room AC	0.10	0.9%	1,577.1	2.8%
Water heating	**13.3**	**100%**	**322,149.1**	**100%**
Electric water heater	2.93	22.0%	27,361.2	8.5%
Natural gas water heater	7.08	53.1%	187,572.4	58.2%
Propane/LPG water heater	0.52	3.9%	17,533.8	5.4%
Fuel oil water heater	2.80	21.0%	89,681.8	27.8%
Regional subtotal	37.4		1,414,061.2	
Space heating	**19.4**	**100%**	**1,220,359.0**	**100%**
Electric heat pump	0.69	3.6%	9,528.2	0.8%
Electric heater	1.38	7.1%	38,577.5	3.2%
Natural gas furnace	14.91	76.9%	1,007,014.8	82.5%
Propane/LPG furnace	1.71	8.8%	110,737.9	9.1%
Fuel oil furnace	0.69	3.6%	54,500.6	4.5%
Space cooling	**18.6**	**100%**	**125,209.6**	**100%**
Central air conditioner	14.64	78.6%	111,213.5	88.8%
Room air conditioner	3.62	19.4%	11,851.6	9.5%
Both central and room AC	0.36	1.9%	2,144.4	1.7%
Water heating	**23.0**	**109%**	**450,429.6**	**100%**
Electric water heater	5.56	24.2%	60,561.6	13.4%
Natural gas water heater	13.60	59.3%	348,376.4	77.3%
Propane/LPG water heater	0.99	4.3%	40,391.1	9.0%
Fuel oil water heater	2.80	21.0%	1,100.5	0.2%
Regional subtotal	61.0		1,795,998.2	
Space heating	**28.0**	**100%**	**692,639.8**	**100%**
Electric heat pump	6.04	21.6%	39,701.8	5.7%
Electric heater	8.02	28.6%	105,666.7	15.3%
Natural gas furnace	11.58	41.3%	416,522.4	60.1%
Propane/LPG furnace	1.92	6.9%	91,162.6	13.2%
Fuel oil furnace	0.45	1.6%	39,586.2	5.7%
Space cooling	**28.0**	**100%**	**443,245.8**	**100%**
Central air conditioner	22.71	81.0%	388,678.9	87.7%
Room air conditioner	4.64	16.5%	39,477.2	8.9%
Both central and room AC	0.70	2.5%	15,089.7	3.4%
Water heating	**31.9**	**112%**	**521,217.2**	**100%**
Electric water heater	16.67	52.3%	166,429.5	31.9%
Natural gas water heater	11.53	36.2%	314,584.5	60.4%
Propane/LPG water heater	0.86	2.7%	35,951.7	6.9%
Fuel oil water heater	2.80	21.0%	4,251.5	0.8%
Regional subtotal	87.9		1,657,102.8	
Space heating	**15.6**	**100%**	**473,587.2**	**100%**
Electric heat pump	0.79	5.1%	5,269.7	1.1%
Electric heater	2.72	17.4%	31,853.3	6.7%
Natural gas furnace	11.26	72.0%	378,182.1	79.9%
Propane/LPG furnace	0.66	4.2%	35,628.5	7.5%
Fuel oil furnace	0.21	1.3%	22,653.6	4.8%
Space cooling	**9.5**	**100%**	**78,108.0**	**100%**
Central air conditioner	7.74	81.7%	73,231.3	93.8%
Room air conditioner	1.49	15.8%	3,433.9	4.4%
Both central and room AC	0.24	2.5%	1,442.8	1.8%
Water heating	**19.5**	**107%**	**409,343.8**	**100%**
Electric water heater	3.41	17.5%	39,301.4	9.6%
Natural gas water heater	12.56	64.5%	338,378.5	82.7%
Propane/LPG water heater	0.72	3.7%	30,576.5	7.5%
Fuel oil water heater	2.80	21.0%	1,087.4	0.3%
Regional subtotal	44.6		961,039.0	
			5.8 Quad Btu	

Notes: *Btu, British thermal units; quad, quadrillion.*

3.2 State-of-the-Art GHP System

The state-of-the-art GHP system presented in this study consists of a packaged water-to-air GHP unit with a two-stage scroll compressor and variable-speed electronically commutated motor fan, a properly sized and highly energy-efficient loop fluid circulator, and a properly designed and installed vertical-borehole ground heat exchanger. The nominal cooling efficiency of the two-stage GHP unit is an energy efficiency ratio (EER)[3] of 18.2 at full capacity and an EER of 27 at 76 percent of full capacity. The nominal heating efficiency of the two-stage GHP unit has a COP of 4 at full capacity and a COP of 4.5 at 76 percent of full capacity.[4]

The ground heat exchanger is sized to maintain the fluid temperature from the ground loop [the EFT to the GHP unit] within the range of 30°F–95°F for given building loads, ground thermal properties, and undisturbed ground temperature.

The state-of-the-art GHP system can contribute to WH through the use of a desuperheater, which heats the water whenever the GHP runs. In this study, an electric storage-type water heater with an energy factor (EF) of 88 is assumed as the main water heating device, which is assisted by the GHP desuperheater.

3.3 Reference Building

Given the vast number and wide variation of homes in the United States, it is not practical to model each of the existing single-family homes. On the other hand, the relative difference in annual energy consumption between the state-of-the-art GHP system and existing SH–SC–WH systems for providing the same energy service depends more on the characteristics of the compared systems, weather, and geological conditions than the building itself. Therefore, one reference building representing typical U.S. single-family homes (including internal loads from lighting, appliances, cooking, and occupants) is used in this study to calculate the relative difference in annual energy consumption between the state-of-the-art GHP system and existing SH–SC–WH systems. The description of this reference building is provided in Appendix A.

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[3] The EER is the cooling capacity (in British thermal units [Btu]/hour) of the unit divided by its electrical input (in watts) at standard conditions.

[4] The COP and EER are measured at AHRI/ISO/ASHRAE/ANSI 13256-1 rating conditions: for cooling at full capacity, EFT is 77°F; for heating at full capacity, EFT is 32°F.

3.4 Calculation Tool

The annual delivered energy consumption of the state-of-the-art GHP system and typical existing SH–SC–WH systems was calculated with GeoDesigner, a well-established energy analysis program developed by ClimateMaster, Inc.

GeoDesigner uses the ASHRAE bin analysis method to calculate the energy consumption of GHP and other residential SH–SC–WH systems. Compared with more sophisticated hourly energy simulation programs, bin analysis is less accurate in estimating the impacts of weather elements (i.e., solar, wind, precipitation, and so on) and the heat gain from activities inside the building (e.g., lighting, cooking, and showering) on building heating and cooling loads. Bin analysis also limits the capability for a more detailed analysis of the electrical demand of the building and a more accurate calculation of ground heat exchanger temperatures.

However, although GeoDesigner and the more sophisticated programs sometimes differ in the predicted total energy consumption of particular SH–SC–WH systems, the relative difference in energy consumption between the state-of-the-art GHP system and the existing SH–SC–WH systems predicted by GeoDesigner is fairly close to that predicted by the more sophisticated programs.

Because, as described below, it is the relative difference in annual energy consumption between different SH–SC–WH systems that is needed for this study, and considering the advantages of GeoDesigner, including user-friendly interfaces and reports, robust and fast calculations, and the capability for performing an energy analysis for a wide range of residential SH–SC–WH systems, GeoDesigner was selected for this study. A more detailed description of the algorithms, capabilities, and limitations of GeoDesigner is given in Appendix B.

3.5 Calculation Procedure for Energy Savings and CO_2 Emissions Reduction

The efficiencies of ASHPs and air conditioners are affected by the outdoor ambient temperature, and the efficiency of a GHP system is influenced by the fluid temperature from the ground heat exchanger, which is determined by the building heating and cooling loads, the size of the ground heat exchanger, and geological conditions (i.e., the ground thermal properties) where the system is installed. Therefore, to obtain an estimate of the regional average of the relative difference in annual energy consumption between the GHP system and existing SH–SC–WH systems, different weather and geological conditions within the region were accounted for in this study. As a simplification, I assume that the weather and undisturbed ground temperatures are identical across a climate zone within a census region. Ground thermal property values that are very common in the United States are used for all of the climate zones (representing the typical thermal properties of granite, limestone, and sandstone with 1.4 British thermal units (Btu)/hour-ft-F thermal conductivity and 0.04 ft^2/hour thermal diffusivity). I first calculated the delivered energy consumed annually by each of the typical existing SH–SC–WH systems and the state-of-the-art GHP system for providing the same SH–SC–WH service in each climate zone within a particular census region. Then I used the population associated with each climate zone as a weighting factor to calculate the regional average of annual delivered energy consumption for each of the compared systems. Finally, I computed the regional relative difference in annual delivered energy consumption between the state-of-the-art GHP system and each of the existing SH–SC–WH systems.

The procedure and formulas used for estimating the annual national potential savings in delivered energy from retrofitting U.S. single-family homes with GHP systems is described below.

Step 1:

Calculate the peak heating and cooling loads of the reference building at various locations that represent major climate zones with each of the four U.S. census regions.

Step 2:

Calculate the annual delivered energy consumption of each compared SH–SC–WH system with GeoDesigner based on the peak heating and cooling loads determined in Step 1 and the associated weather and geological conditions.

Step 3:

Calculate the regional average of annual delivered energy consumption of a particular SH–SC–WH system serving the reference building with Equation 1.

$$Avg\_Sys\_DE(j,k) = \frac{\sum_{i=1}^{n} Sys\_DE(i,j,k) \cdot CZ(i,k)}{\sum_{i=1}^{n} CZ(i,k)} \tag{1}$$

where

$Avg\_Sys\_DE(j,k)$ is the average annual delivered energy consumption of SH–SC–WH system *j* in census region *k*;

$Sys\_DE(i,j,k)$ is the annual delivered energy consumption of SH–SC–WH system *j* in climate zone *i* of census region *k*;

$CZ(i,k)$ is the population in climate zone *i* of census region *k*; and

n is the number of major climate zones in census region *k*.

Step 4:

Calculate the regional average relative differences in annual delivered energy consumption between the state-of-the-art GHP system and each of the typical existing SH–SC–WH systems with Equation 2.

$$RD\_DE(j,k) = \frac{Avg\_Sys\_DE(j,k) - Sys\_DE\_GHP(k)}{Avg\_Sys\_DE(j,k)} \qquad (2)$$

where

$RD\_DE(j,k)$ is the regional average relative difference in annual delivered energy consumption between the state-of-the-art GHP system and SH–SC–WH system *j* in census region *k* and

$Sys\_DE\_GHP(k)$ is the average annual energy consumption of the state-of-the-art GHP system in census region *k*.

Step 5:

Calculate the annual savings in delivered energy from GHP retrofits in a particular region with Equation 3.

$$Reg\_DE(k) = \sum_{j=1}^{m} SFHS\_DE(j,k) \cdot Penetration \cdot RD\_DE(j,k) \qquad (3)$$

where

$Reg\_DE(k)$ is the annual savings in delivered energy in census region *k*;

$SFHS\_DE(j,k)$ is the annual delivered energy consumed by existing SH–SC–WH system *j* in census region *k*;

$Penetration$ is the assumed fraction of existing U.S. single-family homes captured by GHP retrofits; and

m is the number of existing SH–SC–WH systems used in U.S. single-family homes.

Step 6:

Calculate the national potential savings in delivered energy from retrofitting existing U.S. single-family homes with the state-of-the-art GHP system with Equation 4.

$$National\_DE = \sum_{k=1}^{4} Reg\_DE(k) \qquad (4)$$

Following this procedure, I estimated the national potential of savings in energy expenditure and reductions in primary energy consumption and CO_2 emissions. In these calculations, the annual delivered energy consumption of each compared SH–SC–WH system was replaced with the associated energy expenditure, primary energy consumption, or CO_2 emissions using corresponding regional utility rates, conversion factors between delivered and primary energy, and emissions factors of various fuels used by the compared SH–SC–WH systems.

3.6 Calculation Procedure for Summer Peak Electrical Demand Reduction

Because no similar regional data are available from EIA for summer peak electrical demand of residential buildings when this study was performed, the potential reduction in peak demand from GHP retrofits is estimated from the bin analysis data generated by GeoDesigner.

In general, the summer peak electrical demand of single-family homes is coincident with the peak electrical demand for SC. Therefore, the reduction in summer peak electrical demand is determined in this study as the reduction of electrical demand for SC at its peak. The calculation is expressed in Equation 5.

$$PEDFSC = \frac{kWh\_MaxTemp}{Hr\_MaxTemp \times Fraction\_HP} \tag{5}$$

where

$PEDFSC$ is the peak electrical demand for SC, kilowatt (kW);

$kWh\_MaxTemp$ is the electrical energy consumed for SC when outdoor ambient temperature is within the highest temperature bin of a particular location, kWh (kilowatt-hour);

$Hr\_MaxTemp$ is the number of hours when outdoor ambient temperature is within the highest temperature bin of a particular location, hour; and

$Fraction\_HP$ is the percentage of $Hr\_MaxTemp$ when the heat pump runs.

The above-calculated peak electrical demand for cooling is further normalized by dividing it by the coincident peak cooling load (expressed in tons) of the reference building at the particular location, in kW/ton.

The regional average summer peak electrical demand for SC for the state-of-the-art GHP system and typical existing SC systems are determined by applying the population weighting factor of each climate zone to the normalized electrical demands calculated for each climate zone within a particular census region. The regional total summer peak electrical demand for SC is the product of three variables:

- the average normalized summer peak electrical demand for SC per household in a census region (kW/ton),
- the average cooling tonnage per household in a census region (ton), and
- the total number of households in a census region that use SC.

3.7 Selected Locations for Energy Analysis

The 2004 International Energy Conservation Code (IECC) climate zones for the United States are used in this study. These climate zones were developed based on an analysis of the 4,775 National Oceanic and Atmospheric Administration weather sites and statistical analysis of regional information, and are used in ASHRAE standards 90.1 and 90.2, the ASHRAE Advanced Energy Design Guide Series, and DOE’s Building America program. Figure 3 shows the 2004 IECC climate zones, which are assigned using county boundaries.

Figure 3. 2004 IECC Climate Zones of the United States

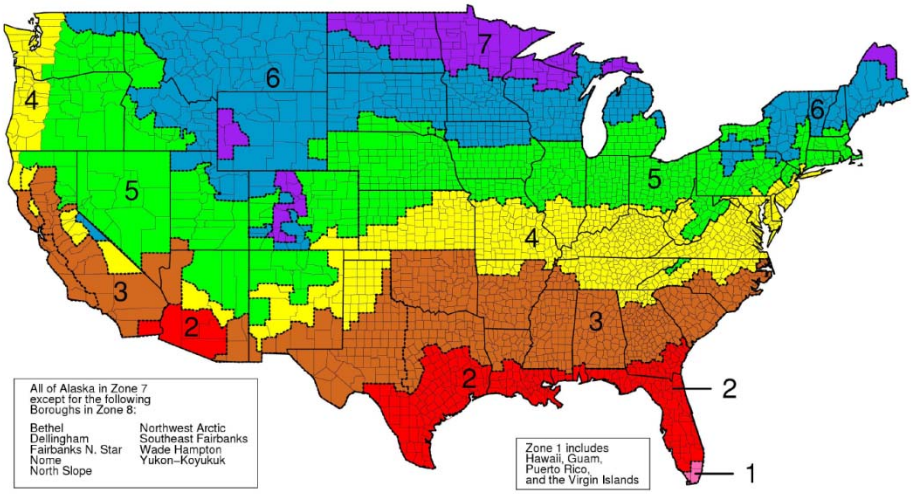
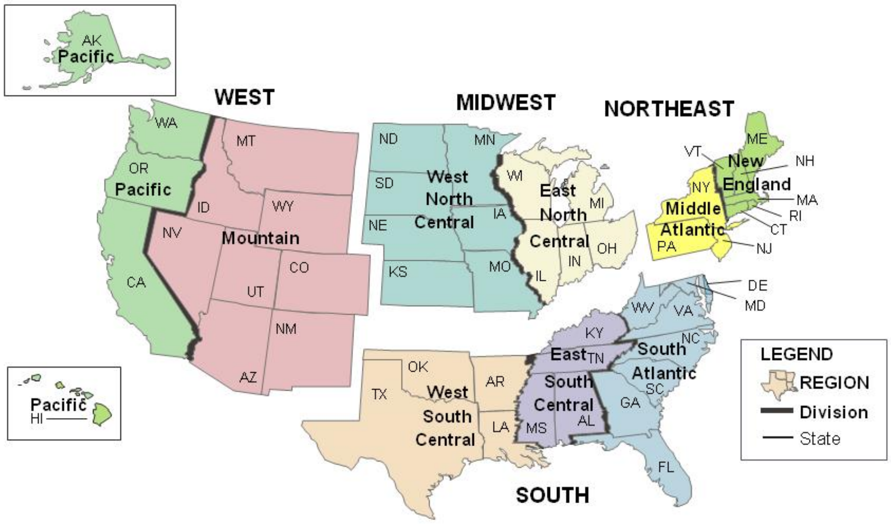


Figure 4. U.S. Census Regions and Divisions



Comparing the map of U.S. census regions in Figure 4 with the climate zones in Figure 3 shows that each census region covers multiple climate zones. Table 3 lists the percentage of the population in each climate zone in each census region. Where the percentage of the population in a climate zone is very low (less than 5 percent of the total population in the census region), that climate zone is omitted from the calculations. One location (a city) was selected to represent each of the 14 climate zones included in this study.

Table 3. Percentage of Population in Each Climate Zone within Each of the U.S. Census Regions

Climate zones	U.S. census regions			
	Northeast	Midwest	South	West
1A	—	—	4.0%	1.9%
1B	—	—	—	—
2A	—	—	**29.2%**	—
2B	—	—	0.4%	**7.4%**
3A	—	—	**35.1%**	—
3B	—	—	1.8%	**44.7%**
3C	—	—	—	**11.5%**
4A	**40.1%**	**18.8%**	**28.2%**	—
4B	—	—	0.5%	2.6%
4C	—	—	—	**11.8%**
5A	**51.5%**	**60.2%**	0.9%	—
5B	—	—	—	**16.4%**
5C	—	—	—	—
6A	**8.3%**	**18.4%**	—	—
6B	—	—	—	3.5%
7A	0.1%	2.5%	—	—
7B	—	—	—	0.3%
8A	—	—	—	—
8B	—	—	—	—

Note: Bold cells represent climate zones that have more than 5 percent of the total population in a particular census region.

The peak heating and cooling loads for the reference building at each of the 14 locations were calculated using eQUEST, a DOE-2–based building energy analysis program; the results are listed in Table 4. These peak heating and cooling loads, along with other user-specified parameters (e.g., location/bin-weather data, SH–SC–WH system type and efficiency, number of occupants, and hot water temperature), are used by GeoDesigner to calculate the annual delivered energy consumption of various SH–SC–WH systems serving the building.

Table 4. Peak Heating and Cooling Loads for the Reference Building in 14 Representative Locations (Cities)

Census region	Climate zone	City	State	Peak heating load	Peak cooling load (Tot)	Peak cooling load (Sen)
				Btu/Hr	Btu/Hr	Btu/Hr
Northeast	4A	Philadelphia	PA	29,204	20,650	15,116
Northeast	5A	Boston	MA	32,695	15,307	11,358
Northeast	6A	Bangor	ME	44,309	18,761	14,165
Midwest	4A	Kansas city	MO	33,772	25,286	18,358
Midwest	5A	Chicago	IL	40,490	20,092	14,627
Midwest	6A	Minneapolis	MN	45,452	18,191	13,570
South	2A	Houston	TX	22,004	25,113	18,458
South	3A	Atlanta	GA	26,436	23,884	18,152
South	4A	Nashville	TN	35,860	24,489	18,489
West	2B	Phoenix	AZ	14,191	26,598	25,215
West	3B	Sacramento	CA	15,890	19,388	17,120
West	3C	San Francisco	CA	14,734	13,589	12,828
West	4C	Portland	OR	25,756	15,076	12,860
West	5B	Denver	CO	40,817	15,118	15,118

3.8 Estimated Benefits

The potential benefits from retrofitting U.S. single-family homes with the state-of-the-art GHP system were estimated using the procedures described in previous sections. The estimated national potential for each of the four major benefits of GHP retrofits—energy savings, reductions in CO_2 emissions, avoided summer peak electrical demand, and energy expenditure savings—all at various market penetration rates, are presented in the following sections. The energy consumption, CO_2 emissions, summer peak electrical demand, and energy expenditures of each of the compared SH–SC–WH systems at each of the 14 representative locations, as well as the population-weighted average for each census region, are listed in Appendix C.

3.8.1 Energy Savings

The estimated regional and national potential savings in delivered energy are presented in Table 5. Table 5 summarizes the regional average of the delivered energy consumed by the state-of-the-art GHP system and the existing SH–SC–WH systems, respectively, for providing the same energy services to the reference building. As described previously, these regional averages have taken into account the impacts of typical weather, geological conditions, and population distribution within the region. Table 5 also lists the regional average of savings in delivered energy from retrofitting the existing SH–SC–WH systems with the state-of-the-art GHP system. The savings is then expressed as a percentage of the delivered energy consumed by the existing SH–SC–WH systems. Table 5 provides the regional total of delivered energy consumed by SH–SC–WH systems in single-family homes, which is obtained from the Public Use Microdata Files of the latest RECS (EIA 2005). Table 5 presents the estimated regional potential in savings of delivered energy at various market penetration rates.

As shown in Table 5, although the annual consumption of delivered energy for a particular SH–SC–WH system varied significantly among the census regions, the relative differences between the state-of-the-art GHP system and the existing SH–SC–WH systems were not very sensitive to the census region. Compared with SH–SC–WH systems typically used in existing single-family homes, the state-of-the-art GHP system consumed 60–86 percent less delivered energy for SH, 60–80 percent less delivered energy for SC, and 34–62 percent less delivered energy for WH. If all SH–SC–WH systems in existing U.S. single-family homes are replaced with state-of-the art GHP systems, an estimated 4.2 quadrillion (quad) Btu of delivered energy will be saved each year; this equals 72.1 percent of all delivered energy currently consumed for SH–SC–WH in U.S. single-family homes. However, if only 20 percent of U.S. single-family homes were retrofitted with the state-of-the-art GHP system, the savings of delivered energy would be about 0.8 quad Btu, which is a 14.4 percent reduction from current consumption levels.

By converting the delivered energy consumption data (both the calculated delivered energy consumption for SH–SC–WH in the reference building and the documented delivered energy consumption for all existing U.S. single-family homes) to the associated primary energy consumption with the conversion factors listed in Table 6, the national potential for savings in annual primary energy consumption is estimated, as shown in Table 7. The primary energy conversion factors for electricity and fossil fuels were adopted from a recent report by the National Renewable Energy Laboratory (NREL 2007). Although the primary energy conversion factors for other fossil fuels are independent of the location where the delivered energy is consumed, the primary energy conversion factor for electricity depends on the energy portfolio for electricity generation for the particular location, and these portfolios will probably include more renewable or green energy in the future. However, because the primary energy conversion factors for electricity at each census region were not available when this study was conducted, the 2005 national average of the primary energy conversion factor for electricity was used.

Table 5. National Savings of Delivered Energy from GHP Retrofits for Existing U.S. Single-Family Homes

Census region	SH-SC-WH system types	Regional average delivered energy cons. by existing SH-SC-WH system in reference building	Regional average delivered energy cons. by GHP system in reference building	Regional average savings of delivered energy in reference building	Percentage savings of delivered energy from GHP retrofit	Regional delivered energy cons. for SH-SC-WH in all single-family homes (RECS 2005)	Estimated regional potential in savings of delivered energy: 20% market penetration rate for GHP retrofit	40% market penetration rate for GHP retrofit	60% market penetration rate for GHP retrofit	80% market penetration rate for GHP retrofit	100% market penetration rate for GHP retrofit
		Million Btu	Million Btu	Million Btu	%	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu
Northeast	**Space heating**					**1,036.1**	**170.9**	**341.8**	**512.6**	**683.5**	**854.4**
	Electric heat pump	41.5	14.4	27.1	65.3%	1.9	0.2	0.5	0.7	1.0	1.2
	Electric heater	56.5	14.4	42.1	74.5%	15.5	2.3	4.6	6.9	9.3	11.6
	Natural gas furnace	78.4	14.4	64.0	81.7%	545.3	89.1	178.1	267.2	356.3	445.3
	Propane/LPG furnace	76.3	14.4	61.9	81.2%	26.6	4.3	8.6	12.9	17.3	21.6
	Fuel oil furnace	89.0	14.4	74.7	83.9%	446.9	74.9	149.9	224.8	299.8	374.7
	Space cooling					**55.8**	**8.5**	**16.9**	**25.4**	**33.8**	**42.3**
	Central air conditioner	5.8	1.5	4.3	73.7%	35.7	5.3	10.5	15.8	21.0	26.3
	Room air conditioner	7.5	1.5	6.0	79.7%	18.6	3.0	5.9	8.9	11.8	14.8
	Both central and room AC	6.6	1.5	5.1	77.1%	1.6	0.2	0.5	0.7	1.0	1.2
	Water heating					**322.1**	**37.4**	**74.8**	**112.1**	**149.5**	**186.9**
	Electric water heater	16.7	10.4	6.3	37.8%	27.4	2.1	4.1	6.2	8.3	10.3
	Natural gas water heater	26.0	10.4	15.7	60.2%	187.6	22.6	45.2	67.8	90.4	113.0
	Propane/LPG water heater	25.3	10.4	15.0	59.1%	17.5	2.1	4.1	6.2	8.3	10.4
	Fuel oil water heater	25.5	10.4	15.1	59.4%	89.7	10.7	21.3	32.0	42.6	53.3
	Regional total SH-SC-WH					**1,414.1**	**216.7**	**433.4**	**650.2**	**866.9**	**1,083.6**
Midwest	**Space heating**					**1,220.4**	**195.8**	**391.6**	**587.4**	**783.2**	**979.0**
	Electric heat pump	56.6	18.2	38.5	67.9%	9.5	1.3	2.6	3.9	5.2	6.5
	Electric heater	67.1	18.2	48.9	72.9%	38.6	5.6	11.3	16.9	22.5	28.1
	Natural gas furnace	93.2	18.2	75.0	80.5%	1,007.0	162.1	324.3	486.4	648.5	810.7
	Propane/LPG furnace	90.6	18.2	72.5	80.0%	110.7	17.7	35.4	53.1	70.8	88.5
	Fuel oil furnace	105.8	18.2	87.6	82.8%	54.5	9.0	18.1	27.1	36.1	45.1
	Space cooling					**125.2**	**17.2**	**34.5**	**51.7**	**69.0**	**86.2**
	Central air conditioner	8.3	2.6	5.6	68.1%	111.2	15.1	30.3	45.4	60.6	75.7
	Room air conditioner	10.7	2.6	8.1	75.4%	11.9	1.8	3.6	5.4	7.2	8.9
	Both central and room AC	9.5	2.6	6.9	72.2%	2.1	0.3	0.6	0.9	1.2	1.5
	Water heating					**450.4**	**53.0**	**106.0**	**159.1**	**212.1**	**265.1**
	Electric water heater	18.6	11.1	7.5	40.4%	60.6	4.9	9.8	14.7	19.6	24.4
	Natural gas water heater	29.1	11.1	18.0	61.8%	348.4	43.1	86.2	129.3	172.4	215.5
	Propane/LPG water heater	28.3	11.1	17.2	60.7%	40.4	4.9	9.8	14.7	19.6	24.5
	Fuel oil water heater	28.5	11.1	17.4	61.0%	1.1	0.1	0.3	0.4	0.5	0.7
	Regional total SH-SC-WH					**1,796.0**	**266.1**	**532.1**	**798.2**	**1,064.2**	**1,330.3**
South	**Space heating**					**692.6**	**112.7**	**225.4**	**338.0**	**450.7**	**563.4**
	Electric heat pump	20.5	7.8	12.8	62.2%	39.7	4.9	9.9	14.8	19.7	24.7
	Electric heater	33.8	7.8	26.1	77.1%	105.7	16.3	32.6	48.9	65.1	81.4
	Natural gas furnace	47.0	7.8	39.3	83.5%	416.5	69.6	139.1	208.7	278.2	347.8
	Propane/LPG furnace	45.8	7.8	38.0	83.0%	91.2	15.1	30.3	45.4	60.6	75.7
	Fuel oil furnace	53.4	7.8	45.7	85.5%	39.6	6.8	13.5	20.3	27.1	33.8
	Space cooling					**443.2**	**54.9**	**109.8**	**164.8**	**219.7**	**274.6**
	Central air conditioner	14.7	5.7	9.0	61.0%	388.7	47.4	94.8	142.2	189.6	237.0
	Room air conditioner	19.1	5.7	13.4	70.0%	39.5	5.5	11.0	16.6	22.1	27.6
	Both central and room AC	16.9	5.7	11.2	66.0%	15.1	2.0	4.0	6.0	8.0	10.0
	Water heating					**521.2**	**57.5**	**114.9**	**172.4**	**229.8**	**287.3**
	Electric water heater	15.6	9.3	6.4	40.7%	166.4	13.5	27.1	40.6	54.1	67.7
	Natural gas water heater	24.4	9.3	15.1	62.0%	314.6	39.0	78.0	117.1	156.1	195.1
	Propane/LPG water heater	23.7	9.3	14.5	60.9%	36.0	4.4	8.8	13.1	17.5	21.9
	Fuel oil water heater	23.9	9.3	14.6	61.2%	4.3	0.5	1.0	1.6	2.1	2.6
	Regional total SH-SC-WH					**1,657.1**	**225.1**	**450.1**	**675.2**	**900.2**	**1,125.3**
West	**Space heating**					**473.6**	**77.5**	**155.0**	**232.5**	**310.0**	**387.5**
	Electric heat pump	20.7	8.2	12.5	60.2%	5.3	0.6	1.3	1.9	2.5	3.2
	Electric heater	34.0	8.2	25.7	75.7%	31.9	4.8	9.6	14.5	19.3	24.1
	Natural gas furnace	47.0	8.2	38.8	82.5%	378.2	62.4	124.7	187.1	249.5	311.8
	Propane/LPG furnace	45.8	8.2	37.5	82.0%	35.6	5.8	11.7	17.5	23.4	29.2
	Fuel oil furnace	53.4	8.2	45.1	84.5%	22.7	3.8	7.7	11.5	15.3	19.2
	Space cooling					**78.1**	**9.6**	**19.2**	**28.7**	**38.3**	**47.9**
	Central air conditioner	8.1	3.2	4.9	60.8%	73.2	8.9	17.8	26.7	35.6	44.5
	Room air conditioner	10.6	3.2	7.4	69.8%	3.4	0.5	1.0	1.4	1.9	2.4
	Both central and room AC	9.3	3.2	6.2	65.9%	1.4	0.2	0.4	0.6	0.8	1.0
	Water heating					**409.3**	**45.1**	**90.2**	**135.3**	**180.4**	**225.5**
	Electric water heater	16.0	10.7	5.4	33.6%	39.3	2.6	5.3	7.9	10.6	13.2
	Natural gas water heater	25.1	10.7	14.4	57.5%	338.4	38.9	77.8	116.7	155.6	194.5
	Propane/LPG water heater	24.4	10.7	13.7	56.2%	30.6	3.4	6.9	10.3	13.8	17.2
	Fuel oil water heater	24.5	10.7	13.9	56.6%	1.1	0.1	0.2	0.4	0.5	0.6
	Regional total SH-SC-WH					**961.0**	**132.2**	**264.4**	**396.5**	**528.7**	**660.9**
National total of delivered energy savings [quad Btu]							**0.8**	**1.7**	**2.5**	**3.4**	**4.2**
Percentage savings							**14.4%**	**28.8%**	**43.2%**	**57.7%**	**72.1%**

Note: quad, quadrillion.

Table 6. Source Energy Factors for Fuel or Electricity Delivered to Buildings

Fuel	Conversion factor
Natural gas	1.092
Propane	1.151
Heating oil	1.158
Electricity	3.365

As shown at the bottom of Table 7, a total of 3.8 quad Btu of primary energy, which corresponds to 41.1 percent of primary energy currently consumed for SH–SC–WH in existing U.S. single-family homes, could be saved each year by retrofitting all existing U.S. single-family homes with state-of-the-art GHP systems. The savings of primary energy is linearly correlated with the market penetration rate of GHP retrofits.

Because the primary energy conversion factor for electricity is larger than that for fossil fuels, the savings in primary energy for SH and WH is lower than the savings in delivered energy. The primary energy consumption for WH actually increases when existing water heaters fired with fossil fuels are replaced with electric water heaters assisted with GHP unit desuperheaters. If, by policy, the existing water heaters fired with fossil fuels were not replaced with desuperheater-assisted electric water heaters, the maximum savings of primary energy from GHP retrofits rises from 3.8 quad Btu to **4.2 quad Btu**, which is **45.1 percent** of primary energy currently consumed for SH–SC–WH in existing U.S. single-family homes.

Table 7. National Savings of Primary Energy from GHP Retrofits for Existing U.S. Single-Family Homes

Census region	SH-SC-WH system types	Regional average primary energy cons. by existing SH-SC-WH system in reference building	Regional average primary energy cons. by GHP system in reference building	Regional average savings of primary energy cons. in reference building	Percentage savings of primary energy cons. from GHP retrofit	Regional primary energy cons. for SH-SC-WH in all single-family homes (RECS 2005)	Estimated regional potential in savings of primary energy cons.				
							20% market penetration rate for GHP retrofit	40% market penetration rate for GHP retrofit	60% market penetration rate for GHP retrofit	80% market penetration rate for GHP retrofit	100% market penetration rate for GHP retrofit
		Million Btu	Million Btu	Million Btu	%	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu	Trillion Btu
Northeast	**Space heating**					**1,202.0**	**122.7**	**245.5**	**368.2**	**491.0**	**613.7**
	Electric heat pump	139.5	48.4	91.2	65.3%	6.3	0.8	1.6	2.5	3.3	4.1
	Electric heater	190.0	48.4	141.6	74.5%	52.2	7.8	15.6	23.4	31.1	38.9
	Natural gas furnace	88.4	48.4	40.0	45.3%	595.5	53.9	107.8	161.8	215.7	269.6
	Propane/LPG furnace	91.5	48.4	43.1	47.2%	30.6	2.9	5.8	8.7	11.5	14.4
	Fuel oil furnace	108.4	48.4	60.1	55.4%	517.5	57.3	114.7	172.0	229.3	286.7
	Space cooling					**187.8**	**28.5**	**56.9**	**85.4**	**113.8**	**142.3**
	Central air conditioner	19.5	5.1	14.3	73.7%	120.0	17.7	35.4	53.0	70.7	88.4
	Room air conditioner	25.3	5.1	20.1	79.7%	62.5	10.0	19.9	29.9	39.9	49.8
	Both central and room AC	22.4	5.1	17.2	77.1%	5.3	0.8	1.6	2.5	3.3	4.1
	Water heating					**420.9**	**(7.9)**	**(15.8)**	**(23.7)**	**(31.6)**	**(39.5)**
	Electric water heater	56.1	34.9	21.2	37.8%	92.1	7.0	13.9	20.9	27.9	34.8
	Natural gas water heater	27.9	34.9	-7.0	-25.0%	204.8	(10.2)	(20.5)	(30.7)	(41.0)	(51.2)
	Propane/LPG water heater	28.9	34.9	-5.9	-20.5%	20.2	(0.8)	(1.7)	(2.5)	(3.3)	(4.1)
	Fuel oil water heater	29.5	34.9	-5.4	-18.3%	103.9	(3.8)	(7.6)	(11.4)	(15.2)	(19.0)
	Regional total SH-SC-WH					**1,810.7**	**143.3**	**286.6**	**429.9**	**573.2**	**716.5**
Midwest	**Space heating**					**1,452.1**	**132.9**	**265.9**	**398.8**	**531.7**	**664.7**
	Electric heat pump	190.6	61.1	129.5	67.9%	32.1	4.4	8.7	13.1	17.4	21.8
	Electric heater	225.8	61.1	164.7	72.9%	129.8	18.9	37.9	56.8	75.7	94.7
	Natural gas furnace	105.0	61.1	43.8	41.8%	1,099.7	91.9	183.7	275.6	367.4	459.3
	Propane/LPG furnace	108.7	61.1	47.6	43.8%	127.5	11.2	22.3	33.5	44.6	55.8
	Fuel oil furnace	128.8	61.1	67.6	52.5%	63.1	6.6	13.3	19.9	26.5	33.2
	Space cooling					**421.3**	**58.0**	**116.0**	**174.0**	**232.1**	**290.1**
	Central air conditioner	27.8	8.9	18.9	68.1%	374.2	51.0	101.9	152.9	203.8	254.8
	Room air conditioner	36.1	8.9	27.2	75.4%	39.9	6.0	12.0	18.0	24.1	30.1
	Both central and room AC	31.9	8.9	23.1	72.2%	7.2	1.0	2.1	3.1	4.2	5.2
	Water heating					**632.0**	**(0.2)**	**(0.3)**	**(0.5)**	**(0.7)**	**(0.9)**
	Electric water heater	62.7	37.4	25.3	40.4%	203.8	16.4	32.9	49.3	65.8	82.2
	Natural gas water heater	31.2	37.4	-6.2	-19.9%	380.4	(15.1)	(30.3)	(45.4)	(60.6)	(75.7)
	Propane/LPG water heater	32.3	37.4	-5.0	-15.5%	46.5	(1.4)	(2.9)	(4.3)	(5.8)	(7.2)
	Fuel oil water heater	32.9	37.4	-4.4	-13.5%	1.3	(0.0)	(0.1)	(0.1)	(0.1)	(0.2)
	Regional total SH-SC-WH					**2,505.4**	**190.8**	**381.6**	**572.3**	**763.1**	**953.9**
South	**Space heating**					**1,094.8**	**134.2**	**268.3**	**402.5**	**536.7**	**670.8**
	Electric heat pump	69.1	26.1	42.9	62.2%	133.6	16.6	33.2	49.8	66.4	83.1
	Electric heater	113.9	26.1	87.7	77.1%	355.6	54.8	109.6	164.4	219.2	274.0
	Natural gas furnace	53.1	26.1	27.0	50.8%	454.8	46.2	92.5	138.7	185.0	231.2
	Propane/LPG furnace	55.0	26.1	28.9	52.5%	104.9	11.0	22.0	33.1	44.1	55.1
	Fuel oil furnace	65.2	26.1	39.1	59.9%	45.8	5.5	11.0	16.5	22.0	27.5
	Space cooling					**1,491.5**	**184.8**	**369.6**	**554.4**	**739.2**	**924.0**
	Central air conditioner	49.6	19.3	30.2	61.0%	1,307.9	159.5	319.0	478.5	638.0	797.6
	Room air conditioner	64.4	19.3	45.0	70.0%	132.8	18.6	37.2	55.8	74.3	92.9
	Both central and room AC	57.0	19.3	37.6	66.0%	50.8	6.7	13.4	20.1	26.8	33.5
	Water heating					**949.9**	**30.9**	**61.8**	**92.6**	**123.5**	**154.4**
	Electric water heater	52.6	31.2	21.4	40.7%	560.0	45.5	91.1	136.6	182.1	227.7
	Natural gas water heater	26.1	31.2	-5.1	-19.3%	343.5	(13.3)	(26.6)	(39.9)	(53.2)	(66.4)
	Propane/LPG water heater	27.1	31.2	-4.1	-15.0%	41.4	(1.2)	(2.5)	(3.7)	(5.0)	(6.2)
	Fuel oil water heater	27.6	31.2	-3.6	-12.9%	4.9	(0.1)	(0.3)	(0.4)	(0.5)	(0.6)
	Regional total SH-SC-WH					**3,536.2**	**349.8**	**699.7**	**1,049.5**	**1,399.4**	**1,749.2**
West	**Space heating**					**605.1**	**64.5**	**128.9**	**193.4**	**257.9**	**322.3**
	Electric heat pump	69.8	27.8	42.0	60.2%	17.7	2.1	4.3	6.4	8.5	10.7
	Electric heater	114.3	27.8	86.6	75.7%	107.2	16.2	32.5	48.7	64.9	81.2
	Natural gas furnace	52.7	27.8	24.9	47.3%	413.0	39.1	78.2	117.2	156.3	195.4
	Propane/LPG furnace	54.6	27.8	26.8	49.1%	41.0	4.0	8.1	12.1	16.1	20.1
	Fuel oil furnace	64.6	27.8	36.8	57.0%	26.2	3.0	6.0	9.0	12.0	15.0
	Space cooling					**262.8**	**32.2**	**64.5**	**96.7**	**128.9**	**161.2**
	Central air conditioner	27.4	10.7	16.7	60.8%	246.4	30.0	60.0	89.9	119.9	149.9
	Room air conditioner	35.5	10.7	24.8	69.8%	11.6	1.6	3.2	4.8	6.5	8.1
	Both central and room AC	31.5	10.7	20.7	65.9%	4.9	0.6	1.3	1.9	2.6	3.2
	Water heating					**538.2**	**(18.1)**	**(36.1)**	**(54.2)**	**(72.3)**	**(90.4)**
	Electric water heater	54.0	35.9	18.1	33.6%	132.2	8.9	17.8	26.6	35.5	44.4
	Natural gas water heater	26.8	35.9	-9.0	-33.6%	369.5	(24.9)	(49.7)	(74.6)	(99.4)	(124.3)
	Propane/LPG water heater	27.9	35.9	-8.0	-28.8%	35.2	(2.0)	(4.0)	(6.1)	(8.1)	(10.1)
	Fuel oil water heater	28.4	35.9	-7.5	-26.4%	1.3	(0.1)	(0.1)	(0.2)	(0.3)	(0.3)
	Regional total SH-SC-WH					**1,406.2**	**78.6**	**157.3**	**235.9**	**314.5**	**393.1**
National total of primary energy savings [quad Btu]							**0.8**	**1.5**	**2.3**	**3.1**	**3.8**
Percentage savings							**8.2%**	**16.5%**	**24.7%**	**32.9%**	**41.2%**

3.8.2 Reductions in CO_2 Emissions

By converting the delivered energy consumption data—both the calculated delivered energy consumptions for various SH–SC–WH systems in the reference building and the documented delivered energy consumption for all existing U.S. single-family homes—to the associated CO_2 emissions with the conversion factors listed in Table 8, the national potential reductions in annual CO_2 emissions was determined (Table 9). These emissions factors for electricity and fossil fuels (which account for emissions both from on-site combustion and from pre-combustion activities, including extracting and delivering the fossil fuels to the point of use) were adopted from a recent report by NREL (2007).

Table 8. Emissions Factors for Fuels and Electricity

Fuel	CO_2 equivalent emissions factor	
Natural gas	150.80	lb per Mcf
Propane	16.06	lb per gallon
Heating oil	26.90	lb per gallon
Electricity	1.67	lb per kWh

Note: Mcf, thousand cubic feet.

As shown at the bottom of Table 9, 244.6 million metric tons of CO_2 emissions, which account for 40.8 percent of all the CO_2 emissions associated with SH–SC–WH in existing U.S. single-family homes, could be saved each year by GHP retrofits at the 100 percent market penetration rate.

As with primary energy, the CO_2 emissions associated with WH increased when existing water heaters fired by fossil fuels were replaced with desuperheater-assisted electric water heaters. If, by policy, these water heaters were not replaced with desuperheater-assisted electric water heaters, the maximum reduction of CO_2 emissions from GHP retrofits would rise from 244.8 to **271.9 million metric tons**, which is **45.3 percent** of all CO_2 emissions associated with SH–SC–WH in existing U.S. single-family homes.

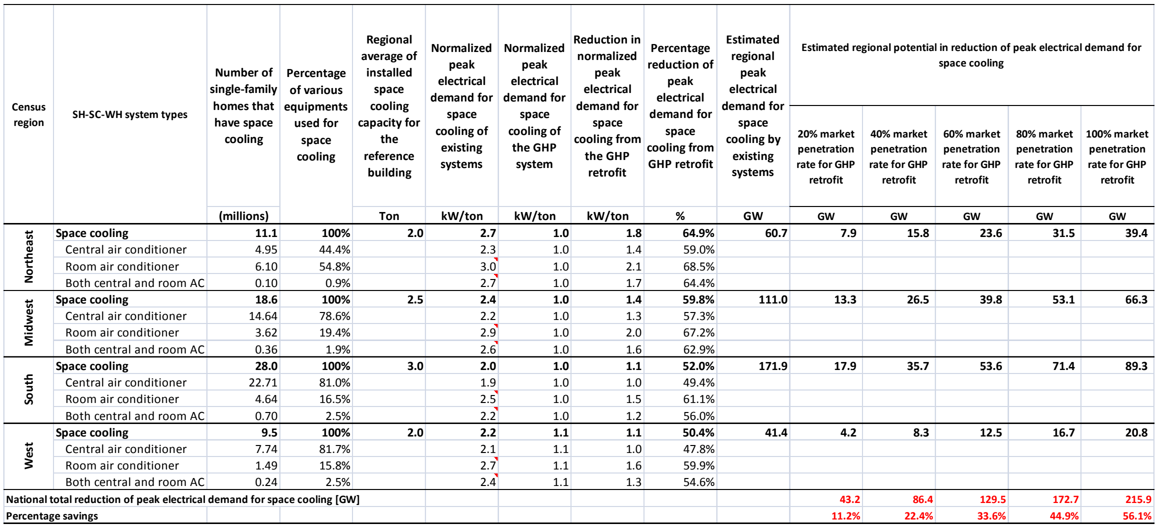
Table 9. National Total of Reduced CO_2 Emissions from GHP Retrofit for Existing U.S. Single-Family Homes

Census region	SH-SC-WH system types	Regional average CO_2 emission by existing SH-SC-WH system in reference building	Regional average CO_2 emission by GHP system in reference building	Regional average reduction of CO_2 emission in reference building	Percentage reduction of CO_2 emission from GHP retrofit	Regional CO_2 emission for SH-SC-WH in all single-family homes (RECS 2005)	Estimated regional potential in reduction of CO_2 emissions				
							20% market penetration rate for GHP retrofit	40% market penetration rate for GHP retrofit	60% market penetration rate for GHP retrofit	80% market penetration rate for GHP retrofit	100% market penetration rate for GHP retrofit
		lb	lb	lb	%	Million lb	Million lb	Million lb	Million lb	Million lb	Million lb
Northeast	**Space heating**					**179,480.4**	**18,961.6**	**37,923.3**	**56,884.9**	**75,846.5**	**94,808.2**
	Electric heat pump	20,287.6	7,031.2	13,256.3	65.3%	914.8	119.5	239.1	358.6	478.2	597.7
	Electric heater	27,621.8	7,031.2	20,590.6	74.5%	7,593.3	1,132.1	2,264.1	3,396.2	4,528.3	5,660.4
	Natural gas furnace	12,138.6	7,031.2	5,107.4	42.1%	79,834.7	6,718.1	13,436.3	20,154.4	26,872.6	33,590.7
	Propane/LPG furnace	13,978.7	7,031.2	6,947.5	49.7%	4,659.8	463.2	926.4	1,389.6	1,852.8	2,316.0
	Fuel oil furnace	17,971.3	7,031.2	10,940.0	60.9%	86,477.8	10,528.7	21,057.4	31,586.0	42,114.7	52,643.4
	Space cooling					**27,303.6**	**4,138.2**	**8,276.4**	**12,414.5**	**16,552.7**	**20,690.9**
	Central air conditioner	2,829.2	745.0	2,084.3	73.7%	17,444.7	2,570.2	5,140.5	7,710.7	10,281.0	12,851.2
	Room air conditioner	3,674.3	745.0	2,929.4	79.7%	9,087.2	1,449.0	2,897.9	4,346.9	5,795.8	7,244.8
	Both central and room AC	3,251.8	745.0	2,506.8	77.1%	771.7	119.0	238.0	356.9	475.9	594.9
	Water heating					**61,279.9**	**(978.6)**	**(1,957.2)**	**(2,935.8)**	**(3,914.4)**	**(4,893.0)**
	Electric water heater	8,153.8	5,070.0	3,083.8	37.8%	13,388.0	1,012.7	2,025.3	3,038.0	4,050.7	5,063.4
	Natural gas water heater	3,813.4	5,070.0	(1,256.7)	-33.0%	27,462.1	(1,810.0)	(3,620.0)	(5,430.0)	(7,240.0)	(9,050.0)
	Propane/LPG water heater	4,438.2	5,070.0	(631.9)	-14.2%	3,074.2	(87.5)	(175.1)	(262.6)	(350.1)	(437.7)
	Fuel oil water heater	4,936.7	5,070.0	(133.3)	-2.7%	17,355.7	(93.7)	(187.5)	(281.2)	(374.9)	(468.7)
	Regional total SH-SC-WH					**268,063.8**	**22,121.2**	**44,242.4**	**66,363.6**	**88,484.8**	**110,606.0**
Midwest	**Space heating**					**200,935.8**	**17,731.8**	**35,463.7**	**53,195.5**	**70,927.4**	**88,659.2**
	Electric heat pump	27,711.8	8,887.5	18,824.3	67.9%	4,662.2	633.4	1,266.8	1,900.2	2,533.6	3,167.0
	Electric heater	32,836.8	8,887.5	23,949.3	72.9%	18,876.2	2,753.4	5,506.9	8,260.3	11,013.8	13,767.2
	Natural gas furnace	14,416.8	8,887.5	5,529.3	38.4%	147,434.8	11,309.2	22,618.3	33,927.5	45,236.6	56,545.8
	Propane/LPG furnace	16,604.4	8,887.5	7,716.9	46.5%	19,415.4	1,804.7	3,609.3	5,414.0	7,218.6	9,023.3
	Fuel oil furnace	21,346.6	8,887.5	12,459.1	58.4%	10,547.2	1,231.2	2,462.4	3,693.6	4,924.8	6,156.0
	Space cooling					**61,265.7**	**8,435.8**	**16,871.6**	**25,307.5**	**33,743.3**	**42,179.1**
	Central air conditioner	4,040.4	1,289.7	2,750.7	68.1%	54,417.4	7,409.5	14,819.0	22,228.5	29,638.0	37,047.5
	Room air conditioner	5,247.3	1,289.7	3,957.6	75.4%	5,799.1	874.7	1,749.5	2,624.2	3,499.0	4,373.7
	Both central and room AC	4,643.8	1,289.7	3,354.2	72.2%	1,049.3	151.6	303.2	454.7	606.3	757.9
	Water heating					**87,932.8**	**(549.9)**	**(1,099.9)**	**(1,649.8)**	**(2,199.8)**	**(2,749.7)**
	Electric water heater	9,112.5	5,434.7	3,677.8	40.4%	29,633.1	2,392.0	4,784.0	7,176.0	9,568.0	11,959.9
	Natural gas water heater	4,261.9	5,434.7	(1,172.8)	-27.5%	51,005.0	(2,807.1)	(5,614.2)	(8,421.3)	(11,228.4)	(14,035.5)
	Propane/LPG water heater	4,960.2	5,434.7	(474.5)	-9.6%	7,081.7	(135.5)	(271.0)	(406.5)	(541.9)	(677.4)
	Fuel oil water heater	5,517.4	5,434.7	82.7	1.5%	213.0	0.6	1.3	1.9	2.6	3.2
	Regional total SH-SC-WH					**350,134.4**	**25,617.7**	**51,235.4**	**76,853.1**	**102,470.9**	**128,088.6**
South	**Space heating**					**155,756.0**	**18,978.0**	**37,956.0**	**56,934.0**	**75,912.0**	**94,890.0**
	Electric heat pump	10,043.7	3,799.3	6,244.4	62.2%	19,426.3	2,415.6	4,831.1	7,246.7	9,662.3	12,077.8
	Electric heater	16,557.1	3,799.3	12,757.8	77.1%	51,703.3	7,967.8	15,935.7	23,903.5	31,871.4	39,839.2
	Natural gas furnace	7,301.0	3,799.3	3,501.7	48.0%	60,982.1	5,849.7	11,699.3	17,549.0	23,398.6	29,248.3
	Propane/LPG furnace	8,404.0	3,799.3	4,604.7	54.8%	15,983.3	1,751.5	3,503.0	5,254.5	7,006.1	8,757.6
	Fuel oil furnace	10,804.6	3,799.3	7,005.3	64.8%	7,660.9	993.4	1,986.8	2,980.2	3,973.7	4,967.1
	Space cooling					**216,882.6**	**26,872.3**	**53,744.5**	**80,616.8**	**107,489.1**	**134,361.3**
	Central air conditioner	7,209.4	2,813.2	4,396.2	61.0%	190,182.8	23,194.4	46,388.8	69,583.2	92,777.6	115,972.0
	Room air conditioner	9,362.9	2,813.2	6,549.7	70.0%	19,316.4	2,702.5	5,405.0	8,107.6	10,810.1	13,512.6
	Both central and room AC	8,286.1	2,813.2	5,473.0	66.0%	7,383.5	975.4	1,950.7	2,926.1	3,901.4	4,876.8
	Water heating					**134,618.6**	**4,030.2**	**8,060.3**	**12,090.5**	**16,120.7**	**20,150.9**
	Electric water heater	7,644.4	4,536.8	3,107.6	40.7%	81,434.9	6,621.0	13,242.0	19,863.0	26,484.0	33,105.0
	Natural gas water heater	3,574.5	4,536.8	(962.3)	-26.9%	46,057.6	(2,479.9)	(4,959.8)	(7,439.7)	(9,919.6)	(12,399.5)
	Propane/LPG water heater	4,160.1	4,536.8	(376.6)	-9.1%	6,303.3	(114.1)	(228.3)	(342.4)	(456.5)	(570.7)
	Fuel oil water heater	4,627.4	4,536.8	90.7	2.0%	822.8	3.2	6.4	9.7	12.9	16.1
	Regional total SH-SC-WH					**507,257.2**	**49,880.4**	**99,760.9**	**149,641.3**	**199,521.7**	**249,402.2**
West	**Space heating**					**84,164.0**	**8,756.5**	**17,512.9**	**26,269.4**	**35,025.8**	**43,782.3**
	Electric heat pump	10,148.6	4,036.4	6,112.2	60.2%	2,578.5	310.6	621.2	931.8	1,242.4	1,553.0
	Electric heater	16,624.4	4,036.4	12,588.0	75.7%	15,586.0	2,360.3	4,720.7	7,081.0	9,441.4	11,801.7
	Natural gas furnace	7,233.1	4,036.4	3,196.7	44.2%	55,368.8	4,894.1	9,788.2	14,682.2	19,576.3	24,470.4
	Propane/LPG furnace	8,340.6	4,036.4	4,304.2	51.6%	6,246.7	644.7	1,289.4	1,934.2	2,578.9	3,223.6
	Fuel oil furnace	10,721.8	4,036.4	6,685.4	62.4%	4,384.0	546.7	1,093.4	1,640.2	2,186.9	2,733.6
	Space cooling					**38,218.7**	**4,687.0**	**9,374.0**	**14,060.9**	**18,747.9**	**23,434.9**
	Central air conditioner	3,980.4	1,559.2	2,421.2	60.8%	35,832.5	4,359.2	8,718.4	13,077.7	17,436.9	21,796.1
	Room air conditioner	5,169.3	1,559.2	3,610.1	69.8%	1,680.2	234.7	469.4	704.1	938.8	1,173.4
	Both central and room AC	4,574.8	1,559.2	3,015.6	65.9%	706.0	93.1	186.1	279.2	372.3	465.4
	Water heating					**74,343.0**	**(3,123.7)**	**(6,247.5)**	**(9,371.2)**	**(12,495.0)**	**(15,618.7)**
	Electric water heater	7,848.4	5,214.7	2,633.8	33.6%	19,230.4	1,290.7	2,581.3	3,872.0	5,162.7	6,453.3
	Natural gas water heater	3,669.2	5,214.7	(1,545.4)	-42.1%	49,541.2	(4,173.2)	(8,346.4)	(12,519.7)	(16,692.9)	(20,866.1)
	Propane/LPG water heater	4,270.4	5,214.7	(944.2)	-22.1%	5,360.9	(237.1)	(474.1)	(711.2)	(948.3)	(1,185.4)
	Fuel oil water heater	4,750.1	5,214.7	(464.5)	-9.8%	210.4	(4.1)	(8.2)	(12.3)	(16.5)	(20.6)
	Regional total SH-SC-WH					**196,725.7**	**10,319.7**	**20,639.4**	**30,959.1**	**41,278.8**	**51,598.5**
National total of CO_2 emissions reduction [Million Metric Ton]							**49.0**	**97.9**	**146.9**	**195.8**	**244.8**
Percentage savings							**8.2%**	**16.3%**	**24.5%**	**32.7%**	**40.8%**

3.8.3 Reductions in Summer Peak Electrical Demand

The national total reduction in summer peak electrical demand was calculated following the procedure described in Section 3.6, and the results are listed in Table 10. As shown at the bottom of Table 10, **215.9 gigawatts (GW) of summer peak electrical demand** could be avoided if state-of-the-art GHP retrofits were deployed in all U.S. single-family homes. According to EIA (2008), the total U.S. net summer electric generating capacity as of December 31, 2008, was 1,010 GW. The 215.9 GW peak demand reduction from GHP retrofits could reduce the total required summer electric generating capacity in the United States by about 21 percent.

Table 10. National Total of Reduced Summer Peak Electrical Demand from GHP Retrofit for Existing U.S. Single-Family Homes



Census region	SH-SC-WH system types	Number of single-family homes that have space cooling	Percentage of various equipments used for space cooling	Regional average of installed space cooling capacity for the reference building	Normalized peak electrical demand for space cooling of existing systems	Normalized peak electrical demand for space cooling of the GHP system	Reduction in normalized peak electrical demand for space cooling from the GHP retrofit	Percentage reduction of peak electrical demand for space cooling from GHP retrofit	Estimated regional peak electrical demand for space cooling by existing systems	Estimated regional potential in reduction of peak electrical demand for space cooling				
										20% market penetration rate for GHP retrofit	40% market penetration rate for GHP retrofit	60% market penetration rate for GHP retrofit	80% market penetration rate for GHP retrofit	100% market penetration rate for GHP retrofit
		(millions)		Ton	kW/ton	kW/ton	kW/ton	%	GW	GW	GW	GW	GW	GW
Northeast	**Space cooling**	**11.1**	**100%**	**2.0**	**2.7**	**1.0**	**1.8**	**64.9%**	**60.7**	**7.9**	**15.8**	**23.6**	**31.5**	**39.4**
	Central air conditioner	4.95	44.4%		2.3	1.0	1.4	59.0%						
	Room air conditioner	6.10	54.8%		3.0	1.0	2.1	68.5%						
	Both central and room AC	0.10	0.9%		2.7	1.0	1.7	64.4%						
Midwest	**Space cooling**	**18.6**	**100%**	**2.5**	**2.4**	**1.0**	**1.4**	**59.8%**	**111.0**	**13.3**	**26.5**	**39.8**	**53.1**	**66.3**
	Central air conditioner	14.64	78.6%		2.2	1.0	1.3	57.3%						
	Room air conditioner	3.62	19.4%		2.9	1.0	2.0	67.2%						
	Both central and room AC	0.36	1.9%		2.6	1.0	1.6	62.9%						
South	**Space cooling**	**28.0**	**100%**	**3.0**	**2.0**	**1.0**	**1.1**	**52.0%**	**171.9**	**17.9**	**35.7**	**53.6**	**71.4**	**89.3**
	Central air conditioner	22.71	81.0%		1.9	1.0	1.0	49.4%						
	Room air conditioner	4.64	16.5%		2.5	1.0	1.5	61.1%						
	Both central and room AC	0.70	2.5%		2.2	1.0	1.2	56.0%						
West	**Space cooling**	**9.5**	**100%**	**2.0**	**2.2**	**1.1**	**1.1**	**50.4%**	**41.4**	**4.2**	**8.3**	**12.5**	**16.7**	**20.8**
	Central air conditioner	7.74	81.7%		2.1	1.1	1.0	47.8%						
	Room air conditioner	1.49	15.8%		2.7	1.1	1.6	59.9%						
	Both central and room AC	0.24	2.5%		2.4	1.1	1.3	54.6%						
National total reduction of peak electrical demand for space cooling [GW]										**43.2**	**86.4**	**129.5**	**172.7**	**215.9**
Percentage savings										**11.2%**	**22.4%**	**33.6%**	**44.9%**	**56.1%**

3.8.4 Savings in Consumer Energy Expenditures

By converting the delivered energy consumption data (both the calculated delivered energy consumption for SH–SC–WH in the reference building and the documented delivered energy consumption for all existing U.S. single-family homes) to the associated energy expenditures with the regional average utility rates for fuels and electricity listed in Table 11, the national potential savings in annual energy expenditures for SH–SC–WH was determined and is shown in Table 12. The regional average utility rates for fuels and electricity were obtained from the EIA *Short-Term Energy Outlook* (EIA 2010 a).

Table 11. Utility Rates for Fuels and Electricity in Each Census Region

Census region	Gas $/Mcf		Oil $/gallon_O		Propane $/gallon_P		Electric $/MWh	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Northeast	14.92	17.20	2.918	2.835	2.653	2.66	154.655	164.314
Midwest	10.93	13.54	2.826	2.796	1.909	1.84	97.984	105.770
South	14.67	18.77	2.866	2.734	2.429	2.33	105.899	110.320
West	10.31	11.30	2.978	2.968	2.354	2.23	109.361	118.881

Note: Mcf, thousand cubic feet.

As shown at the bottom of Table 12, $53.4 billion of consumer energy expenditures, which accounts for 49.3 percent of all energy expenditures associated with SH–SC–WH in existing U.S. single-family homes, could be saved each year by GHP retrofits at the 100 percent market penetration rate.

Unlike primary energy and CO_2 emissions, energy expenditures associated with WH were reduced when existing water heaters were replaced with desuperheater-assisted electric water heaters, except for the replacement of natural gas water heaters in the Northeast and West census regions. If the existing water heaters fired with fossil fuels were not replaced with desuperheater-assisted electric water heaters, the maximum savings of consumer energy expenditures from GHP retrofits would be reduced from US$53.4 to US**$52.2 billion**, which is **48.2 percent** of all consumer energy expenditures for SH–SC–WH in existing U.S. single-family homes.

Table 12. National Total of Reduced Energy Expenditures from GHP Retrofits for Existing U.S. Single-Family Homes

Census region	SH-SC-WH system types	Regional average energy expenditure by existing SH-SC-WH system in reference building	Regional average energy expenditure by GHP system in reference building	Regional average savings of energy expenditure in reference building	Percentage savings of energy expenditure from GHP retrofit	Regional energy expenditure for SH-SC-WH in all single-family homes (RECS 2005)	Estimated regional potential in savings of energy expenditure				
							20% market penetration rate for GHP retrofit	40% market penetration rate for GHP retrofit	60% market penetration rate for GHP retrofit	80% market penetration rate for GHP retrofit	100% market penetration rate for GHP retrofit
		$	$	$	%	Million $	Million $	Million $	Million $	Million $	Million $
Northeast	**Space heating**					**18,834.3**	**2,186.7**	**4,373.3**	**6,560.0**	**8,746.6**	**10,933.3**
	Electric heat pump	1878.8	651.1	1227.6	65.3%	84.7	11.1	22.1	33.2	44.3	55.4
	Electric heater	2558.0	651.1	1906.8	74.5%	703.2	104.8	209.7	314.5	419.4	524.2
	Natural gas furnace	1194.7	651.1	543.5	45.5%	7,896.5	718.5	1,437.0	2,155.5	2,874.1	3,592.6
	Propane/LPG furnace	2240.7	651.1	1589.5	70.9%	769.8	109.2	218.4	327.7	436.9	546.1
	Fuel oil furnace	1929.8	651.1	1278.7	66.3%	9,380.0	1,243.0	2,486.0	3,729.0	4,972.1	6,215.1
	Space cooling					**2,686.4**	**407.2**	**814.3**	**1,221.5**	**1,628.7**	**2,035.8**
	Central air conditioner	278.4	73.3	205.1	73.7%	1,716.4	252.9	505.8	758.7	1,011.6	1,264.5
	Room air conditioner	361.5	73.3	288.2	79.7%	894.1	142.6	285.1	427.7	570.3	712.8
	Both central and room AC	319.9	73.3	246.6	77.1%	75.9	11.7	23.4	35.1	46.8	58.5
	Water heating					**6,566.7**	**49.4**	**98.9**	**148.3**	**197.7**	**247.2**
	Electric water heater	778.7	484.2	294.5	37.8%	1,278.5	96.7	193.4	290.1	386.8	483.5
	Natural gas water heater	406.0	484.2	-78.2	-19.3%	2,923.9	(112.6)	(225.2)	(337.8)	(450.4)	(563.0)
	Propane/LPG water heater	733.9	484.2	249.7	34.0%	508.3	34.6	69.2	103.8	138.4	173.0
	Fuel oil water heater	527.9	484.2	43.7	8.3%	1,855.9	30.7	61.5	92.2	122.9	153.7
	Regional total SH-SC-WH					**28,087.4**	**2,643.3**	**5,286.5**	**7,929.8**	**10,573.0**	**13,216.3**
Midwest	**Space heating**					**15,482.7**	**1,757.3**	**3,514.5**	**5,271.8**	**7,029.0**	**8,786.3**
	Electric heat pump	1625.9	521.5	1104.5	67.9%	273.5	37.2	74.3	111.5	148.7	185.8
	Electric heater	1926.6	521.5	1405.2	72.9%	1,107.5	161.6	323.1	484.7	646.2	807.8
	Natural gas furnace	1029.5	521.5	508.1	49.3%	10,685.3	1,054.6	2,109.3	3,163.9	4,218.5	5,273.1
	Propane/LPG furnace	1907.0	521.5	1385.6	72.7%	2,308.1	335.4	670.8	1,006.2	1,341.6	1,677.0
	Fuel oil furnace	2175.9	521.5	1654.5	76.0%	1,108.2	168.5	337.0	505.6	674.1	842.6
	Space cooling					**3,880.3**	**534.3**	**1,068.6**	**1,602.9**	**2,137.1**	**2,671.4**
	Central air conditioner	255.9	81.7	174.2	68.1%	3,446.5	469.3	938.6	1,407.8	1,877.1	2,346.4
	Room air conditioner	332.3	81.7	250.7	75.4%	367.3	55.4	110.8	166.2	221.6	277.0
	Both central and room AC	294.1	81.7	212.4	72.2%	66.5	9.6	19.2	28.8	38.4	48.0
	Water heating					**6,794.4**	**252.5**	**505.0**	**757.4**	**1,009.9**	**1,262.4**
	Electric water heater	555.9	331.5	224.4	40.4%	1,807.7	145.9	291.8	437.8	583.7	729.6
	Natural gas water heater	345.7	331.5	14.2	4.1%	4,137.7	34.0	68.0	102.0	136.0	170.0
	Propane/LPG water heater	579.1	331.5	247.5	42.7%	826.7	70.7	141.4	212.0	282.7	353.4
	Fuel oil water heater	576.6	331.5	245.0	42.5%	22.3	1.9	3.8	5.7	7.6	9.5
	Regional total SH-SC-WH					**26,157.4**	**2,544.0**	**5,088.0**	**7,632.1**	**10,176.1**	**12,720.1**
South	**Space heating**					**13,674.6**	**1,946.4**	**3,892.8**	**5,839.2**	**7,785.5**	**9,731.9**
	Electric heat pump	636.9	240.9	396.0	62.2%	1,231.9	153.2	306.4	459.5	612.7	765.9
	Electric heater	1049.9	240.9	809.0	77.1%	3,278.6	505.3	1,010.5	1,515.8	2,021.0	2,526.3
	Natural gas furnace	690.0	240.9	449.1	65.1%	5,930.6	772.0	1,544.0	2,315.9	3,087.9	3,859.9
	Propane/LPG furnace	1218.9	240.9	978.0	80.2%	2,417.1	387.9	775.8	1,163.6	1,551.5	1,939.4
	Fuel oil furnace	1118.1	240.9	877.2	78.5%	816.3	128.1	256.2	384.3	512.3	640.4
	Space cooling					**14,327.3**	**1,775.2**	**3,550.4**	**5,325.6**	**7,100.7**	**8,875.9**
	Central air conditioner	476.3	185.8	290.4	61.0%	12,563.5	1,532.2	3,064.5	4,596.7	6,128.9	7,661.1
	Room air conditioner	618.5	185.8	432.7	70.0%	1,276.0	178.5	357.1	535.6	714.1	892.6
	Both central and room AC	547.4	185.8	361.5	66.0%	487.8	64.4	128.9	193.3	257.7	322.2
	Water heating					**11,396.0**	**797.2**	**1,594.3**	**2,391.5**	**3,188.6**	**3,985.8**
	Electric water heater	494.9	293.7	201.2	40.7%	5,271.8	428.6	857.2	1,285.9	1,714.5	2,143.1
	Natural gas water heater	396.2	293.7	102.5	25.9%	5,105.4	264.2	528.4	792.6	1,056.9	1,321.1
	Propane/LPG water heater	615.9	293.7	322.2	52.3%	933.2	97.6	195.3	292.9	390.5	488.2
	Fuel oil water heater	481.7	293.7	188.0	39.0%	85.6	6.7	13.4	20.1	26.7	33.4
	Regional total SH-SC-WH					**39,397.9**	**4,518.7**	**9,037.4**	**13,556.2**	**18,074.9**	**22,593.6**
West	**Space heating**					**6,375.0**	**743.1**	**1,486.1**	**2,229.2**	**2,972.3**	**3,715.3**
	Electric heat pump	664.6	264.3	400.3	60.2%	168.9	20.3	40.7	61.0	81.4	101.7
	Electric heater	1088.7	264.3	824.3	75.7%	1,020.7	154.6	309.1	463.7	618.3	772.8
	Natural gas furnace	493.0	264.3	228.6	46.4%	3,784.5	351.1	702.1	1,053.2	1,404.2	1,755.3
	Propane/LPG furnace	1182.3	264.3	918.0	77.6%	915.7	142.2	284.4	426.6	568.8	711.0
	Fuel oil furnace	1157.8	264.3	893.4	77.2%	485.3	74.9	149.8	224.7	299.6	374.5
	Space cooling					**2,720.6**	**333.6**	**667.3**	**1,000.9**	**1,334.6**	**1,668.2**
	Central air conditioner	283.3	111.0	172.4	60.8%	2,550.8	310.3	620.6	930.9	1,241.3	1,551.6
	Room air conditioner	368.0	111.0	257.0	69.8%	119.6	16.7	33.4	50.1	66.8	83.5
	Both central and room AC	325.7	111.0	214.7	65.9%	50.3	6.6	13.3	19.9	26.5	33.1
	Water heating					**5,651.1**	**(99.3)**	**(198.6)**	**(297.9)**	**(397.2)**	**(496.5)**
	Electric water heater	536.3	356.3	180.0	33.6%	1,314.1	88.2	176.4	264.6	352.8	441.0
	Natural gas water heater	262.9	356.3	-93.5	-35.6%	3,549.2	(252.4)	(504.8)	(757.3)	(1,009.7)	(1,262.1)
	Propane/LPG water heater	609.0	356.3	252.6	41.5%	764.5	63.4	126.8	190.3	253.7	317.1
	Fuel oil water heater	524.9	356.3	168.6	32.1%	23.3	1.5	3.0	4.5	6.0	7.5
	Regional total SH-SC-WH					**14,746.8**	**977.4**	**1,954.8**	**2,932.2**	**3,909.6**	**4,887.0**
National total of energy expenditure savings [Billion $]							**10.7**	**21.4**	**32.1**	**42.7**	**53.4**
Percentage savings							**9.9%**	**19.7%**	**29.6%**	**39.4%**	**49.3%**

4. Valuing Investment in GHP Systems Compared to Alternatives

In this section, the GHP retrofit investment is valued in two different ways based on the predicted energy savings and installed cost premium of the GHP retrofit compared with alternative retrofit solutions. The first evaluation focuses on the net present value (NPV) over the life of the GHP retrofit investment, which is the difference between the installed cost premium of the GHP retrofit and the discounted present value of the saved energy costs over the life of the investment. The NPV is calculated with Equation 6.

$$NPV = \sum_{j=1}^{m}(E_j \cdot CEC_j) \times \sum_{i=1}^{n}\frac{(1+e)^{i-1}}{(1+d)^{i}} - CP \tag{6}$$

E_j is the annual savings of energy type j;

CEC_j is the current energy cost per unit of energy type j;

i is the year;

e is the average annual escalation rate of energy prices;

d is the discount rate;

n is the service life of the GHP retrofit (i.e., the period of the calculation); and

CP is the cost premium of the GHP retrofit compared with alternative systems.

The second evaluation calculates the levelized cost of energy efficiency (LCOEE) of the GHP retrofit. The LCOEE is analogous to the levelized cost of energy (LCOE), which is widely used in the utility industry to assess the investment in energy-generation systems, including all of the costs over the lifetime of such a system: initial investment, operation and maintenance, and cost of capital. An NPV equation is written and solved to determine the value of LCOE such that the project's NPV is zero. This means that the LCOE is the minimum price at which energy must be sold for an energy project to break even. Similar to LCOE, LCOEE is the minimum price at which the *saved energy* must be valued for the investment in the GHP retrofit to break even. The calculation of LCOEE is expressed in Equation 7.

$$LCOEE = \frac{\sum_{i=1}^{n} \frac{I_i + M_i}{(1+d)^i}}{ES \cdot \sum_{i=1}^{n} \frac{(1+e)^{i-1}}{(1+d)^i}} \tag{7}$$

I_i is the investment expenditure (including principal and interest) in year i,

M_i is the operation and maintenance expenditures in year i, and

ES is the annual energy savings achieved by the energy efficiency system (i.e., the GHP retrofit).

In the following sections, energy consumption and expenditures are presented for a few alternative retrofit solutions (Section 4.1), the retrofit costs of the state-of-the-art GHP system and the alternatives are summarized (Section 4.2), the financial parameters used in the evaluations are discussed (Section 4.3), and finally the estimated NPV and LCOEE of the GHP retrofit at various discount rates are determined (Sections 4.4 and 4.5).

4.1 Energy Consumption and Expenditures of Alternative Retrofit Solutions

Five alternative retrofit solutions are compared with the state-of-the-art GHP system. Brief descriptions of each alternative are provided in Table 13. All of these retrofit solutions are intended to reduce energy consumption and cost for SH and SC. However, unlike the conventional alternatives, the state-of-the-art GHP system also has an integral component called a desuperheater, which generates hot water very efficiently whenever the unit operates for heating or cooling. As discussed in Section 3, the desuperheater usually works with an electric storage-type water heater, and the desuperheater-assisted electric water heater will reduce the primary energy consumption for WH when replacing the existing electric water heater (without desuperheater). However, because the desuperheater-assisted electric water heater may consume more primary energy than a conventional fossil fuel–fired water heater, it is assumed in this study that the existing conventional fossil fuel–fired water heaters are not replaced with the desuperheater-assisted electric water heater.

Table 13. List of Alternative SH–SC Systems for Residential Retrofit

Name	**Description**	**Note**
Alt #1	SEER 13 AC and 80 AFUE natural gas furnace	Minimum allowed
Alt #2	SEER 21 AC and 93 AFUE natural gas furnace	State-of-the-art
Alt #3	SEER 13 ASHP with supplemental electrical heater	Minimum allowed
Alt #4	SEER 19 ASHP with supplemental electrical heater	State-of-the-art
Alt #5	SEER 19 ASHP with supplemental 93 AFUE natural gas furnace	State-of-the-art

Notes: AFUE, annual fuel utilization efficiency; SEER, seasonal energy efficiency ratio.

As stated previously, source energy consumption accounts for all of the primary energy consumed in generating and delivering energy to the building site. It thus is used as a metric to compare the various retrofit solutions. The national total annual source energy consumption for SH–SC–WH that would occur after retrofitting all existing U.S. single-family homes with each of the five alternative solutions is calculated using the same procedure as described in Section 3, and the results are listed in Table 14. Also shown in Table 14 is the national total source energy consumption of existing SH–SC–WH systems in all U.S. single-family homes, which is calculated from the delivered energy consumption data in RECS (EIA 2005). Based on these data and the total number of existing U.S. single-family homes with SH–SC–WH systems in 2005 (79.3 million households), the average annual source energy savings per single-family home achieved from the GHP retrofit compared with the alternative solutions are calculated and listed in the far right column of Table 14.

Table 14. Source Energy Savings from GHP Retrofits vs. Alternatives

System type	National total annual source energy consumption for SH-SC-WH in U.S. single-family homes	National total annual source energy savings (compared with existing systems)	National average of annual source energy savings per single-family home (compared with existing systems)	National average of annual source energy savings per single-family home from GHP retrofit (compared with alternatives)
	Quad BTU	Quad BTU	MBTU	MBTU
Existing SH-SC-WH systems	9.3			
State-of-the-art GHP system	5.1	4.2	53.0	
Alt #1	8.3	1.0	12.6	40.4
Alt #2	7.3	2.0	25.2	27.7
Alt #3	10.2	**-0.9**	**-11.3**	64.3
Alt #4	10	**-0.7**	**-8.8**	61.8
Alt #5	7.3	2.0	25.2	27.7

Note: MBTU, million British thermal units

As shown in Table 14, retrofitting the existing SH–SC systems with Alt #3 and Alt #4, which use ASHPs and auxiliary electric resistance heaters, actually increases the annual source energy consumption because of an increased use of electricity at an efficiency level too low to offset the high source energy conversion factor (3.365) for electricity. This result indicates that retrofitting existing SH–SC systems with Alt #3 and Alt #4 may not be a good strategy for reducing source energy consumption and GHG emissions, especially when the electricity is generated with fossil fuels and the auxiliary electric resistance heater has to run frequently to supplement the ASHP.[5] The table also shows that Alt #5 (a 19 seasonal energy efficiency ratio [SEER] ASHP supplemented with a 93 annual fuel utilization efficiency [AFUE] gas furnace) consumes almost the same amount of source energy as does Alt #2, which is a combination of a SEER 21 air conditioner and 93 AFUE gas furnace. As a result, in the following economic analysis, only Alt #1 and Alt #2 are included.

The national total annual savings in energy expenditures resulting from the GHP retrofit versus the two alternatives (Alt #1 and Alt #2) are summarized in Table 15. In the same table, the average annual energy expenditures for the state-of-the-art GHP system and the two alternatives per single-family home are also presented. The far right column of the table shows the average savings per home in annual energy expenditures from the GHP retrofit versus the two alternatives. On average, retrofitting the existing SH–SC systems with the state-of-the-art GHP system saves $469 and $332 each year compared with Alt #1 and Alt #2, respectively.

Table 15. Annual Savings in Energy Expenditures Resulting from GHP Retrofits vs. Alternatives

System type	National total annual energy expenditure for SH-SC-WH in U.S. single-family homes	National total annual energy expenditure savings (compared with existing systems)	National average of annual energy expenditure for SH-SC-WH per single-family home	National average of annual energy expenditure savings per single-family home from various retrofits (compared with alternative systems)
	Billion $	Billion $	$	$
Existing SH-SC-WH systems	108.4		1367.0	
State-of-the-art GHP system	56.2	52.2	708.7	
Alt #1	93.4	15.0	1177.8	469.1
Alt #2	82.5	25.9	1040.4	331.7

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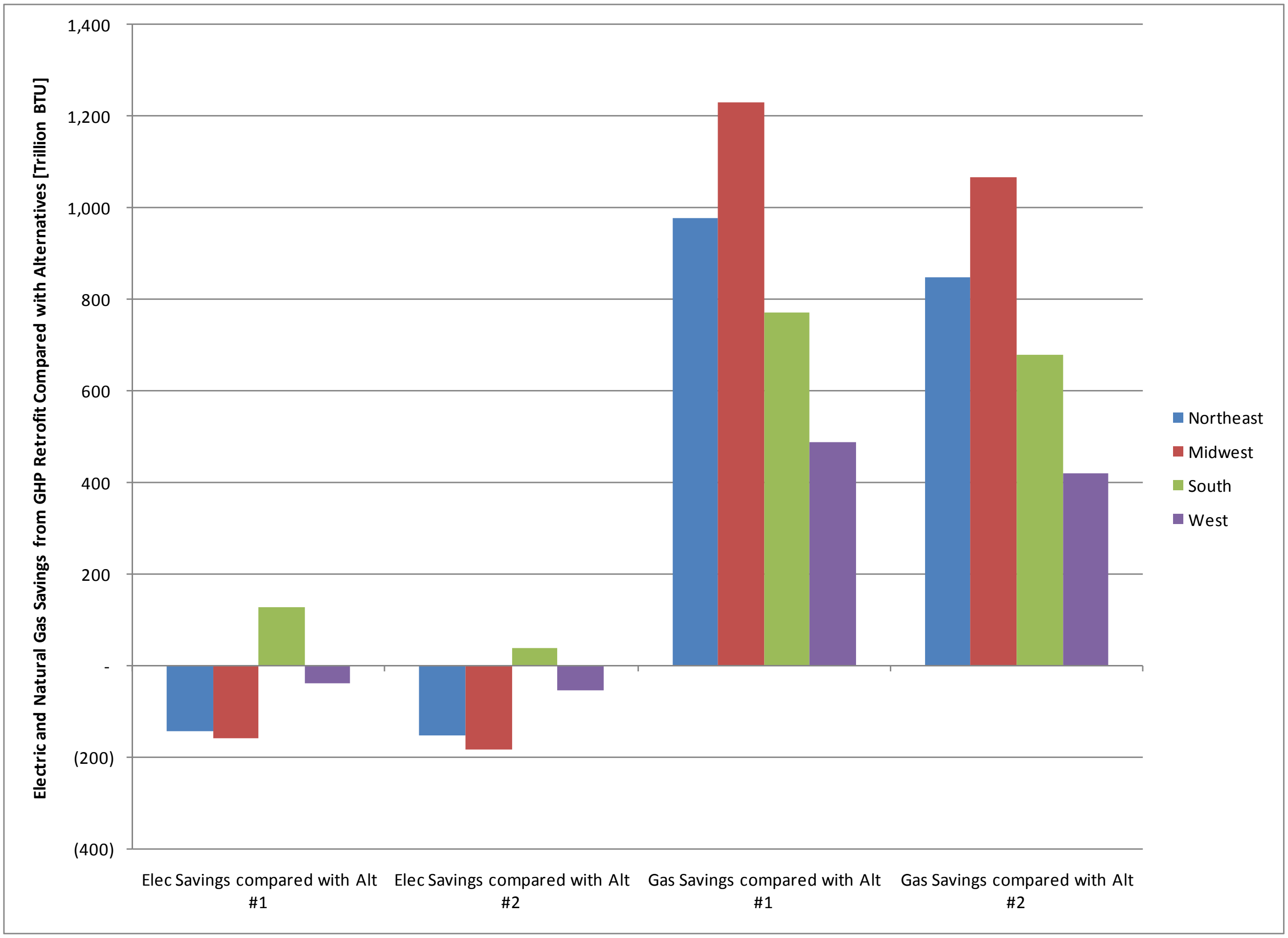
[5] The heating capacity and efficiency of ASHPs degrade significantly at low ambient temperatures, and the “defrosting operation” often results in uncomfortable “cold air blow” inside the building. It is thus common that electric resistance heat will kick in to override the heat pump when the ambient temperature is below 35°F.

Figure 5 shows annual savings in electricity and natural gas from the GHP retrofit compared with Alt #1 and Alt #2 in each of the four census regions. As shown in Figure 5, the GHP retrofit significantly reduces the consumption of natural gas (as a result of the displacement of natural gas furnaces), but it slightly increases the electricity consumption in all census regions except in the South, where savings in electricity for SC and WH (only in homes with existing electric water heaters) more than offsets the electricity consumed by the GHP units for SH.

Figure 5. Saved Electricity and Natural Gas from GHP Retrofits vs. Alternatives in Each Census Region



4.2 Retrofit Cost of the GHP System and Alternatives

Only a few published papers and reports were found that documented the installed cost of GHP systems. Kavanaugh (1995) reported that the average cost of a 3-ton GHP system with vertical ground heat exchanger was $8,997. The average cost of the vertical ground heat exchanger was $1,028 per installed cooling ton. These average costs were in 1995 U.S. dollars and were obtained from a national survey of the cost of purchasing and installing GHP systems. The average cost of each major component of the GHP system and an analysis of the potential for cost reduction were presented in the report and are summarized in Table 16.

Table 16. Components of GHP System Cost and Estimated Potential Cost Reductions

Itemized cost	3-ton GHP system installed cost (Kavanaugh 1995)		3-ton GHP system cost reduction potential (Kavanaugh 1995)	
	1995 $	2010 $	1995 $	2010 $
Ground loop	$3,077	$4,330	($360)	($507)
Heat pump (include pump)	$2,717	$3,823	($1,160)	($1,632)
Indoor installation	$1,898	$2,671	($540)	($760)
Ductwork	$1,305	$1,836	$0	$0
Total installed cost	**$8,997**	**$12,661**		

A recent report (DOD 2007) indicates that the average cost of GHP systems installed in residences of DOD facilities is $4,600 in 2006$ for each cooling ton of capacity or $13,800 for a 3-ton system. This cost is higher than that reported in the table above, but it includes the extra costs associated with projects at DOD facilities (e.g., Davis Beacon wages, secure facility access costs, training costs, and transaction costs for multiple levels of oversight). When these factors are considered, the DOD experience appears comparable to the table above.

As described in the *Buildings Energy Data Book* (DOE 2009), the typical size of U.S. single-family homes is 1,900 ft^2. Given the floor space, insulation, and air-tightness characteristics typical of existing housing stock, a 3-ton GHP system is assumed in this study to be the average for U.S. single-family homes.

In this study, except for the cost of the state-of-the-art GHP unit, all other cost components of the 3-ton GHP system with vertical ground heat exchanger are adopted from Kavanaugh (1995), with a correction for 2.47 percent annual inflation between 1995 and 2010. The cost of the state-of-the-art GHP unit (with desuperheater), central air conditioners, and gas furnaces are the typical list prices available in the current market. The costs of indoor installation and adaptation to existing ductwork are assumed to be identical for the GHP system and the alternatives, so they were not included in the calculation of the cost premium for the GHP retrofit.

The total retrofit and comparable costs of the 3-ton state-of-the-art GHP system and the two alternative systems are presented in 2010 dollars in Table 17. As shown in the table, the national average cost of retrofitting existing SH–SC systems with the 3-ton state-of-the-art GHP system is more than double the cost ($11,241 vs. $4,500) of Alt #1—a new, minimum code–compliant, conventional SH–SC system. However, if the estimated cost reduction potential (Kavanaugh 1995) is fully realized, the cost of the GHP retrofit will be reduced by 19 percent, to $9,102. Though it is still about double the cost for Alt #1, it is very close to the cost of Alt #2—the state-of-the-art conventional SH–SC system ($9,102 vs. $8,642).

Table 17. Costs of the State-of-the-Art GHP System and Alternative Systems

System	Component	Average market cost	Reduced cost
State-of-the-art GHP system	Ground loop	$4,330	$3,823
	Heat pump (include pump)	$6,911	$5,279
	Indoor installation	$2,671	$1,911
	Ductwork	$1,836	$1,836
	Total installed cost	$15,748	$12,849
	Retrofit cost (without indoor installation and ductwork)	**$11,241**	**$9,102**
Alternatives	Component	Alternative #1 SEER 13 AC and 80 AFUE gas furnace	Alternative #2 SEER 21 AC and 93 AFUE gas furnace
	AC unit	$2,500	$5,142
	Gas furnace	$2,000	$3,500
	Indoor installation	$2,671	$2,671
	Ductwork	$1,836	$1,836
	Total installed cost	$9,007	$13,149
	Retrofit cost (without indoor installation and ductwork)	**$4,500**	**$8,642**

4.3 Variables and Parameters Used in the Calculations

In this study, we assume that the homeowner pays for the retrofit with cash at the beginning of year one so that there is no interest cost. It is also assumed that the life of the investment is 20 years, which is the typical service life of the GHP unit. Although the ground heat exchanger would typically remain in service for a much longer time period than the GHP unit, this simplified analysis does not address this value. And although the maintenance cost of a GHP system is typically lower than that of conventional systems, it is also not accounted for in this study. As a result, calculations for NPV and LCOEE of the GHP retrofit are simplified to include only four variables—the cost premium of the 3-ton GHP retrofit (obtained from Table 17), annual savings in energy consumption or energy expenditures from the GHP retrofit, the average annual energy escalation rate, and the discount rate over the life of the investment. The predicted annual savings in energy expenditures per single-family home listed in Table 15 are used to calculate the NPV of the GHP retrofit. The predicted savings in delivered energy include both natural gas and electricity. To calculate the LCOEE of the GHP retrofit, the avoided natural gas consumption is converted to *indirect electricity savings* as described in Section 4.5, and the total (direct and indirect) electricity savings from the GHP retrofit compared with the alternatives is listed in Table 19.

The two key financial parameters, the average annual energy escalation rate and the discount rate over the life of the investment, are discussed in the following paragraphs.

Energy Escalation Rate

The average annual energy escalation rate for 2010 through 2030 was determined with the Energy Escalation Rate Calculator developed for DOE’s Federal Energy Management Program (2010). This tool calculates the average rate (across all energy forms) of energy price escalation over the duration of the analysis period, weighted by the proportions of each energy type saved by the project. Because most energy savings from the GHP retrofit come from avoided natural gas consumption, as shown in Figure 5, the calculated average escalation rate is appropriately weighted toward the escalation rate of the natural gas price over the 20-year period, which is 5.14 percent based on a 3.4 percent inflation rate.

Discount Rate

The 2010 real discount rate for public investment and regulatory analysis is 7 percent. However, historical data show that the discount rate has varied widely in past years from 0.5 to 14 percent (Federal Reserve Bank of New York 2010). As a result, instead of assuming a particular discount rate, a series of discount rates ranging from 0 to 15 percent with an interval of 3 percent are used in the calculations for the NPV and LCOEE of the GHP retrofit.

4.4 Predicted NPV from Investment in GHP Retrofits

The NPV of GHP retrofits in four scenarios is calculated with various discount rates using Equation 6. The four scenarios are as follows:

- state-of-the-art GHP system vs. Alt #1
- state-of-the-art GHP system (with reduced cost) vs. Alt #1
- state-of-the-art GHP system vs. Alt #2
- state-of-the-art GHP system (with reduced cost) vs. Alt #2

The predicted national average NPV gained from retrofitting a typical existing single-family home with the state-of-the-art GHP system in the above four scenarios and with various discount rates are listed in Table 18. As indicated in Equation 6, a positive value of the calculated NPV means that the discounted present values of the saved future energy costs exceed the cost premium of the

GHP retrofit. Correspondingly, a negative NPV means that the cost premium is not offset by future energy cost savings. The calculated NPV is also presented in Figure 6 to illustrate its relationship with the discount rate.

As a reality check, the simple payback periods[6] of the investments are also calculated and summarized in Table 18. As shown in the table, compared with Alt #1, the national average simple payback period for the GHP retrofit at current market prices is 14.4 years and falls to 9.8 years if the 19 percent cost reduction potential suggested by Kavanaugh (1995) is fully realized. Considering the higher cost of the state-of the-art GHP units, these results are in line with the 8.6- to 12-year simple payback periods indicated in the DOD (2007) report. The simple payback period for the GHP retrofit becomes much shorter when compared with the state-of-the-art conventional system (Alt #2). With the 19 percent cost reduction, the simple payback period of the GHP retrofit is only 2.4 years.

Data in Table 18 and Figure 6 show that the NPV of the GHP retrofit is higher when compared with the state-of-the-art conventional system (Alt #2) than with the minimum code–compliant conventional system (Alt #1). This result is not surprising because the cost premium of the GHP retrofit is much lower compared with Alt #2, especially when the 19 percent cost reduction potential of the GHP system is fully realized. When compared with Alt #2, investments in the GHP retrofit at current market prices show a positive NPV over the 20-year life, even when future energy cost savings are discounted at rates as high as 14 percent. However, when compared with Alt #1, investment in the GHP retrofit at current market prices will yield a positive NPV only when the discount rate is lower than 8 percent. If the 19 percent cost reduction potential of GHP systems can be fully realized, investments in the GHP retrofit generally have positive NPVs even with high discount rates, especially when compared with the state-of-the-art conventional system (Alt #2). This result implies that, with currently enacted federal tax credits, which offset 30 percent of the installed cost of GHP systems (valid through 2016), investments in GHP retrofits are currently quite attractive across the board, presuming that homeowners are earning income and paying taxes.

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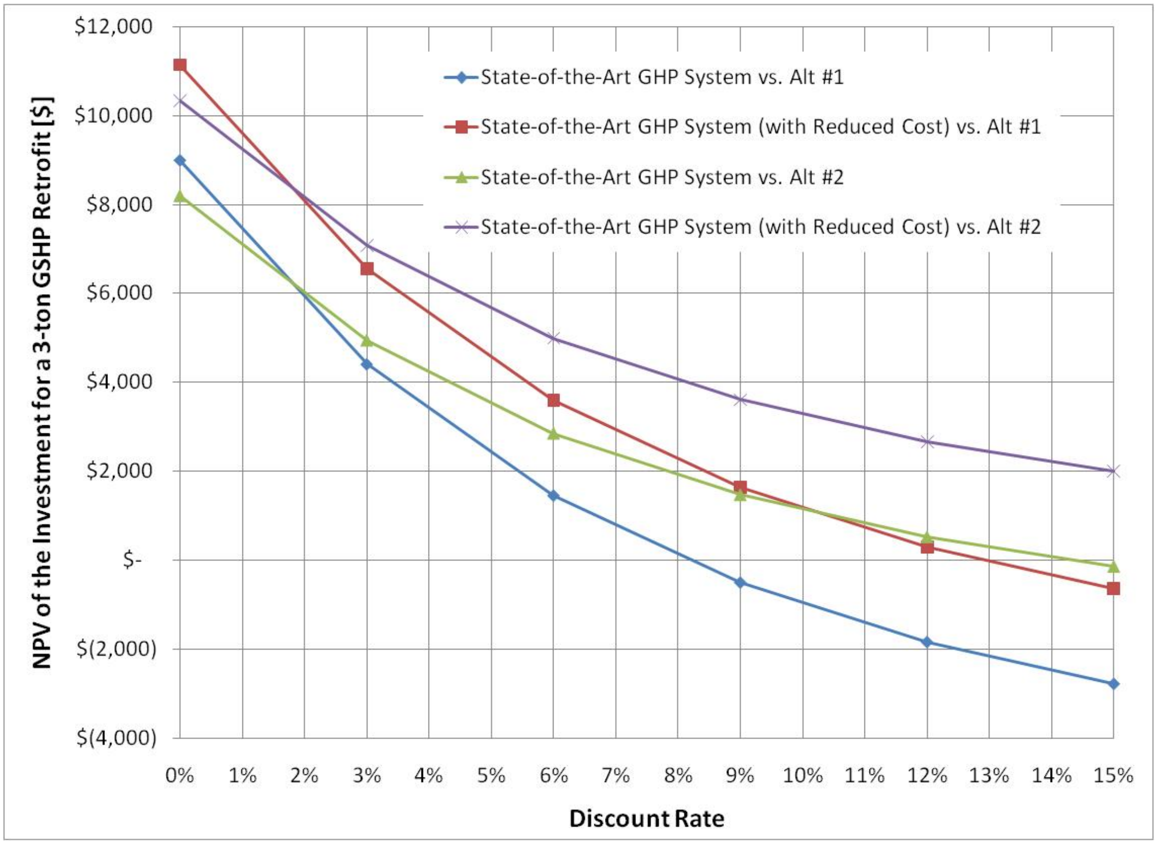
[6] Simple payback is calculated by dividing the cost premium of the GHP retrofit by the energy expenditure savings in the first year, with neither energy cost escalation nor discount rate accounted for.

Table 18. Simple Payback Period and NPV for a 3-ton GHP System Retrofits at Various Discount Rates

Comparison pairs	Simple payback period	Discount rate					
	Year	0%	3%	6%	9%	12%	15%
State-of-the-art GHP system vs. alt #1	-14.4	$ 9,002	$ 4,411	$ 1,460	$ (497)	$ (1,834)	$ (2,775)
State-of-the-art GHP system (with reduced cost) vs. alt #1	-9.8	$ 11,141	$ 6,550	$ 3,599	$ 1,642	$ 305	$ (636)
State-of-the-art GHP system vs. alt #2	-8.9	$ 8,189	$ 4,943	$ 2,857	$ 1,474	$ 528	$ (137)
State-of-the-art GHP system (with reduced cost) vs. alt #2	-2.4	$ 10,328	$ 7,082	$ 4,996	$ 3,612	$ 2,667	$ 2,002

Figure 6. NPV of Investment for a 3-ton GHP Retrofit at Various Discount Rates



4.5 Predicted LCOEE of GHP Retrofits

Typically, levelized costs are calculated based on the savings of one type of energy, such as electricity. However, as shown in Figure 5, although the GHP retrofit reduces natural gas consumption, it also increases or decreases the consumption of electricity. To account for these two types of energy in the LCOEE calculation, the avoided natural gas consumption is converted to *indirect electricity savings*, which is the electricity that can be generated and delivered to a residence using the avoided natural gas consumption at the residence. Therefore, the total saved energy used in the LCOEE calculation is the sum of the indirect electricity savings (representing savings in natural gas) and the direct savings (positive or negative) of delivered electricity at the residence. The typical thermal efficiency of combined-cycle natural gas power plants (50 percent; NGSA 2010) and the national average of transmission and distribution losses of electricity (9.9 percent; NREL 2007) are used to calculate the indirect electricity savings. The estimated total (direct and indirect) electricity savings from the GHP retrofit compared with Alt #1 and Alt #2 are listed in Table 19.

Table 19. Total (Direct and Indirect) Electricity Savings from the GHP Retrofit Compared with Alt #1 and Alt #2

Base case	National total (direct and indirect) electricity savings from GHP retrofit	National average of annual (direct and indirect) electricity savings per single-family home from GHP retrofit
	Trillion W-Hr	kWh
Alt #1	432.0	5,448
Alt #2	340.0	4,288

The LCOEE of the GHP retrofit in the four scenarios described in Section 4.4 and at various discount rates are calculated using Equation 7, and the results are listed in Table 20. Similar to LCOE (for energy generation systems), which is the minimum price at which the *generated energy* must be sold for an energy project to break even, LCOEE is the minimum price at which the *saved energy* must be valued for the investment in GHP retrofits to break even. As shown in Table 20, the LCOEE of the GHP retrofit is always less than the annual average residential electricity price in 2010, which is 11.5 cents per kWh (EIA 2010 b), compared with Alt #2. Compared with Alt #1, the state-of-the-art GHP at current market prices is better than breakeven up to a discount rate of 7 percent and, with the previously discussed 19 percent cost reduction, is better than breakeven up to a discount rate of 12 percent.

Table 20. LCOEE (Cents/kWh) of GHP Retrofit in Four Scenarios and at Various Discount Rates

Comparison pairs	Discount rate					
	0%	3%	6%	9%	12%	15%
State-of-the-art GHP system vs. alt #1	6.2	8.3	10.8	13.6	16.6	19.8
State-of-the-art GHP system (with reduced cost) vs. alt #1	4.2	5.7	7.4	9.3	11.3	13.5
State-of-the-art GHP system vs. alt #2	3.0	4.1	5.3	6.6	8.1	9.7
State-of-the-art GHP system (with reduced cost) vs. alt #2	0.5	0.7	0.9	1.2	1.4	1.7

4.6 Uncounted Values and Benefits

Because of the lack of established valuing mechanisms and insufficient resources to develop the methods, the calculations for NPV and LCOEE for the GHP retrofit in this analysis do not account for several benefits achieved from the GHP retrofits, including reductions of CO_2 emissions and summer peak electrical demand. In addition, the vertical ground loop heat exchanger, which is made of HDPE pipe, normally has a service life far longer than 20 years[7] and can still be fully functional after the 20-year period considered in the NPV calculations. However, this value was not accounted for in the NPV calculations. These excluded benefits are believed to be substantial.

As shown in Table 21, compared with Alt #1 (SEER 13 air conditioner), the state-of-the-art GHP system reduces summer peak electrical demand by 0.5–1 kW per cooling ton depending on where the building is located. However, the reduction of summer peak electrical demand is less than 0.3 kW/ton when the GHP system is compared with Alt #2 (SEER 21 air conditioner). When deployed on a large scale, the GHP retrofit could defer or obviate the need for significant amounts of new electricity generation capacity. According to a recent report (Lazard 2008), the capital cost of a new combined-cycle natural gas power plant is $900–$1,100 per kW, and the cost is three to five times higher if the electricity is generated with renewable energy or in decarbonized fossil fuel power plants. Obviously, if the summer peak electrical demand reduction from GHP retrofits is valued more

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[7] Many installations of HDPE pipe in water applications are already reaching 50 years of successful service. The polyethylene pipe industry estimates a service life for HDPE pipe to conservatively be 50-100 years. This relates to savings in replacement costs for generations to come (PPI 2009).

highly by including the avoided capital cost of new electricity generation capacity, the cost premium of the GHP retrofit would be significantly reduced.

Table 21. Peak Electrical Demand for Cooling in Four U.S. Census Regions

System	Peak electrical demand for cooling [kW/ton]			
	Northeast	Midwest	South	West
State-of-the-art GHP	0.96	0.96	0.98	1.09
Atl #1	1.95	1.89	1.55	1.76
Atl #2	1.23	1.16	1.20	1.27

Table 22 compares the CO_2 emissions of the state-of-the-art GHP system with those of Alt #1 and Alt #2 in the four U.S. census regions. Data in Table 22 indicate that the state-of-the-art GHP system can reduce CO_2 emissions by an average of 2.5 and 1.6 metric tons per U.S. single-family home compared with Alt #1 and Alt #2, respectively.

Table 22. CO_2 Reduction Potential of GHP Retrofits Compared with Alternatives

System type	National total annual CO_2 emissions for SH-SC-WH in U.S. single-family homes	National total annual CO_2 emissions reduction (compared with existing systems)	National average of annual CO_2 emissions reduction per single-family home (compared with existing systems)	National average of annual CO_2 emissions reduction per single-family home from GHP retrofit (compared with alternatives)
	million metric ton	million metric ton	metric ton	metric ton
Existing SH-SC-WH systems	599.7			
State-of-the-art GHP system	328	271.7	3.4	
Alt #1	522.9	76.8	1.0	2.5
Alt #2	458.7	141.0	1.8	1.6

If the residual value of the ground heat exchangers and the reductions in summer peak electrical demand and CO_2 emissions can be fairly valued in the economic analysis, GHP retrofits will appear more favorable using the NPV and LCOEE metrics.

4.7 Electric Service Upgrade: A Potential Additional Retrofit Issue and Cost Not Evaluated

A potentially significant additional retrofit cost that is not included in the analysis is possible additional cost for upgrading the residence's electric service, load panel, and added circuits that may often be necessary when retrofitting older residences, especially those residences that now use gas furnaces or boilers for heating and hot water, and with small or without any air conditioner. Retrofitting a residence that already has an electric heating system and/or have an air conditioning system that needs more electrical power than the new GHP unit and the circulation pump will not incur this additional cost, since peak electric loads and electric consumption are reduced by the GHP system, hence the residence's electric system should already be adequate.

5. Conclusions

This report assesses the potential national benefits from retrofitting U.S. single-family homes with state-of-the-art GHP systems at various penetration rates. The assessment is conducted using energy consumption data for SH–SC–WH in existing U.S. single-family homes obtained from the RECS (EIA 2005) and relative differences in annual energy consumption between the state-of-the-art GHP system and existing residential SH–SC–WH systems. The impacts of various climate and geological conditions, as well as the efficiency and market share of existing residential SH–SC–WH systems, have been taken into account in the assessment.

The analysis shows that replacing all SH–SC–WH systems in existing U.S. single-family homes with properly designed, installed, and operated state-of-the-art GHP systems would yield significant benefits each year, including a savings of 4.2 quad Btu primary energy, a reduction of 271.7 million metric tons of CO_2 emissions, savings of $52.2 billion in energy expenditures, and a reduction of 215.9 GW in summer peak electrical demand. The analysis also shows that the benefits of GHP retrofits are significant even at much lower market penetration rates.

An economical analysis shows that, compared with conventional residential SH and SC systems, investments in retrofitting existing single-family homes with the state-of-the-art GHP system will yield a positive NPV over a 20-year period at current market prices and without any financial incentives when the discount rate is lower than 8 percent. The levelized-cost analysis shows that saving energy with the GHP retrofit is cheaper than generating and delivering electricity to residences when the discount rate is lower than 8 percent. With the enacted federal tax credits for 30 percent of the installed cost of a GHP system (valid through 2016), investments in the state-of-the-art GHP system could be profitable even at higher discount rates. The GHP retrofit decision would be more favorable should the value of the ground loop heat exchanger and the value of reduced CO_2 emissions and summer peak electrical demand be accounted for.

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Appendix A. Description of Reference Single-Family Home

The selected reference single-family home, a one-story, slab-on-grade, wood-frame house, is depicted in Figure A-1. Its key characteristics are listed in Table A-1.

Figure A-1. Illustration of the Selected Reference Single-Family Home

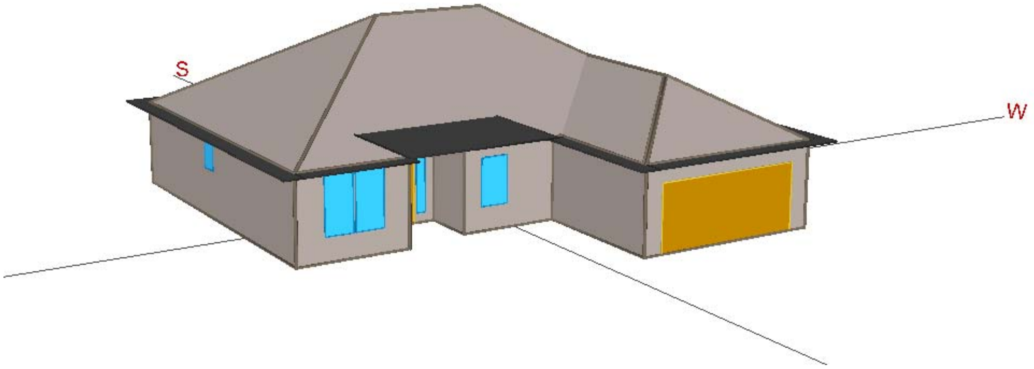

Table A-1. Key Characteristics of the Selected Reference Single-Family House

Main entrance orientation	North
Conditioned floor area	1,618 sf
Construction	Wood frame
Story	One
Ceiling insulation	R-38 blown cellulose at ceiling
Walls insulation	R-19 blown cellulose + R-3 insulating sheathing
Foundation insulation	Slab on grade, R-4 perimeter insulation
Windows	Double-glazed; U = 0.5, SHGC = 0.57; Mostly south-facing with overhang
Infiltration rate	0.19 ACH
Lighting	90% compact fluorescent lighting
Appliances and miscellaneous	ENERGY STAR refrigerator, clothes washer, dishwasher, TV, computer
Air-handler location	In conditioned space (utility room)
Ducts	In vented attic, R-6 insulation, 5% or less leakage to the outside

Notes: ACH, air change per hour; SHGC, solar heat gain coefficient

Appendix B. Description of GeoDesigner Software

GeoDesigner estimates annual energy consumption and expenditures for space heating, space cooling, and water heating (SH–SC–WH) in single-family homes that use a geothermal heat pump (GHP) system or other typical residential SH–SC–WH systems.

GeoDesigner uses the ASHRAE (American Society of Heating Refrigeration and Air-Conditioning Engineers) modified bin analysis method to calculate SH and SC loads (the amount of heat that needs to be removed from or added into the space to maintain a certain temperature set point) of a single-family home at various outdoor dry-bulb temperatures, which are sorted into discrete groups (bins) with the number of hours of occurrence of each temperature bin. The calculation is based on user-specified peak heat loss and heat gain from the building envelope at design conditions (the highest and lowest outdoor dry-bulb temperatures) and approximations for miscellaneous electric load, solar heat gain, occupancy level, and construction quality (air tightness of the building). GeoDesigner has a library of the bin weather data for most major cities in the United States as well as the design outdoor dry-bulb temperature (adopted from the ASHRAE handbook), the deep earth temperature, and the surface soil temperature swing and delay (adopted from the design and installation manual of International Ground Source Heat Pump Association [IGSHPA]) at each of the locations.

GeoDesigner calculates the domestic hot water load of a single-family home based on the average city water supply temperature where the building is located, user-specified hot water supply temperature, and the number of occupants in the building. The calculated domestic hot water load is constant across all temperature bins.

GeoDesigner has a library of performance data for GHP units and conventional SH–SC–WH equipment, including air-source heat pump (ASHP) units, air conditioners, furnaces or boilers, and water heaters. The library covers a wide range of equipment with efficiencies varying from less than the minimum allowed by the current code to the highest available from state-of-the-art equipment. The fuel types of furnaces or boilers and water heaters include electricity, natural gas, heating oil, and propane or liquefied petroleum gas.

GeoDesigner allows users to select ground heat exchangers from a large collection, including vertical bores, horizontal loops, pond loops, and well water. It offers two options for the design of selected ground heat exchangers: auto-sized or user-specified. The sizing algorithms implemented in GeoDesigner for various types of ground heat exchangers are adopted from the design and installation manual of IGSHPA.

To simulate the annual energy consumption of a GHP system, GeoDesigner calculates the ground heat exchanger leaving fluid temperature (LFT), which is the entering fluid temperature (EFT) of the heat pump unit, based on the design of the selected ground heat exchanger and the SH or SC loads at each temperature bin. With these calculated EFTs and the performance curves of the user-selected heat pump unit (obtained from the manufacturer's catalog data), which correlate the heat pump capacity and efficiency with the EFT, GeoDesigner calculates the power consumption of the GHP system for the provision of SH or SC loads at each temperature bin over the entire year. The heat pump efficiency accounts for all of the power consumptions from the heat pump compressor, fan, and circulation pump.[8] The efficiency degradation resulting from the cycling loss of the heat pump at part-load conditions is also taken into account in the calculation. When the desuperheater option is selected, GeoDesigner calculates the contribution of the desuperheater for WH and the associated power consumption.

Similarly, the annual energy consumption of the ASHP or air-conditioning (AC) unit is determined based on the SH or SC loads and the outdoor dry-bulb temperature at each temperature bin, as well as the performance curves of the user-selected ASHP or AC unit (obtained from manufacturer's catalog data), which correlate the ASHP or AC capacity and efficiency with the outdoor dry-bulb temperature. The auxiliary heating, either supplementing or overriding the ASHP, is accounted for in the energy calculation for the ASHP system.

The energy consumption of the furnace or boiler and water heater (non heat pump–type) is calculated in a straightforward manner with the total SH and WH loads and the efficiencies of the selected furnace or boiler and water heater. Electric consumptions associated with the fossil fuel–fired furnace or boiler and water heater are included in the energy calculation.

With decades of continued development, GeoDesigner has become very user-friendly and robust in performing energy analysis for residential SH–SC–WH systems. It has been widely used in the design and energy analysis for residential GHP applications. A recent report shows that the energy consumption predicted by GeoDesigner matches the metered data fairly well (Ellis 2008).

GeoDesigner still has some limitations. First, compared with more sophisticated hourly energy simulation, the bin analysis used by GeoDesigner is relatively less accurate in estimating the impacts of other weather elements (e.g., solar, wind, and precipitation) and the heat gain from

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[8] The fan power is adopted from manufacturers' catalog data for 0.5 inch (water column) external static pressure, and the pumping power is estimated for typical total length or depth of the loop or well plus head loss in the heat pump (condenser) and assuming typical pump efficiencies.

activities inside the building (e.g., lighting, cooking, and showering) on the building heating and cooling loads. The bin analysis also limits the capability for a more detailed analysis of the electrical demand of the building. Second, the algorithm used by GeoDesigner for calculating the ground heat exchanger LFT does not account for the loading history of the ground and, as a result, may underestimate the LFT at some temperature bins, especially those most likely occurring at the end of a heating or cooling season.

A comparison of results with other, more sophisticated, hourly energy analysis programs shows that, although GeoDesigner and the more sophisticated programs sometimes differ in the predicted total energy consumption of a particular SH–SC–WH system, the relative differences in energy consumption among different SH–SC–WH systems predicted by GeoDesigner is fairly close to those predicted by the more sophisticated programs.

Appendix C. Population-Weighted Average Energy Consumption, CO_2 Emissions, and Energy Expenditure of Each Typical SH–SC–WH System in Each Census Region

C-1. Northeast Region

Delivered Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Heat Mcf	Cool MWh	HW Mcf	Heat MWh	Heat Gal	Cool MWh	HW Gal	Heat MWh	Heat Gal	Cool MWh	HW Gal
Northeast	**4A**	**PA**	**Philadelphia**	**Philadelphia**	**21,879,116**	**40.1%**	**3.6**	**0.8**	**3.3**	**10.0**	**2.4**	**5.2**	**14.3**	**2.5**	**5.2**	**0.5**	**64.1**	**2.5**	**27.0**	**0.5**	**700.8**	**2.5**	**295.1**	**0.7**	**537.5**	**2.5**	**195.9**
Northeast	**5A**	**MA**	**Boston**	**Suffolk**	**28,102,970**	**51.6%**	**4.2**	**0.4**	**3.6**	**12.1**	**1.5**	**5.6**	**16.6**	**1.6**	**5.6**	**0.6**	**74.6**	**1.6**	**28.8**	**0.6**	**815.6**	**1.6**	**314.7**	**0.7**	**625.6**	**1.6**	**209.0**
Northeast	**6A**	**ME**	**Bangor**	**Penobscot**	**4,515,671**	**8.3%**	**7.2**	**0.2**	**3.5**	**22.8**	**0.9**	**5.9**	**26.9**	**0.9**	**5.9**	**0.9**	**120.9**	**0.9**	**30.5**	**0.9**	**1,321.9**	**0.9**	**333.3**	**1.1**	**1,013.9**	**0.9**	**221.4**
				Total	**54,497,757**	**100%**																					
				Pop Wgt Avg			**4.2**	**0.5**	**3.5**	**12.1**	**1.8**	**5.5**	**16.5**	**1.9**	**5.5**	**0.6**	**74.2**	**1.9**	**28.2**	**0.6**	**811.5**	**1.9**	**308.4**	**0.7**	**622.4**	**1.9**	**204.8**
				Arithmatic Average			5.7	0.3	3.6	17.5	1.2	5.7	21.8	1.3	5.7	0.7	97.8	1.3	29.7	0.7	1,069	1.3	324	0.9	820	1.3	215

Energy Expenditures

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $
Northeast	**4A**	**PA**	**Philadelphia**	**Philadelphia**	**21,879,116**	**40.1%**	**550.1**	**130.1**	**520.2**	**1,550.4**	**395.0**	**832.5**	**2,209.2**	**412.6**	**832.5**	**80.4**	**956.1**	**412.6**	**433.5**	**80.4**	**1,859.5**	**412.6**	**783.6**	**104.4**	**1,568.4**	**412.6**	**563.6**
Northeast	**5A**	**MA**	**Boston**	**Suffolk**	**28,102,970**	**51.6%**	**656.5**	**63.8**	**578.5**	**1,869.2**	**254.5**	**888.0**	**2,571.1**	**265.9**	**888.0**	**85.5**	**1,112.7**	**265.9**	**462.4**	**85.5**	**2,164.1**	**265.9**	**835.8**	**111.0**	**1,825.4**	**265.9**	**601.2**
Northeast	**6A**	**ME**	**Bangor**	**Penobscot**	**4,515,671**	**8.3%**	**1,117.1**	**35.7**	**562.8**	**3,529.7**	**148.4**	**937.9**	**4,166.8**	**154.9**	**937.9**	**135.5**	**1,803.3**	**154.9**	**489.7**	**135.5**	**3,507.2**	**154.9**	**885.2**	**175.9**	**2,958.3**	**154.9**	**636.7**
				Total	**54,497,757**	**100%**																					
				Pop Wgt Avg			**652.0**	**88.1**	**553.8**	**1,878.8**	**302.1**	**869.9**	**2,558.0**	**315.6**	**869.9**	**87.6**	**1,107.1**	**315.6**	**453.1**	**87.6**	**2,153.1**	**315.6**	**818.9**	**113.7**	**1,816.1**	**315.6**	**589.1**
				Arithmatic Average			886.8	49.7	570.6	2,699.4	201.4	913.0	3,368.9	210.4	913.0	110.5	1,458.0	210.4	476.1	110.5	2,836	210.4	860	143.4	2,392	210.4	619

Primary Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU
Northeast	**4A**	**PA**	**Philadelphia**	**Philadelphia**	**21,879,116**	**40.1%**	**40.9**	**9.1**	**37.5**	**115.1**	**27.6**	**60.0**	**164.1**	**28.8**	**60.0**	**6.0**	**70.7**	**28.8**	**29.8**	**6.0**	**73.4**	**28.8**	**30.9**	**7.8**	**86.3**	**28.8**	**31.5**
Northeast	**5A**	**MA**	**Boston**	**Suffolk**	**28,102,970**	**51.6%**	**48.8**	**4.5**	**41.7**	**138.8**	**17.8**	**63.9**	**190.9**	**18.6**	**63.9**	**6.4**	**82.3**	**18.6**	**31.8**	**6.4**	**85.4**	**18.6**	**33.0**	**8.2**	**100.5**	**18.6**	**33.6**
Northeast	**6A**	**ME**	**Bangor**	**Penobscot**	**4,515,671**	**8.3%**	**83.0**	**2.5**	**40.5**	**262.1**	**10.4**	**67.5**	**309.4**	**10.8**	**67.5**	**10.1**	**133.3**	**10.8**	**33.6**	**10.1**	**138.5**	**10.8**	**34.9**	**13.1**	**162.8**	**10.8**	**35.6**
				Total	**54,497,757**	**100%**																					
				Pop Wgt Avg			**48.4**	**6.2**	**39.9**	**139.5**	**21.1**	**62.6**	**190.0**	**22.1**	**62.6**	**6.5**	**81.9**	**22.1**	**31.1**	**6.5**	**85.0**	**22.1**	**32.3**	**8.4**	**100.0**	**22.1**	**32.9**
				Arithmatic Average			65.9	3.5	41.1	200.5	14.1	65.7	250.2	14.7	65.7	8.2	107.8	14.7	32.7	8.2	112	14.7	34	10.7	132	14.7	35

CO_2 Emissions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb
Northeast	**4A**	**PA**	**Philadelphia**	**Philadelphia**	**21,879,116**	**40.1%**	**5,940.2**	**1,322.6**	**5,447.5**	**16,741.8**	**4,014.7**	**8,717.4**	**23,855.2**	**4,193.4**	**8,717.4**	**868.4**	**9,666.3**	**4,193.4**	**4,071.6**	**868.4**	**11,255.5**	**4,193.4**	**4,738.7**	**1,127.3**	**14,460.0**	**4,193.4**	**5,271.0**
Northeast	**5A**	**MA**	**Boston**	**Suffolk**	**28,102,970**	**51.6%**	**7,089.2**	**648.0**	**6,057.1**	**20,183.6**	**2,586.8**	**9,298.6**	**27,762.9**	**2,702.1**	**9,298.6**	**923.5**	**11,249.7**	**2,702.1**	**4,343.0**	**923.5**	**13,099.2**	**2,702.1**	**5,054.6**	**1,198.8**	**16,828.7**	**2,702.1**	**5,622.4**
Northeast	**6A**	**ME**	**Bangor**	**Penobscot**	**4,515,671**	**8.3%**	**12,062.4**	**362.4**	**5,893.4**	**38,114.4**	**1,508.0**	**9,821.3**	**44,993.7**	**1,574.8**	**9,821.3**	**1,462.9**	**18,231.7**	**1,574.8**	**4,599.4**	**1,462.9**	**21,229.2**	**1,574.8**	**5,353.0**	**1,899.0**	**27,273.3**	**1,574.8**	**5,954.3**
				Total	**54,497,757**	**100%**																					
				Pop Wgt Avg			**7,040.0**	**895.2**	**5,798.8**	**20,287.6**	**3,070.7**	**9,108.6**	**27,621.8**	**3,207.4**	**9,108.6**	**946.1**	**11,192.5**	**3,207.4**	**4,255.3**	**946.1**	**13,032.7**	**3,207.4**	**4,952.5**	**1,228.1**	**16,743.2**	**3,207.4**	**5,508.9**
				Arithmatic Average			9,575.8	505.2	5,975.3	29,149.0	2,047.4	9,559.9	36,378.3	2,138.4	9,559.9	1,193.2	14,740.7	2,138.4	4471.2	1,193.2	17,164	2,138.4	5,204	1,548.9	22,051	2,138.4	5,788

C-2. Midwest Region

Delivered Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Heat Mcf	Cool MWh	HW Mcf	Heat MWh	Heat Gal	Cool MWh	HW Gal	Heat MWh	Heat Gal	Cool MWh	HW Gal
Midwest	**4A**	**MO**	**Kansas**	**Jackson**	**12,501,407**	**19.3%**	**3.7**	**1.7**	**2.9**	**10.6**	**4.0**	**5.0**	**13.6**	**4.2**	**5.0**	**0.6**	**61.1**	**4.2**	**25.9**	**0.6**	**668.0**	**4.2**	**283.0**	**0.7**	**512.4**	**4.2**	**188.0**
Midwest	**5A**	**IL**	**Chicago**	**Cook**	**39,992,232**	**61.8%**	**5.2**	**0.6**	**3.3**	**16.5**	**2.1**	**5.5**	**19.6**	**2.1**	**5.5**	**0.6**	**87.9**	**2.1**	**28.5**	**0.6**	**961.1**	**2.1**	**311.5**	**0.8**	**737.1**	**2.1**	**206.8**
Midwest	**6A**	**MN**	**Minneapolis**	**Hennepin**	**12,213,811**	**18.9%**	**7.3**	**0.4**	**3.5**	**23.0**	**1.5**	**5.8**	**26.1**	**1.5**	**5.8**	**0.9**	**117.1**	**1.5**	**29.9**	**0.9**	**1,280.3**	**1.5**	**326.8**	**1.1**	**982.0**	**1.5**	**217.0**
				Total	**64,707,450**	**100%**																					
				Pop Wgt Avg			**5.3**	**0.8**	**3.3**	**16.6**	**2.3**	**5.5**	**19.7**	**2.4**	**5.5**	**0.7**	**88.2**	**2.4**	**28.3**	**0.7**	**964.7**	**2.4**	**308.9**	**0.9**	**739.9**	**2.4**	**205.1**
				Arithmatic Average			6.2	0.5	3.4	19.8	1.8	5.6	22.8	1.8	5.6	0.7	102.5	1.8	29.2	0.7	1,121	1.8	319	1.0	860	1.8	212

Energy Expenditures

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $
Midwest	**4A**	**MO**	**Kansas**	**Jackson**	**12,501,407**	**19.3%**	**366.5**	**182.5**	**295.2**	**1,037.4**	**421.8**	**510.5**	**1,334.2**	**440.6**	**510.5**	**56.2**	**667.8**	**440.6**	**316.8**	**56.2**	**1,275.4**	**440.6**	**530.7**	**73.0**	**1,448.2**	**440.6**	**528.4**
Midwest	**5A**	**IL**	**Chicago**	**Cook**	**39,992,232**	**61.8%**	**511.7**	**63.1**	**335.6**	**1,618.4**	**216.9**	**560.1**	**1,919.3**	**226.6**	**560.1**	**62.3**	**960.7**	**226.6**	**348.7**	**62.3**	**1,834.9**	**226.6**	**583.9**	**80.9**	**2,083.4**	**226.6**	**581.4**
Midwest	**6A**	**MN**	**Minneapolis**	**Hennepin**	**12,213,811**	**18.9%**	**712.1**	**39.2**	**355.4**	**2,253.0**	**155.9**	**588.5**	**2,556.9**	**162.9**	**588.5**	**83.8**	**1,279.8**	**162.9**	**365.8**	**83.8**	**2,444.4**	**162.9**	**612.6**	**108.7**	**2,775.5**	**162.9**	**610.0**
				Total	**64,707,450**	**100%**																					
				Pop Wgt Avg			**521.5**	**81.7**	**331.5**	**1,625.9**	**245.0**	**555.9**	**1,926.6**	**255.9**	**555.9**	**65.2**	**964.3**	**255.9**	**345.7**	**65.2**	**1,841.8**	**255.9**	**579.1**	**84.6**	**2,091.3**	**255.9**	**576.6**
				Arithmatic Average			611.9	51.2	345.5	1,935.7	186.4	574.3	2,238.1	194.7	574.3	73.0	1,120.2	194.7	357.2	73.0	2,140	194.7	598	94.8	2,429	194.7	596

Primary Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU
Midwest	**4A**	**MO**	**Kansas**	**Jackson**	**12,501,407**	**19.3%**	**43.0**	**19.8**	**33.3**	**121.6**	**45.8**	**57.6**	**156.4**	**47.8**	**57.6**	**6.6**	**67.4**	**47.8**	**28.6**	**6.6**	**70.0**	**47.8**	**29.6**	**8.6**	**82.3**	**47.8**	**30.2**
Midwest	**5A**	**IL**	**Chicago**	**Cook**	**39,992,232**	**61.8%**	**60.0**	**6.9**	**37.8**	**189.7**	**23.6**	**63.1**	**225.0**	**24.6**	**63.1**	**7.3**	**96.9**	**24.6**	**31.4**	**7.3**	**100.7**	**24.6**	**32.6**	**9.5**	**118.4**	**24.6**	**33.2**
Midwest	**6A**	**MN**	**Minneapolis**	**Hennepin**	**12,213,811**	**18.9%**	**83.5**	**4.3**	**40.1**	**264.1**	**16.9**	**66.3**	**299.7**	**17.7**	**66.3**	**9.8**	**129.2**	**17.7**	**33.0**	**9.8**	**134.1**	**17.7**	**34.2**	**12.7**	**157.7**	**17.7**	**34.9**
				Total	**64,707,450**	**100%**																					
				Pop Wgt Avg			**61.1**	**8.9**	**37.4**	**190.6**	**26.6**	**62.7**	**225.8**	**27.8**	**62.7**	**7.6**	**97.3**	**27.8**	**31.2**	**7.6**	**101.0**	**27.8**	**32.3**	**9.9**	**118.8**	**27.8**	**32.9**
				Arithmatic Average			71.7	5.6	39.0	226.9	20.2	64.7	262.3	21.1	64.7	8.6	113.0	21.1	32.2	8.6	117	21.1	33	11.1	138	21.1	34

CO_2 Emissions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Region	Clm Zone	State	City	County	Population	P.W.F.	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb
Midwest	**4A**	**MO**	**Kansas**	**Jackson**	**12,501,407**	**19.3%**	**6,245.8**	**2,880.8**	**4,839.7**	**17,680.3**	**6,660.0**	**8,368.4**	**22,738.8**	**6,957.2**	**8,368.4**	**958.6**	**9,213.9**	**6,957.2**	**3,905.7**	**958.6**	**10,728.7**	**6,957.2**	**4,545.7**	**1,244.3**	**13,783.3**	**6,957.2**	**5,056.3**
Midwest	**5A**	**IL**	**Chicago**	**Cook**	**39,992,232**	**61.8%**	**8,720.7**	**997.0**	**5,501.0**	**27,583.4**	**3,425.2**	**9,181.7**	**32,712.5**	**3,577.1**	**9,181.7**	**1,062.1**	**13,255.3**	**3,577.1**	**4,297.8**	**1,062.1**	**15,434.6**	**3,577.1**	**5,002.0**	**1,378.7**	**19,829.0**	**3,577.1**	**5,563.9**
Midwest	**6A**	**MN**	**Minneapolis**	**Hennepin**	**12,213,811**	**18.9%**	**12,137.6**	**619.6**	**5,826.6**	**38,400.0**	**2,461.6**	**9,647.6**	**43,579.5**	**2,571.8**	**9,647.6**	**1,427.9**	**17,658.7**	**2,571.8**	**4,508.9**	**1,427.9**	**20,561.9**	**2,571.8**	**5,247.7**	**1,853.5**	**26,416.1**	**2,571.8**	**5,837.2**
				Total	**64,707,450**	**100%**																					
				Pop Wgt Avg			**8,887.5**	**1,289.7**	**5,434.7**	**27,711.8**	**3,868.2**	**9,112.5**	**32,836.8**	**4,040.4**	**9,112.5**	**1,111.1**	**13,305.7**	**4,040.4**	**4,261.9**	**1,111.1**	**15,493.2**	**4,040.4**	**4,960.2**	**1,442.4**	**19,904.3**	**4,040.4**	**5,517.4**
				Arithmatic Average			10,429.2	808.3	5,663.8	32,991.7	2,943.4	9,414.6	38,146.0	3,074.5	9,414.6	1,245.0	15,457.0	3,074.5	4403.4	1,245.0	17,998	3,074.5	5,125	1,616.1	23,123	3,074.5	5,701

C-3. South Region

Delivered Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
		State	City	County	Population	P.W.F.	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Heat Mcf	Cool MWh	HW Mcf	Heat MWh	Heat Gal	Cool MWh	HW Gal	Heat MWh	Heat Gal	Cool MWh	HW Gal
South	**2A**	**TX**	**Houston**	**Harris**	**30,898,043**	**31.6%**	**1.1**	**2.4**	**2.4**	**2.5**	**5.3**	**4.1**	**5.4**	**5.5**	**4.1**	**0.2**	**24.4**	**5.5**	**21.3**	**0.2**	**266.8**	**5.5**	**232.8**	**0.2**	**204.6**	**5.5**	**154.6**
South	**3A**	**GA**	**Atlanta**	**Fulton**	**37,141,601**	**37.9%**	**2.2**	**1.3**	**3.0**	**5.4**	**3.5**	**4.7**	**9.9**	**3.7**	**4.7**	**0.4**	**44.4**	**3.7**	**24.5**	**0.4**	**485.4**	**3.7**	**267.7**	**0.5**	**372.3**	**3.7**	**177.8**
South	**4A**	**TN**	**Nashville**	**Davidson**	**29,844,870**	**30.5%**	**3.5**	**1.4**	**2.7**	**10.4**	**3.7**	**4.9**	**14.6**	**3.8**	**4.9**	**0.5**	**65.4**	**3.8**	**25.2**	**0.5**	**715.1**	**3.8**	**275.4**	**0.7**	**548.4**	**3.8**	**182.9**
				Total	**97,884,514**	**100%**																					
				Pop Wgt Avg			**2.3**	**1.7**	**2.7**	**6.0**	**4.1**	**4.6**	**9.9**	**4.3**	**4.6**	**0.4**	**44.5**	**4.3**	**23.7**	**0.4**	**486.4**	**4.3**	**259.0**	**0.5**	**373.1**	**4.3**	**172.0**
				Arithmatic Average			2.3	1.7	2.7	6.1	4.2	4.6	10.0	4.4	4.6	0.4	44.7	4.4	23.7	0.4	489	4.4	259	0.5	375	4.4	172

Energy Expenditures

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $
South	**2A**	**TX**	**Houston**	**Harris**	**30,898,043**	**31.6%**	**118.1**	**268.0**	**258.4**	**265.8**	**584.8**	**443.9**	**575.8**	**610.7**	**443.9**	**18.9**	**357.8**	**610.7**	**356.0**	**18.9**	**647.9**	**610.7**	**553.4**	**24.5**	**586.5**	**610.7**	**432.8**
South	**3A**	**GA**	**Atlanta**	**Fulton**	**37,141,601**	**37.9%**	**236.2**	**146.7**	**321.7**	**573.8**	**388.7**	**511.7**	**1,047.8**	**405.9**	**511.7**	**38.7**	**651.2**	**405.9**	**409.5**	**38.7**	**1,179.0**	**405.9**	**636.6**	**50.2**	**1,067.3**	**405.9**	**497.9**
South	**4A**	**TN**	**Nashville**	**Davidson**	**29,844,870**	**30.5%**	**374.0**	**149.5**	**295.4**	**1,099.7**	**406.5**	**526.7**	**1,543.4**	**424.6**	**526.7**	**55.5**	**959.1**	**424.6**	**421.2**	**55.5**	**1,736.7**	**424.6**	**654.8**	**72.0**	**1,572.1**	**424.6**	**512.1**
				Total	**97,884,514**	**100%**																					
				Pop Wgt Avg			**240.9**	**185.8**	**293.7**	**636.9**	**456.0**	**494.9**	**1,049.9**	**476.3**	**494.9**	**37.5**	**652.5**	**476.3**	**396.2**	**37.5**	**1,181.4**	**476.3**	**615.9**	**48.7**	**1,069.4**	**476.3**	**481.7**
				Arithmatic Average			305.1	148.1	308.5	836.7	397.6	519.2	1,295.6	415.2	519.2	47.1	805.1	415.2	415.4	47.1	1,458	415.2	646	61.1	1,320	415.2	505

Primary Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU
South	**2A**	**TX**	**Houston**	**Harris**	**30,898,043**	**31.6%**	**12.8**	**27.9**	**27.4**	**28.8**	**60.9**	**47.2**	**62.4**	**63.6**	**47.2**	**2.0**	**26.9**	**63.6**	**23.5**	**2.0**	**27.9**	**63.6**	**24.4**	**2.7**	**32.9**	**63.6**	**24.8**
South	**3A**	**GA**	**Atlanta**	**Fulton**	**37,141,601**	**37.9%**	**25.6**	**15.3**	**34.2**	**62.2**	**40.5**	**54.4**	**113.6**	**42.3**	**54.4**	**4.2**	**49.0**	**42.3**	**27.0**	**4.2**	**50.8**	**42.3**	**28.0**	**5.4**	**59.8**	**42.3**	**28.6**
South	**4A**	**TN**	**Nashville**	**Davidson**	**29,844,870**	**30.5%**	**40.6**	**15.6**	**31.4**	**119.3**	**42.3**	**56.0**	**167.4**	**44.2**	**56.0**	**6.0**	**72.1**	**44.2**	**27.8**	**6.0**	**74.9**	**44.2**	**28.8**	**7.8**	**88.1**	**44.2**	**29.4**
				Total	**97,884,514**	**100%**																					
				Pop Wgt Avg			**26.1**	**19.3**	**31.2**	**69.1**	**47.5**	**52.6**	**113.9**	**49.6**	**52.6**	**4.1**	**49.1**	**49.6**	**26.1**	**4.1**	**50.9**	**49.6**	**27.1**	**5.3**	**59.9**	**49.6**	**27.6**
				Arithmatic Average			33.1	15.4	32.8	90.7	41.4	55.2	140.5	43.2	55.2	5.1	60.6	43.2	27.4	5.1	63	43.2	28	6.6	74	43.2	29

CO_2 Emissions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb
South	**2A**	**TX**	**Houston**	**Harris**	**30,898,043**	**31.6%**	**1,862.1**	**4,056.4**	**3,991.3**	**4,191.7**	**8,852.7**	**6,857.0**	**9,080.6**	**9,245.1**	**6,857.0**	**297.3**	**3,679.5**	**9,245.1**	**3,212.0**	**297.3**	**4,284.5**	**9,245.1**	**3,738.3**	**385.9**	**5,504.3**	**9,245.1**	**4,158.3**
South	**3A**	**GA**	**Atlanta**	**Fulton**	**37,141,601**	**37.9%**	**3,724.1**	**2,221.1**	**4,969.9**	**9,048.1**	**5,883.4**	**7,904.1**	**16,523.7**	**6,143.9**	**7,904.1**	**609.6**	**6,695.5**	**6,143.9**	**3,694.6**	**609.6**	**7,796.3**	**6,143.9**	**4,299.9**	**791.2**	**10,016.0**	**6,143.9**	**4,783.0**
South	**4A**	**TN**	**Nashville**	**Davidson**	**29,844,870**	**30.5%**	**5,898.4**	**2,262.9**	**4,562.4**	**17,341.3**	**6,154.0**	**8,136.2**	**24,339.0**	**6,427.8**	**8,136.2**	**875.1**	**9,862.3**	**6,427.8**	**3,800.2**	**875.1**	**11,483.8**	**6,427.8**	**4,422.8**	**1,135.9**	**14,753.3**	**6,427.8**	**4,919.6**
				Total	**97,884,514**	**100%**																					
				Pop Wgt Avg			**3,799.3**	**2,813.2**	**4,536.8**	**10,043.7**	**6,903.2**	**7,644.4**	**16,557.1**	**7,209.4**	**7,644.4**	**591.9**	**6,709.0**	**7,209.4**	**3,574.5**	**591.9**	**7,812.1**	**7,209.4**	**4,160.1**	**768.4**	**10,036.2**	**7,209.4**	**4,627.4**
				Arithmatic Average			4,811.3	2,242.0	4,766.2	13,194.7	6,018.7	8,020.2	20,431.4	6,285.9	8,020.2	742.3	8,278.9	6,285.9	3747.4	742.3	9,640	6,285.9	4,361	963.6	12,385	6,285.9	4,851

C-4. West Region

Delivered Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
		State	City	County	Population	P.W.F.	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Cool MWh	HW MWh	Heat MWh	Heat Mcf	Cool MWh	HW Mcf	Heat MWh	Heat Gal	Cool MWh	HW Gal	Heat MWh	Heat Gal	Cool MWh	HW Gal
West	2B	AZ	Phoenix	Maricopa	4,970,848	8.1%	0.9	2.9	2.1	2.1	6.5	4.0	4.5	6.8	4.0	0.2	20.3	6.8	20.5	0.2	222.0	6.8	224.0	0.2	170.2	6.8	148.8
West	3B	CA	Sacramento	Sacramento	29,832,102	48.7%	1.6	1.0	3.0	3.2	2.3	4.5	6.8	2.5	4.5	0.2	30.5	2.5	23.1	0.2	333.5	2.5	252.4	0.3	255.8	2.5	167.6
West	3C	CA	San Francisc	San Francisco	7,694,875	12.6%	1.5	0.8	3.2	3.0	1.9	4.5	6.3	2.0	4.5	0.2	28.3	2.0	23.1	0.2	309.4	2.0	252.4	0.2	237.3	2.0	167.6
West	4C	OR	Portland	Clackmas	7,844,547	12.8%	3.7	0.2	3.5	7.7	0.7	5.3	14.7	0.8	5.3	0.4	65.9	0.8	27.4	0.4	720.5	0.8	299.4	0.6	552.6	0.8	198.9
West	5B	CO	Denver	Denver	10,934,600	17.8%	5.2	0.5	3.4	16.8	1.6	5.4	20.2	1.7	5.4	0.6	90.7	1.7	28.1	0.6	991.7	1.7	307.1	0.8	760.6	1.7	203.9
				Total	61,276,972	100%																					
				Pop Wgt Avg			2.4	0.9	3.1	6.1	2.3	4.7	10.0	2.4	4.7	0.3	44.7	2.4	24.3	0.3	488.4	2.4	265.9	0.4	374.6	2.4	176.6
				Arithmatic Average			3.4	0.5	3.4	9.2	1.4	5.1	13.7	1.5	5.1	0.4	61.6	1.5	26.2	0.4	674	1.5	286	0.5	517	1.5	190

Energy Expenditures

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $	Heat $	Heat $	Cool $	HW $
West	2B	AZ	Phoenix	Maricopa	4,970,848	8.1%	100.6	345.0	243.1	228.7	771.4	452.7	494.7	805.7	452.7	18.0	209.2	805.7	221.5	18.0	522.5	805.7	513.1	23.4	506.9	805.7	442.3
West	3B	CA	Sacramento	Sacramento	29,832,102	48.7%	171.5	119.7	347.7	348.5	279.1	509.1	743.3	291.5	509.1	21.5	314.4	291.5	249.6	21.5	785.1	291.5	578.1	28.0	761.7	291.5	498.4
West	3C	CA	San Francisc	San Francisco	7,694,875	12.6%	162.7	92.6	361.5	324.8	223.0	509.1	689.7	233.0	509.1	20.0	291.7	233.0	249.6	20.0	728.4	233.0	578.1	26.0	706.7	233.0	498.4
West	4C	OR	Portland	Clackmas	7,844,547	12.8%	403.4	25.1	404.2	845.2	85.4	603.6	1,606.0	89.2	603.6	46.6	679.3	89.2	296.0	46.6	1,696.2	89.2	685.7	60.5	1,645.7	89.2	591.1
West	5B	CO	Denver	Denver	10,934,600	17.8%	563.8	55.4	393.4	1,834.5	190.0	619.6	2,210.4	198.4	619.6	67.8	934.9	198.4	303.6	67.8	2,334.6	198.4	703.3	88.0	2,265.0	198.4	606.2
				Total	61,276,972	100%																					
				Pop Wgt Avg			264.3	111.0	356.3	664.6	271.3	536.3	1,088.7	283.3	536.3	32.5	460.4	283.3	262.9	32.5	1,149.8	283.3	609.0	42.2	1,115.5	283.3	524.9
				Arithmatic Average			376.6	57.7	386.4	1,001.5	166.1	577.4	1,502.1	173.5	577.4	44.8	635.3	173.5	283.1	44.8	1,586	173.5	656	58.2	1,539	173.5	565

Primary Energy Consumptions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU	Heat MBTU	Heat MBTU	Cool MBTU	HW MBTU
West	2B	AZ	Phoenix	Maricopa	4,970,848	8.1%	10.6	33.3	24.5	24.0	74.5	45.6	52.0	77.8	45.6	1.9	22.4	77.8	22.6	1.9	23.2	77.8	23.5	2.5	27.3	77.8	23.9
West	3B	CA	Sacramento	Sacramento	29,832,102	48.7%	18.0	11.6	35.0	36.6	27.0	51.2	78.1	28.2	51.2	2.3	33.6	28.2	25.5	2.3	34.9	28.2	26.4	2.9	41.1	28.2	26.9
West	3C	CA	San Francisc	San Francisco	7,694,875	12.6%	17.1	8.9	36.4	34.1	21.5	51.2	72.4	22.5	51.2	2.1	31.2	22.5	25.5	2.1	32.4	22.5	26.4	2.7	38.1	22.5	26.9
West	4C	OR	Portland	Clackmas	7,844,547	12.8%	42.4	2.4	40.7	88.8	8.2	60.7	168.7	8.6	60.7	4.9	72.7	8.6	30.2	4.9	75.5	8.6	31.4	6.4	88.8	8.6	31.9
West	5B	CO	Denver	Denver	10,934,600	17.8%	59.2	5.4	39.6	192.7	18.4	62.4	232.1	19.2	62.4	7.1	100.0	19.2	31.0	7.1	103.9	19.2	32.2	9.2	122.2	19.2	32.8
				Total	61,276,972	100%																					
				Pop Wgt Avg			27.8	10.7	35.9	69.8	26.2	54.0	114.3	27.4	54.0	3.4	49.3	27.4	26.8	3.4	51.2	27.4	27.9	4.4	60.2	27.4	28.4
				Arithmatic Average			39.6	5.6	38.9	105.2	16.0	58.1	157.7	16.8	58.1	4.7	68.0	16.8	28.9	4.7	71	16.8	30	6.1	83	16.8	31

CO$_2$ Emissions

		Main Heating Fuel Type					Geothermal (with electric Aux Heater)			Heat Pump (with electric Aux Heater)			Electric (with central AC)			Natural Gas (with central AC)				Propane (with central AC)				Oil (with central AC)			
Cen Regic	Clm Zone	State	City	County	Population	P.W.F.	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb	Heat Lb	Heat Lb	Cool Lb	HW Lb
West	2B	AZ	Phoenix	Maricopa	4,970,848	8.1%	1,536.4	4,846.3	3,557.1	3,492.0	10,836.6	6,624.9	7,554.8	11,317.6	6,624.9	275.6	3,061.2	11,317.6	3,091.4	275.6	3,564.5	11,317.6	3,597.9	357.7	4,579.4	11,317.6	4,002.1
West	3B	CA	Sacramento	Sacramento	29,832,102	48.7%	2,618.6	1,681.7	5,088.5	5,322.3	3,921.2	7,449.9	11,350.8	4,094.8	7,449.9	329.0	4,599.4	4,094.8	3,483.5	329.0	5,355.6	4,094.8	4,054.2	427.1	6,880.4	4,094.8	4,509.7
West	3C	CA	San Francisc	San Francisco	7,694,875	12.6%	2,485.0	1,300.9	5,290.6	4,959.9	3,132.9	7,449.9	10,532.0	3,273.2	7,449.9	305.6	4,267.6	3,273.2	3,483.5	305.6	4,969.3	3,273.2	4,054.2	396.7	6,384.1	3,273.2	4,509.7
West	4C	OR	Portland	Clackmas	7,844,547	12.8%	6,160.6	352.4	5,915.1	12,907.4	1,199.1	8,832.6	24,525.1	1,252.5	8,832.6	711.4	9,937.7	1,252.5	4,131.9	711.4	11,571.6	1,252.5	4,808.9	923.5	14,866.1	1,252.5	5,349.1
West	5B	CO	Denver	Denver	10,934,600	17.8%	8,608.9	778.2	5,756.5	28,014.3	2,668.7	9,066.4	33,754.6	2,787.2	9,066.4	1,035.4	13,677.6	2,787.2	4,237.5	1,035.4	15,926.3	2,787.2	4,931.8	1,344.0	20,460.6	2,787.2	5,485.8
				Total	61,276,972	100%																					
				Pop Wgt Avg			4,036.4	1,559.2	5,214.7	10,148.6	3,811.2	7,848.4	16,624.4	3,980.4	7,848.4	496.7	6,736.3	3,980.4	3,669.2	496.7	7,843.8	3,980.4	4,270.4	644.8	10,077.0	3,980.4	4,750.1
				Arithmatic Average			5,751.5	810.5	5,654.1	15,293.9	2,333.5	8,449.6	22,937.2	2,437.6	8,449.6	684.1	9,294.3	2,437.6	3951.0	684.1	10,822	2,437.6	4,598	888.1	13,904	2,437.6	5,115

Notes: HW, hot water; MBTU, million British thermal units; P.W.F., population weighting factors.