ASSESSMENT OF NATIONAL BENEFITS OF RETROFITTING EXISTING SINGLE-FAMILY HOMES IN UNITED STATES WITH GROUND-SOURCE HEAT PUMP SYSTEMS[1]

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Abstract: This report assesses the potential national benefits of retrofitting U.S. single-family homes with state-of-the-art ground-source heat pump (GSHP) 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 GSHP 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.

Key Words: residential, ground source heat pump, retrofit, benefits

1 INTRODUCTION

The ground source heat pump (GSHP) is a proven technology capable of significantly reducing energy use and summer peak electrical demand in buildings. In the United States, 67.4 percent of the 127.8 million households (U.S. Census Selected Housing Characteristics: 2006–2008) live in single-family homes, most of which have space conditioning and/or water heating (WH) (DOE 2009). Many of these 86.1 million single-family homes are good candidates for GSHP retrofits because:

- on average, about 73 percent of the delivered (site) energy consumed in single-family homes is used for space conditioning and WH—about 43 percent for space heating (SH) alone (DOE 2009);
- the conventional space conditioning and WH equipment used in existing single-family homes usually has 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 probably 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 even horizontal ground heat exchangers required for GSHP systems.

However, only about 1 million GSHP units have been installed in the United States over the past decades. Given the 127.8 million households in the United States, even if all 1 million

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GSHP units were installed in residential buildings, they would account for less than 1 percent of the entire U.S. housing stock.

A study conducted by Oak Ridge National Laboratory (Hughes 2008) concludes, from a survey of U.S. GSHP industry experts, that high initial costs to consumers, a lack of knowledge and/or trust in GSHP system benefits, limited design and installation infrastructures for GSHP systems, and a lack of new technologies and techniques are the most significant barriers to the wide application of GSHP.

This paper assesses the technical potential for primary (source) 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 GSHP systems.

2 METHODOLOGY

This assessment is based on site energy consumption data for existing residential SH–SC–WH systems, which is obtained from the Residential Energy Consumption Survey (EIA 2005), and the relative differences in site energy consumption between existing residential SH–SC–WH systems and a state-of-the-art GSHP system, which is determined with GeoDesigner®, a well-established residential energy analysis software developed by ClimateMaster, Inc. The various climate and geological conditions across the United States are accounted for in the calculation of the relative differences in site energy consumption. Based on the calculated site energy savings, the corresponding source energy savings, energy expenditure savings, and CO_2 emission reductions are calculated with national averages of the source-to-site energy conversion factors and emissions factors for various fuels. The reduction of summer peak electrical demand is also estimated based on the reduced demand for cooling energy resulting from the GSHP retrofit. The calculation procedures and data used in the assessment are discussed in following sections.

2.1 Calculation Procedures

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

Step 1:

Calculate the peak heating and cooling loads of a reference building (discussed later in this document) at various locations that represent major climate zones within each of the four U.S. census regions.

Step 2:

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

Step 3:

Calculate the regional average of annual site energy consumption of a particular SH–SC–WH system serving the reference building with Eq. (1).

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

where

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

$Sys\_DE(i,j,k)$ is the annual site 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*;

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

Step 4:

Calculate the regional average relative differences in annual site energy consumption between the state-of-the-art GSHP system and each of the typical existing SH–SC–WH systems with Eq. (2).

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

where

$RD\_DE(j,k)$ is the regional average relative difference in annual site energy consumption between the state-of-the-art GSHP 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 GSHP system in census region *k*

Step 5:

Calculate the annual savings in site energy from GSHP retrofits in a particular region with Eq. (3).

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

where

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

$SFHS\_DE(j,k)$ is the annual site 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 GSHP retrofits;

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 site energy from retrofitting existing U.S. single-family homes with the state-of-the-art GSHP system with Eq. (4).

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

The national potential of savings in source energy and energy expenditure, as well as the reduction of CO_2 emissions, is estimated following the same procedure. However, in these calculations, the annual site energy consumption of each compared SH–SC–WH system is replaced with the associated source energy consumption, energy expenditure, or CO_2

emissions, which are converted from the site energy consumption using corresponding conversion factors between source and site energy, regional utility rates, or emissions factors of various fuels as summarized in Tables 1 through 3.

Table 1: National average of source-to-site energy conversion factors for fuels and electricity consumed in buildings

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

Source: NREL 2007.

Table 2: National average of emissions factors for fuels and electricity

Fuel	CO_2 equivalent emissions factor			
Natural gas	150.80	lb per Mcf	0.002416	kg/m3
Propane	16.06	lb per gallon	1.927	kg/L
Heating oil	26.90	lb per gallon	3.595	kg/L
Electricity	1.67	lb per kWh	0.758	kg/kWh

Source: NREL 2007. Mcf – thousand cubic feet

Table 3: Utility rates of 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

Source: EIA 2010. Note - $1.00/Mcf = 0.035 $/m^3; $1.00/gallon = 263.16 $/m^3

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 Eq. (5).

$$PEDFSC = \frac{kWh\_MaxTemp}{Hr\_MaxTemp \times Fraction\_HP} \qquad (5)$$

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;

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

The 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 GSHP system and typical existing SC systems is 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.

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

The U.S. Energy Information Administration (EIA) keeps track of the annual delivered (site) energy[2] consumption of the entire U.S. residential sector through national area probability–sample surveys[3]. From the Public Use Microdata Files of the latest survey (EIA 2005), data for SH–SC–WH system types and associated annual site energy use for existing U.S. single-family homes were extracted and used in this study. Table 4 summarizes the SH–SC–WH systems that are most widely used in existing U.S. single-family homes and their energy efficiencies (EIA 2000; DOE 2005).

Table 4: Typical SH–SC–WH systems used in U.S. single-family homes

Energy services	Existing systems and equipment	Rated efficiencies
Space heating	Air-source heat pump (ASHP)	3.2 COP (at 8.3 °C [47 °F] outdoor temperature)
	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	Central air conditioner	10 SEER (2.93 cooling SPF)

[2] Energy delivered to a building without adjustment for the energy consumed to produce and deliver the energy.
[3] 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.

	(CAC)/ASHP	
	Room air conditioner (RAC)	7.7 SEER (2.26 cooling SPF)
	Combination of CAC and RAC	7.7–10 SEER (2.26-2.93 cooling SPF)
Water heating	Electric heater	88 EF
	Natural gas heater	58 EF
	Propane or LPG heater	58 EF
	Heating oil heater	58 EF

AFUE – annual fuel utilization efficiency, %; EF – energy factor, %

The annual site energy consumption data for typical SH–SC–WH systems in existing U.S. single-family homes in each census region are presented in Figures 1 through 3. As shown in these figures, natural gas is the prominent fuel for SH and WH in all the census regions, but there is substantial consumption of heating oil for SH and WH in the Northeast. The energy consumption for SC is low except in the South, and the total national site energy consumption for SC is only about 1/5 of that for SH.

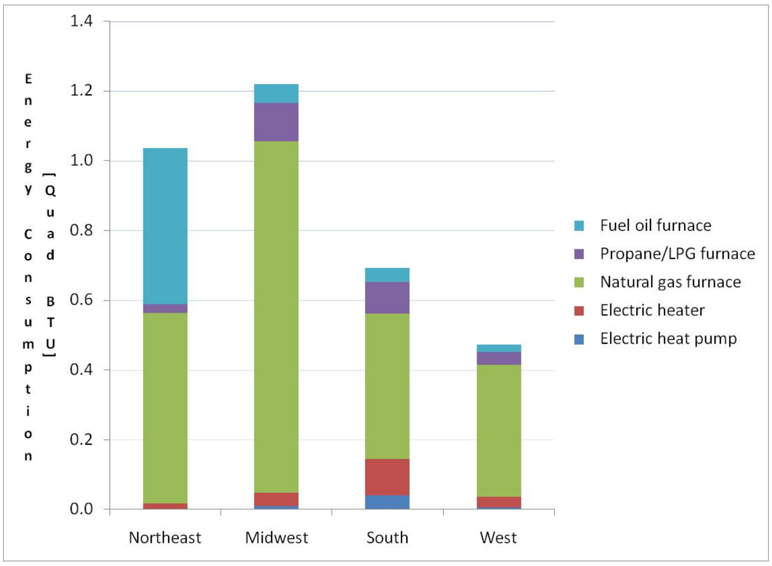

Figure 1: Annual site energy consumption of typical space heating systems in existing U.S. single-family homes in each census region

Notes: (quad = quadrillion; BTU = British thermal unit; 1 quad BTUs = 1.055 EJ).

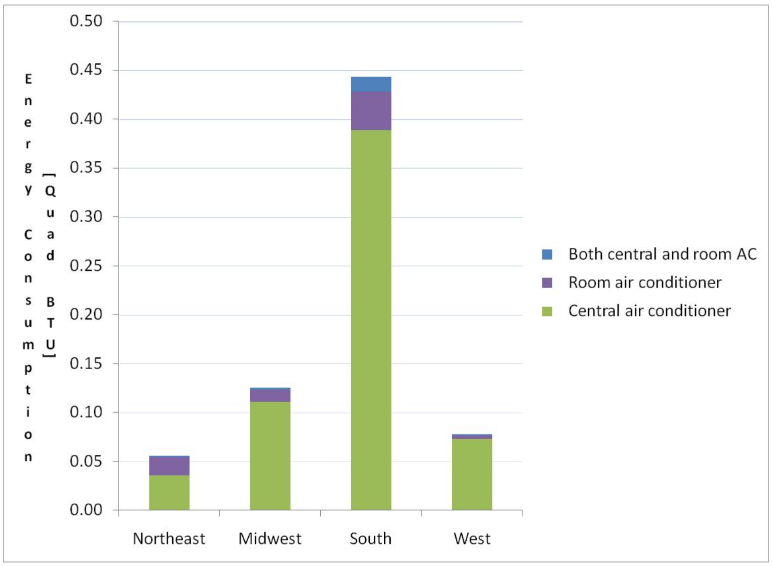

Figure 2: Annual site energy consumption of typical space cooling systems in existing U.S. single-family homes in each census region
Notes: (quad = quadrillion; BTU = British thermal unit; 1 quad BTUs = 1.055 EJ).

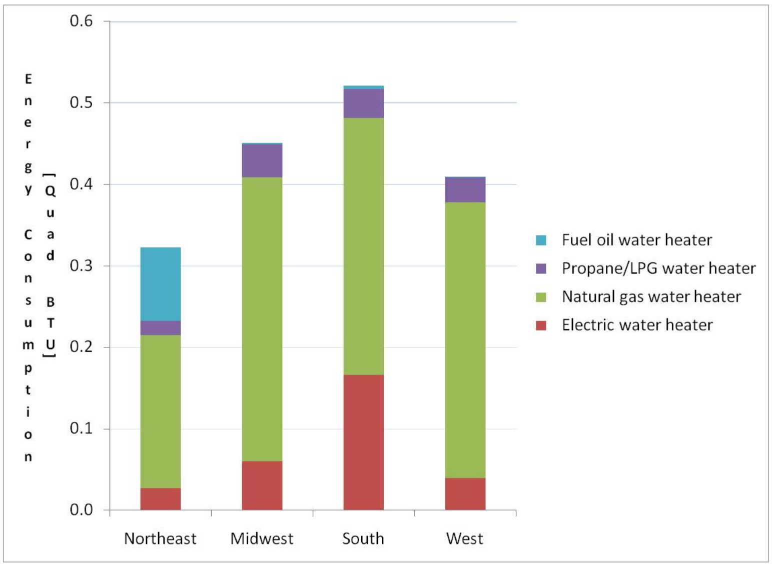

Figure 3: Annual site energy consumption of typical water heating systems in existing U.S. single-family homes in each census region
Notes: (quad = quadrillion; BTU = British thermal unit; 1 quad BTUs = 1.055 EJ).

2.3 State-of-the-Art GSHP System

The state-of-the-art GSHP system presented in this study consists of a packaged water-to-air GSHP 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 GSHP unit is an energy efficiency ratio (EER)[4] of 18.2 (cooling COP of 5.33) at full capacity and an EER of 27 (cooling COP of 7.91) at 76 percent of full

[4] 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.

capacity. The nominal heating efficiency of the two-stage GSHP unit has a COP of 4 at full capacity and a COP of 4.5 at 76 percent of full capacity.[5]

The ground heat exchanger is sized to maintain the fluid temperature from the ground loop (the entering fluid temperature [EFT] to the GSHP unit) within the range of 30–95°F (-1–35°C) for given building loads, ground thermal properties, and undisturbed ground temperature.

The state-of-the-art GSHP system can contribute to WH through the use of a desuperheater, which heats the water whenever the GSHP unit runs. In this study, we assume that an electric storage type water heater with an energy factor (EF) of 88 is used as the main WH device of the GSHP system, which is assisted by the desuperheater, and that existing water heaters fired with fossil fuels will not be replaced with desuperheater-assisted electric water heaters.

2.4 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 GSHP system and existing SH–SC–WH systems for providing the same energy service depends more on the characteristics of the compared systems, climate, and geological conditions than on 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 GSHP system and existing SH–SC–WH systems. The selected reference single-family home is a 150 m^2 (1615 ft^2) one-story, slab-on-grade, wood-frame house as depicted in Figure 4.

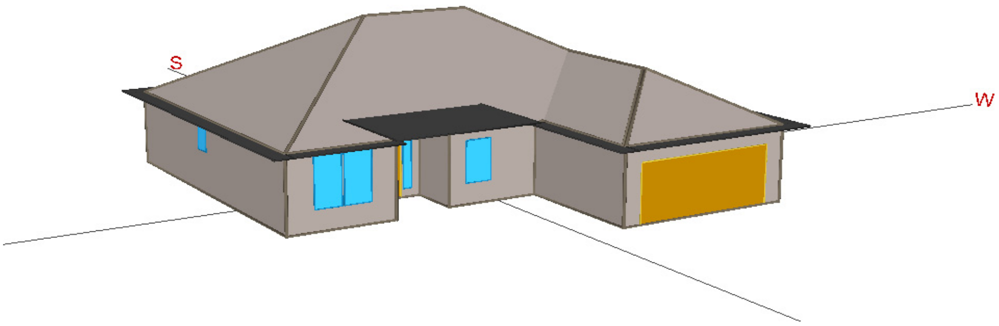

Figure 4: Illustration of the selected reference single-family home

2.5 Climate Zones

The 2004 International Energy Conservation Code climate zones for the United States are used in this study. Table 5 lists the percentage of the population in each climate zone in each of the U.S. census regions. 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 this study. One location (a city) was selected to represent each of the 14 climate zones included in this study.

Table 5: Percentage of population in each climate zone within each of the U.S. census regions

[5] The COP and EER are measured at AHRI/ISO/ASHRAE/ANSI 13256-1 rating conditions: for cooling at full capacity, EFT is 77°F (25 °C); for heating at full capacity, EFT is 32°F (0 °C).

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	—	—	—	—

2.6 Calculation Tool

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

GeoDesigner® uses the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) bin analysis method to calculate the energy consumption of GSHP 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 (e.g., solar, wind, precipitation) 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 GSHP system and the existing SH–SC–WH systems predicted by GeoDesigner® is fairly close to that predicted by the more sophisticated programs.

Because (as previously noted) 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 to perform an energy analysis for a wide range of residential SH–SC–WH systems—GeoDesigner® was selected for this study.

3 RESULTS AND DISCUSSIONS

The potential benefits from retrofitting U.S. single-family homes with the state-of-the-art GSHP systems were estimated using the procedures described in previous sections. The estimated national potential for each of the four major benefits of GSHP retrofits—energy savings, reductions in CO_2 emissions, avoided summer peak electrical demand, and energy expenditure savings—all at various market penetration rates, are summarized in Table 6. 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 given in Appendix C of the full report of this study (Liu 2010).

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 GSHP systems would yield the following benefits annually:

- a savings of **4.2 quadrillion British thermal units (4.43 Exajoules, EJ) in primary (source) 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 **271.7 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 **48.1 percent** reduction in energy costs for SH–SC–WH in these homes; and
- a reduction of **215.9 gigawatt 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 maximum level of these benefits, the benefits of GSHP retrofits are still very significant even at lower market penetration rates, as shown in Table 6.

Table 6: Potential benefits of retrofitting existing U.S. single-family homes with state-of-the-art GSHP 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: (quad = quadrillion; BTU = British thermal unit; 1 quad BTUs = 1.055 EJ; MM ton= million metric ton; GW=gigawatt).

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