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Environ. Res. Lett. **2** (2007) 044001 (8pp) doi:10.1088/1748-9326/2/4/044001

Strategic GHG reduction through the use of ground source heat pump technology

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Received 26 August 2007
Accepted for publication 26 October 2007
Published 9 November 2007
Online at stacks.iop.org/ERL/2/044001

Abstract

Higher energy prices and concern about climate change is drawing increasing attention to ground source heat pump (GSHP) systems. Their clear advantage lies in being able to provide heating using 25 to 30% of the energy consumed by even the most efficient conventional alternatives. Their drawback has been high capital costs and uncertainty about whether the emissions associated with the electric power used to energise the system has higher system-wide emissions than the highest-efficiency furnaces. This study delineates circumstances under which GSHP systems achieve net emission reductions, for different electricity generation methods, heat pump efficiencies, and heating loads. We illustrate the effect of relative fuel prices on annual operating savings using fuel prices in multiple countries. Annual operating savings determine how rapidly the technology achieves payback and then generates return on the initial capital investment. Finally, we highlight the least cost supply curve for using GSHP to reduce greenhouse gas emissions. Using the United States as a base reference case, this study explores the potential of GSHP in cold-climate countries worldwide.

Keywords: ground source heat pump (GSHP), residential energy, greenhouse gas reduction, renewable energy

1. Introduction

As early as 1993 the US Environmental Protection Agency (EPA) endorsed ground source heat pump (GSHP) systems as the most energy-efficient, environmentally clean, and cost-effective space conditioning systems available (US Environmental Protection Agency 1993). GSHPs are heat pumps that collect and transfer heat from the earth through a series of buried pipes containing a working fluid, which is typically composed of a mixture of water and antifreeze solutions such as methanol, ethanol, or glycol. The configuration of the underground loop facilitating the transfer can either be horizontal or vertical (trenches or wells, respectively, are used during the installation process). Using an electrically powered unit known as a heat pump, the heat obtained from under the ground is concentrated for inside use (Natural Resources Canada 2002). Heat pumps do not generate electricity or heat, but they instead facilitate the transfer of thermal energy from one location (the ground) to where it is needed (e.g. indoors). System component descriptions of GSHP systems are available in the literature (Hanova 2007, Chiasson 1999, etc).

We quantify the achievable greenhouse gas (GHG) reductions based on parameters including heating load, fuel choice, heat pump efficiency, and electricity carbon intensity. We aim to provide a comparative mechanism through which emission profiles of various fuel choices can be explored.

Since the installation of a heating or cooling system is a decision that will affect a homeowner's comfort and pocketbook for numerous years (US Department of Energy 1999), we outline the conditions under which the environmental and financial benefits of GSHP for individual applications are maximized. While the primary focus of this

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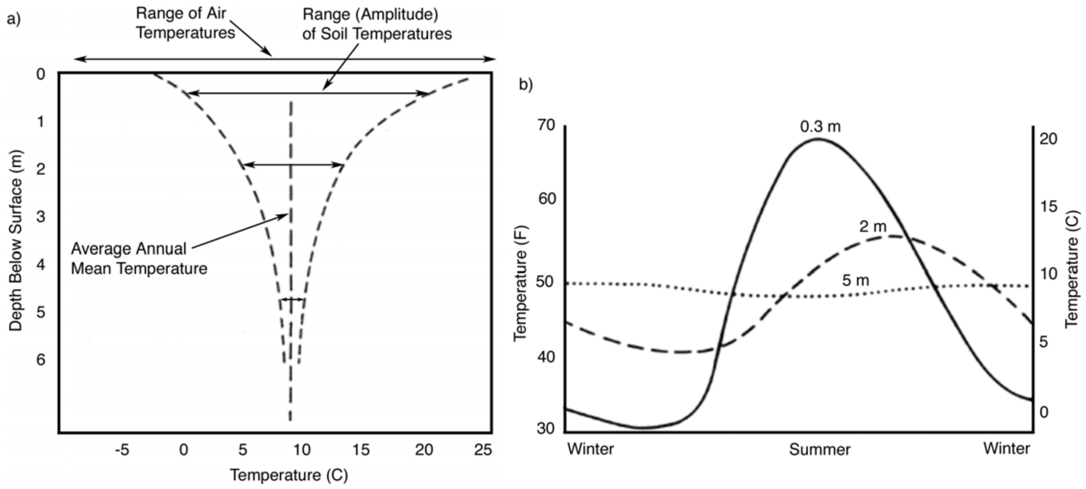

Figure 1. Depth dependence of annual range of ground temperatures in Ottawa, Canada (source Williams and Gold 1976, National Research Council of Canada 2003).

study is on residential uses of GSHP, the results are transferable to other applications where low-grade heat is desired, e.g. crop and lumber drying, industrial process heating and cooling needs, horticulture, and ice melting on sidewalks, roads, and bridges (Green and Nix 2006).

GSHP has strong economies of scale and our assessment has strong implications for community/city planning and development, but is also relevant to policy-makers who seek to reduce residential and commercial building energy use and their associated emissions.

2. Availability of thermal resources

Surface ground temperatures are affected by meteorological factors including incoming solar radiation (insolation), snow cover, air temperature, precipitation and thermal properties of soils. The aforementioned factors fluctuate between summer and winter months; however, temperatures below 10 m are relatively constant. Figure 1 illustrates two simplified schematics of ground temperature fluctuations, at various depths in Ottawa (Canada).

Fluctuation in the upper few metres can be estimated using sinusoidal functions (Hillel 1982, Marshall and Holmes 1988, Wu and Nofziger 1999). The surface temperature penetrates with decreasing intensity into the ground, and the speed and depth to which the heat is transported depend on the thermal conductivity of the subsurface (Henning and Limberg 1995). The diurnal changes affect the ground to a depth of 0.3–0.8 m, while annual penetration of temperature fluctuations is generally less than 10 m (Farouki 1986).

Contrary to a common presumption in some reference material, GSHPs do not work by exploiting the ability of the earth to absorb the sun's energy as heat. This misconception is most likely held because approximately 51% of insolation is absorbed by land and oceans (National Aeronautics and Space Administration 2005). While surficial sediment temperatures more directly affect horizontal ground loop systems, heat pumps in these configurations extract energy from the subsurface despite insolation variations, rather than because of them[4].

Surficial temperature fluctuations induced by solar radiation are superimposed on a constant and larger scale heat flow that originates inside the earth (this energy source is not susceptible to cloud cover, weather, or climatic influences). The depths at which temperatures stabilize indicate the interface at which seasonal influences are fully overwhelmed by the heat flowing to the surface from inside the earth. The energy generated inside the earth originates from numerous sources such as the decay of radioactive elements (Henning and Limberg 1995) and the release of gravitational potential of descending material (Buffet 2000).

The temperature naturally increases with depth in the earth at a rate known as the geothermal gradient ($\sim$30 °C km^{-1}). This rate varies, and tectonically active regions are associated with higher heat flows. These areas are identified as having high-grade geothermal resources, which can be mined and utilized for electricity generation (figure 2). However, since GSHPs reach very shallow depths (generally not exceeding 60 m), the performance or efficiency of GSHPs are independent of the heat transfer intensity of these gradients (Green and Nix 2006, Geothermal Education Office 2000).

Parameters influencing GSHPs are soil/rock thermal conductivity, the hydraulic properties of each soil layer, meteorological data, system design, and daily heating and cooling loads. GSHPs may not be feasible in all locations if the site-specific locations, such as soil properties or drilling conditions, are not ideal. While site investigations determine the local suitability of GSHP, this technology must also meet additional categories of feasibility, including economic profitability, as discussed in the following sections.

[4] Unlike GSHPs, air source heat pumps are primarily dependent on incoming solar radiation, and are therefore affected by air temperature fluctuations.

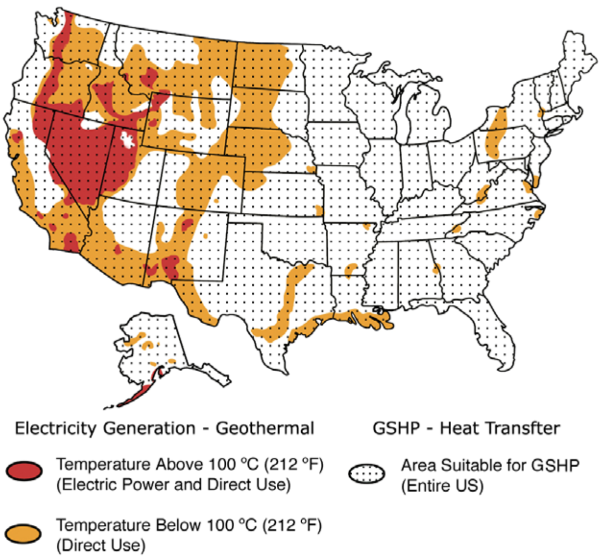

Figure 2. Large-scale geothermal and GSHP potential in the United States. Electricity generation from geothermal energy is suitable in areas with high heat flows. Shallow heat stored underground can be used for direct purposes using GSHPs; ground coupled heat pumps are suitable throughout the US and the world (sources Green and Nix 2006, Geothermal Education Office 2000).

3. Emission reduction potential

In order to assess the environmental feasibility of heat pumps, we compare the emissions associated with heat pump operation to conventional heating systems emissions. Heat pumps use electricity to move heat from underground into a home.

The overall potential for GHG reductions is determined by lifecycle emissions of each energy source, and the efficiency of energy conversion used to meet heating loads. Natural gas produces emissions of 51 kg CO_2e/GJ according to US EPA figures, while heating oil is associated with emissions of 73 kg CO_2e/GJ. The emissions associated with electric heat are dependent on electricity generation sources; coal-fired power plants will yield larger emissions than renewable energy sources. Carbon dioxide intensities of delivered electricity also vary with the geographical extent of studies (i.e. regional emissions vary from those of a utility territory). The results presented here are applicable to a variety of scales, as they enable the reader to use emission intensities associated with a scale that is relevant.

We assume radiant electric elements achieve efficiencies close to 100%, with natural gas and oil systems achieving efficiencies of 95% and 85%, respectively (for space and water heating). GSHP systems commonly operate at efficiency ranges equivalent to 300 and 500%, which translate into coefficients of performance (COP) of 3 and 5, respectively. Using these efficiencies, we assess the environmental performance of GSHP for an annual heating load of 80 GJ, the average Canadian heating load for a single detached home. Using the data provided in figure 3, one can estimate annual emission reductions given any COP and CO_2 intensity of delivered electricity. The CO_2 intensity of the electricity consumed should include generation, transmission, and distribution losses, as well as emissions associated with electricity imports.

Relative to natural gas and heating oil, the threshold of electric CO_2 intensity at which heat pumps become environmentally feasible varies with the efficiency levels of both conventional and GSHP systems. Unlike the comparison to natural gas or heating oil, emission reductions available through GSHP relative to electric heating increase substantially in regions where electricity contains a higher CO_2 content.

4. Implications for emission reduction strategies

Fuel switching from natural gas and heating oil systems will yield the largest environmental benefits where the CO_2 intensity of electricity is low. Conversely, GSHPs achieve especially high levels of emission reductions relative to radiant electric in regions where the CO_2 intensity of electricity is highest. The following observations can serve as guidelines for policies that most effectively target specific market segments to achieve the largest possible emission reductions through the use of GSHP technology.

(1) In each scenario an increase in heat pump efficiency (coefficient of performance) will result in larger emission reductions.
(2) Relative to both natural gas and heating oil, an increase in CO_2 intensity of delivered electricity will decrease emission reductions.
(3) Relative to electric radiant heating, regions with very polluting electricity generation methods benefit most by replacing this heating system type with GSHP.
(4) Homes with larger heating loads correspond with higher emissions and GSHP offers larger emission reduction potential.

5. Economic feasibility

GSHP is feasible if the electricity costs required to drive the heat pump provide annual operating savings relative to conventional system costs. To quantify the range of annual savings, we compare GSHP operating costs to those of conventional space and water heating systems (figure 4). We assume an average COP of 4 and demonstrate the variation of savings for a typical detached home (heating load of 80 GJ/yr). Using the most recently available price data[5] from the US Energy Information Administration (2007), we illustrate that significant savings can be recovered in most countries. In regions where electricity prices are significantly higher than natural gas costs the financial returns of GSHP are questionable. GSHP systems are preferable to electric and heating oil systems in all countries for which data are available.

A country's location within the financial incentive spectrum will vary depending on expected changes in fuel price over the lifetime of the system. In countries where regional pricing differences exist, such as Canada, some locations may

[5] Prices include taxes and are based on the most currently available data (ranging from 2004 to 2007).

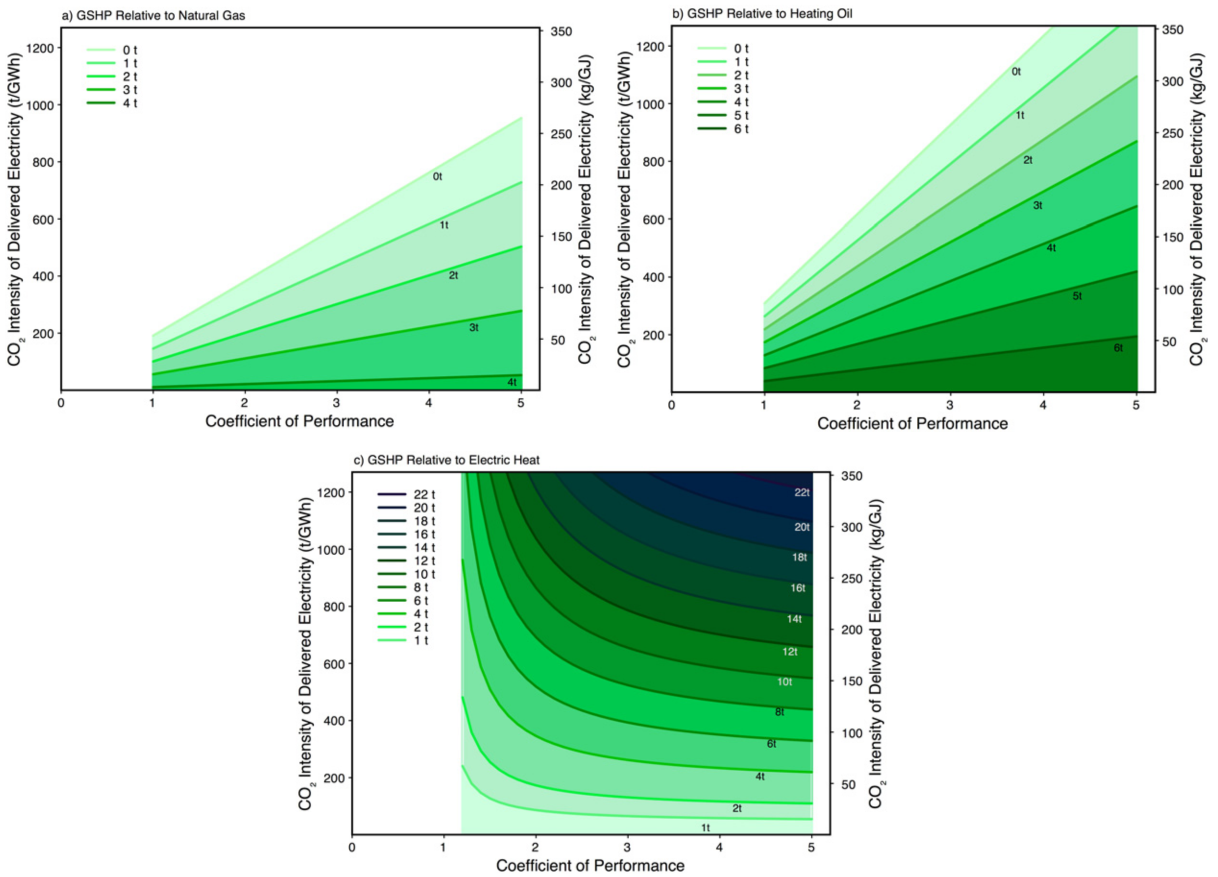

Figure 3. GHG emission reductions of ground source heat for an 80 GJ heating load. Relative to (a) natural gas and (b) heating oil, the CO_2 intensity threshold at which heat pumps become environmentally feasible increases with higher heat pump efficiency. However, relative to electric heating (c), the GHG reductions available through GSHP increase substantially where electricity contains a higher CO_2 content.

be more suitable for GSHP than others. The graphs in figure 4 also allow home and business owners to anticipate the effects of fuel price fluctuations on GSHP feasibility.

The payback period of GSHPs for residential application typically ranges between <10 and 20 years, varying with capital investment costs and a region's fuel prices, and relative fuel price increases. After the payback threshold has been reached, the GSHP continues to provide annual operating savings until the end of the lifetime of the system. After the payback period, GSHPs generate a return on investment exceeding typical investment options offered to average homeowners. Increased property value and the high return on investment are considerations that could by systematically incorporated into mortgage assessments.

6. Scale effects

Both annual operating savings and GHG emission reductions increase with larger heating loads. In this section we explore how economies of scale affect the environmental and fiscal performance of GSHP. The threshold at which GSHP becomes environmentally advisable is directly related to the CO_2 content of electricity used by the heat pump, its COP, and the efficiency of the conventional heating system. Interestingly, the threshold itself is independent of heating load relative to natural gas and oil heating systems. Relative to 95% efficient natural gas furnaces, GSHP systems operating at COP 4 provide emission savings at electricity CO_2 intensities below 760 t/GWh (figure 5(a)). Relative to 85% efficient heating oil furnaces this CO_2 electricity intensity threshold is crossed at 1240 t/GWh (figure 5(b)). Heat pumps always reduce emissions relative to electric heating, but GHSP is particularly advisable in regions/countries with CO_2-intensive electricity generation (figure 5(c)).

GHG savings for COPs and furnace efficiencies other than those outlined above can be derived from equations (1) through (3). Conventional fuel emissions can be calculated using a variety of methodologies; a life cycle approach, for instance, must include upstream emissions in these calculations:

$$\text{GHG Savings} = \text{Conventional Fuel Emissions} - \text{Heat Pump Emissions} \quad (1)$$

$$\text{Conventional Fuel Emissions} = \frac{\text{HL} * \text{FI}}{\text{Eff} * 1000} \quad (2)$$

$$\text{Heat Pump Emissions} = \frac{\text{HL} * 278 * \text{EI}}{\text{COP} * 1000\,000}, \quad (3)$$

where HL represents the heating load in GJ, FI is the CO_2

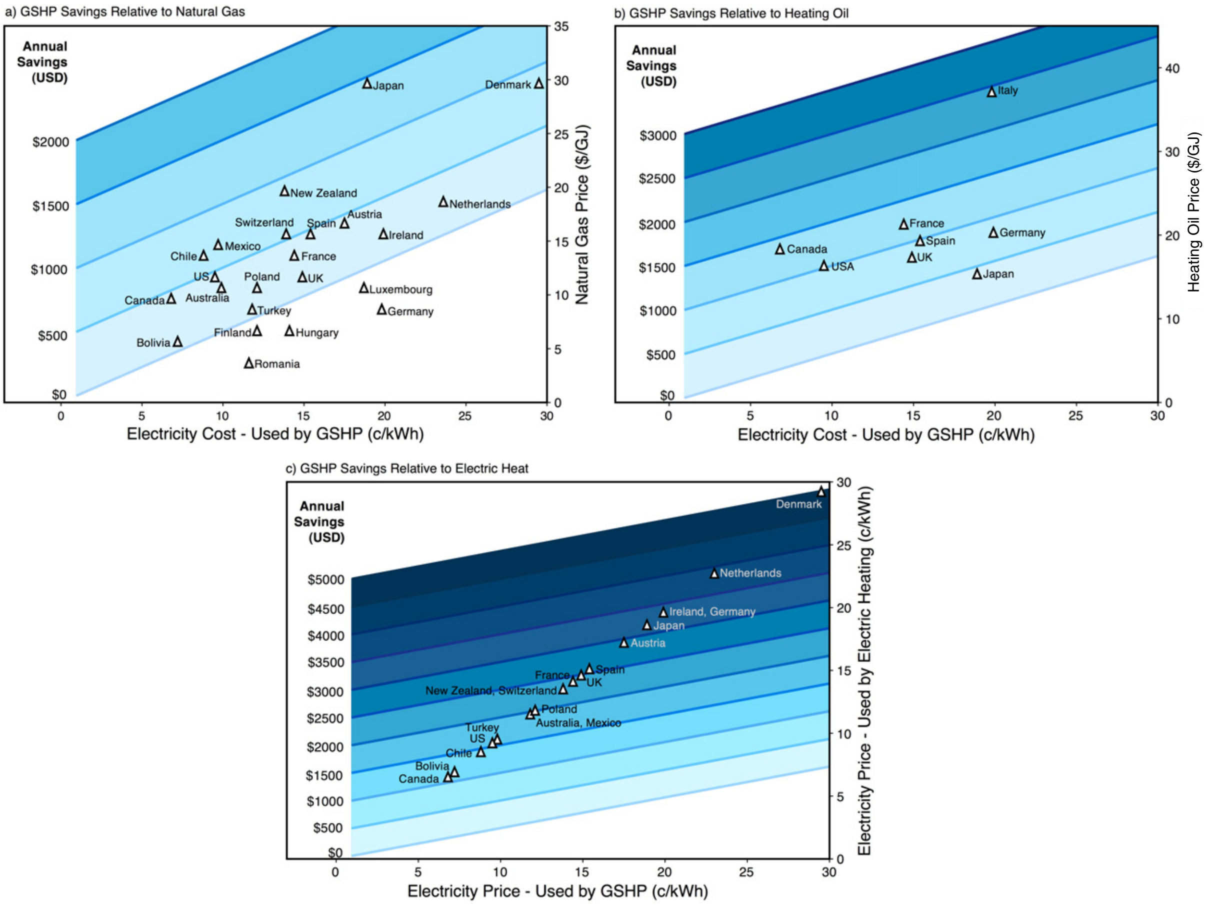

Figure 4. Annual operating savings of GSHP for 80 GJ heating loads relative to (a) natural gas, (b) heating oil, and (c) electric heating. International fuel prices are superimposed to provide approximate savings of GSHP at a COP of 4.

intensity of fuel in kg CO_2/GJ, Eff is the conventional heating system efficiency in per cent, COP is the efficiency of the heat pump, and EI is the CO_2 electricity intensity in t/GWh. The emission reductions of GSHP systems relative to natural gas and heating oil are given by the following equation:

$$\text{GHG Savings} = \frac{\text{HL}}{1000}\left(\frac{\text{FI}}{\text{Eff}} - \frac{0.278 \times \text{EI}}{\text{COP}}\right). \quad (4)$$

Using similar calculations for electric heat, we can calculate the emissions reductions relative to electric heating using

$$\text{GHG Savings} = \frac{\text{HL} \times \text{EI}}{3600}\left(\frac{1}{\text{Eff}} - \frac{1}{\text{COP}}\right). \quad (5)$$

Rearranging equation (4) we can solve for a CO_2 intensity threshold of electricity at which GSHP becomes environmentally preferable to natural gas or heating oil; the threshold calculation is given by

$$\text{EI} = \frac{\text{FI} \times \text{COP}}{0.278 \times \text{Eff}}. \quad (6)$$

Scale effects are also evident in annual operational savings of GSHP systems, as larger heating loads tend to correspond with larger annual savings. Using 13 cents per kWh (c/kWh) as[6] the baseline for price comparisons, we illustrate the annual operational savings of GHSP (figure 6). With regard to electric heating, electricity prices can vary slightly depending on the amount of electricity consumed. Smaller amounts of electricity (i.e. as used by the heat pump) can have a larger unit price than large quantities, such as those required by electric heating. We include electricity unit price variations for completeness.

The minimum natural gas or heating oil price required for GSHP to be cost-effective can be calculated using

$$\text{Fuel Price} = \frac{\text{Elec Price} \times 2.78 \times \text{Eff}}{\text{COP}}, \quad (7)$$

where Fuel Price is given in \$/GJ, Elec Price represents the electricity price in c/kWh, Eff is the furnace efficiency in per cent, and COP is the heat pump coefficient of performance. A more general formula can be used to calculate the annual operational savings for natural gas or heating oil, given by

$$\text{Savings} = \frac{\text{HL} \times \text{Fuel Price}}{\text{Eff}} - \frac{\text{HL} \times 2.78 \times \text{Elec Price}}{\text{COP}}. \quad (8)$$

[6] 13 c/kWh is the median electricity price of countries shown in figure 4.

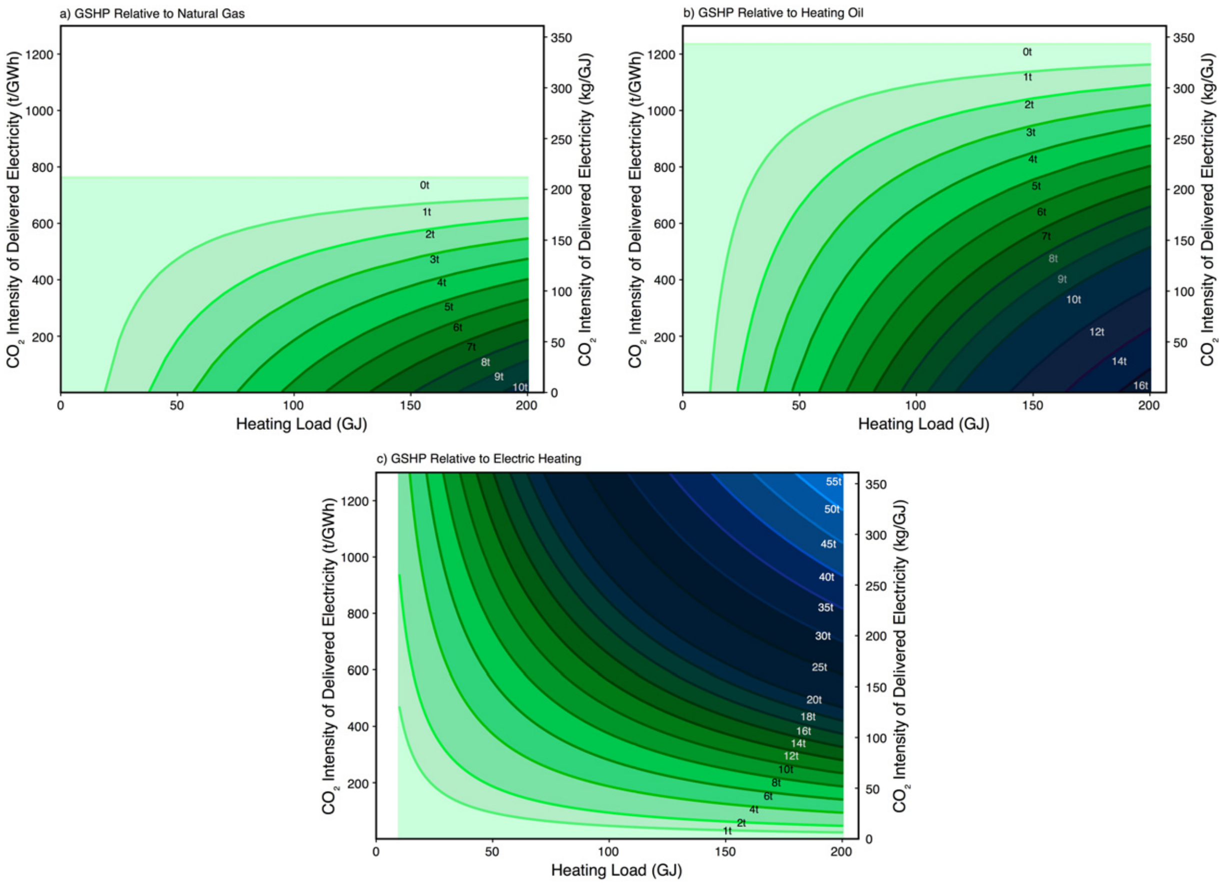

Figure 5. Emission reductions of a GSHP system operating at COP 4 for three main heating fuels. (a) Natural gas furnaces operating at 95% efficiency are more advisable than GSHP at electricity CO_2 intensities above 762 t/GWh. (b) GSHP is advisable relative to high-efficiency heating oil furnaces below electricity CO_2 intensities of 1235 t/GWh. (c) GSHP always yields large emission savings relative to electric heating.

7. Discussion

Surveys conducted by utility companies indicate a higher level of customer satisfaction with GSHP relative to conventional systems[7]; for instance, more than 95% of all GSHP users would recommend a similar system to their friends and family (US Department of Energy 1999). This technology also allows homeowners to have a sense of empowerment in relation to climate change mitigation that environmentally conscious homeowners describe to be rewarding.

The environmental advantages of this technology are observed when emissions of conventional heating technologies are contrasted to GSHP. Conventional radiant electric heat (when not combined with GSHP) is the most polluting heating technology in regions with high carbon intensity electricity; mandating an emission standard for electrically heated homes could prove an essential strategy for reaching a nation's emission targets. Policies could require that users of radiant heating systems under these conditions would need to (a) commit to purchasing green electricity and/or (b) use a GSHP-driven heating system. Conversely, GSHP provides the largest emission savings relative to natural gas and heating-oil-fired systems where the electricity used by heat pumps is derived from environmentally sound primary fuels.

The results of this study can also be applied to regions where air conditioning is the primary energy demand. GSHP provides both heating and cooling energy services; however, it may not be appropriate to contrast savings from both energy services to a base case where a customer would not have chosen to install air-conditioning equipment. This study suggests that each location should be considered based on its specific climatological conditions.

The results presented here serve as a tool to estimate the emission and operating cost savings in order to facilitate better decision-making with respect to GSHP and conventional systems, particularly with the tradeoffs between operating costs and upfront capital costs. The worldwide market diffusion of GSHP systems is growing, but has been limited so far despite widespread environmental and operating benefits. There are several reasons for this: (1) system designs have not been standardized and the actual performance of systems has sometimes fallen short of its promise, (2) the initial capital costs are significant, (3) substantial educational infrastructure investments are required to address the current shortage

[7] GSHP systems provide increased comfort by eliminating hot/cold spots and temperature fluctuations.

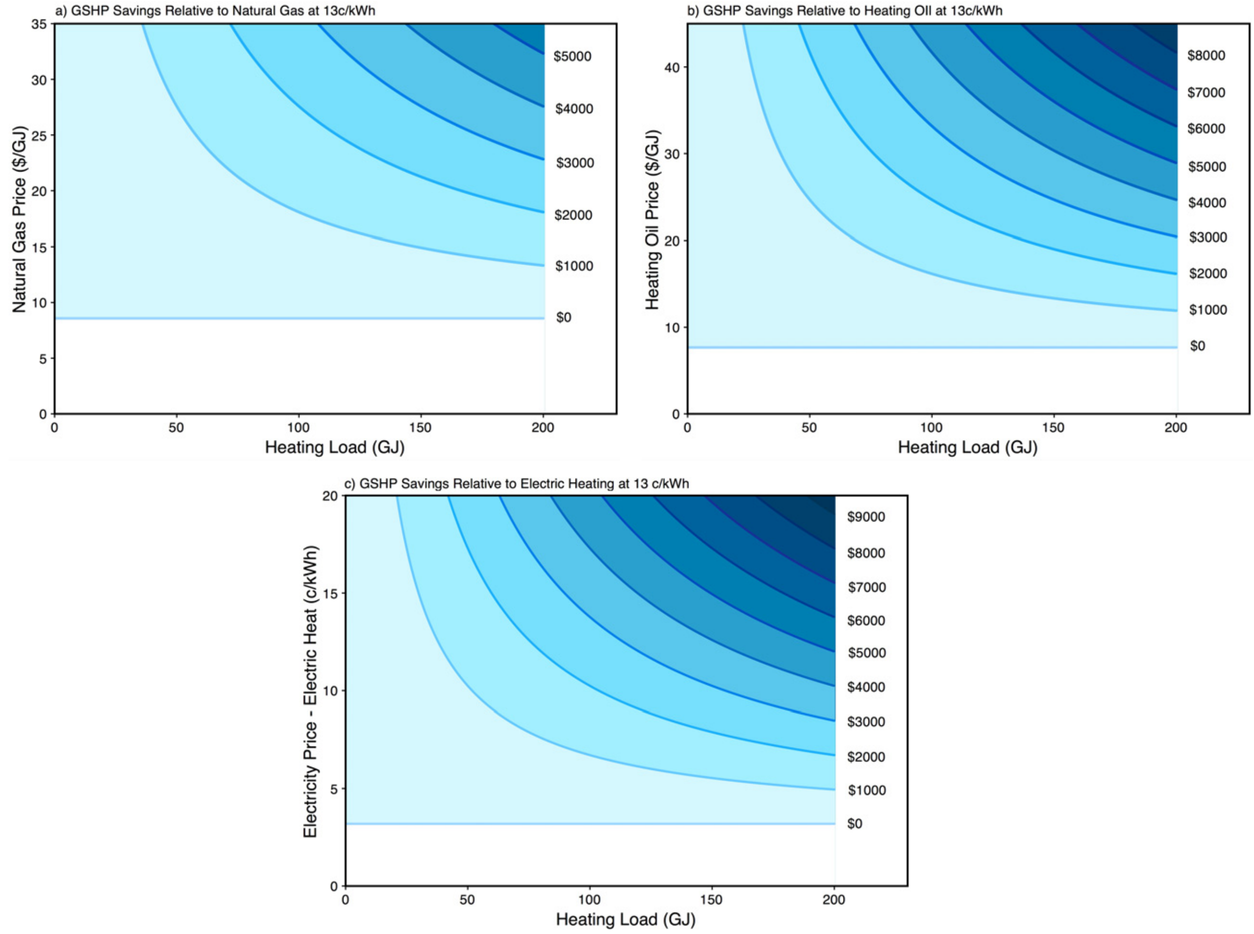

Figure 6. Annual operational savings of GSHP at electricity prices of 13c/kWh; GSHP becomes feasible at a natural gas price of 8.58 $/GJ, and heating oil costs of 7.67 $/GJ.

of skilled tradespersons, (4) effective policy direction has yet to facilitate increased adoption of this technology, and (5) economies of scale and scope are rarely exploited.

Since larger homes (or commercial and institutional buildings) are associated with higher heating loads, GSHP can provide significantly larger environmental and financial benefits for these installations. A policy option that could be explored in these instances is the introduction of emission standards on a per home basis, which would require owners of larger homes to significantly reduce their emissions through technologies such as GSHP. Furthermore, an overdue paradigm shift involves the recognition that one of the long-term benefits of this technology (i.e. after a GSHP system achieves payback) is that it generates a significant annual 'return on investment'.

High satisfaction rates, GHG emission reductions, and economic feasibility attest to this technology's viability. Tapping into the environmental and fiscal benefits that GSHPs offer is only possible if government policies and business strategies affecting homeowners' fuel choices reflect preference toward technologies with long-term environmental and economic benefits.

Acknowledgments

This research was also made possible through support from the Climate Decision Making Center (CDMC) located in the Department of Engineering and Public Policy. This Center has been created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University. The authors gratefully acknowledge financial support from Free Energy Solutions Inc. and the Natural Sciences and Engineering Research Council of Canada (NSERC). We sincerely thank Lynn Mueller for sharing his expertise and insights with us during the research process.

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