Effect of Residential Ground Source Heat Pump System Design on CO_2 Emissions in Sweden

Jeffrey D. Spitler, PhD, PE
Fellow ASHRAE

Mei Yung Wong
Student Member ASHRAE

Signhild E.A. Gehlin, PhD
Member ASHRAE

ABSTRACT

Residential ground source heat pump systems in heating-dominated climates often incorporate auxiliary electric resistance heating. This is utilized for some portion of the winter heating – it could be intended only for rare, emergency use, or it could be intended to provide a significant fraction of the annual winter heating. In Sweden, where a typical ground source heat pump provides both heating via radiant panels and domestic hot water, the auxiliary electric resistance heating is activated when there are high domestic hot water loads or when ground heat exchanger temperatures fall to low values. Two design parameters have a strong effect on when and how much the electric resistance heating is used: ground heat exchanger size and heat pump capacity (i.e. of the vapor compression cycle.). In turn, the resulting pattern of electric resistance heating and electricity consumption has a significant influence on emissions associated with electric power generation. This influence may be more significant than might be inferred from simple annual emissions factors – the highest heating requirements occur when it is very cold and that is coincident with when Sweden imports electricity that may be produced with fossil fuels.

A range of system designs with different ground heat exchanger designs and heat pump capacities serving a typical renovated 1940s-era house in Stockholm are simulated to estimate hourly electricity consumptions. A range of data sets and models for estimating CO_2 *emissions are applied and both the effect of the system design and the various assumptions used in the emission analysis are investigated.*

INTRODUCTION

Ground source heat pumps (GSHP) are commonly used in about a fifth of all single-family houses in Sweden for space heating and domestic hot water (DHW) production. This paper presents an investigation of the effects of GSHP system design on CO_2 emissions due to manufacturing, installation, and operation. The emissions due to operation are dependent on both the amount of electricity consumption and its distribution over the year – as the electricity generation mix varies over the year, the resulting CO_2 emissions per unit of electricity consumption also vary. Much of Sweden's electricity production comes from hydro and nuclear power, both of which have relatively low CO_2 emissions. (Note both hydro and nuclear power have non-zero CO_2 emissions due to manufacturing of equipment, construction, etc.) The remaining energy is produced from other renewable resources such as wind, biomass, etc., and a small fraction of fossil fuels. Therefore, most of the production within Sweden has relatively small CO_2 emissions. However, Sweden imports electricity from other countries during peak heating in wintertime and the main sources of electricity production in some of these countries (Denmark, Germany, Finland and Poland) are fossil fuels, which tends to increase the CO_2 emissions of the Swedish over all electricity mix. So, the degree to which electricity consumption of GSHP system coincides with peak electricity demands is of some interest. This paper goes beyond annual emission factor approaches to look at monthly distribution of electricity consumption, power generation, and resulting emissions for a range of GSHP system designs.

Jeffrey D Spitler is a professor in the School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Oklahoma.
Mei Yung Wong is a student in the School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Oklahoma.
Signhild Gehlin is a technical expert at the Swedish Centre for Shallow Geothermal Energy, Lund, Sweden.

METHODOLOGY-ELECTRICITY CONSUMPTION

This paper extends the results of a previous paper (Gehlin and Spitler 2014) which investigated electricity consumption for a renovated 1940s era house in middle Sweden. Domestic hot water (DHW) loads are taken from the Swedish Energy Agency (Energimyndigheten 2009) Modeling of the heat pump and ground heat exchanger are briefly described below. A total of 121 combinations of borehole depth and heat pump sizes were simulated to determine hourly electricity consumption. The key new contribution, calculation of emissions using several different approaches, is described in detail in the next section.

Heat Pump Model

The residential GSHPs used in Scandinavia have several key differences from heat pumps commonly used in North America. A key feature is the integrated DHW generation and storage, where there is a double walled DHW tank within the heat pump unit storing 160-200 liters (42-53 gallons) of hot water. No desuperheater is typically used and the water is heated with hot water coming from the heat pump. Other features include non-reversible heating only, fluid to water distribution, back up electric resistance immersion water heater and a user controlled setpoint for internal controls with priority given to DHW heating, as described in detail by Gehlin and Spitler (2014).

The heat pump model used here implements these features where DHW heating loads are met first and any excess capacity of the pump goes into building heating. If the heat pump does not cover the full capacity required, the electric resistance immersion water heater will be used and it is specified such that all the loads are met. This model is a quasi-steady state model and thus assumes that the DHW heating loads that occur in any hour are met that hour.

Ground Heat Exchanger Model

Ground heat exchangers in Scandinavia are commonly un-grouted, groundwater-filled closed loops, using a single U-tube. The borehole is drilled in hard crystalline rock with high groundwater level and the U-tube is suspended in the borehole. The groundwater is protected from surface pollution by a steel casing on the upper borehole (about 6m or 20ft). The ground heat exchanger model used was described by Yavuzturk and Spitler (1999) and several validations have been previously described, e.g. Gentry et. al. (2006).

Description of Test Cases

To examine the effect of system design on electricity consumption, 121 combinations of heat pump size and borehole depth are simulated. The heat pump capacity varied from 5-15 kW (17,060-51,180 Btu/hr) in increments of 1kW (3412 Btu/hr) and the borehole depths varied from 100-300m (328-984 ft) in 20m (65.3 ft) increments. For each case, the simulation was done for a five year period and results from the fifth year were used to determine the electricity consumption and emissions.

Weather Data

Building heating loads were generated with Energy Plus for both a typical weather year from the International Weather for Energy Calculations (IWEC) data (ASHRAE 2001) and the actual 2012 weather. One reason for using actual 2012 weather data is that better emissions data are available for 2012, and since one of our approaches involved using actual monthly distributions of electricity production sources, it seemed most appropriate to use loads calculated for that particular weather year. The 2012 heating loads are about 9% higher than the IWEC heating loads. However, as the results from both the typical weather year and 2012 are similar, we only present the results from the typical weather year.

METHODOLOGY-EMISSIONS

In this section, we describe the approaches used to determine the annual and life cycle emissions for the 121 different GSHP system designs. For annual emissions, previous studies, e.g. Saner et al. (2010), have taken a relatively simple approach, using an annual distribution of electricity production sources in a given country. If CO_2 emissions per kWh are assigned to each electricity production source, an overall emissions factor in kg of CO_2 per kWh of electricity can be calculated as a weighted average. This is then multiplied by the annual electricity consumption to estimate the annual emissions. We will refer to this approach as the annual emissions factor approach.

A possible problem with the annual emissions factor approach is that it neglects the time-varying distribution of electricity production sources. It seems likely that Swedish GSHP systems tend to switch to electrical resistance heating under peak heating load conditions at the same time as national electricity consumption peaks, requiring import of power with higher CO_2 emissions. To analyze this problem more fully, data on how the electricity production sources change with time are needed. Ideally, this data would be very granular - hourly or shorter time steps. Furthermore, as the electricity production mix depends on weather, it seems appropriate that either a model would be used to match up typical electricity production mix to weather conditions, or heating loads would be calculated for the actual weather data that led to the actual electricity production mix.

Alas, this ideal situation does not exist! The best available data are available on a monthly time step, and have only been available since 2010 from the European Network of Transmission System Operators for Electricity (ENTSO-E 2013). Also, the electricity production mix does not depend only on the current weather conditions, but also such difficult-to-correlate factors such as rainfall in the previous months, scheduled and unscheduled maintenance, etc.

Therefore, in addition to the annual emissions factor approach, we have developed several approaches that make use of the available monthly data. We concede that these approaches are still fairly coarse; however, we are not aware of any previous studies of annual emissions that have gone into this much detail, and so are breaking some new ground.

This section covers first the annual emissions factor approach, then a monthly emissions model that we developed for estimating monthly CO_2 emissions based on regressions of power generation sources to monthly mean air temperatures, based on September 2011- August 2013. An alternative approach is to use 2012 heating loads combined with 2012 monthly power generation mixes. Finally, we discuss methods that we used for determining emissions due to manufacturing of equipment, borehole drilling, and installation of ground heat exchangers.

Power Generation Emissions

Monthly power generation source data for Sweden from September 2011-August 2013 were obtained from the European network database (ENTSO-E 2013). Over 2/3 of Sweden's electrical energy production comes from hydro and nuclear. The exports were subtracted from the total production and the imports were added to get the total consumption. In order to get a detailed breakdown of import sources, the production mix from each import country is determined. Applying the percent distributions to the respective imports, the amount of electricity imported that is produced from each source can be determined. This is incorporated into the final consumption mix where the percent breakdown accounts for both the exports and imports.

Knowing the distribution of power generation sources, we estimated the emissions based on published data. We developed two models or sets of emission factors that give the life cycle CO_2 production per kWh of electricity production. ("Life cycle" emissions here include emissions due to manufacturing of the heat pump and ground heat exchanger components, drilling the borehole, and producing the electricity required to operate the heat pump.) The first set developed is labeled "PSEF-A" in Table 1. Later, we found the Dones, et al. (2007) publication that gave a more detailed explanation; this set of emissions factors is labeled "PSEF-B" in Table 1. Which is "right"? It's impossible to know the exact life cycle emissions from the actual sources; we use the two models here to help test the uncertainty in using such published data.

Table 1. Two Emission Factor Data Sets

Production Source	PSEF-A Emissions* (kg CO_2/kWh)	PSEF-A Reference	PSEF-B Emissions* (kg CO_2/kWh)	PSEF-B Reference
Hydro	0.0115	Pehnt (2006)	0.006	Dones et al. (2007)
Nuclear	0.066	Sovacool (2008)	0.011	Dones et al. (2007)
Lignite	1.375	Dones et al. (2002)	1.280	Dones et al. (2007)
Coal	1.005	Gangnon et al. (2002)	0.850	Dones et al. (2007)
Gas	0.443	Gangnon et al. (2002)	0.619	Dones et al. (2007)
Oil	0.778	Gangnon et al. (2002)	0.590	Dones et al. (2007)
Unattributed Fossil Fuels	0.9	(Average of fossil fuel emissions)	0.853	(Average of fossil fuel emissions)
Wind	0.01	Pehnt (2006)	0.014	Dones et al. (2007)
Biomass	0.028	Pehnt (2006)	0.028	Pehnt (2006)
Solar	0.013	Pehnt (2006)	0.013	Pehnt (2006)
Unattributed Renewables	0.014	(Average of renewable sources emissions)	0.025	(Average of renewable sources emissions)

* Emission factors may be converted to lbm CO_2/kWh by multiplying by 2.2.

Power Generation Weighted (PGW) Emission Factors

Table 1 gives emission factors for each source of electricity production. It is convenient to weight these by the fraction of each power source so as to give a power generation weighted (PGW) emission factor that may be directly applied to the energy consumption. The key remaining question is "what time period would be appropriate over which to determine and apply the emission factors?" Past studies have used annual emission factors that treat every kWh of electricity used as the same regardless of the actual distribution of power generation sources. We also introduce monthly emission factors below.

Table 2 shows a range of annual PGW emission factors, starting with one from the literature. The next three rows show annual emission factors computed from ENTSO-E data with either PSEF-A or PSEF-B. These are calculated by simply taking the total annual production from each source, applying either PSEF-A or PSEF-B to find the total emissions and dividing by the total annual consumption to obtain emissions. However, all of these approaches ignore the varying distribution of power generation sources over the year. For comparison purposes, the last row shows factors that are weighted by the monthly electricity consumption for the system with the 10 kW heat pump and the 200 m deep borehole; these values only deviate slightly from the annual factors that ignore the distribution of consumption. One interesting feature, confirmed in the next section, is that the annual emission factors vary widely. During 2009-2010 (Energimyndigheten 2013) there were some major repairs being done on the Swedish nuclear reactors, and full capacity was not reached until 2012. This meant lower nuclear power production and increased need for alternative power production such as coal and oil with additional CO_2 emissions.

Table 2. Annual PGW Emission Factors for Sweden

Model	Emission Factor (kg CO_2/kWh) PSEF-A	Emission Factor (kg CO_2/kWh) PSEF-B
Swedish Electricity Grid Mix, Saner et al. (2010)	0.105*	
ENTSO-E 2010	0.111	0.088
ENTSO-E 2011	0.082	0.060
ENTSO-E 2012	0.061	0.039
ENTSO-E 2012, Consumption-weighted	0.063	0.041

*Saner et al. (2010) use neither PSEF-A nor PSEF-B, but use an earlier set of data, circa 2004.

The ENTSO-E database for 2010-2012 was used to calculate monthly PGW emission factors using PSEF-B, as shown in Figure 1. The monthly PGW emission factors vary widely from year to year. One approach to applying these factors is to use them for a specific year with loads generated for a specific year – we did this for 2012. However, this has the limitation of not being generalizable to future years.

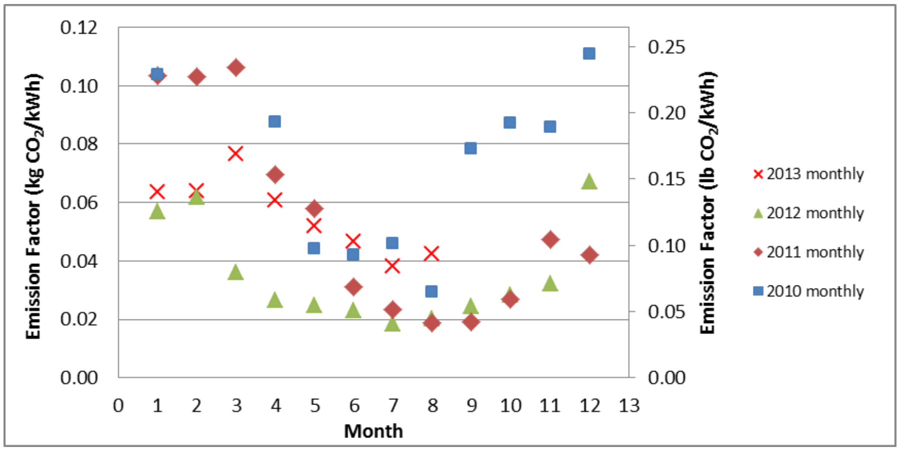
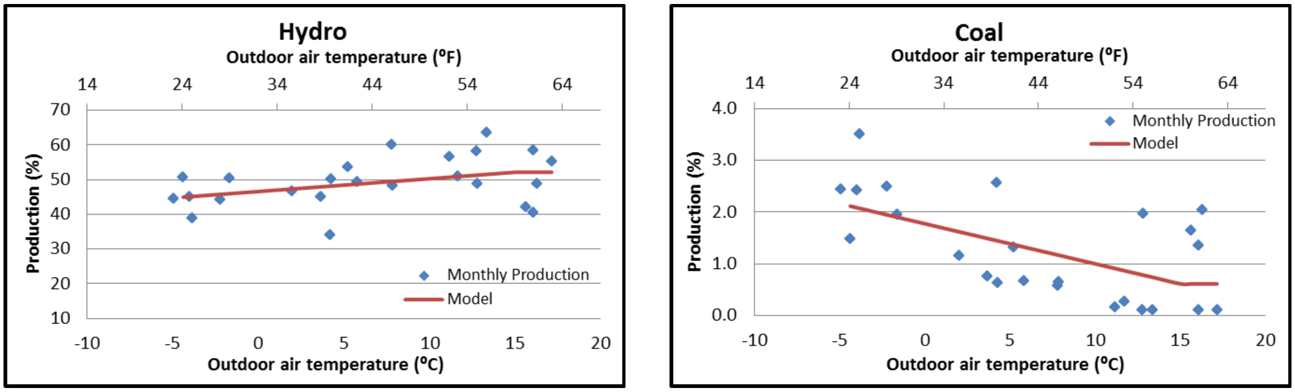


Figure 1 Monthly Emission factors for each month in Sweden in 2010-2013

To address this limitation, we have developed a "power generation mix" (PGM) model that predicts the monthly fraction of each electricity production source with the intention that it could be suitable for use with a simulation of a building using a typical weather year. Given the limited amount of historical data, we settled on a very simple model – the fraction of power generated by each source is fit as a piecewise linear function of mean monthly air temperatures. Two samples are shown in Figure 2. These fits clearly show that there are more factors influencing the source fractions than just the mean monthly air temperature.



(a) Hydro Power Production (b) Coal Power Production

Figure 2 Linear fit example for (a) Hydro Power Production and (b) Coal Power Production

Initial Emissions

The emissions due to manufacturing of the heat pump and drilling of the borehole were modelled according to the heat pump capacity and borehole size. Heat pump weights given by the manufacturer were fitted as a function of heat pump capacity. The percentage weight for each component (Nibe 2012) and corresponding emission factors, summarized in Table 3 were then used to determine the initial emissions due to manufacturing. These values were normalized to a per annum basis by dividing them by the estimated service life of 20 years. (USDoE 2011) Similarly, emission factors were estimated for drilling the borehole and for manufacturing the various components, as summarized in Table 4. The resulting emissions for any borehole length can then be determined and are divided by an estimated life of 50 years. (US DoE 2011)

Table 3. Components of a typical Swedish Heat Pump

Material/ Component	Percent of total mass (%)	Estimated emissions (kg CO_2/kg mass)	Material/ Component	Percent of total mass (%)	Estimated emissions (kg CO_2/kg mass)
Stainless Steel(1)	76.5	3.0	ABS-Plastic(1)	2.2	3.8
Iron(1)	2	1.5	Electronics(2)	2	3.2
Copper(1)	4	2.4	Dye(3)	0.5	3.1
Brass(1)	2	4.1	Wood(3)	3	0.7
Aluminum(1)	0.2	9.0	Propylene Insulation(3)	2.2	3.4
Zink(1)	0.2	1.9	Refrigerant (HFC-132a) (4)	1.3	7.5
Ester Oil(1)	0.8	2.9			
Rubber(1)	0.8	3.9	Circulation Pump(1)	-	2.2

(1) Reference: Eriksson and Göräng (2013)
(2) Assuming Eriksson and Göräng (2013) data for 25% copper, 25% Stainless steel and 50% ABS Plastic
(3) Reference: Hammond and Jones (2011)
(4) As no emissions data for production of R407c could be located, emission data for HFC-132a (Campbell and McCulloch 1998) is used.

Table 4. Borehole Components

Material/ Component	Mass per borehole (kg) (lb)	Mass per unit length of borehole (kg/100m) (lb/100ft)	Emissions (kg CO_2/ kg mass)	Reference
U tube pipe	-	55.3 (37.2)	1.8	Eriksson and Göräng (2013)
Propylene Glycol	-	121.8 (81.8)	3.2	Archer Daniels Midland Company (2013)
Steel pipe	48.9 (107.8)	-	3.0	Eriksson and Göräng (2013)
Concrete	92.8 (204.6)	-	0.1	Hammond and Jones (2011)
Horizontal Piping	2.2 (4.9)	-	1.8	Eriksson and Göräng (2013)
Pipe Insulation	1.0 (2.2)	-	4.3	Eriksson and Göräng (2013)
Well top	0.5 (1.1)	-	1.5	Eriksson and Göräng (2013)
Connection	0.2 (0.4)	-	1.9	Eriksson and Göräng (2013)
End weight	10.5 (23.1)	-	2.2	Eriksson and Göräng (2013)
Diesel	-	250 (168)	3.5	Eriksson and Göräng (2013)

RESULTS

Annual emissions were calculated for all 121 combinations of borehole depth and heat pump capacity. To first illustrate the difference in the different calculation procedures, Figure 3 shows annual emissions calculated for an intermediate case – 10 kW (34 MBTUH) nominal capacity heat pump with a 200 m (656 ft) deep borehole for nine different evaluation options. The total heating provided is 26,187 kWh with a total electricity consumption of 9241 kWh. The first two, both of which use the PGM model to estimate the amount of electricity utilized from each source, show the sensitivity to the different sets of PSEF; PSEF-B gives an estimate that is about 25% lower. Comparing the 3rd and 4th values to the 1st and 2nd shows the difference between using the PGM model and using the actual 2012 monthly power generation mix. As can be observed in Figure 1, 2012 had relatively low emission factors so using those values represents approximately a 25% decrease compared to the PGM model. Columns 5-7 represent annual emission factors based on actual power sources; these calculations do not include changing electricity production mix over the year. The differences from year-to-year can be quite significant. Finally, the last column represents use of a published annual emission factor. There is more than a factor-of-two difference between the lowest estimate and the highest estimate – so the power generation data and method for calculating the emissions represent a significant source of uncertainty.

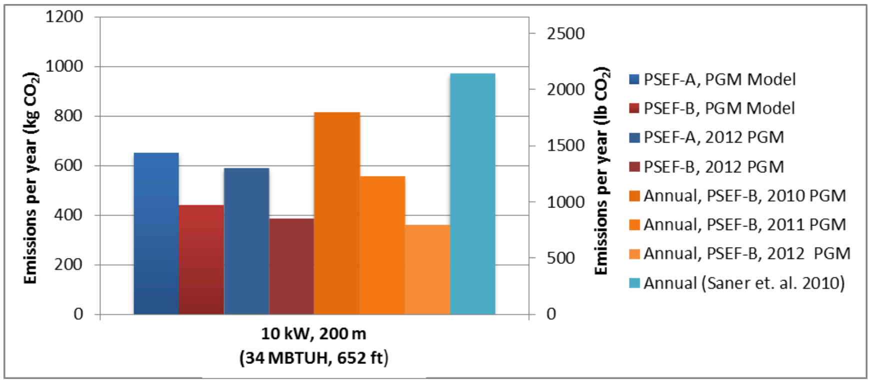


Figure 3 Comparison of different approaches for calculating annual emissions

However, to make a comparison of all 121 combinations of heat pump sizes (between 5 kW and 15 kW) and borehole depths (100-300m) we decided to use PSEF-B with the PGM model; heating loads are calculated with the IWEC weather year. (Emissions due to loads calculated with the actual 2012 weather year have the exact trends and vary by about 3-5% from those due to loads calculated with the IWEC weather year.) Annualized emissions due to manufacturing the heat pump, drilling the borehole, and installing the U-tube are included in the annualized totals. Figure 4(left) shows the annualized emissions plotted against the first cost. As found by Gehlin and Spitler (2014) when comparing the normalized cost to the first cost, the results form a Pareto front – a family of optimal solutions that give the best combinations of the borehole lengths and heat pump sizes. Figure 4(right) shows the distribution of emissions more clearly.

The total emissions are calculated to include the initial annualized emissions from the heat pump and borehole components and the annual emissions from operation of the heat pump. The emissions from operation are based on the PSEF-B and the PGM model. Total annualized emissions are plotted against nominal borehole load, first cost, normalized cost and a comparison of emissions of the three base cases is made.

Figure 5 shows the contributions of the annual emissions and the initial emissions to the annualized emissions. As expected, as the initial emissions increase due to a larger heat pump and deeper borehole, the annual operation emissions decrease due to more efficient operation. The initial emissions are significant enough to be accounted for in the analysis.

CONCLUSIONS AND RECOMMENDATIONS

From the standpoint of CO_2 emissions in Sweden, the larger heat pump and deeper borehole gives significantly improved performance. As shown by Gehlin and Spitler (2014) these same combinations also give the lowest life cycle cost, but have a significantly higher investment cost. In addition, this study has illustrated some of the limitations in available emissions data – better time resolution and more accurate source emissions data would be highly desirable, as would further development of models that could be used to predict time-varying emissions for typical weather years.

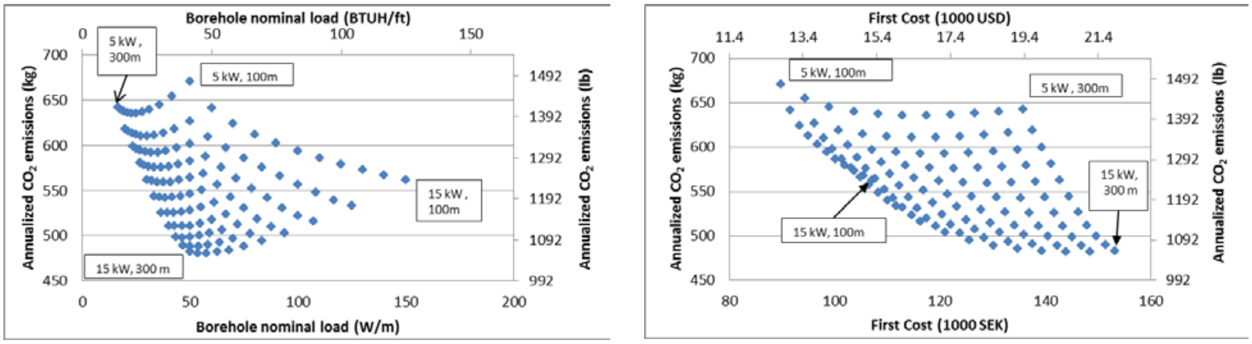


Figure 4 Annualized CO_2 Emissions vs. First Cost and Borehole Nominal Load

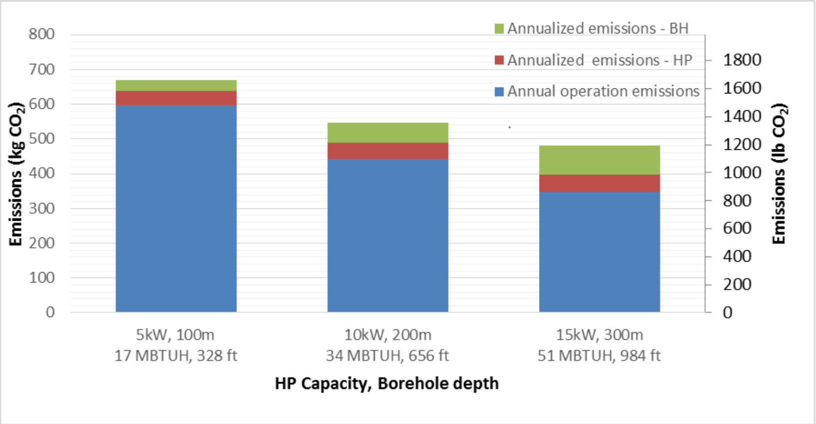


Figure 5 Comparison of annualized initial CO_2 emissions and annual CO_2 emissions from operation

REFERENCES

Archer Daniels Midland Company. 2013. Life Cycle Analysis of Propylene Glycol. http://www.adm.com/en-US/products/evolution/Propylene-Glycol/Pages/Life_Cycle_Analysis.aspx [Consulted 28 November 2013]

ASHRAE. 2001. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM, Atlanta: ASHRAE

Campbell N.J. and A. McCulloch (1998). The Climate Change Implications of Manufacturing Refrigerants: A Calculation of 'Production' Energy Contents of Some Common Refrigerants. *TransIChemE* 76B.

Dones R., C. Bauer, R. Bolliger, B. Burger, T. Heck, and A. Röder. 2007. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. Ecoinvent report No. 5, Paul Scherrer Institut, Switzerland.

Dones R., T. Heck, and S. Hirschberg. 2003. Greenhouse gas emissions from energy systems: Comparison and overview. PSI Annual Report 2003 Annex IV, Paul Scherrer Institut, Villigen, Switzerland.

Energimyndigheten (Swedish Energy Agency). 2013. Energy in Sweden 2012. Available online at: http://www.energimyndigheten.se/Global/Engelska/Facts%20and%20figures/Energy_in_sweden_2012.pdf

Energimyndigheten (Swedish Energy Agency). 2009. Mätning av kall- och varmvattenanvändning i 44 hushåll. (Measurement of cold and hot water usage in 44 households). ER 2009:26. In Swedish.

Eriksson, M. and M. Görang. 2013. Kontorsskyla - Kan borrhålskyla ersätta en kylmaskin? M.S. Thesis. Mälardalens Högskola Eskilstuna Västeras. In Swedish.

European Network of Transmission System Operators for Electricity (ENTSO-E). 2013. https://www.entsoe.eu/ [Consulted 11 July 2013, 6 December 2013]

Hammond G. and C. Jones. 2011. Inventory of Carbon and Energy (ICE) Version2.0 Summary Tables. Univ of Bath, UK.

Gagnon, L., C. Bélanger, and Y. Uchiyama. 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy* 30(14): 1267-1278.

Gehlin, S. E. A. and J. D. Spitler 2014. Design of Residential Ground Source Heat Pump Systems for Heating Dominated Climates - Trade-Offs Between Ground Heat Exchanger Design and Supplementary Electric Resistance Heating. ASHRAE Conference Paper, January 2014.

Gentry, J.E., J.D. Spitler, D.E. Fisher, X. Xu. 2006. *Simulation of Hybrid Ground Source Heat Pump Systems and Experimental Validation*. Proceedings of the 7th Int. Conf. on System Simulation in Buildings, Liège, Belgium. Dec. 11-13, 2006

Nibe. 2012. Bygg-/Miljövarudeklaration. Nibe F1245-2. Varugrupp F1245.

Pehnt, M. 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy* 31(1):55-71.

Saner, D., R. Juraske, M. Kübert, P. Blum, S. Hellweg and P. Bayer 2010. Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable and Sustainable Energy Reviews* 14(7): 1798-813.

Sovacool, B. K. 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy* 36(8):2950-2963.

USDoE. 2011. Guide to Geothermal Heat Pumps. *Energy Efficiency and Renewable Energy DOE/EE*-0385.

Yavuzturk, C., J.D. Spitler. 1999. A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers. ASHRAE Transactions. 105(2):475-485.

Spitler, J.D., M.Y. Wong, and S.E.A. Gehlin. 2014. *Effect of Residential Ground Source Heat Pump System Design on CO_2 Emissions in Sweden*. ASHRAE Annual Conference, Seattle, Washington. June 28-July 2.