Life Cycle Assessment of a Non-Conventional Deep Insulated Single Hole (DISH) Ground Source Heat Pump and Comparison with Conventional Heating, Ventilation and Cooling Methods

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ABSTRACT

Within the heating, cooling and ventilation (HVAC) sectors, ground source heat pumps (GSHPs) offer a potentially low-fuel, low-carbon solution to the impending global energy crisis. This study investigates the Deep Insulated Single Hole (DISH) system, an unconventionally deep (300m+) GSHP, and its potential for reduced GHG emissions compared to other HVAC scenarios. A comprehensive "cradle-to-grave" life cycle analysis is implemented using SimaPro software to examine DISH emissions in Wisconsin. Assuming the current Wisconsin electrical grid of 5.5% renewables, heating and cooling loads of a 185m^2 residence, a COP of 4 and a 25-year lifetime, an average of 272 metric ton CO_2 equivalent emissions is calculated for DISH. Top contributors are heat-exchanger operation (93.3%), borehole drilling (2.4%), and circulation pump operation (1.5%). This amounts to GHG savings of 10% and 19% over vertical and horizontal GSHPs and 27% over natural gas systems. Sensitivity analyses determine that a COP of 5 could save 38% and a 50% renewable grid could save 68% GHG emissions over natural gas. As fossil fuel use dwindles and the grid becomes cleaner, DISH may emerge as the least carbon-intensive HVAC method. Since this is an order of magnitude assessment, system uncertainties motivate future research.

1. Introduction

1.1 Energy and HVAC

The world is at the dawn of an energy transformation. As the discovery of new resources is dwindling, energy demand is increasing due to expanding population and developing nations. From 2000 to 2010, world energy consumption increased by 23 percent and it is projected to grow by 56 percent between 2010 and 2040 (EIA 2013). Meanwhile there is a growing concern surrounding warming of the earth due to greenhouse gas (GHG) emissions from fossil fuel energy sources. Though carbon dioxide (CO2) is naturally emitted through the carbon cycle, fossil fuel burning has been directly tied to the exponential atmospheric increase since the Industrial Revolution (US DoS 2007). Fossil fuels coal, petroleum, and natural gas currently account for 80% of world energy use and 77.5% in the US. CO2 concentrations are at a record high of 397.23 parts per million (CO2 Now 2013) and at the current growth rate the consumption of fossil fuels alone is projected to increase emissions by 46 percent by 2040 (EIA 2013). Extensive climate research has demonstrated the connection between increased GHG concentrations and global temperature rise, shifting snow and rainfall patterns, extreme climate events, among other effects (US EPA 2013). The superposition of these issues and concerns has created urgent global pressure to develop and integrate innovative and renewable energy solutions into all sectors of society.

The heating and cooling of buildings comprises a substantial portion of world energy use and thus is an important focus area. In 2009, residential energy use accounted for 22% of total annual energy consumption in the United States (US EIA 2013). Since the US alone consumes 19% of the world's energy, this accounts for 4% of global consumption. Heating ventilation and cooling (HVAC) comprise 48% residential energy consumption in the US and 57% total in Wisconsin as shown in Figure 1. Including water heating, these figures increase to 66% nationally and 72% statewide.

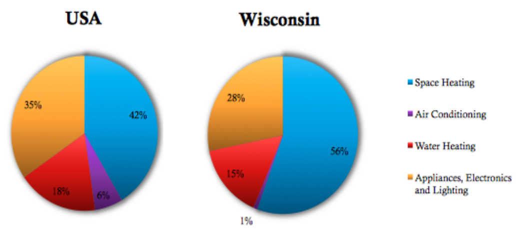

Figure 1: Residential energy consumption by end-use in the United States and in Wisconsin in 2009, adapted from US Energy Information Administration, Annual Energy Review 2013

In the United States, 55.4% of HVAC is attributed to natural gas (EIA 2009). This is due to the widespread use of natural gas furnaces for space heating. Though typically the least expensive option (EIA 2013), natural gas is a fossil fuel and thus contributes to global warming. In light of the energy crisis, heating and cooling solutions with lower GHG emissions are essential. This study focuses on the emissions and practicality of ground source heat pump (GSHP) systems as an alternative form of HVAC.

1.2 Introduction to Ground Source Heat Pumps (GSHP)

Ground source heat pumps (GSHP), also known as Geothermal Heat Pumps, GeoExchange, Thermal Exchange, or Energy Exchange (Dickie 2010), provide a potential energy solution for heating and cooling buildings. Though only contributing a mere 0.2% to HVAC, GSHP use is predicted to increase exponentially in upcoming decades (Saner et al. 2010). Rather than directly consume fuel or electricity, GSHPs use the earth as a heat source and heat sink and thus can be applied even in areas with low geothermal gradient. Depending on location, the temperature beneath the top six meters of the earth's crust remains relatively constant at 50-60ºF. The first GSHPs were open-loop system, which send groundwater directly to a heat exchanger, but more common today are closed-loop GSHPs (Rafferty 2000). Horizontal systems circulate fluid through horizontal pipes in trenches at least five feet below the ground. Horizontal systems work well for small heating and cooling loads and large plots of land. Since drilling is not required, horizontal systems often have a low upfront cost. Vertical GSHPs consist of a hole bored vertically into the ground, typically 80 to 110 m (260 to 360 ft) deep (Natural Resources Canada 2009), with "U-tube" pipes inserted down. Borehole drilling increases the cost but allows for greater heat transfer in smaller land areas.

In a closed-loop system a carrier fluid, typically water mixed with antifreeze, circulates through pipes in a borehole or trench in the ground to take advantage of this essential heat bank. Low-grade heat is transferred from the ground to the fluid for heating during the winter and vise versa during the summer. Heat is transferred through a heat exchanger from the carrier fluid to a refrigerant, which is compressed and evaporated in a heat pump to extract heat for the building in the form of hot water or warm air. Electricity input is needed only to "move heat" from the ground to the residence using heat exchangers and circulation pumps.

GSHPs operate according to the basic thermodynamic principles of heat transfer. Complex models and equations exist to determine the length of a borehole necessary for a functional GSHP to provide a specified quantity of heat transfer (ASHRAE 2007). To ease calculation, the following simplified linear model developed from Fourier's Law is used to determine heat transfer $q$in a borehole (Ingersoll et al. 1954):

$$q = L \times (t_g - t_w) \times \lambda \text{ [W]} \quad (1)$$

where L is the borehole length [m], t_g the ground temperature [K], t_w the temperature of the water entering the ground [K] and λ the thermal conductivity surrounding the borehole [W/mK]. Ground temperature is taken to be constant in this approximation. Higher thermal conductivity, longer length and elevated ground temperatures thus yield increased transfer of energy from the ground.

In GSHPs and any typical refrigeration system, energy efficiency is measured by the coefficient of performance (COP) and the energy efficiency ratio (EER). COP is the ratio of a system's output energy to its input energy. Conventional ground source heat pumps have a COP of 3-4 i.e. an efficiency of 300-400%, far greater than the theoretical 100% limit for all other sources of HVAC. COP is calculated using power or energy with the following formula (Dickie 2010):

$$\text{COP} = \frac{\text{total heating capacity [BTU/hr]}}{\text{power input[W]} \times 3.412\text{[BTU/hrW]}} = \frac{e + q}{e} \quad (2)$$

where e is the electricity input energy and q is the heat transferred from the ground. During the life cycle of a GSHP, electricity input e is needed only to run the compressor within the heat exchanger and the circulation pumps. While COP is used to define efficiency during heating, EER is a term specifically applied to cooling (Dickie 2010). It is defined as:

$$\text{EER [BTU/hrW]} = \frac{\text{total cooling load [BTU's/hr]}}{\text{power input [W]}} \quad (3)$$

Typically, high-enthalpy systems such as Enhanced Geothermal Systems (EGS) are drilled very deep and used to generate electricity. GSHPs, on the other hand, are low-enthalpy, used only for HVAC, and range from 23 to 150 m (75 to 500 ft) deep (Natural Resources Canada 2009). For residential use boreholes are rarely deeper than 100 m, since borehole depth is limited by the drastically increased difficulty and cost of drilling into bedrock layers. The Deep Insulated Single Hole (DISH) system, proposed by the University of Wisconsin Madison, is an unconventionally deep (~300m) vertical ground source heat pump that provides an elevated entering water temperature (EWT) to a closed loop heat exchange system (Tinjum 2013). This high temperature eliminates the need for antifreeze and allows the use of pure water as the ground fluid. The DISH system is hypothesized to have a high COP due to elevated thermal conductivity in the bedrock layers and an increased temperature due to exposure to the geothermal gradient. Thus, it offers potential advantages over conventional vertical loops, horizontal loops and natural gas heating systems for HVAC applications. Though cost is an important factor, this study aims to explore and quantify potential environmental advantages in terms of greenhouse gas (GHG) emissions over the entire lifetime. Drilling and electricity use are expected to be the key emitters, but the exact emission balance between drilling and electricity use is what motivates this study.

1.3 Introduction to Life Cycle Analysis (LCA)

Accurately assessing environmental impact requires a developed and widely accepted methodology. Life Cycle Analysis (LCA, also known as Life Cycle Assessment) was developed in the early 1990s and has become an increasingly popular methodology to evaluate environmental impacts of a product across its entire life from material extraction to end of life, i.e. from “cradle-to-grave” (PRé Consultants 2010). In an age of “greenwashing” where the word “sustainability” is casually tossed around, LCA uses real scientific analysis as method of judging product’s environmental impact rather than assumptions based on marketing or historical evidence. By explicitly defining inputs, outputs, boundaries and assumptions, LCA develops a clear criterion from which to compare products with similar functions.

All LCA’s require of four key phases defined by ISO 14040 and 14044 (Rebitzer et al. 2004). First, the “Goal and Scope” defines parameters and boundary conditions of each study. This section assigns a “functional unit” (FU) to the product as a comparison basis to other products with a similar function. The “Life Cycle Inventory” (LCI) is the data collection stage in which all raw materials and energy processes are defined and linked to emissions and material depletions that will occur. Next, in the “Life Cycle Impact Assessment” (LCIA) LCI results are aggregated and adjusted into “midpoint” and “endpoint” characterization categories in order to understand their environmental relevance. The final LCA stage, “Interpretation”, assesses the significance of the LCIA results in the context of the goal and scope and conducts an uncertainty analysis and sensitivity analyses on the data (PRé Consultants 2010).

Though a wide range of products use LCA, one of its most pivotal implementations is determining the environmental impact of energy sources, or life cycle energy assessment (LCEA). Considering increasing energy demand and the concern over global warming, Global Warming Potential (GWP) is an important characterization category of LCA (Radaal et al. 2011). GWP is considered a midpoint category, typically quantified by GHG emissions using units of “CO2 equivalence” (CO2 eq). Although the predominant atmospheric GHG is carbon dioxide (CO2) (84%), methane, nitrous oxide, carbon monoxide and fluorinated gases contribute significantly (EPA 2013). The CO2 equivalence value of each GHG differs by analysis method.

1.4 Related Work

Since the 1980s, hundreds of studies have been conducted analyzing GHG emissions of energy sources and yielding a wide range of results. The International Panel on Climate Change (IPCC) aggregated these papers and conducted a harmonization of the CO2 emissions for coal, natural gas, petroleum, nuclear, wind, solar, hydroelectric and biogas electricity production (2011). It must be noted that, while fossil fuel sources emit GHGs onsite and renewable sources do not, the emissions considered in LCEAs are both localized and delocalized and are associated with plant construction, operation, uranium mining and milling, and plant decommissioning (Sovacool 2008). Since GSHPs do not directly produce electricity, they were neglected in the IPCC study.

GSHPs have been cited in industry and literature as “renewable energy,” a “green solution” and even “carbon neutral” (Baxi 2013). Though there have been studies on GHG emissions, no extensive LCA background exists to firmly support these claims. A Europe-specific cradle-to-grave LCA on GSHPs found average GHG emissions of 63 metric tons (mt) CO2 equivalent (eq) for a lifetime of 20 years (Saner et al. 2010). This study used the Continental European electricity mix with 0.599 kg CO2 eq/kWh but performed case studies on specific locations. Comparing GSHPs to alternate HVAC sources showed savings ranging from -31% to 88% depending on electrical grid, location, climate and passive cooling capabilities. This study, as well as a large majority of GHSP LCAs, is specific to Europe and thus results cannot be simply extrapolated to the US.

A study from the US Air Force analyzed CO_2 emissions and costs due to the electricity input of GSHPs over a life cycle in all 50 US states and compared these emissions and costs to conventional natural gas AC split systems (Fredin 2009). Average GHG emissions in Wisconsin were 329.5 mt CO2 eq and calculated to emit 21% more than the natural gas system. Though the Air Force study contained Wisconsin-specific data, it considers only CO2 emissions rather than total greenhouse gas emissions and focuses only on the emissions during the operation of the GSHP rather than cradle-to-grave emissions. A third study conducted by the Energy Center of Wisconsin contrasted costs and emissions of GSHPs for five building scenarios in three regions of Wisconsin (Hackle 2010). In a residential scenario, GSHPs demonstrated CO2 savings of 359, 2,323 and 34,900 lbs CO2 eq over natural gas, propane and electricity only configurations. Like Fredin’s study, only electrical input over operation was considered. Other emissions are considered but they are calculated individually rather than in terms of GWP. All these studies agree that GHG emissions vary primarily due to grid composition. However, to date there has been no cradle-to-grave analysis comparing total GHG emissions of unconventionally deep GSHPs to other GSHP configurations in Wisconsin.

2. Materials and Methods

2.1 Goal and Scope

The main goals of this study are as follows:

1. Determine greenhouse gas (GHG) emissions from the Deep Insulated Single Hole (DISH) GSHP system in Wisconsin (note: emissions are NOT localized, but rather attributed to energy processes during life cycle)
2. Compare GHG emissions over the lifecycle of DISH to
    a. a conventional vertical GSHP configuration with three boreholes (VERT)
    b. a conventional horizontal GSHP (HORZ)
    c. a conventional split system natural gas air conditioning unit (NGAC)
3. Determine the top contributors to these emissions

These goals are accomplished by performing a “cradle-to-grave” LCA to trace the energy flows and resources for all stages of the life. Historically, LCAs were conducted using simple equivalence equations. With the addition of many materials and iterative looped processes, it becomes increasingly more complex to trace each step. To ease calculation this LCA is carried out using SimaPro 7.3.3 software, a market-leading LCA software developed by the Dutch company PRé Consultants. Material and energy flows are organized according to the four LCA stages: goal and scope, LCI, LCIA and interpretation. SimaPro has direct links to LCI databases and LCIA methods.

2.1.1 Functional Unit and Site Description

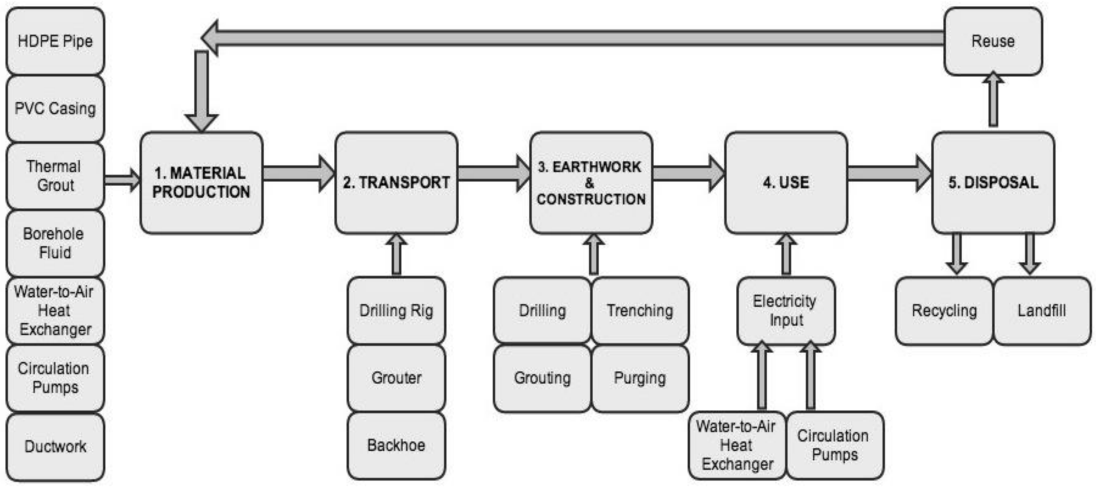

Figure 2: Life-cycle stages of the DISH system from material inputs to disposal and main flows of each unit process.

The life cycle of a GSHP consists of flows into and out of nature and the technosphere defined by the functional unit (FU). The functional unit is the fundamental flow in which all other resource flows relate to, and measures the function of product (PRé Consultants 2010). In this study, the FU is the heat flow required to provide space heating and cooling to a single-family residence in central Wisconsin over a 25 years. The house size is assumed 185m^2, the median size of a single-family residence in the Midwest (US Census 2010). Although the ground loop components are predicted to have a lifetime of at least 50 years and up to 256 years according to some studies (Tarnowski and Baldauf 2006), the heat exchanger and duct system are cited to demand repairs after 25 years. With replacements of aboveground parts GSHPs have the potential for a longer lifetime, but it is standard to assume a worst-case scenario life of 25 years. The site is essentially idealized but modeled around a residence near Grand Marsh, Wisconsin, where UW Madison has recently installed a vertical triple-well system.

There are complex ways to model heating load and heat transfer from GSHP systems on monthly, daily and hourly bases. Adapting heating load data from a similar study using Trane Trace 2000 software, this study assumes a heating load of 48.9 kBTU/hr (14.3 kW) and a cooling load of 43.2 kBTU/hr (12.7 kW) (Fredin 2009). Degree days measure the number of hours per year the GSHP needs to work at full power, both in heating and cooling mode. Wisconsin's climate is heating dominated, and using Fredin's analysis this study assumes 2,548 heating degree days (HDD) and 513 cooling degree days (HDD). Annual energy consumption is assumed to remain constant over the entire lifetime. Thus, over a 25-year lifetime, a total of 1,075,265 kWh of energy is applied to heating and cooling the building.

The geology at the site is assumed overburden soils, Cambrian sandstone and Precambrian granite with depths defined in Table 1 (Clayton 1987). Though not constant across the state, this is a typical stratigraphy of Wisconsin and matches the conditions at our base site in Grand Marsh.

Table 1: Geological strata of the site based on Grand Marsh, WI, and associated thermal conductivity of each rock formation according to Kavanaugh et al. (1997)

Strata	Depth start (m)	Thermal Conductivity* (W/mK)	Average TC* (W/mK)
Overburden Soils	0 - 45	1.5 - 2.4	1.95
Cambrian Sandstone	45 - 115	2.1 - 3.5	2.80
Precambrian Granite	115+	1.9 - 5.2	3.55

* adapted from Kavanaugh (1997)

2.1.2 System Description

The life cycle of DISH consists of five stages: production of all materials in the ground loop and heat exchanger, transportation of materials to the site, earthwork and construction onsite (primarily drilling the borehole), operation and disposal. These stages and main inputs are shown in Figure 2.

To achieve the functional unit, the DISH system is defined in this analysis as a single 1,185 foot deep well with a single HDPE U-tube and water as the carrier fluid. The well is cased in PVC to 60 m (200 ft) and grouted. In heating dominated climates, such as Wisconsin, trenches must be drilled below the deepest annual frost line (42" in Wisconsin), so in our case a 1.5 m (5 ft) trench depth is assumed

(Wisconsin State Climatology Office 2013). The DISH proposal couples a water-to-water heat exchanger with a water-to-air heat exchanger and a buffer tank in order to provide heating and cooling to air, domestic hot water use and radiant floor heating. For simplicity, this study considers only the space heating component of DISH (i.e. water-to-air heat exchanger, fan coils and duct system) and disregards the water heating load (water-to-water heat exchanger, buffer tank and floor coils).

To conduct a comparison, alternative scenarios are selected that fulfill the same functional unit as DISH. First, a triple-well vertical GSHP ("VERT") model is drawn directly from the system at Grand Marsh, with borehole depths of 103 m, 111 m and 148 m. Second, a typical horizontal GSHP ("HORZ") is considered. For simplification pipe length in the horizontal system is taken equal to that in VERT. The trench is assumed five feet deep and 2,000 m in area, the same area as the house. The literature cites average COPs of 3.0 for horizontal GSHPs (Wu et al. 2010) and 3.5 for vertical GSHPs (Hackel 2010), so these values are taken. Heat exchangers and pumps are the same for all GSHPs. Since natural gas accounts for over half of HVAC energy, use a natural gas furnace as the final another alternate scenario. Natural gas only provides heating, so furnaces are coupled with a typical air conditioner to comprise a natural gas air conditioning (NGAC) split system unit.

Though not yet confirmed, the COP of the DISH geothermal system was predicted to be as large as 5 (Tinjum 2013). In order to estimate the electricity inputs of a GSHP, the system's COP and EER must be determined using real-time data or a complete model. A simple linear model is implemented based on equations 1 and 2. Thermal conductivity λ of each system is taken to be the average of each stratigraphic layer normalized over the total length of the borehole. This method gives approximate thermal conductivities shown in Table 2. Assuming the input electricity is less than the heat transfer from the ground, COP is approximately proportional to thermal conductivity. Assuming COPs of 3.0 and 3.5 for the HORZ and VERT systems, the linear trend for DISH is solved to find a COP of 3.9. Considering a constant entering water temperature t_w and greater ground temperature t_g for the DISH system, this value is rounded up to 4. All calculations assume linearity but are sufficient for this study. The EER of each system is assigned a value of 14.4 based on Wisconsin-specific calculations through the Air-Conditioning, Heating and Refrigeration Institute (AHRI) (Fredin 2009). Results are summarized in Table 2.

Table 2: Well depths, thermal conductivity and coefficient of performance assumptions for the three GSHP systems targeted in this study

System	Well Depth (ft)	Avg Thermal Conductivity (W/mK)	COP	EER
HORZ	5	2	3.0	14.4
VERT	337/364/484	2.7	3.5	14.4
DISH	1185	3.3	4.0	14.4

2.2 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) is the data collection stage of LCA. The inventory is composed of inputs to and outputs from nature, the technosphere and the econosphere and defines emissions to air, water and soil (PRé Consultants 2010). In this study input parameters and emission information were gathered from the Ecoinvent 2.2 unit process database, the world's largest and most widely accepted LCI database (Frischknecht and Jungbluth 2007). Unit processes track all materials and sub-processes which compose a process. Data unavailable on Ecoinvent was adapted from two other databases, Industry Data 2.0 and USLCI, as well as published literature and equipment specifications.

In all LCA calculations and every database, unit processes inherently come with uncertainty. This uncertainty is due to reliability, completeness, temporal correlation, geographical correlation, further technical correlation and sample size of data in question (PRé Consultants 2006) and can be modeled on SimaPro. This study assumes lognormal standard deviations of 1.50 for all material production data and an uncertainty of 2.00 for all earthwork, transportation, use and decommission data. This choice, though arbitrary itself, is intended to reflect that a greater number of estimates in a process increases its statistical uncertainty. According to SimaPro uncertainty from technosphere flows is rarely above 2.00 (PRé Consultants 2006), and since all inputs in this study come from the technosphere the uncertainty choice is justified.

2.2.1 Material Production

Materials can be categorized by the three loops of the GSHP system: ground-loop, refrigeration-loop and distribution-loop. Production of machines used in the earthwork and construction processes are considered negligible. All material inputs are quantified by mass and are summarized in Table 3. All inputs are from the Ecoinvent 2.2 database except for PVC, which is taken from the USLCI database.

High-density polyethylene (HDPE) pipe is typically used as the borehole U-tube and supply and return headers because of its durability and low cost (Dickie 2010). This study uses SDR 11 2" HDPE pipe. Since 5-6 m spacing is recommended between boreholes (Kavanaugh et al. 1997), header lengths are assumed 22 feet for DISH and longer for VERT and pipe mass is calculated accordingly. In all cases, tap water is the carrier fluid and required mass is computed from pipe length. The Grand Marsh wells are cased in PVC to increase system strength and limit thermal conductivity in upper, less-conductive regions of the well. PVC is typically chosen because it is lightweight, resistant to corrosion, inexpensive and relatively easy to install. Other common casing materials are carbon steel, stainless steel, concrete or no casing at all, but PVC casing is used as a worst-case scenario. 200 ft of Schedule 40 8" PVC casing are inserted into each well during drilling. Below 200 ft the borehole has no casing and is drilled with a diameter of 6".

In the United States, boreholes are required to be backfilled with thermal grout (Dickie 2010). Grouting serves two primary functions: to fill the hole with a seal to limit groundwater contamination and to enhance thermal conductivity and heat transfer to the fluid. Historically grouts were pure bentonite clay or cement, but now grouts are typically a mixture of silica sand, bentonite and water, with ratios dependent on the target thermal conductivity. This study uses a 1:4:2.9 ratio of TG Lite bentonite to silica sand to water to achieve a target thermal conductivity of 1.52 W/mK (GeoPro Inc. 2013). Grout is calculated to fill all empty space between the borehole and the HDPE pipe.

The refrigeration loop consists of circulation pumps and water-to-air heat pump. Two stainless steel Grundfos 15-55SF/LC circulation pumps are used and mass is assumed to be 100% stainless steel. This study uses a WaterFurnace Envision Geothermal/Water Source Heat Pump, model NDV038, with a a R-410A scroll compressor, air coils and a blower (WaterFurnace 2012). Heat pumps are composed primarily of sheet steel, galvanized steel, copper, a refrigerant and water. Considering heat pump and fan coil inputs from a LCA study by Shah et al. (2007), the mass of the WaterFurnace heat pump is multiplied by a correction factor to estimate the material inputs as shown in Table 3. The NGAC system has no ground-loop components and uses a natural gas furnace and standard AC unit rather than a heat pump. Input values are taken directly from the Shah study, justified due to similar site conditions: a 1,950 square foot residence occupied by a single family. WaterFurnace and the AC use R-410a, a zeotropic refrigerant blend of 50% R-32 and 50% R-125. R-134a is available in the EcoInvent 2.0 database and is similar to R-410a in many regards. Both refrigerants are replacements for R-22a and have no contribution to ozone depletion. According to ANSI/ASHRAE (2010), R-134a has a global warming potential (GWP) of 1300 (i.e. 1300 kg CO2 equivalent) and R-410a has a GWP of 1730 (Sand et al. 1997 & Daikin McQuay 2002), so R-134a is used with a correction factor of 1730/1300. Although some sources claim that refrigerants must be changed annually due to leakage (Forse 2005) change is assumed unnecessary.

Lastly, heated or cooled air is distributed for both GSHP and NGAC scenarios from the fan coil unit to the residence through a duct network along the ceiling and floors. The duct system in this study is also adapted directly from Shah et al. (2007), with 0.76 mm galvanized steel sheets and 50 mm fiberglass insulation.

2.2.2 Transport

LCI's must account for the transportation of all materials and construction equipment to the site, which is taken to be Grand Marsh, Wisconsin. In this study, the origin of some materials are known and others are not. Bentonite comes from Mills, Wyoming, silica sand from Portage, Wisconsin, and the WaterFurnace heat exchanger from Fort Wayne, Indiana. When origin is unknown, this study assumes a transport distance of 100km. Transport is assumed by truck for all inputs except for the heat exchanger, which travels 675 km (420 mi) by rail and then the rest of the way by truck. Transport values are input to SimaPro using "Tonne-km" (tkm) units, which is equal to the mass of the object in metric tonnes (MT) multiplied by total transport distance in kilometers.

2.2.3 Earthwork and Construction

The primary energy processes in GSHP installation are trenching the site, drilling the borehole(s), grouting the borehole(s) and purging air out of the system. Densities, energy densities and specific energies of fuels were taken from the Wolfram Alpha online database. For electricity processes this study does not take into account the grid at each material production site but rather assumes the grid incorporated into SimaPro. Equipment specifics and fuel use are taken from the actual construction process at the base site at Grand Marsh.

During the trenching process, a backhoe is used to dig a trench to install the boreholes. For best results fluid should leave the borehole at a lower depth than it enters the mechanical room. HDPE pipes must be covered by deep soil in order to minimize effect of climate on water temperature. Ease of trench digging is a variable of soil compaction and soil type. The Grand Marsh scenario is taken, where a New Holland LB90B backhoe (100 HP diesel engine) spent 5.5 hours trenching an area of approximately 1.85 m^2. The following equation is used to estimate E_t, the energy required for trenching, in all scenarios:

$$E_{t-GSHP}\,[MJ] = 0.787\;HP_{eng}A_t \tag{4}$$

where HP_{eng} is the horsepower of the engine [HP] and A_t the area of the trench $[\,ft^2]$. DISH's trench is approximately one third the size of VERT's, and $A_t = 185\,m^2$ for HORZ. In the horizontal case, groundwork consists of only trenching and no drilling.

There are many methods to drill boreholes depending on the geology and depth required. Drilling through bedrock granite is far more energy intensive than drilling through sandstone (MIT and DOE 2006). Using a Simco 7000 rotary drilling rig with a diesel engine, assuming Table 1 stratigraphy, and using fuel consumption estimates from industry (Vande Yacht 2013) a simple linear model is developed to estimate drilling energy consumption E_d:

$$E_d\,[MJ] = \rho_{dies}Se_{dies}[1.201\;d_{ss} + 8.445\;(d_w - d_{ss})] \tag{5}$$

where ρ_{dies} is the density of diesel [kg/cm^3], Se_{dies} the specific energy of diesel [MJ/kg], d_{ss} is the depth of the sandstone and soil composite layer [m] and d_w the total length of the well [m]. The difference $d_w - d_{ss}$ represents the penetration into the granite layer. The limited model assumes well depths of 75 m minimum, but is applicable here as an order of magnitude estimate. For more specific inputs it is suggested to use complex modelling, such as Cost of Renewable Energy Spreadsheet Tool (CREST) developed by the NREL to balance installation and operation costs.

A grouter, in this case a 24 HP gasoline-powered GeoLoop 50-500, mixes grout and pumps it into the well through a tremie pipe. With the total volume of grout as defined in material production and a flow rate of 30 gal/min as listed in the equipment specifications (Geoloop 2013), the following equation determine the total gasoline F_g used:

$$F_g[gal] = \frac{HP_{eng}\;[HP]\times V_g\;[gal]\times\;0.0447\;[MJ/HPmin]}{v_g\;[gal/min]\times Se_{gas}[MJ/kg]\times\rho_{gas}[gal/kg]} \tag{6}$$

where HP_{eng} is the horsepower of the engine [HP], V_g the volume of grout used [cm^3], v_g the flow rate of grout through the tremie pipe [cm^3/s], Se_{gas} the specific energy of gasoline [MJ/kg] and ρ_{gas} the density of gasoline [g/cm^3]. No grout is used in HORZ.

Lastly, air must be purged out of the HDPE pipes to ensure steady flow. Using a 2 HP Purge Pro from Geothermal Supply Co. (Walker 2013) that operates off 120V electricity, purging energy E_p is estimated using:

$$E_p\;[kWh] = 0.7457\times HP_{eng}\times t_p \tag{7}$$

where HP_{eng} is the horsepower of the engine and t_p the time spent purging. Approximately one hour is spent purging for VERT, and thus for DISH and HORZ as well since pipe length is essentially the same. Pipe fusion was found to contribute only 0.001 kWh, so smaller energy processes such as fusion are excluded. There are no significant energy processes affiliated with the NGAC system, since it requires only placement of parts by hand.

2.2.4 Operation

Energy inputs during the use phase consist of electricity used by the heat exchangers and circulation pumps. The site at Grand Marsh, which much of this study is modeled off, is in the process of tracking this data but it is not in usable form at the time of writing. For the purposes of this study GHSP energy use is estimated with a simple model based on climate and building load. This model, adapted from Fredin's thesis (2009), divides the building load into heating and cooling consumption. Fredin's model has four annual electricity inputs determined by the following equations:

$$\text{GSHP Cooling [kWh]} = \frac{\text{Cooling Load [BTU/hr]} \times \text{CDD [hr]}}{\text{EER [BTU/hrW]} \times 1000\;\text{[W/kW]}} \tag{8}$$

$$\text{GSHP Circ. Pump Cooling [kWh]} = \frac{\text{Pump Power [W]} \times \text{CDD [hr]}}{\text{Motor Efficiency [\%]} \times 1000\;\text{[W/kW]}} \tag{9}$$

$$\text{GSHP Heating [kWh]} = \frac{\text{Heating Load [BTU/hr]} \times \text{HDD [hr]}}{\text{COP} \times 3145\;\text{[BTU/kWh]}} \tag{10}$$

$$\text{GSHP Circ. Pump Heating [kWh]} = \frac{\text{Pump Power [W]} \times \text{HDD [hr]}}{\text{Motor Efficiency [\%]} \times 1000\;\text{[W/kW]}} \tag{11}$$

Energy loads, degree days and COP's are taken from Table 2. Motor efficiency is taken as 88% (WaterFurnace 2012) and combined circulating pump power 50W (Grundfos Alpha 2013). Solving and summing equations 8-11, total annual electricity input is determined and then extrapolated to the entire 25-year lifetime to get LCI inputs for the use phase shown in Table 3.

The natural gas air conditioning split system (NGAC) uses natural gas for heating and electricity for both air conditioning and to run the fan in the furnace. Assuming equal lifetime and equal heating and cooling loads for a natural gas system, the following equations calculate electricity and natural gas use (Fredin 2009):

$$\text{NGAC Cooling [kWh elec.]} = \frac{\text{Cooling Load [BTU/hr]} \times \text{CDD [hr]}}{\text{EER [BTU/hrW]} \times 1000\;\text{[W/kW]}} \tag{12}$$

$$\text{NGAC Heating [kWh elec.]} = \frac{\text{Fan Power [W] x HDD [hr]}}{\text{Motor Efficiency [\%]} \times 1000 \text{ [W/kW]}} \quad (13)$$

$$\text{NGAC Heating [kWh NG]} = \frac{\text{Heating Load [BTU/hr]} \times \text{HDD [hr]}}{\text{AFUE} \times 3145 \text{ [BTU/kWh]}} \quad (14)$$

where EER is taken to be 14.4, the annual fuel utilization efficiency (AFUE) of natural gas is given a mid-efficiency value of 80% (Canada Mortgage and Housing Corporation 2008), motor efficiency 85% and fan power ⅓ HP (249 W).

Electricity inputs are modeled off of the current electrical grid in Wisconsin. Though it is recommended to use marginal electricity for the purpose of GSHP (Hackle 2010), for simplification this study uses average Wisconsin electricity values from 2011 as reported by the EIA (2013) with 62.5% coal and only 5.5% renewables. These values are programmed into the SimaPro product stage database for analysis.

Table 3: Life cycle inventory input materials and processes for DISH, VERT, HORZ and NGAC systems

Component	Material/Process	Unit	DISH	VERT	HORZ
Material Production					
Thermal Grout	Bentonite Grout	kg	1,100	1,450	0
	Silica Sand	kg	4,400	5,800	0
	Tap Water	kg	3,209	4,229	0
Pipe	HDPE Pipe	kg	670	776	670
Casing	PVC Pipe	kg	489	1,467	0
Borehole Fluid	Tap Water	kg	1,562	1,562	1,562
Water-to-Air Heat Exchanger	Steel	kg	113	113	113
	Galvanized Steel	kg	44	44	44
	Copper	kg	14	14	14
	Refrigerant R-140A	kg	2	2	2
	Tap Water	kg	5	5	5
Circulation Pumps	Stainless Steel	kg	6	6	6
Ductwork	Galvanized Steel	kg	265	265	265
	Fiberglass	kg	140	140	140
Transport					
All (except Heat Exchanger)	Truck	tkm	3,851	4,606	872
Heat Exchanger	Freight	tkm	107	107	107
Earthwork & Construction					
Drilling	Diesel	MJ	70,028	26,924	0
Trenching	Diesel	MJ	492	1,476	7,380.00
Grouting	Gasoline	gal	0.18	0.54	0
Purging	120V Electricity	kWh	1.5	1.5	1.5
Operation					
Heat Exchanger	120V Electricity	kWh	276,352	310,335	355,645
Circulation Pumps	120V Electricity	kWh	4,504	4,504	4,504
Decommission					
Materials	Recycle	%	90	90	90
	Landfill	%	10	10	10

Component	Material/Process	Unit	NGAC
Material Production			
NG Furnace	Steel	kg	46
	Galvanized Steel	kg	18
	Aluminum	kg	9
	Copper	kg	3
AC Unit	Steel	kg	78
	Galvanized Steel	kg	35
	Copper	kg	17
	Aluminum	kg	17
	Refrigerant	kg	6
Ductwork	Galvanized Steel	kg	265
	Fiberglass	kg	140
Transport			
All	Truck	tkm	63
Operation			
NG Furnace	Natural Gas Combustion	kWh	1,189,387
AC Unit	120V Electricity	kWh	57,907
Decommission			
Materials	Recycle	%	90
	Landfill	%	10

2.2.5 Disposal

After a GSHP's 25-year lifetime, several disposal scenarios are possible. Refrigeration and distribution loop components can be replaced and reconnected with the ground loop for at least one more life cycle, but a worst-case scenario of complete decommission is taken. For this study water is removed from U-tube, pipes are cut at ground level, but the rest of the system lays intact underground to allow the possibility of reuse in the future. The refrigeration and distribution loops for GSHP and NGAC are treated as explained in Shah's study (2007), with 90% of the materials by mass recycled and the remaining 10% disposed in a landfill. To input this scenario into SimaPro, a new waste scenario is modeled off of "Waste Scenario US/U" from the Ecoinvent 2.2 database (Hischier et al. 2010)

2.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) connects each of the inventory inputs to their corresponding environmental impact. Resource and emission flows from the inventory are connected to a series of midpoint and endpoint indicators. Required LCIA structure, determined by ISO 14044, consists of (1) selection of relevant impact categories and models, (2) *classification* of each inventory entry to impact categories and (3) *characterization* of these impacts using equivalence factors determined by selected assessment method (PRé Consultants 2010). Additionally, normalization and weighting may be applied to determine the relative impact of each category.

SimaPro incorporates dozens of impact assessment methods in order to select one most relevant for each particular study. This study uses the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2), an impact assessment method developed specifically for the US by the Environmental Protection Agency (EPA) (Hischier et al. 2010). Though TRACI 2 contains a variety of midpoint impact categories, this LCA focuses only on Global Warming Potential (GWP) defined as "potential global warming based on chemical's radiative forcing and lifetime" (Bare et al. 2002). US specific characterization factors are used for carbon dioxide and carbon monoxide biogenic and fossil flows from the Ecoinvent database, as shown in Table 4.

Table 4: Biogenic and fossil characterization factors for CO and CO2 used in TRACI 2, adapted from Hischier et al. 2010

ecoinvent name	GWP characterization factor (kg CO_2-Eq)
Carbon dioxide, biogenic	0
Carbon dioxide, fossil	1.00
Carbon monoxide, biogenic	0
Carbon monoxide, fossil	1.57
Methane, biogenic	23
Methane, fossil	23

3. Results and Analysis

3.1 DISH System

The compiled inventory of each stage of the DISH system's life is assessed using global warming characterization from TRACI 2. Over its entire 25-year life cycle, the DISH GSHP was calculated to emit 271,618 kg CO2 equivalent. The operation phase of the heat pump is associated with the most emissions. Specifically, electricity to run the compressor in the water-to-air heat exchanger is shown significantly to be the largest contributor to global warming, responsible for over 93% of total emissions as demonstrated in Figure 3. All emissions associated with electricity use are directly connected to the percentage of fossil fuels on the electrical grid.

The second GHG highest contributor is the drilling of the 1,185 foot borehole (2.4%). Rotary drilling rigs function by combusting diesel fuel, shown to emit 10.1 kg CO2 per gallon (EPA 2013) and 13.9 kg CO2 equivalent per gallon. As expected, drilling a deep well results in significant GHG emissions but they are over an order of magnitude less significant than heat pump operation. The third contributor is the electricity to run the circulating pump during DISH operation (1.5%). These emissions also correlate to the associated emissions with the Wisconsin electrical grid. However, associated emissions are two orders of magnitude less than emissions from running the heat exchanger.

The production of system's ductwork, HDPE pipe and PVC casing contribute 0.7%, 0.7% and 0.6% to total GHG emissions. Although these are primary contributors during the assembly of the GSHP, they are shown to be practically negligible when considered over the entire lifetime. All other factors -- production of other materials, all transportation of materials and earthwork excluding drilling -- contribute less than 0.3% to total emissions, so can be considered inconsequential for this study.

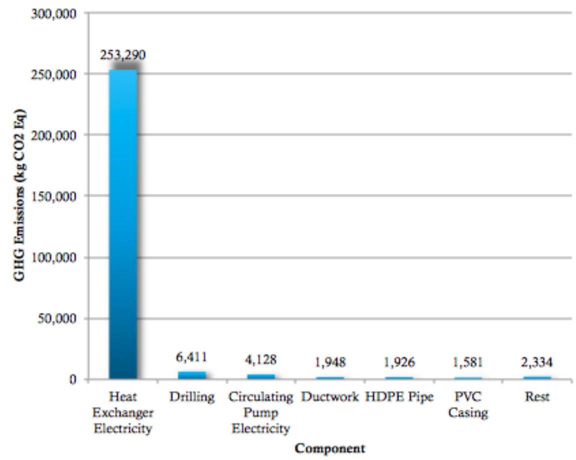

Figure 3: Largest contributors to total greenhouse gas emissions (271,618 kg CO2 Eq) of the DISH GSHP during the entire 25-year lifetime in order of contribution

3.2 Comparison

GHG emissions affiliated with the DISH system must be compared to HVAC alternative scenarios to assess their relevance and implications. All stages of the life cycle of the two other GSHPs, VERT and HORZ, and the conventional natural gas alternative NGAC are analyzed using TRACI 2 GWP impact assessment method and are plotted next to DISH in Figure 4.

VERT has the highest emissions during material production, followed by DISH, NGAC and lastly HORZ. This is due largely in part to the use of PVC to case all three boreholes, which accounts for 47% of all emissions during its material production. DISH only has one borehole and HORZ has none. During earthwork and construction, as expected the DISH system emits the most: 40% more than VERT and 14% more than HORZ. Although VERT requires drilling and around three times more trenching and HORZ requires around fifteen times more trenching energy, the emissions due to drilling the 1,185 foot borehole in DISH far surpass those due to trenching. Emissions during transportation contribute less than 5% of total emissions during assembly, so they can be considered negligible. DISH emissions during material production and VERT emissions during earthwork and construction compensate, thus during assembly DISH and VERT are essentially tied as the biggest emitters, with DISH leading by only 3%. Disposal contributes less than transportation, so it is also negligible.

The operation phase of the life cycle shows an entirely different trend. GHG emissions increase almost linearly, with DISH emitting 11% less than

VERT, 22% less than HORZ and 29% less than NGAC. The emissions from the GSHPs are due directly to electricity consumption. From these calculations, the Wisconsin grid emits 0.92 kg CO2 eq/kWh. Since DISH consumes 11% less electricity than VERT and 22% less that HORZ and since all scenarios use the same electrical grid, these results are trivial. For the NGAC scenario, emissions during operation are due to the superposition of natural gas combustion and electricity use. Although natural gas is shown to emit 0.27 kg CO2 eq/kWh (71% less than the electrical grid), the NGAC system consumes 71% more total energy than HORZ. Since some of this energy is electricity to run the air conditioner, NGAC operation cumulatively emits more.

For each scenario, emissions during operation are more than an order of magnitude greater than those in all other life stages combined. Furthermore, the emission difference between successive scenarios during operation is greater than total emissions in all other stages. Thus, over an entire lifetime the GHG emission trend from the operation phase significantly dominates: collectively, DISH saves on average 10% emissions over VERT, 19% over HORZ and 28% over NGAC.

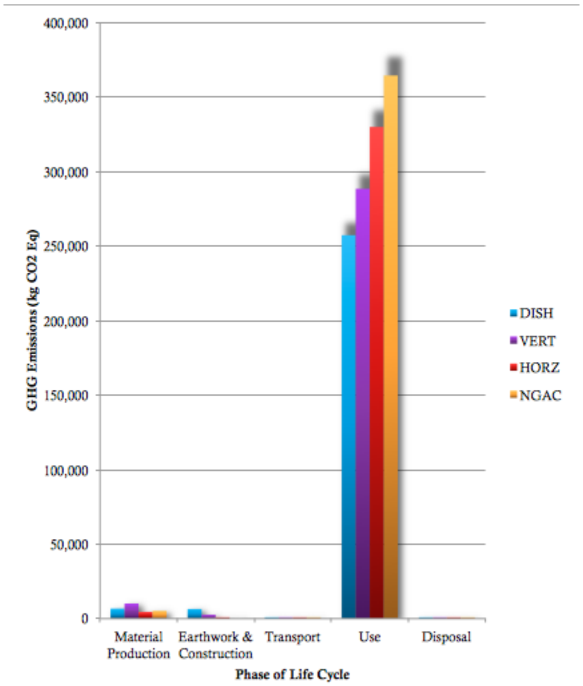

Figure 4: Comparison of greenhouse gas emissions during each phase of a 25-year life cycle for DISH, VERT, HORZ and NGAC scenarios.

3.3 Uncertainty Analysis

Before drawing any conclusions based off of the calculated life cycle emissions, it must be noted that LCA delivers average emission values for each system. As explained in the inventory analysis, each data entry in SimaPro is subject to some degree of imprecision. Uncertainty analysis, required by the final interpretation stage of LCA, documents the effect of imprecise data on the results of the impact assessment. This allows for the comparison of the precision of different data sets. Using TRACI 2, Monte Carlo regressions are conducted on the GHG emission results from all four systems using 1000 iterations at a confidence level of 68.3% (one standard deviation i.e. “one sigma”) and results are plotted in Figure 5.

Accounting for data uncertainty, the maximum emissions for DISH are approximately equal to the average emissions for the NGAC system and the minimum emissions for NGAC are approximately equal to the average emissions for DISH. Although the average values show a near linear trend in which DISH emits less than other alternatives, all that can really be concluded is that each scenario emits the same order of magnitude of greenhouse gases. The maximum values of uncertainty were chosen for a worst-case scenario analysis, so it is possible that in reality the standard deviation is smaller and the average trend is more precise. Further study must be done to truly determine the strength of this data set.

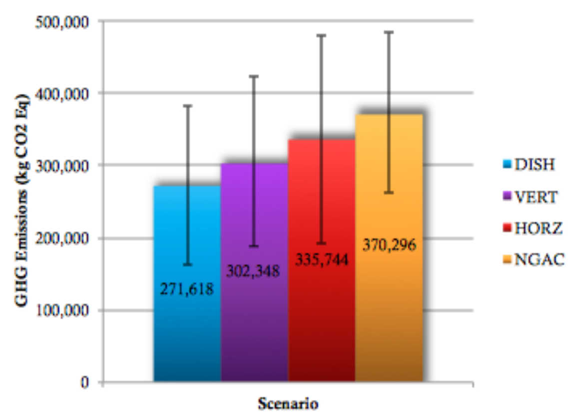

Figure 5: Comparison of total life cycle greenhouse gas emissions over 25-year life cycles using Monte Carlo uncertainty analysis to one sigma (68.3% uncertainty)

3.4 Sensitivity Analysis

In addition to uncertainty analysis, LCA interpretation requires implementation of a systematic change of variable input parameters to identify the most critical parameters and motivate further data collection. The following sensitivity analyses compare the DISH system and the NGAC system.

A GSHP's coefficient of performance dictates the required electricity consumption of the heat exchanger. For DISH this study estimates a COP of 4, but further modeling and field data are needed to determine the exact COP. Since the operation phase is significantly the largest contributor to emissions, it is important to understand how life cycle GHG emissions change with COP. Equations 5-9 are manipulated for various COP values between 2.5 and 5 and an impact assessment is conducted for DISH at these various COPs. Figure 6 plots the associated emissions against the GHG emissions for NGAC. The data relation for DISH resembles a power series trend, and fitting the data to a curve using Excel gives the following equation for global warming potential (GWP) in kg CO2 equivalent:

$$\mathrm{GWP} = 820{,}152(\mathrm{COP})^{-0.796} \qquad (15)$$

NGAC is associated with emission of 370,296 kg CO2 equivalent. Solving equation 15 for this value gives a COP of 2.72. Thus, DISH systems with a COP greater than 2.72 should have fewer GHG emissions than the NGAC system. If DISH was found to have a COP of 5, the value predicted in the DISH proposal, it would save 37% GHG emissions over a conventional NGAC system.

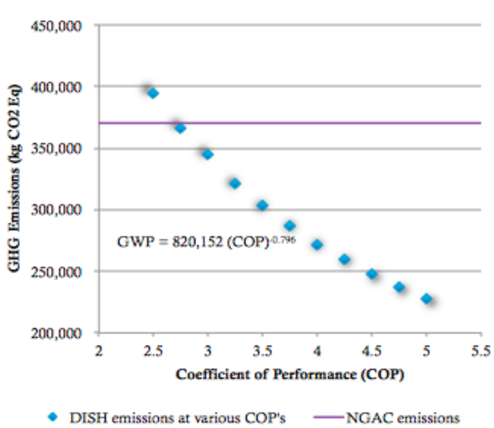

Figure 6: Sensitivity analysis of GHG emissions from the DISH system for various coefficient of performance (COP) values between 2.5 and 5 plotted against the emissions due to a NGAC system.

DISH and NGAC emit on about the same order of magnitude with the current Wisconsin grid. However, EIA projects shares of renewables to increase and shares of coal to decrease nationally in the following decades (EIA 2013). Political and economic pressures have pushed 27 US states including Wisconsin to adopt various Renewable Portfolio Standards (RPS). Wisconsin's neighbors, Minnesota, Illinois and Ohio, all require 25% renewables by 2025 (C2ES 2013). Currently Wisconsin has 5.5% renewables, and its RPS requires 10% by 2015 (Tuerk et al. 2013). Though lawmakers currently have no subsequent percentage benchmarks in mind, it is likely that this number will increase in the future. To conduct a sensitivity analysis to gauge the interplay between a cleaner electrical grid and GHG emissions from DISH, five hypothetical grid projections are calculated up to 50% renewables in increasing increments of 10%. To simply model these projections, contributions from coal are directly replaced by contributions from wind energy and the electrical grid is taken to be constant over the entire 25-year lifetime.

Projections for the DISH and NGAC systems are plotted in Figure 7. With Wisconsin's RPS, DISH GHG savings over NGAC should increase from 27% to 30% by 2015. Assuming a linear model, the slope for DISH increases over five times faster than that of NGAC. If Wisconsin reaches a 30% renewable grid, which is in the range of RPS goal for other US states, DISH could save 48% emissions. With a 50% renewable grid, up to 68% emissions could be saved. At this point, DISH and NGAC emissions are no longer on the same order of magnitude.

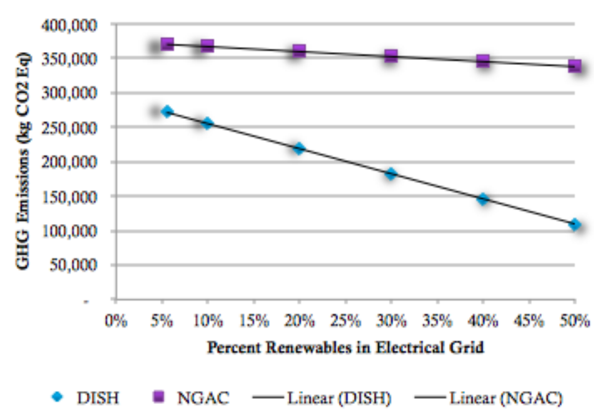

Figure 7: Sensitivity analysis of GHG emissions from the DISH system for hypothetical grids in which energy generated from coal is replaced with energy generated from wind.

4. Conclusion

Ground source heat pumps are considered environmentally friendly due to their low emission of greenhouse gases (GHGs). For conventional GSHPs, one study from Europe showed GHG emissions around 63 metric tons (mt) kg CO2 eq and a Wisconsin specific study found average emissions of 329.5 mt. This study uses a comprehensive LCA to quantify the GHG emissions of DISH, a unconventional GSHP with a single 1,185 ft. deep borehole, in a Wisconsin residence. Assuming a COP of 4.0, the DISH system on average emits 272 mt CO2 equivalent over its entire 25-year lifetime during material production, transportation of materials, earthwork and construction, operation and disposal. The top three contributors to these emissions are electricity to operate the heat exchanger (93.3%), diesel combusted to drill the borehole (2.4%) and electricity to run the circulating pump (1.5%). In terms of emissions, the burden of drilling deep into bedrock was shown practically insignificant in comparison to electricity use during system operation.

To understand the significance of these emissions DISH was compared to other HVAC options. DISH was shown to save 10% GHG emissions over a triple-borehole vertical GSHP (VERT), 19% over a conventional horizontal GSHP (HORZ) and 27% -- 99 mt total -- over a natural gas-air conditioning split system (NGAC). The data trend is that GHG savings increase with deeper well configurations. However, accounting for the statistical uncertainty of inventory data all that can be concluded is that these four systems lie within the same order of magnitude. To one standard deviation, DISH emissions lie between 188 and 422 mt and no GSHP system is substantially more carbon neutral than a NGAC alternative. But what happens if system efficiency or grid cleanliness improves? Assuming a COP of 5.0 DISH could save 37% GHG emissions over a NGAC system and with a 50% renewable grid DISH saves 68% emissions. Other HVAC sources such as oil fired boilers emit even more over a lifetime than NGAC (Saner et al. 2010), so as the grid becomes cleaner DISH will become the least carbon intensive option.

For a single unit the DISH saves less than 100 mt CO2 equivalent over a lifetime which alone is negligible. What if emissions savings are scaled up to the entire state? As a final thought experiment, it is supposed that all NGAC systems in Wisconsin are immediately replaced with DISH systems. Wisconsin consumes 132 Trillion BTU annually for HVAC purposes alone (EIA 2009). According to Figure 1, 55.4% of this energy use is attributed to natural gas. This would account for around 450,000 NGAC systems in the state. Replacing each of these with a GSHP would save 1.8 million metric tons of GHG emissions from entering the atmosphere annually and reduce Wisconsin's GHG emissions by 1.5%. To take it a step further, assuming the entire US had Wisconsin's climate, ground conditions and grid, emissions are scaled up to the entire US population to find GHG savings of 97.5 million mt CO2 eq. Making this change could also reduce national emissions by 1.5% and thus global emissions on the order of 0.3%.

This analysis is just a basic framework and order of magnitude estimate to determine whether or not GSHP are a feasible heating and cooling solution specifically in Wisconsin. Certain pitfalls within research methodology and assumptions must be accounted for to explain error and suggest further research. There is inherent uncertainty in SimaPro databases, spawning from model choices and incompleteness of data sets that cannot be accounted for statistically. The EcoInvent database is specific to Switzerland and many other inputs are based on European data. The real lifetime of a NGAC system is estimated as 20 years, so the 25-year lifetime assumed this study is a best-case scenario for NGAC (Shah et al. 2007). This study estimates 25 years into the future yet assumes static conditions. In reality, there is a complex interplay of variables: the COP may dwindle over the lifetime due to heat depletion and climate fluctuations as the grid becomes cleaner and technological innovations improve. Determining how these variables interact could be a motivation for a future study.

Ultimately, the results of this study will be used to create an interactive spreadsheet for Wisconsin contractors and homeowners to determine GHG emissions of GSHP systems, allowing analysis to compare varying input parameters such as system type, borehole length, ground conditions, building load and climate. For a follow-up study, the most important revision focal point should be determining energy consumption and DISH's COP to greater precision. Since electricity use is the most significant contributor to emissions, this data needs to be the most precise. The only way to precisely measure electricity use is to physically run the GSHP and explicitly measure the power intake of each piece of equipment and the heat transferred from the ground. It is also suggested to use software such as Trane Trace or Trynsys to determine building load, COP and electricity input. Second, the system should be adapted to include domestic water heating using a water-to-water heat exchanger, buffer tank and radiant floor coils as well as a conventional water heater to pair with the NGAC system. Next, comprehensive programming should be implemented to connect the spreadsheet directly to SimaPro or incorporate the relevant GHG emission metrics directly into Excel. When designing low-carbon energy solutions, GHG emissions are just one of many factors to consider. Coupling of a life cycle cost analysis (LCCA), perhaps including potential carbon taxes on emission savings, would strengthen this study and further analyze the feasibility of implementing the DISH system in Wisconsin. Lastly, these calculations should be expanded to encompass the implementation of DISH in the greater Midwest and the United States as a whole to see how DISH would scale up and interact with the shifting global energy economy.

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