PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Energy Efficiency and Life Cycle Assessment of a District-Scale Geothermal Exchange Field

James M. Tinjum[1], Mehmet Yilmaz[1], Evan Heeg[1], Dante Fratta[1], David J. Hart[2], and Shubham Dutt Attri[3]

[1]University of Wisconsin–Madison, Civil and Environmental Engineering, 1415 Engineering Drive, Madison, WI 53706, USA

[2]Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin 53705, USA

[3]University of Wisconsin–Madison, Industrial and Systems Engineering, 1415 Engineering Drive, Madison, WI 53706, USA

Corresponding Author Email: jmtinjum@wisc.edu

Keywords: geothermal exchange, environmental life cycle assessment, energy payback time, global warming potential

ABSTRACT

District-scale Geothermal Heat Exchange (GHX) systems are increasingly portrayed to have significant environmental and economic benefits. However, independent and comprehensive life cycle analysis (LCA) and sustainable energy science are typically not implemented to quantify the full and accurate environmental benefits. A GHX system uses steady subsurface temperature for space conditioning and domestic hot water by circulating mostly water to exchange heat with the subsurface. This clean, quiet, and sustainable heat exchange mechanism is advertised to have convincing cost efficiency in energy consumption. However, long-term feasibility and energy balance assessments of GHX systems are lacking, especially for district-scale systems. To begin filling this gap, we evaluate the environmental 'costs' and embodied energy (e.g., energy payback time) for constructing a district-scale GHX field with 2,596 152-m-deep GHX borings located in the upper Midwest of the US. As this field was fully instrumented during construction and monitored throughout operations, we can calculate that 645.9 TJ of thermal energy has been exchanged since this field came online from early 2015 through September 2022. The energy exchanged varies from a low of 62.4 TJ in 2015 to a high of 94.4 TJ in 2019. With an average household in Wisconsin consuming approximately 8,500 kW h of electricity each year, the yearly average of the district-scale field's exchange of 81 TJ is equivalent to the annual electrical use of 2,650 Wisconsin households. LCA methodology was then used to perform a quantitative, comparative analysis and rating of the material procurement and construction of this district-scale GHX field, including the embodied energy required for material production, manufacturing, transportation, and construction. This embodied energy for field construction equates to 100 TJ, which is "paid back" in 14.5 months by the thermal energy exchanged in the field. The results of the LCA show that top contributors to embodied energy consumption in borefield procurement and construction are related to borehole drilling and well completion; thus, GHX systems that efficiently minimize the number of GHX wells and cumulative vertical length are not only more economically viable, but also more energy sustainable.

1. INTRODUCTION

Geothermal technologies for either direct energy production or energy efficiency continue to grow in popularity and application because of lower environmental impact (e.g., lower carbon footprint, less water use) and lower operating cost. In 2021, approximately $5.76 \cdot 10^4$ TJ (i.e., 0.4% of the total utility-scale energy generation) was produced in the US through geothermal energy systems, including direct use and district heating systems, geothermal power plants, and geothermal heat exchange systems (GHX) that incorporate ground source heat pumps (GSHP) (USEIA 2022). GHX applications, for example, utilize relatively constant ground temperature, even though many parts of the US experience locational and seasonal fluctuation in atmospheric temperature. A GHX is an underutilized method for space conditioning and domestic hot water heating believed to be more energy efficient than conventional HVAC systems (ASHRAE 2011). There are different GHX systems, but the one described here is a vertical well system for district-scale heating and cooling and domestic hot water heating. Water is circulated underground in pipes as the ground is used as a thermal reservoir and, at times, a thermal radiator (Hart et al. 2022). Heat transfer occurs between the closed-loop circulating water and the ground. If a field is thermally unbalanced and does not effectively dissipate the heat input, the field can become thermally inefficient and overheated (Florea et al. 2017). In contact with the circulated water, a heat pump at the surface moves heat via a refrigerant fluid to space-conditioned buildings or to heat domestic hot water. These systems can be installed for a single residential house, district-scale facilities, or anything in between.

GHX systems are regarded as being more energy efficient than conventional heating and cooling systems and have long-term economic benefits (McCabe et al. 2019, Bloom and Tinjum 2016). Although GHX systems are promoted as environmentally friendly, sustainable, and energy-efficient, the environmental impacts that arise from the construction material, water, and energy input and output should be quantified and evaluated through a life cycle assessment (LCA). Accurate and quantitative assessment of environmental impact requires standardized methodology. LCA is such a methodology that evaluates the environmental impacts of a product or process across its entire lifetime, from material extraction to end-of-life, i.e., from "cradle-to-grave" (Metz et al. 2007, BP 2007, PRé Consultants 2010). LCA uses an accepted and systematic form of scientific analysis to quantify the environmental impact of a process rather than using historical precedent or unsubstantiated marketing as evidence. An LCA helps consumers and owners make decisions over the entire life of an engineering product or process to evaluate the economic and environmental impact. Further, LCAs are widely used in renewable energy (including geothermal) applications and projects that may involve economic payback (Bloom and Tinjum 2016, Ren et al. 2020)

The World Commission on Environmental and Development introduced the definition of "Sustainable Development" as development that meets the present needs in a fashion that does not compromise the ability of future generations to meet their own needs (Banerjee 2002, United Nations General Assembly 1987). For example, fossil fuel use/depletion not only impacts the availability of this resource to future generations but also has a negative environmental impact. So, the goal of LCA is to compare the environmental performance of products or services to select the options with the least adverse impact. LCA is a technique for assessing the potential environmental impacts associated with products or services by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory and impact phases to the study objectives (ISO 2006). Hundreds of studies on the life cycle greenhouse gas (GHG) emissions of energy resources have been performed (IPCC 2011)—primarily for coal, natural gas, petroleum, nuclear, and renewable energy facilities (wind, solar, hydroelectric, biogas). Furthermore, LCAs have been performed on a variety of infrastructure products and energy services, such as wind farms (Rajaei and Tinjum 2013), recycled concrete aggregate (Lee et al. 2010), and residential and direct-use geothermal systems (Bloom and Tinjum 2016, Thomas et al. 2021). However, since GSHPs do not produce energy—that is, they decrease energy use or intensity—they are often neglected in LCA studies and were not included, for example, in IPCC (2011).

The effectiveness and efficiency of a geothermal exchange field in life cycle energy terms is, in part, determined using the energy payback time (EPT) concept. We define the EPT for constructing a geothermal exchange field as the time at which the total thermal energy exchanged over the field's operation divided by the energy needed to construct the field is unity. A low EPT shows that the system produces much more energy than consumed during the construction of the system, thus improving the sustainability or utilization of such a system. GHX systems exchange energy with the ground or surface water, and the amount of energy exchanged over a given period can be determined with the correct parameters and calculations. The amount of energy exchanged can be compared to the embedded energy in the GHX system (the amount of energy required to build, maintain, and deconstruct the system) to determine energy payback parameters such as EPT. At smaller scales (i.e., residential to a few buildings), LCAs have shown that GHX systems are economically and environmentally beneficial over the long term (Adolfsson and Rashid 2016, Bloom and Tinjum 2016). However, to our knowledge, a comprehensive LCA on EPT has not been conducted for campus- or district-scale GHX fields.

In the present study, we expand the LCA methodology used for the analysis of campus-scale geothermal exchange by focusing on the infrastructure components (i.e., exchange well construction, laterals and headers, vaults, and collector/distribution trenches) not only in terms of material and resources but also in terms of construction-fuel intensity and energy expenditure. To our knowledge, such detailed Balance-of-Field (BOF) analysis of geothermal field infrastructure components is not included in the LCA of said systems. Two key Energy Payback parameters are the Energy Payback Ratio (EPR) and EPT. The EPR, defined for energy-producing facilities such as wind farms, is the amount of energy produced over the facility's lifetime divided by the amount of energy required to construct, maintain, and deconstruct the system (Gagnon et al. 2002). As the geothermal exchange field discussed in this study is still operating and has significant remaining operating life, we herein conduct an LCA with specific emphasis on EPT for this district-scale geothermal exchange system in the upper Midwest of the US consisting of 2,596 152-m-deep GHX wells.

2. BACKGROUND

2.1 Project Site

Epic Systems (Epic) is an electronic health records company that makes software for medical groups, hospitals, and integrated healthcare organizations. Epic is a leader in energy-efficient and cost-effective commercial building design that is environmentally responsible and sustainable. Epic's commitment to energy efficiency and sustainability is evident with Epic's private photovoltaic installations (2 MW) and wind energy farm (10 MW). In addition, Epic has invested in geothermal reservoir fields to heat and cool their campus fully (Özdoğan Dölçek et al. 2017, McDaniel et al. 2018b). Over 16 years of operating geothermal reservoir fields, Epic achieved extensive knowledge about the nature of district-scale geothermal systems. This working knowledge allows the development of best practices regarding thermal storage via geothermal heat exchange. The 10,000-person Epic campus in Verona, Wisconsin, has 6,100 in-service GHX wells (up to 152-m depth) located across four separate GHX fields with an existing capacity of 42 $MW_{thermal}$—one of the largest shallow, low-temperature GHX systems in the world (Figure 1). With additional closed-loop exchanges in a 2.2-ha stormwater management pond and an 8.5-ha, 14-m-deep Quarry Lake, the total capacity reaches 92 $MW_{thermal}$. The thermal reservoirs provide all heating and cooling needs, hot water heating, and ancillary services such as snowmelt operations and underground parking heating. In addition, this site offers a *natural laboratory* with research advantages. Epic and the UW–Madison Energy Geotechnics research group monitor the facility to properly evaluate the energy balance and enhance the system's performance and sustainability in its operation.

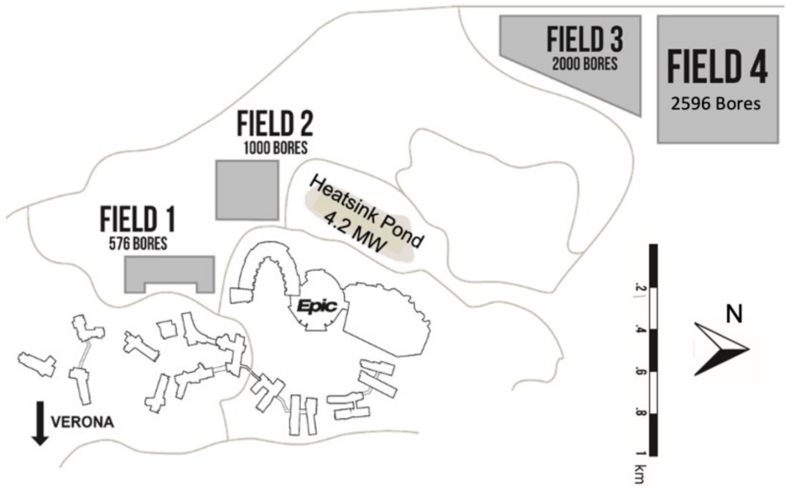

Figure 1: Epic's campus includes four geothermal fields, a cooling pond, and a quarry reservoir (1 km northeast of Field 4).

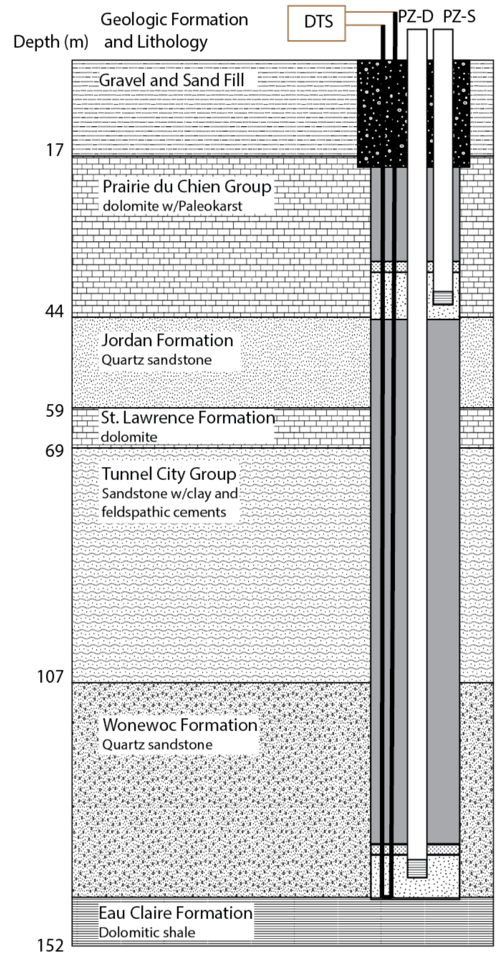

Figure 2: Generalized geology and typical well observation field configuration for Field 4.

2.2 Site Geology

The geology of the Epic's geothermal fields is typical of southern Wisconsin and representative of the soils and lithologies often encountered in the upper Midwest of the United States. Borehole logging captured information about the geology at the site of Field 4. Figure 2 presents a generalized geologic section for Epic's geothermal Field 4. There is approximately 10 m of fill and glacial till, mostly gravel and sand, over bedrock. There are layers of bedrock lithology beneath this overburden, including limestone and sandstone, which is underlain at the bottom by the Eau Claire shale. The water table is present at a depth of about 23 m. The formations' thermal properties were measured on core samples (Meyer 2013, Walker et al. 2015). These various thermal properties impact the field's performance towards a "radiator" or a "reservoir" (Hart et al. 2022). The Eau Claire Formation shale acts as an aquitard, preventing groundwater flow vertically at the base of the geothermal Field 4, and is not reached by the GHX wells. The varying lithologies' thermal and hydraulic conductivities result in differential conductive and advective heat flows. Those flows change significantly with voids in the Prairie du Chien dolomite group found in multiple borings within the geothermal Field 4. The Tunnel City Formation acts like a leaky aquitard, providing some hydraulic separation between the overlying rock and sediment and the Wonewoc Formation. The shallow piezometers indicate groundwater flow is generally to the southwest in the field in the Tunnel City Group and above. In contrast, the deep piezometers indicate groundwater flow in the Wonewoc is to the east during pumping by a nearby municipal well and to the south when the well is not pumping.

2.3 Field Design

Epic's Field 4 is the largest of four geothermal fields at this district-scale geothermal campus (Figure 1). The 152-m-deep boreholes are arranged in a large, grid-like pattern (Figure 3) and spaced at approximately 6.0 m to allow for sufficient heat dissipation and to reduce interference between boreholes. The grout used in the boreholes is also designed to have a high thermal conductivity (2.08 W m^{-1} K^{-1}) to allow for efficient heat exchange between ground and the high-density polyethylene (HDPE) U-loop. The specific grout mix is shown in Table 1. The HDPE horizontal collector piping is buried about 2-m deep, contained in sand backfill, and is overlain by earth backfill. Collector vaults are constructed with concrete and underlain by a thin layer of pea gravel. If you add up all of the vertical HDPE pipes in Field 4, it totals 791 km of piping. Likewise, summing all of the horizontal header and collector piping equals 60 km of piping. The mass of HDPE in the horizontal piping is actually greater than that in the vertical wells because of the larger pipe sections used in the collector system. Finally, the heat budget in the field is monitored by a dynamically calibrated, distributed temperature sensing (DTS) system (McDaniel et al. 2018a).

Table 1. Thermal grout mix used for Field 4.

Item	Thermal Conductivity	Solids		Water		% Solids
		Silica Compound	Power Tec	Volume	Yield	
	[W m^{-1} K^{-1}]	[kg]	[kg]	[m^3]	[m^3]	[kg m^{-3}]
Value	2.08	22.7	9.1	0.062	0.083	5,580

Field 4 has a primary vault (Vault 14) from which water is pumped to secondary vaults (Figure 3). From the secondary vaults, water is pumped to borehole circuits, which typically contain ten boreholes per circuit. The water travels through these ten boreholes in parallel before being collected and returned to the secondary vault. Various HDPE pipe sizes are used in the horizontal components of the circuits to account for changing flow rates as water enters and returns from boreholes. In Field 4, a secondary vault typically supplies water to 36 circuits (360 boreholes). Likewise, Vault 14 supplies water to eight secondary vaults. As the water returns from the borehole circuits, it is pumped from the secondary vaults to Vault 14 and then to a centralized heating/cooling facility to supply dozens of campus buildings for space conditioning.

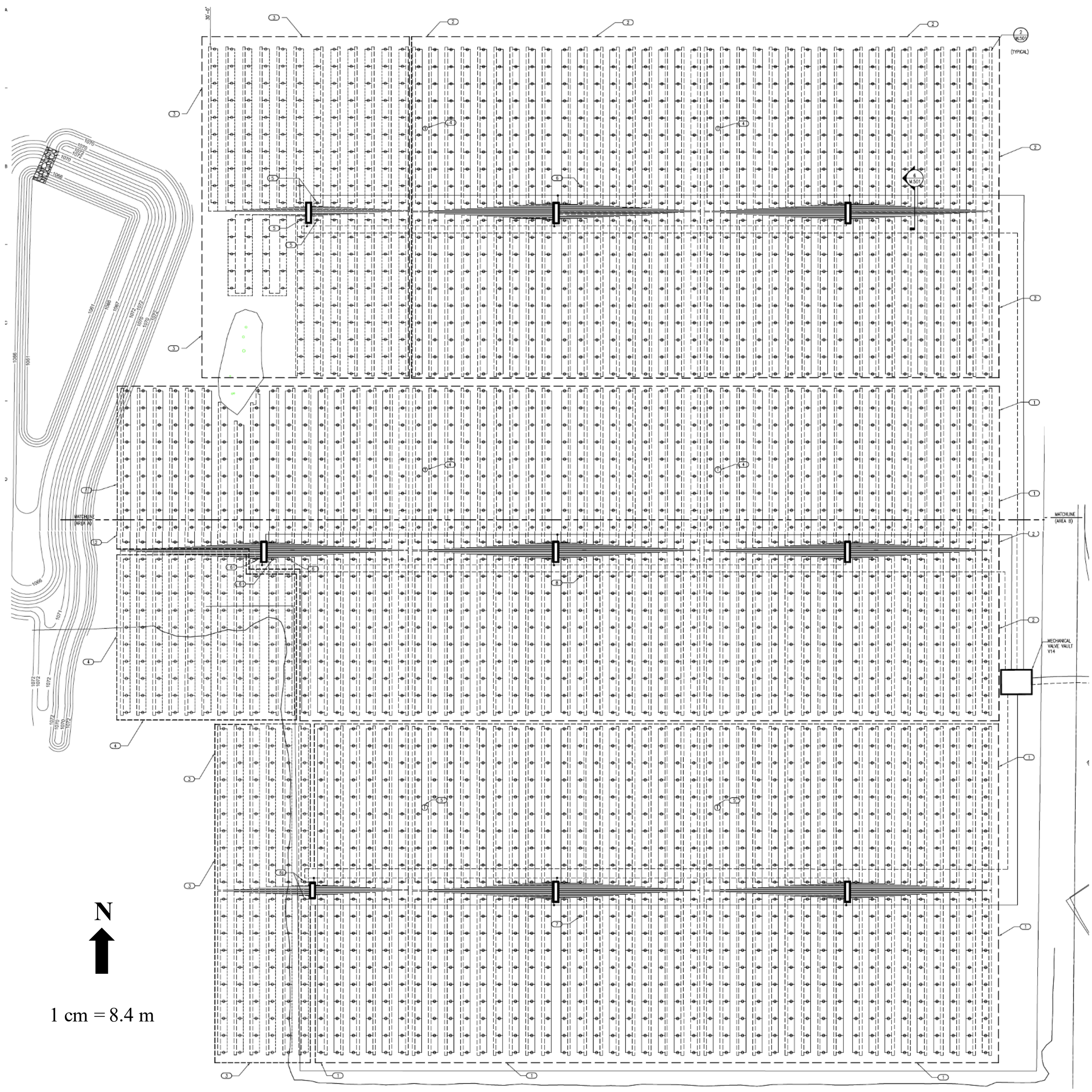

Figure 3: Plan layout of Geothermal Field 4.

3. MATERIALS AND METHODS

3.1 Geothermal Field Energy Exchange

We compute the amount of energy exchanged over time for the GHX system to calculate Energy Payback parameters. The Energy Exchange Rate, ERT, is calculated by finding the product of the density of the exchange fluid (ρ), the specific heat capacity of the exchange fluid (c), the difference between supply and return temperature for the system (ΔT), and the flow rate of the exchange fluid (q):

$$Energy\ Exchange\ Rate = \rho \cdot c \cdot \Delta T \cdot q \qquad (1)$$

At our site, as in most cases, the energy exchange fluid is water, so ρ and c are the density and specific heat capacity of water, respectively. The water flow rate, supply temperature, and return temperature are measured every 15 min for the observed GHX system. So the ERT for the given 15-min interval is multiplied by 15 min to calculate the total energy exchanged over a 15-min interval. Then, the value of the energy exchanged over a certain period is calculated by summing the absolute values of the energy exchange for that period.

In addition, the energy into and out of the geothermal field can be determined by summing either positive or negative exchanges indicating differences in energy flow directions. For our purposes, a positive value represents heat moving from the exchange fluid into the field, while a negative value represents heat moving from the field and into the exchange fluid. All the positive values are summed to find the total heat moved into the field over a period, while all the negative values can be summed to find the total heat moved from the field over the same period.

3.2 Life Cycle Assessment—Goal and Scope

As defined in ISO 14040 and 14044 (Rebitzer et al. 2004), the first of four key phases in any LCA is defining the Goal and Scope, including process parameters and boundary conditions. We performed an LCA to assess the embodied energy associated with constructing the 2,596 geothermal exchange wells in Field 4 (see Figure 1), including raw material extraction, materials processing, manufacture, transportation, and field construction. This assessment quantifies the embodied energy specific to the procurement and construction of the field to assist in evaluating design alternatives. The framework of this LCA three of the five life cycle stages: material production, material and equipment transport, and field construction. The material production stage involves the acquisition of raw materials and the manufacturing of materials. Material transport and construction include the distance to the project site, the methods used to transport materials, the installation of the exchange wells, and the installation of specific surface components (e.g., laterals, headers, and vaults). Figure 4 shows a schematic of the evaluated life cycle stages with a dashed line indicating the boundary of this LCA.

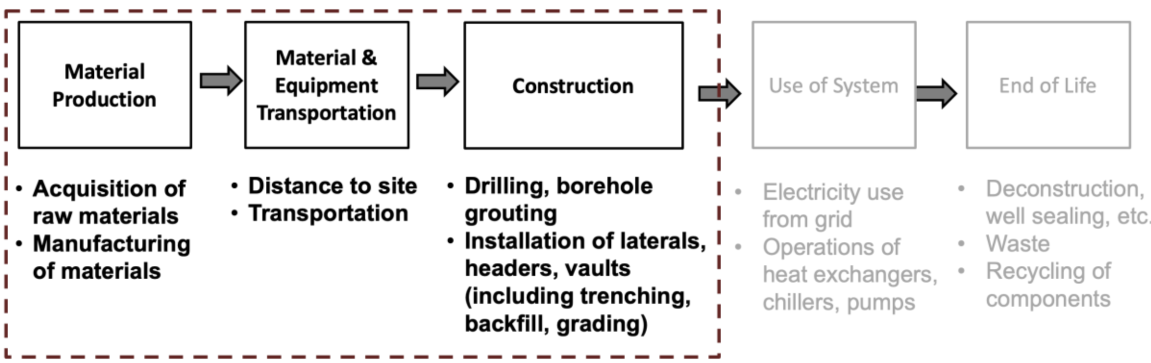

Figure 4: Schematic diagram summarizing the stages of the LCA evaluated (in bold, dashed boundary) within this study.

Our LCA's goal, scope, and system boundary focused on the materials and processes with the most significant environmental impacts. Because material acquisition and installation of geothermal exchange wells typically comprise a significant portion of the system's environmental impacts, the components of drilling and installing GHX wells were investigated in detail. Figure 5 documents the inventory flow diagram showing a breakdown of the scope of the construction and use of the geothermal system.

3.3 Life Cycle Inventory

In the second phase of an LCA—Life Cycle Inventory, LCI—raw materials and energy inputs are defined and linked to emissions and material depletions. For this project, an inventory of impacts was incorporated into an LCA spreadsheet tool as collected using SimaPro version 8.5.2 and TRACI version 2.1 Impact Assessment Methodology. SimaPro is a professional LCA tool used to collect, analyze, and monitor a product's or service's sustainability performance. SimaPro measures the environmental impact of products across all life cycle stages and assists with identifying hotspots in the supply chain, from raw material extraction to manufacturing, distribution, use, and disposal. Figures 4 and 5 summarize the inventory of individual component impacts used within SimaPro.

Relevant to material production, transportation, and construction, estimates for horizontal trenching, backfill, drilling, grouting and HDPE piping were derived from the Geothermal Field 4 design plan sets. The design plan sets show the lengths of piping and trenching and label the use of different pipe sizes. Likewise, the plan sets also show the design of vertical boreholes. HDPE pipe manufacturers provide the weight of HDPE per unit length of pipe for different pipe sizes. With the total lengths of each pipe size calculated from the design plan sets and the weight per unit length of each pipe size, the total mass of HDPE used in piping was calculated. Additionally, the plan sets contained cross-sections of the trenching and boreholes used for trenching, backfill, and grouting volume calculations. The volume of concrete used in the vaults was estimated based on dimensions obtained from the plan sets. It was assumed that there is no losses during the construction.

An important component of analyzing a district-scale geothermal exchange field is the amount of energy required during the construction of the field. Fuel consumption during the transportation of equipment and components and construction activities (e.g., drilling, excavation, and backfill) can account for a significant share of energy consumption. The other primary source of energy consumption is the production of material used in the construction of the geothermal exchange field. Fuel consumption rates were derived from the Department of Energy's "Transportation Energy Handbook" (US DOE 2008), and conversion factors were used to convert BTU to m^3 of diesel fuel per kg·km (Hofstrand 2007). In the present work, we focus on the energy consumption and emissions related to the BOF, including well infrastructure and earthwork.

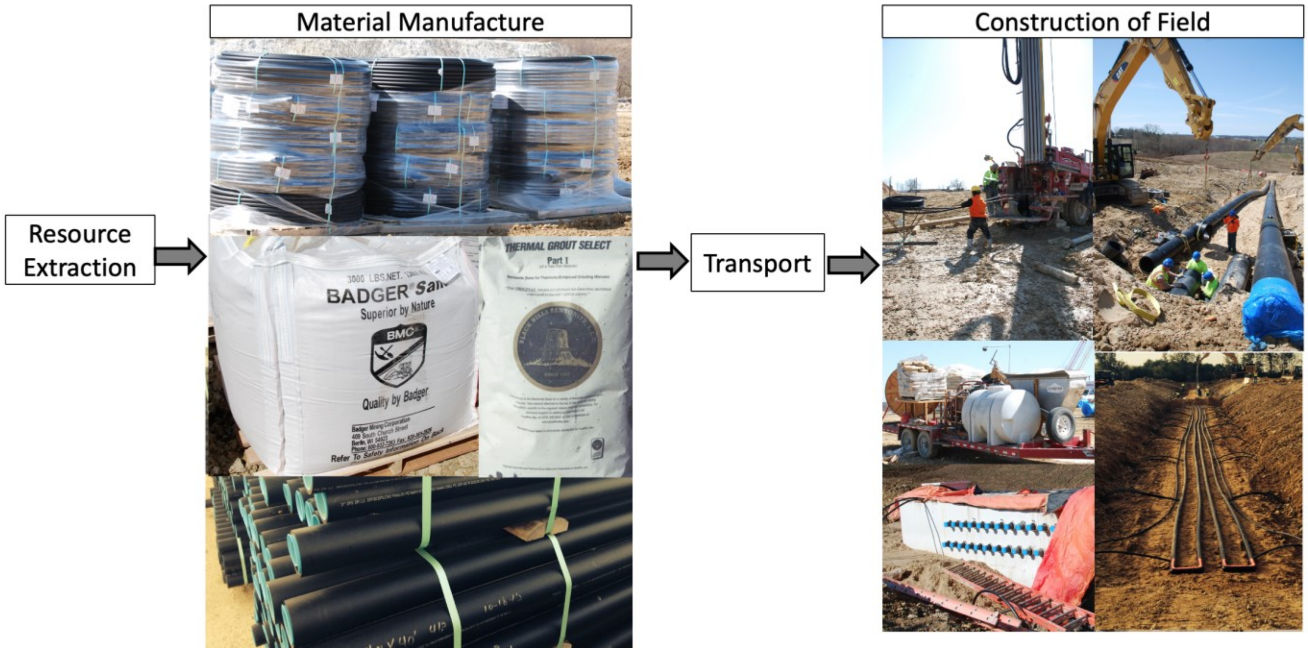

Figure 5: Flow diagram representing the scope of the LCA, including the components that comprise the construction of field 4..

3.4 Life Cycle Impact Assessment, LCIA

The impact categories within this LCA tool are ozone depletion, global warming potential (GWP), smog, acidification, eutrophication, and fossil fuel depletion. Ozone depletion measures the levels of chlorofluorocarbons (CFCs), which are ozone-depleting substances. High concentrations of CFCs lead to more harmful UV radiation reaching the Earth's surface, have adverse human health risks, and pose threats to terrestrial and aquatic ecosystems (Solomon 1999). GWP measures CO_2 levels in the atmosphere, which absorbs sunlight and solar radiation, leading to elevated global temperatures (Eckaus 1992). Smog is a measure of O_3, a reaction of NO_x and volatile organic compounds (VOCs) in the atmosphere, has associated human health risks, and leads to reductions in air quality. Acidification relates to SO_2 concentrations, potential groundwater and surface water impacts, and threats to soil and aquatic organisms. Eutrophication quantifies levels of nitrogen, which is a limiting nutrient. Eutrophication causes dense plant life growth and animal life death in aquatic bodies due to a lack of oxygen. This issue is critical in areas with significant agriculture markets, as fertilizer collects in surface water runoff and deposits nitrogen in surrounding lakes, rivers, and streams (Harris et al. 2017). Lastly, fossil fuel depletion is measured in terms of MJ surplus, defined as the total additional future cost to the global society due to the production of one resource unit. It relates to future global production, specifically resource extraction cost and recycling rate (Ponsioen 2013). These impact categories guide users to evaluate a product's or service's overall environmental impacts.

Each impact category's life cycle impacts for this district-scale geothermal field were compiled. Each impact was queried from the SimaPro database as one unit so that the spreadsheet user can adjust the values for the materials according to the specific design analyzed. Table 2 shows the unit impacts for the geothermal exchange field. Then, Table 3 presents the quantities for each component and their unit impacts. We assume approximate impact values related to the material properties (e.g., type of earth backfill) and transportation of materials such as design input of concrete, backfill, and plastics. Based on our presence on-site during the construction phase, we understand that five drill rigs operated for 12 h d^{-1} over much of the construction phase, and each drilling rig consumed approximately 1.0 m^3 fuel per d (Walker 2023). Moreover, the capacity of a concrete mixer was assumed to be 18.5 t; thus, approximately 17 truckloads of concrete were transferred to the field in total. For the transportation of backfill and HDPE pipes, we assumed that each truck holds 40 t (5 truckloads in total) and 10 t (85 truckloads in total) material, respectively. A sensitivity analysis of the assumptions could be performed to evaluate the variations in embodied energy based on these assumptions. However, such a sensitivity analysis is not within the scope of this paper.

Table 2: Inventory showing the unit impacts of material procurement, transportation, and construction of Field 4.

Lifecycle Stage, Components & Processes		Impact Categories					
Material Production		Impact Inventory					
Materials	**SimaPro Process and Unit**	**Total kg CFC eq**	**Total kg CO_2 eq**	**Total kg O_3 eq**	**Total kg SO_2 eq**	**Total kg N eq**	**Total MJ surplus**
Concrete	1 m^3 Concrete, normal {RoW}| market for | Alloc Def, U	1.85E-05	2.24E+02	1.38E+01	7.22E-01	2.68E-01	1.69E+02
HDPE	1 kg HDPE pipes	0.00E+00	2.48E+00	1.12E-01	9.46E-03	2.16E-04	1.11E+01
Silica Sand	1 kg silica sand (dry, medium fine)	6.01E-06	9.23E-03	1.50E-03	6.10E-04	1.65E-05	1.50E-01
Bentonite	1 kg bentonite	4.70E-08	4.34E-01	1.07E-03	1.07E-03	6.25E-03	1.12E-01
Graphite	1 kg graphite	3.50E-08	1.38E+00	1.32E-03	1.32E-03	7.50E-05	4.50E-01
Material Transport & Construction							
Transportation of Materials	**SimaPro Process and Unit**	**Total kg CFC eq**	**Total kg CO_2 eq**	**Total kg O_3 eq**	**Total kg SO_2 eq**	**Total kg N eq**	**Total MJ surplus**
Transport of backfill	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Transport of other construction materials	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Transport of construction equip.	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Transport of HDPE	from Chicago	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Construction of Wells	**SimaPro Process and Unit**	**Total kg CFC eq**	**Total kg CO_2 eq**	**Total kg O_3 eq**	**Total kg SO_2 eq**	**Total kg N eq**	**Total MJ surplus**
Drilling (comb. of fuel)	1 m Deep well, drilled, for geothermal power {RoW}| deep well drilling, for deep geothermal power | Alloc Def, U	2.51E-04	3.92E+03	2.04E+02	1.89E+01	1.67E+01	2.67E+03
Pumping cement (comb. of fuel)	1 h Machine operation, diesel, < 18.64 kW, generators {GLO}| machine operation, diesel, < 18.64 kW, generators | Alloc Def, U	1.06E-06	4.37E+00	7.25E-01	2.57E-02	4.13E-03	9.35E+00
Pumping water (comb. of fuel)	1 h Machine operation, diesel, < 18.64 kW, generators {GLO}| machine operation, diesel, < 18.64 kW, generators | Alloc Def, U	1.06E-06	4.37E+00	7.25E-01	2.57E-02	4.13E-03	9.35E+00
Trenching	**SimaPro Process and Unit**	**Total kg CFC eq**	**Total kg CO_2 eq**	**Total kg O_3 eq**	**Total kg SO_2 eq**	**Total kg N eq**	**Total MJ surplus**
Excavating	1 h Excavator, technology mix, 100 kW, Construction GLO	4.39E-12	2.00E-03	2.00E-04	9.49E-06	5.40E-07	4.02E-03

Table 3: Total impacts of material procurement, transportation and construction of Field 4.

Lifecycle Stage, Components & Processes					Impact Categories					
Material Production					Total Impact					
Materials	**Design Input**	**Unit**	**Functional Input**	**Unit**	**kg CFC eq**	**kg CO_2 eq**	**kg O_3 eq**	**kg SO_2 eq**	**kg N eq**	**MJ surplus**
Concrete	1.25E+02	m^3	1.25E+02	m^3	2.32E-03	2.80E+04	1.72E+03	9.03E+01	3.35E+01	2.12E+04
HDPE	8.53E+05	kg	8.53E+05	kg	0.00E+00	2.12E+06	9.59E+04	8.07E+03	1.84E+02	9.51E+06
Sand	2.23E+07	kg	2.23E+07	kg	1.34E+02	2.06E+05	3.35E+04	1.36E+04	3.69E+02	3.35E+06
Bentonite	6.09E+06	kg	6.09E+06	kg	2.86E-01	2.64E+06	6.51E+03	6.51E+03	3.80E+04	6.82E+05
Graphite	6.09E+06	kg	6.09E+06	kg	2.13E-01	8.40E+06	8.04E+03	8.04E+03	4.57E+02	2.74E+06
Material Transport & Construction										
Transportation of Materials	**Design Input**	**Unit**	**Functional Input**	**Unit**	**kg CFC eq**	**kg CO_2 eq**	**kg O_3 eq**	**kg SO_2 eq**	**kg N eq**	**MJ surplus**
Transport of Concrete	4.50E+01	mi	2.28E+04	T km	5.24E-04	2.08E+03	1.63E+02	7.81E+00	2.22E+00	4.66E+03
Transport of Backfill	4.50E+01	mi	2.51E+06	T km	5.78E-02	2.29E+05	1.79E+04	8.62E+02	2.45E+02	5.13E+05
Transport of Construction Equip.	4.50E+01	mi	1.45E+04	T km	3.34E-04	1.32E+03	1.03E+02	4.97E+00	1.41E+00	2.96E+03
Transport of Plastic Materials	1.25E+02	mi	1.71E+05	T km	3.94E-03	1.56E+04	1.22E+03	5.87E+01	1.67E+01	3.50E+04
Construction	**Design Input**	**Unit**	**Functional Input**	**Unit**	**kg CFC eq**	**kg CO_2 eq**	**kg O_3 eq**	**kg SO_2 eq**	**kg N eq**	**MJ surplus**
Drilling	519.20	d	31152.00	h	7.83E+00	1.22E+08	6.35E+06	5.88E+05	5.19E+05	8.31E+07
Pumping Grout	519.20	d	10384.00	h	1.10E-02	4.54E+04	7.53E+03	2.66E+02	4.29E+01	9.71E+04
Pumping Water	519.20	d	10384.00	h	1.10E-02	4.54E+04	7.53E+03	2.66E+02	4.29E+01	9.71E+04
Construction of Vaults	30.00	d	360.00	h	3.81E-04	1.57E+03	2.61E+02	9.23E+00	1.49E+00	3.37E+03
Laterals and Headers	300.00	d	3600.00	h	3.81E-03	1.57E+04	2.61E+03	9.23E+01	1.49E+01	3.37E+03
Clearing/Grubbing	300.00	d	3600.00	h	3.81E-03	1.57E+04	2.61E+03	9.23E+01	1.49E+01	3.37E+04
Final Grading	30.00	d	360.00	h	3.81E-04	1.57E+03	2.61E+02	9.23E+00	1.49E+00	3.37E+03
Trenching	**Design Input**	**Unit**	**Functional Input**	**Unit**	**kg CFC eq**	**kg CO_2 eq**	**kg O_3 eq**	**kg SO_2 eq**	**kg N eq**	**MJ surplus**
Excavating	5.19E+02	d	6.23E+03	h	2.73E-08	1.25E+01	1.24E+00	5.92E-02	3.36E-03	2.50E+01

4. INTERPRETATION

4.1 Geothermal Field Energy Exchange

We calculated the energy exchanged, heat into the geothermal field, and heat from the geothermal field for each year from 2015 through September 2022 for Geothermal Field 4. Table 4 shows the results of these calculations. The absolute heat exchanged from 2015 to September 2022 was 646 TJ. The mean absolute heat exchanged per year from 2015 to 2021 was 81.0 TJ. 2022 was not included in the mean calculation, as we only compiled data through September 2022.

Table 4. Absolute energy exchanged and heat into/from the field from 2015 through September of 2022.

Year	Heat (TJ)	Heat into the Field (TJ)	Heat from the Field (TJ)
2015	62.4	62.1	-0.280
2016	91.8	87.1	-4.72
2017	69.1	55.4	-13.7
2018	86.4	60.5	-25.9
2019	94.4	51.8	-42.7
2020	81.7	64.7	-17.0
2021	80.9	65.3	-15.6
2022 (Jan-Sept)	79.1	67.4	-11.7
Total (Jan 2015-Sept 2022)	646	514	-131
Yearly Average (2015-2021)	81.0	63.9	-17.1

The absolute energy exchanged varies from a low of 62.4 TJ in 2015 to a high of 94.4 TJ in 2019. For reference, the average household in Wisconsin consumes approximately 8,500 kW h of electricity each year (US EIA 2009); thus, the yearly average of Epic's Field 4 exchange of 81 TJ is equivalent to 2,650 Wisconsin households on an annual basis. Although the absolute thermal energy exchanged varies yearly, the value remains relatively steady (Table 4). Figure 6 shows the heat into and from the field for each year from 2015 to September 2022; while Figure 7 shows the average heat into and from the field by month for this period. The total heat into and from the field largely depends on how the field is used from year to year. The first year the field was primarily used as a heat sink with limited use as a heat source. Since 2015, the field has continued to be cooling dominant, as the heat into the field is greater that the heat from the field year over year.

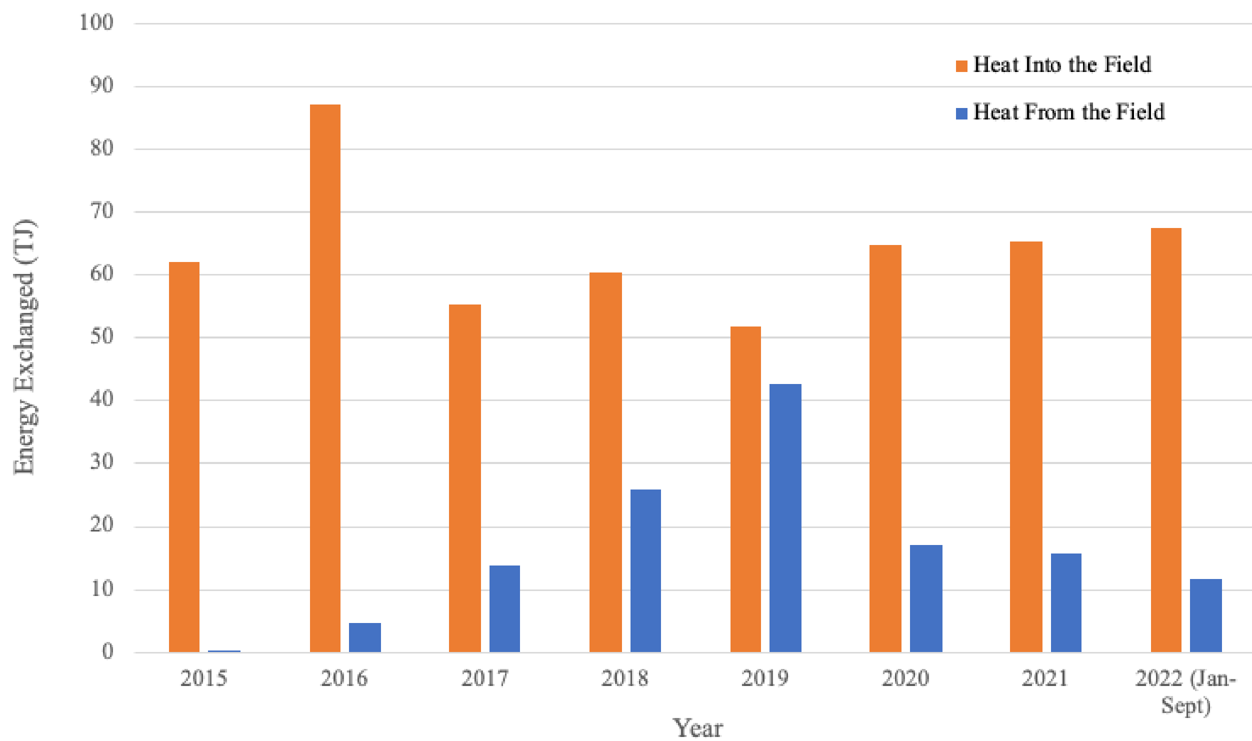

Figure 6: Heat exchanged year-over-year. Values calculated with data from January 2015 through August 2022

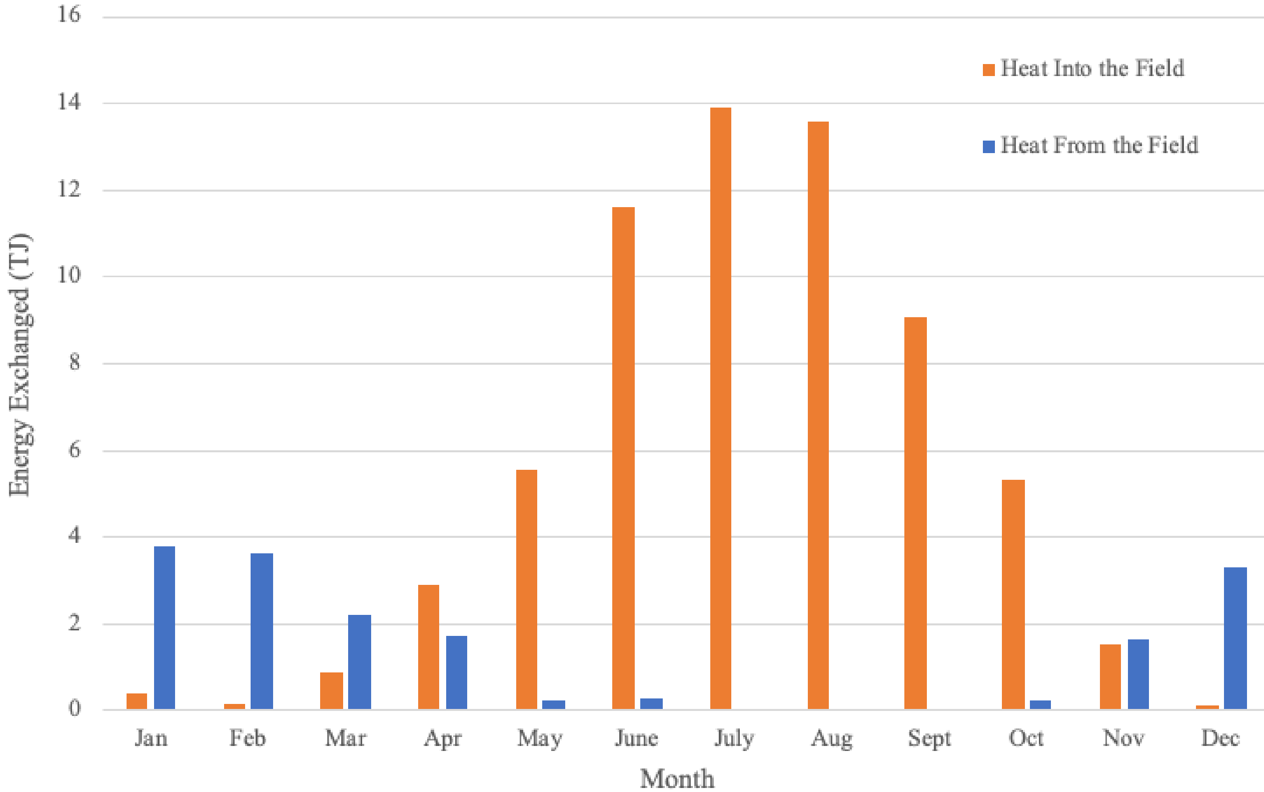

Figure 7: Average heat exchanged monthly. Values calculated with data from January 2015 through August 2022

4.2 Life Cycle Impacts

We use the inventories of unit impacts shown in Table 2 to calculate the life cycle impacts of a district-scale geothermal exchange field (Epic's Field 4). Overall, the construction of the geothermal exchange wells had a significant impact, specifically related to the drilling and installation of the geothermal exchange wells. These impacts could change noticeably depending on the selected inventory from the database in SimaPro® and could be adjusted if better diesel consumption data is compiled. A table showing the overall lifecycle totals for each impact category is summarized in Table 5. As seen in Table 5, drilling and installing the geothermal exchange wells contributes the most to GWP (kg eCO_2). This is also seen in Figure 8, where the stages are compared.

Table 5. Impact totals for each lifecycle stage as well as total lifecycle impacts for Geothermal Exchange Field 4

Stages	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Material Production	1.35E+02	1.34E+07	1.46E+05	3.63E+04	3.91E+04	1.63E+07
Transportation of Materials	6.26E-02	2.48E+05	1.94E+04	9.33E+02	2.65E+02	5.56E+05
Vertical Well Drilling & Grouting	7.85E+00	1.22E+08	6.37E+06	5.89E+05	5.19E+05	8.33E+07
Balance-of-Field	8.38E-03	3.46E+04	5.74E+03	2.03E+02	3.27E+01	4.38E+04
Total	1.43E+02	1.36E+08	6.54E+06	6.26E+05	5.58E+05	1.00E+08

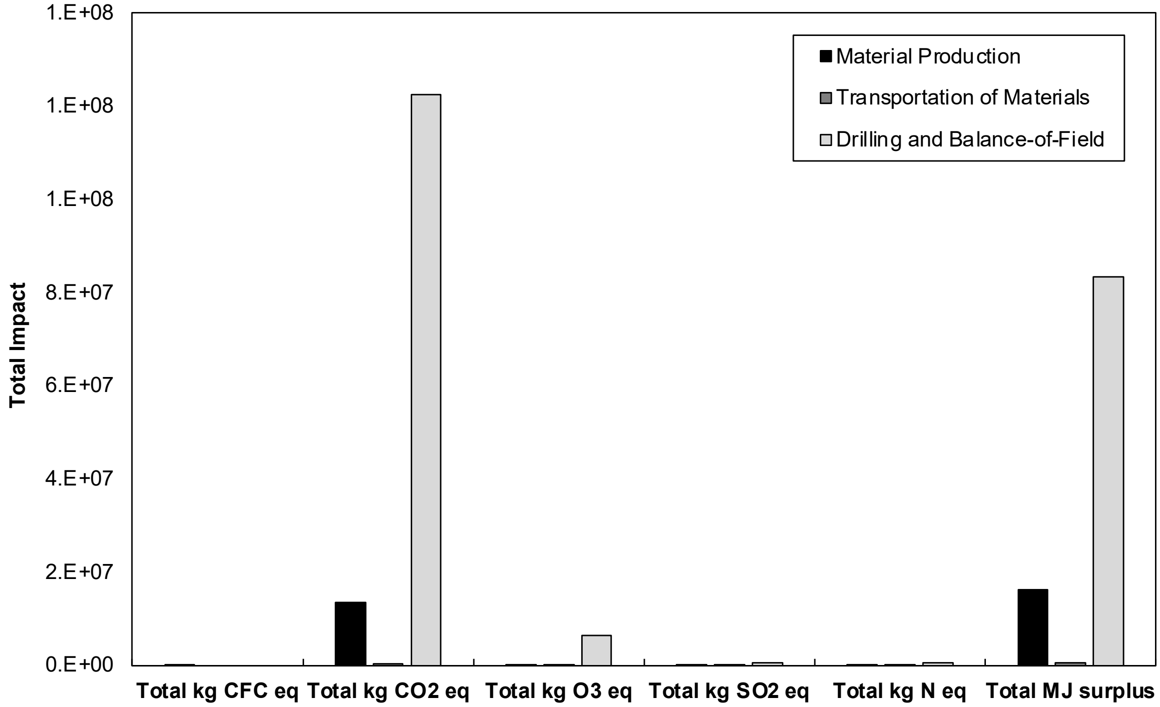

Figure 8: Impact comparison of the life cycle stages.

Figure 8 shows the high impacts associated with the construction phases; specifically, the GWP impact (as measured by CO_2 equivalents) and energy consumption. When investigating those impacts further, the diesel required to drill these 2,596 152-m-deep GHX wells is the top contributor to these impacts. The second largest contributor to GWP and energy consumption is the material production phase. Figure 9 shows the significant embodied energy associated with the drilling of wells compared to other LCA categories, and drilling contributes almost 80% of the overall energy consumption. Embodied energy in the use of diesel, primarily during the material transport and construction phase of the project, is the primary contributor to the fossil fuel depletion associated with the project. However, transportation and Balance-of-Field construction (all construction besides drilling) do not contribute nearly as much to diesel use as in the drilling and grouting of vertical wells. The depth and number of the GHX wells also require a significant amount of HDPE for the exchange loop and horizontal piping system. In many LCAs of geothermal systems, HDPE would be expected to be a top contributor to the overall GWP and embodied energy of the system, and it is a significant contributor in this case as well. This is because HDPE has an embodied energy of 11.1 MJ kg^{-1}.

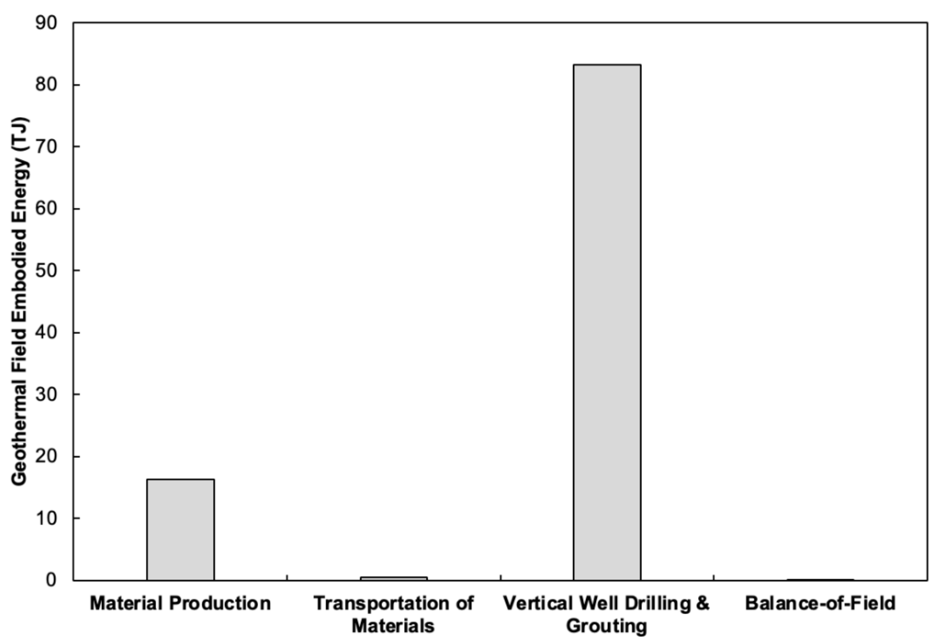

Figure 9: Distribution of embodied energy across the four categories necessary for the construction of GHX Field 4.

5. CONCLUSIONS

We performed a life cycle assessment of a district-scale geothermal exchange field—2,596 152-m-deep boreholes equating to roughly 395 km of vertical drilling—in the upper Midwest of the US to highlight the significant areas of energy consumption and environmental emissions associated with geothermal field development. The equivalent CO_2 emissions and embodied energy required in the drilling of the GHX wells dominate the LCA. In our case, over 80% of the embodied energy is 'consumed' in the drilling process, which also corresponds to over 80% of the CO_2 equivalent emissions. Overall, total embodied energy for field construction equates to 100 TJ, which is "paid back" in 14.5 months by the average absolute thermal energy exchanged in the field. The results of the LCA show that top contributors to embodied energy consumption in borefield procurement and construction are related to borehole drilling and well completion. Thus, GHX systems that efficiently minimize the number of GHX wells and cumulative vertical (and horizontal collector) length are more economically viable and energy sustainable. In addition, the embodied energy in this LCA is very sensitive to the diesel consumption rate per drilled well. Any deviation around the 1.0 m^3 of diesel we estimated to drill each GHX well at this site—such as easier drilling through 'soft' rock or difficult drilling through 'hard' rock or voided rock—would significantly impact the energy payback period.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge Epic Systems Corporation for their generous contributions of time, talent, and resources in the ongoing development of this research. The Morse Company, General Heating and Air Conditioning Inc., Salas O'Brien (formerly MEP Associates), JP Cullen, and Teel Plastics all donated time, materials, and expertise, without which this research would not have been possible. We acknowledge the National Science Foundation for sponsoring undergraduate research opportunities during the early phases of this project under Award # 1156674. We thank Adam McDaniel (Westwood Professional Services) for preparing the initial Matlab code to process and calibrate FO DTS data and Alicia Luebbe (UW–Madison) for conducting quality control checks on the spreadsheets prepared to conduct the LCA. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding organizations.

7. REFERENCES

Adolfsson, M., & Rashid, S.: Life Cycle Assessment and Life Cycle Cost of Heat Exchangers. Thesis, Chalmers University of Technology, (2016).

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): Geothermal Energy In 2011 ASHRAE Handbook - HVAC Applications." Ch. 34, (2011).

Banerjee, S.B.: Teaching Sustainability, A Critical Perspective. International Graduate School of Management.

Bloom, E. and Tinjum, J.M.: Fully Instrumented Lifecycle Analyses for Residential Geo-Exchange System, Proceedings of ASCE Geo-Chicago. ASCE Geotechnical Special Publication 270, (2002), 114–124.

BP.: Sustainability Report, (2002).

Eckaus, R. S.: Comparing the Effects of Greenhouse Gas Emissions on Global Warming, The Energy Journal, 13, (1992). 25–35.

Florea, L.J., Hart, D., Tinjum, J.M., and Choi, C.: Potential Impacts to Groundwater from Ground-Coupled Geothermal Heat Pumps in District Scale. Groundwater, 55, (2017), 8–9.

Fridleifsson, I.R.: The Possible Role and Contribution of Geothermal Energy to the Mitigation of Climate Change. IPCC Scoping Meeting on Renewable Energy Sources. Luebeck, Germany, (2008).

Gagnon L, Belanger C, Uchiyama Y.: Lifecycle Assessment of Electricity Generation Options: The Status of Research in Year 2001. Energy Policy 30, (2002), 1267–1278.

IPCC: Intergovermental Panel on climate Change. Report of the 33rd session of the IPCC, Abu Dhabi, United Arab Emirates, (2011).

ISO. Life Cycle Assessment - Principles and Framework. Retrieved from International Organization for Standardization: https://www.iso.org/obp/ui/#iso:std:iso:14040:en. (2006).

ISO 14040 and ISO 14044. Int J LCA 11, (2006), 80 – 85.

Harris, T. D., Smith, V. H., Graham, J. L., Van de Waal, D. B., Tedesco, L. P., and Clercin, N.: Combined Effects of Nitrogen to Phosphorus and Nitrate to Ammonia Ratios on Cyanobacterial Metabolite Concentrations in Eutrophic Midwestern USA Reservoirs. Inland Waters, 6, (2017), 199-210.

Hart, D.J., Tinjum, J.M., Fratta, D., Thomas, L.K., and Carew E.L.: Radiators or Reservoirs, Heat Budgets in District-Scale Ground-Source Geothermal Exchange Fields. Proceedings, 47th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-223, (2022).

Hofstrand D.: Energy Measurements and Conversions. Iowa State University Extension and Outreach, (2007).

Lee, J.C., Edil, T.B., Tinjum, J.M., and Benson, C.H.: Quantitative Assessment of Environmental and Economic Benefits of Using Recycled Construction Materials in Highway Construction, Transportation Research Record, Journal of the Transportation Research Board. 2158, (2010), 138–142.

McCabe, K., Beckers, K., Young, K.R., and Blair, N.: GeoVision Analysis Supporting Task Force Report: Thermal Applications—Quantifying Technical, Economic, and Market Potential of Geothermal District Heating Systems in the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71715, (2019).

McDaniel. A., Tinjum, J.M., Hart, D., and Fratta, D.: Dynamic Calibration for Permanent Distributed Temperature Sensing Networks, IEEE Sensors Journal, 18(6), (2018a), 2342–2352.

McDaniel. A., Fratta, D., Tinjum, J.M., and Hart, D.: Long-term District-scale Geothermal Exchange Borefield Monitoring with Fiber Optic Distributed Temperature Sensing, Geothermics, 72C, (2018b), 193–204.

Metz, B., Davidson, Bosch, P.R., Dave, R., and Meyer, L.A.: (eds). Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA, (2007).

Meyer, L.: Thermophysical Properties of Wisconsin Rocks for Application in Geothermal Energy (Master's Thesis). University of Wisconsin-Madison, Madison, Wisconsin. (2013).

Özdoğan Dölçek, A., Atkins, I., Harper, M.K., Tinjum, J.M., and Choi, C.Y.: Performance and Sustainability of District-Scale Ground Coupled Heat Pump Systems, Geotechnical and Geological Engineering, 35(2), (2017), 1–14.

Ponsioen, T. The Surplus Cost Method. Retrieved from PRéSustainability: https://www.pre-sustainability.com/news/the-surplus-cost-method-introduction. (2013, March 15).

PRé Consultants. Introduction to LCA with SimaPro 7. 2010. Retrieved from http://www.presustainability.com/download/manuals/SimaPro7Introduction ToLCA.pdf.

Rajaei, M., and Tinjum, J. M.: Life Cycle Assessment of Energy Balance and Emissions of a Wind Energy Plant, Geotechnical and Geological Engineering. doi:10.1007/s10706-013-9637-3. (2013).

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B P., Pennington, D. W.: Life cycle assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications, Environment International, 30, (2004), 701– 20.

Ren, C., Deng, Y., and Cao, S. J.: Evaluation of Polyethylene and Steel Heat Exchangers of Ground Source Heat Pump Systems Based on Seasonal Performance Comparison and Life Cycle Assessment. Energy and Buildings, 162, (2020), 54–64.

Solomon, S.: Stratospheric ozone depletion: A Review of Concepts and History. Reviews of Geophysics, 37,(1999), 275–316

Thomas, L.K., Tinjum, J.M., and Holcomb, F.H.: Environmental Life Cycle Assessment of a Depp Direct-use Geothermal System in Champaign, Illinois. Proceedings, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-216, (2020).

United Nations General Assembly.: Report of the World Commission on Environment and Development: Our Common Future. Annex to Document A/42/427, Development and International Co-operation: Environment, (1987).

US Department of Energy: Transportation Energy Data Book, (2008).

US Energy Information Agency: Residential Energy Consumption Survey, (2009), www.eia.gov/consumption/residential/ [accessed 29 January 2023].

US Energy Information Agency, Electric Power Monthly September, (2022), https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php [Accessed 10 December 2022].

Walker, M.D., Meyer, L.L., Tinjum, J.M., and Hart, D.J.: Thermal Property Measurements of Stratigraphic Units with Modeled Implications for Expected Performance of Vertical Ground Source Heat Pumps, Geotechnical and Geological Engineering, 33(2), (2015), 223–238.

Walker, B. Personal communication between James Tinjum and Bruce Walker of the Wisconsin Geothermal Association, (January 27, 2023).