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Environmental Life Cycle Assessment of a Deep Direct-use Geothermal System in Champaign, Illinois

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ABSTRACT

The feasibility of implementing a deep direct-use (DDU) geothermal energy system (GES) was assessed as the primary thermal energy source in agricultural research facilities (ARF) at the University of Illinois at Urbana-Champaign (U of IL) campus. This district-scale heating and cooling source will exploit the Illinois Basin (ILB), a low-temperature sedimentary basin with multiple potential sources of geothermal energy, including the Mt. Simon Sandstone (MSS). DDU GES are believed to provide lower-emission alternatives compared to traditional heating and cooling methods; however, low-temperature, high-salinity DDU heat sources are less frequently utilized. The primary objective of this project is to investigate the feasibility of implementing a DDU GES at the U of IL. Several system characteristics are investigated, including the deployment and performance of the DDU GES, well-design alternatives, challenges to GES commercialization, levelized cost of heat, and life cycle environmental impacts. The work in this paper focuses on an environmental life cycle assessment (LCA) to quantify the overall environmental impacts and co-benefits of the system. The LCA was performed using a spreadsheet tool that was simultaneously developed to provide insight into the cradle-to-grave environmental impacts associated with the proposed geothermal system, as well as other DDU systems with similar objectives. This tool allows for a more in-depth analysis of the feasibility of DDU GES with respect to the overall environmental impacts of the system. The impact categories that were evaluated within this LCA tool are ozone depletion, global warming potential (GWP), smog, acidification, eutrophication, and fossil fuel depletion. As an example of the environmental LCA results, with respect to the GWP category, if the ARF were heated through the use of the proposed DDU system, the GWP emissions associated with the use of traditional fuels such as propane and natural gas could be offset in approximately 10 years of operation.

1. INTRODUCTION

A recent initiative of the Department of Energy (DOE) seeks to enable the widespread use of lower-temperature geothermal resources that are shallower than conventional hydrothermal sources, but deeper than geothermal heat pump and other traditional direct-use systems (USDOE 2018). These geothermal resources are believed to bring valuable returns on investment in the near-term. Typical DDU GES utilize a flow of geothermal fluid that is capable of providing heating and cooling to buildings. The overall objective of this study is to determine the feasibility of designing a district-scale geothermal heating system for the ARF campus using a DDU technology.

As part of this effort, a Life Cycle Assessment (LCA) spreadsheet tool was developed to analyze potential environmental benefits of a DDU GES. The LCA spreadsheet tool is a unique contribution to the project that provides further insight into the cradle-to-grave environmental impacts associated with the GES system over the operating life time, as well as other DDU GES with similar objectives. The tool allows for a more in-depth analysis of the feasibility of DDU GES with respect to the overall environmental impacts. For the U of IL assessment, a doublet (two-well) system is evaluated, which is connected to aboveground mechanical system to supply heating to the ARF. The additional of new equipment are assessed for the technical and economic feasibility. The results from this study will also allow geothermal resources from the entirety of the ILB to be assessed and allow the DDU technology to be extended to additional areas of the ILB and other low-temperature sedimentary basins with similar characteristics.

2. BACKGROUND

2.1 Direct-Use Geothermal Energy

The direct use of geothermal energy refers to the thermal utilization of geothermal heat in residential, commercial, and industrial facilities that have an inherent need for a reliable supply of heat. Most applications of DDU technologies require geothermal fluids with low-to-moderate temperatures, which are typically found at depths shallower than resources used for traditional high-temperature power generation methods. DDU technologies has the potential to increase the distribution of geothermal energy in areas with lower heat flow that rely on traditional, high-emission sources of heat. According to data reported by the U.S. Energy Information Administration, the total thermal energy from 0 to 260°C used in 2008 was 33.5 EJ, which is approximately one-third of the entire U.S. demand (Fox et al. 2011). Space heating and water heating, which have end-use temperatures ranging from 40 to 60°C, are responsible for 38% of the total thermal energy demand below 260°C. Utilizing geothermal direct-use through the implementation of DDU projects would offer a relatively sustainable and low-emission alternative to the conventional heat sources supplied by fossil fuels (USDOE 2018).

The concept is to use warm and/or hot water from a subsurface aquifer formation and deliver that heat to a surface application. Once the heat is utilized on the surface, the cooler water is returned to the aquifer through an injection well, where it is mixed with the warmer/hotter water in the aquifer and eventually reused. The temperature of the aquifer can decrease over time due to the recycling of used water through the system. The thermal drawdown rate is dependent on a number of factors, including aquifer size and extraction/injection water temperatures.

2.2 Illinois Basin

The MSS has potential as a geothermal energy source based on pre-initial temperatures and flow rates of fluids. The geothermal energy extracted from this formation within the ILB could, theoretically, be used to heat the ARF located at the Energy Farm on the U of IL. A schematic map of the assessment area within the ILB is provided as Figure 1. In Champaign County, the bedrock surface is masked by Quaternary glacial deposits, ranging in thickness from 40–120 m. Pennsylvanian through Cambrian sedimentary rocks lie below, with a thickness of ~1,982 m (~6,500 ft) Precambrian igneous rocks underlie the sedimentary bedrock (Stumpf et al. 2018). A detailed stratigraphy of the ILB can be found in Damico et al. (2020). A test borehole was completed in the study area in 2016 to determine the geothermal gradient in the shallow subsurface. This borehole identified multiple geologic formations in the Quaternary glacial deposits and Pennsylvanian strata, including the Glasford Formation and Herrin Coal that have a thermogeology that significantly impact heat transport (McDaniel et al. 2018).

Numerous studies by the Illinois State Geological Survey have been completed to characterize the deep geologic formations. The MSS is found at depths of 1,334 to 1,887 m. Based on bottomhole temperatures from well logs, formation water temperature of the MSS ranged from 44–46°C (111–115°F) (Stumpf et al. 2018, 2020).

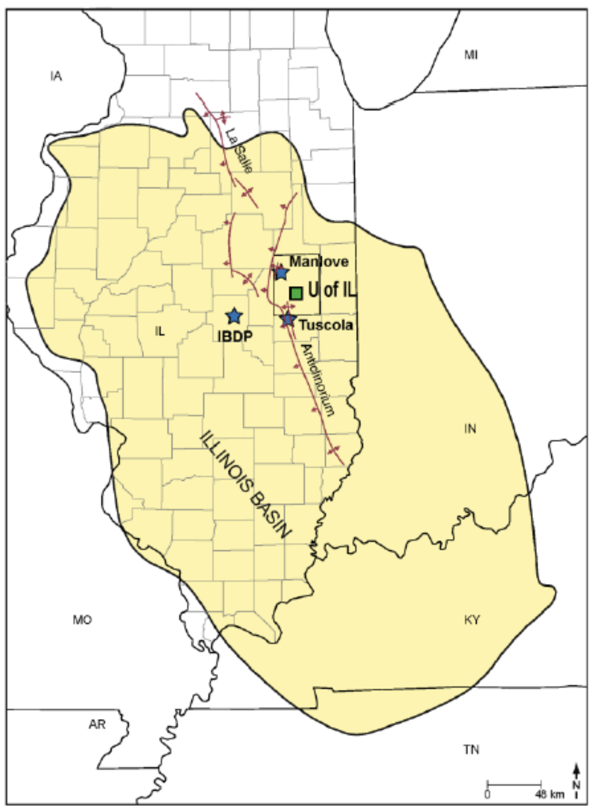


Figure 1: Location of the assessment site within the ILB, shaded in yellow. The study site is denoted by the green box labeled U of IL.

2.3 Life Cycle Assessments

Life Cycle Assessment (LCA) is a technique for assessing the potential environmental aspects and potential aspects associated with a product or service 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 in relation to the study objectives (ISO 2006). Several LCAs have been performed on a variety of products and services, such as wind farms, recycled concrete aggregate, and other geothermal systems.

An LCA of the Glacier Hills Wind Park in south-central Wisconsin was performed in order to highlight the significant areas of energy consumption and emissions associated with wind energy development (Rajaei and Tinjum 2013). A quantitative analysis of the life cycle emissions and environmental impact associated with wind development from construction through operation revealed that transportation of large components from overseas led to significant consumption of fossil fuels, responsible for nearly a quarter of the total greenhouse gas emissions due to transportation. Energy payback time and total equivalent grams of eCO_2 per kWh were also calculated over the lifetime of the wind farm. LCA methodology was also applied to a non-conventional deep insulated single-hole ground source heat pump in order to compare its impacts with conventional heating, ventilation, and cooling methods. The results of the LCA show that top contributors to CO_2 equivalent emissions are heat-exchanger operation, borehole drilling, and circulation pump operation. The sustainability of construction with recycled materials was also evaluated using LCA methodology (Lee 2010). This work involved developing a rating system called the Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^2ST-in-Highways^{TM}). This system compares the environmental and economic life cycle impacts between different construction material methods. Furthermore, this paper developed an AMOEBA graph to compare the impacts between various construction material alternatives and how they reach certain sustainability goals. A similar concept was applied in this LCA methodology for the DDU GES, which is referred to as a spider diagram herein.

3. METHODS AND MATERIALS

3.1 University of Illinois Urbana-Champaign Field Site

The U of IL is a large academic campus with energy needs served by the central Abbott Power Plant, which provides electricity and heat in the form of steam to more than 250 buildings. Currently, there is no significant use of geothermal on the campus, although there are geologic formations below the campus that have been identified as potential sources of low-temperature (<50 °C) geothermal energy (Stumpf et al. 2018). The ARF was analyzed as the end users for the ILB geothermal resource. The study area is located on a 90 km^2 area around the U of IL. There will be six facilities in the ARF in which space heating and pre-heating of domestic water will be used; the Energy Farm, Beef and Sheep Research Laboratory, Poultry Farm, Imported Swine Research Laboratory (ISRL), Dairy Farm, and Feed Mill were analyzed. The heat usage of these facilities varied between buildings as well as seasonally, with annual totals ranging between approximately 791 and 3,348 MMBtu (F&S 2017). A summary of the heat usage for these facilities can be found in Table 1.

Table 1. Energy consumption at the ARF on the U of IL. Fuel type is specified for each location, and varies between propane, natural gas (NG), or combination of the two at specific locations.

ARF Heat Consumption	Energy Farm (Propane)	Beef and Sheep Field Laboratory (NG)	Poultry Farm (NG)	ISRL (NG, Propane)	Dairy Farm (NG)	Feed Mill (NG)	Total
Yearly Total (MMBtu)	2,140	1,006	791	3,348	1,009	1,158	9,452
Annual Avg. Rate (MMBtu/hr)	0.24	0.11	0.09	0.38	0.12	0.13	1.07
Winter 6-month Total (MMBtu/hr)	1,852	959	648	2,995	929	929	8,312
Winter Avg. Rate (MMBtu/hr)	0.42	0.22	0.15	0.68	0.21	0.21	1.89
Maximum Monthly Rate (MMBtu/mo)	365	322	173	770	197	197	2,024
Maximum Monthly Avg. Rate (MMBtu/hr)	0.49	0.45	0.23	1.03	0.26	0.26	2.72

3.2 DDU GES Design

The system will be comprised of both subsurface and surface components. The subsurface components are designed to exploit the geothermal resource in the ILB by using extraction and injection wells equipped with submersible pumps. A concept diagram of the subsurface components GES are shown in Figure 2.The surface equipment includes heat exchangers and possibly a heat pump, as well as a piping system to transport the geothermal fluid to the ARF.

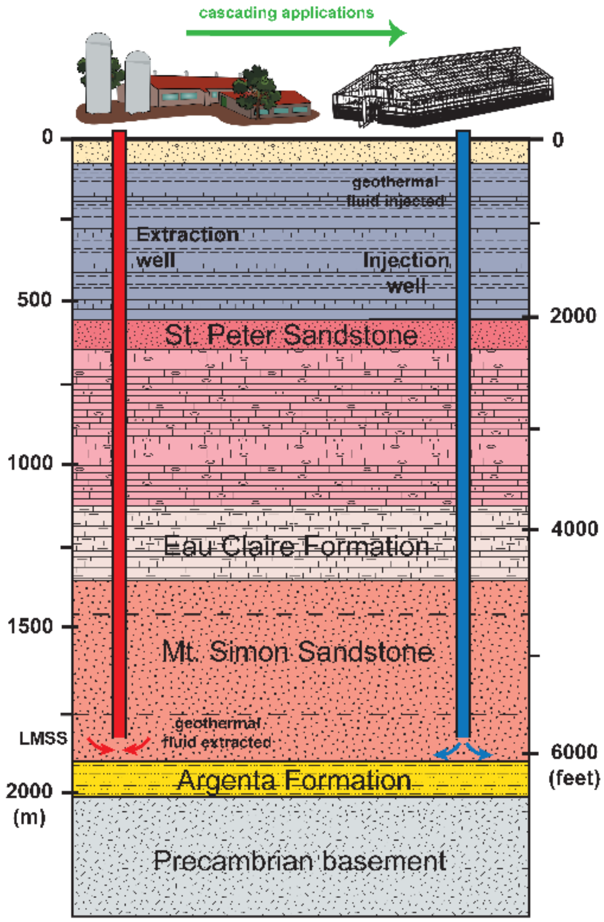
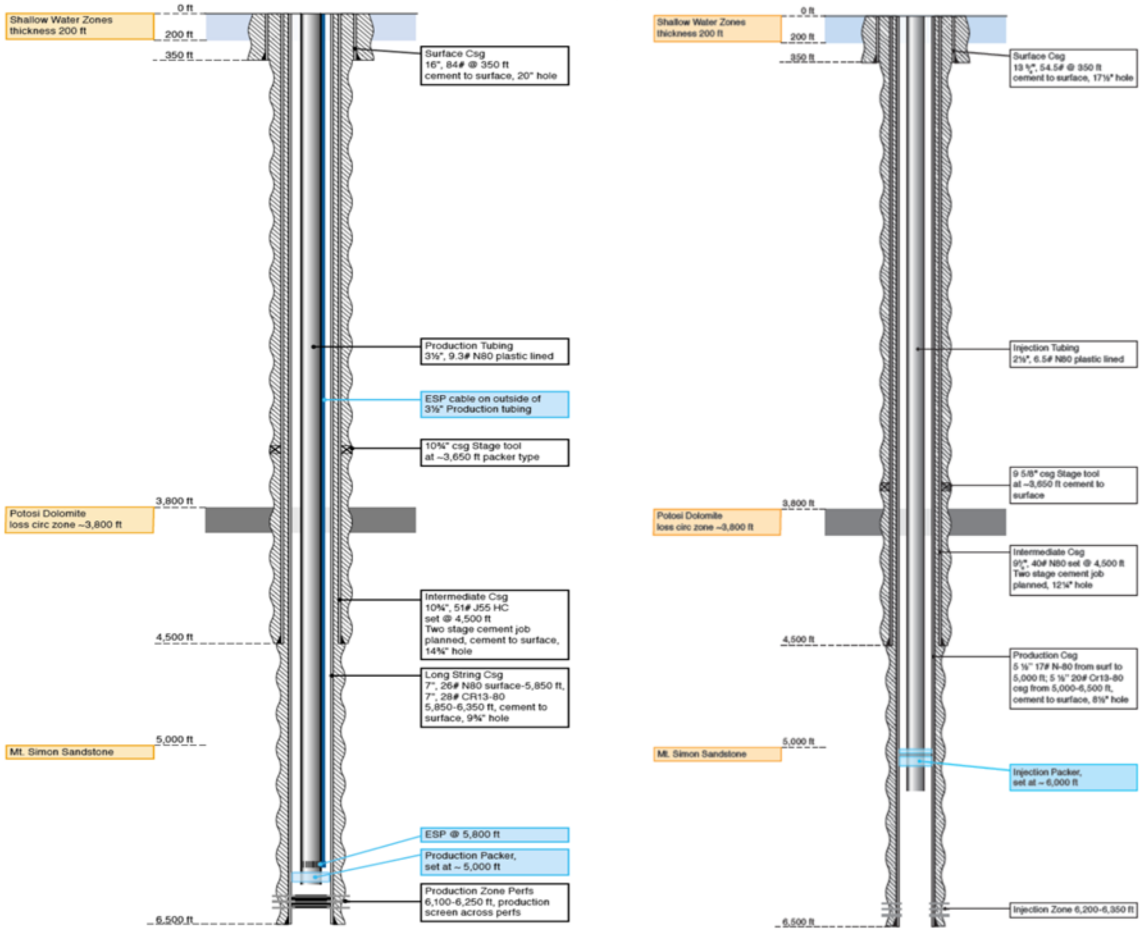


Figure 2: Conceptual diagram of the proposed doublet well system for the DDU GES (Stumpf et al. 2020)

Figure 3 illustrates well designs for the extraction and injection wells. Both wells will be drilled to reach the MSS, with both the extraction and injection wells drilled to a depth of 1981 m (6,500 ft). The extraction well is screened between 1860–1905 m (6,100–6,250 feet) and the injection zone is from 1,890–1,935 m (6,200–6,350 ft). The extraction well contains three casings, a surface casing, an intermediate casing, and a long-string casing. The injection well is designed slightly different, and is comprised of a surface, intermediate, and casing. A more detailed breakdown of the individual well components and materials are described in the following sections. The extraction and injection wells will be located at the margins of the study area, located ~1.5 miles apart (Stumpf et al. 2020). High-density polyethylene (HDPE) pipes will be laid underground to transport the heated supply water to the facilities, and a return line will be placed to discharge the cooler water away from the facilities.

3.3 Methodology

An LCA was performed to assess the environmental impacts associated with the project, including raw material extraction, materials processing, manufacture, distribution, use, disposal, and recycling. The goal of this assessment is to quantify the environmental impacts of the project in order to provide information to assist in evaluating design alternatives. The framework of this LCA is based on four life cycle stages: material production, material transport and construction, use of system, and end of life. The material production stage involves the acquisition of raw materials and manufacturing of materials. Material transport and construction includes a number of parameters including the distance to the project site, the methods used to transport materials, the installation of the extraction and injection wells, as well as the installation of certain surface components (e.g., heat exchangers, generators, pumps, and pipelines). The use of system stage involves the use of electricity, heat transfer to and from the subsurface, operation of a chiller, as well as other operation and maintenance activities. Finally, the end of life stage is focused on the deconstruction and sealing of the extraction and injection wells, well sealing, waste, and transportation of waste. Figure 4 shows a schematic of the four life cycle stages.



(a) (b)

Figure 3: Detailed designs for extraction (a) and injection (b) wells (From Kirksey and Lu 2019).

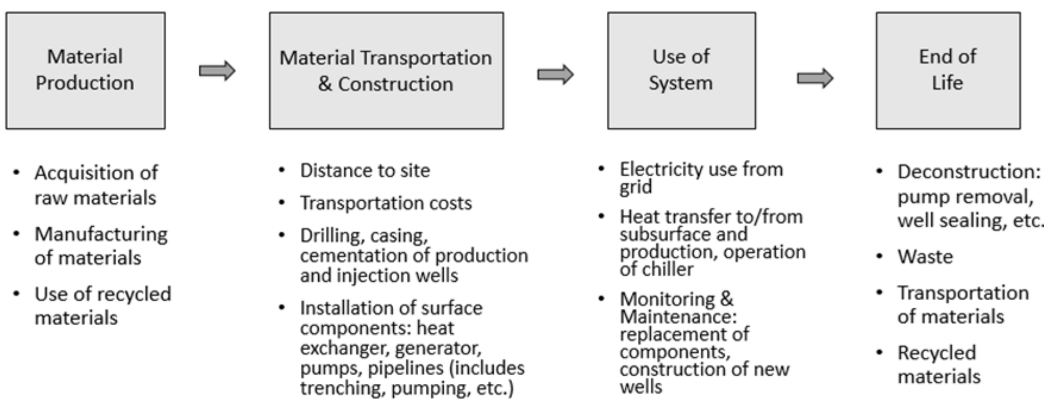


Figure 4: Schematic diagram summarizing the four stages of the LCA.

The goal and scope and system boundary of the LCA was structured to focus on the materials and processes that have the largest environmental impacts. Because material acquisition and installation of the wells typically comprise a significant portion of the environmental impacts of the system, the components of the extraction and injection wells were investigated in detail. An inventory flow diagram showing a breakdown of the scope of the construction and use of the geothermal system is conveyed as Figure 5 (next page).

The inventory of impacts for the LCA spreadsheet tool was 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 the sustainability performance of a product or service. SimaPro measures the environmental impact of products across all life cycle stages, as well as assists with identifying hotspots in the supply chain, from raw material extraction to manufacturing, distribution, use, and disposal. Using the scope diagrams in Figure 5, an inventory of individual component impacts was gathered within SimaPro.

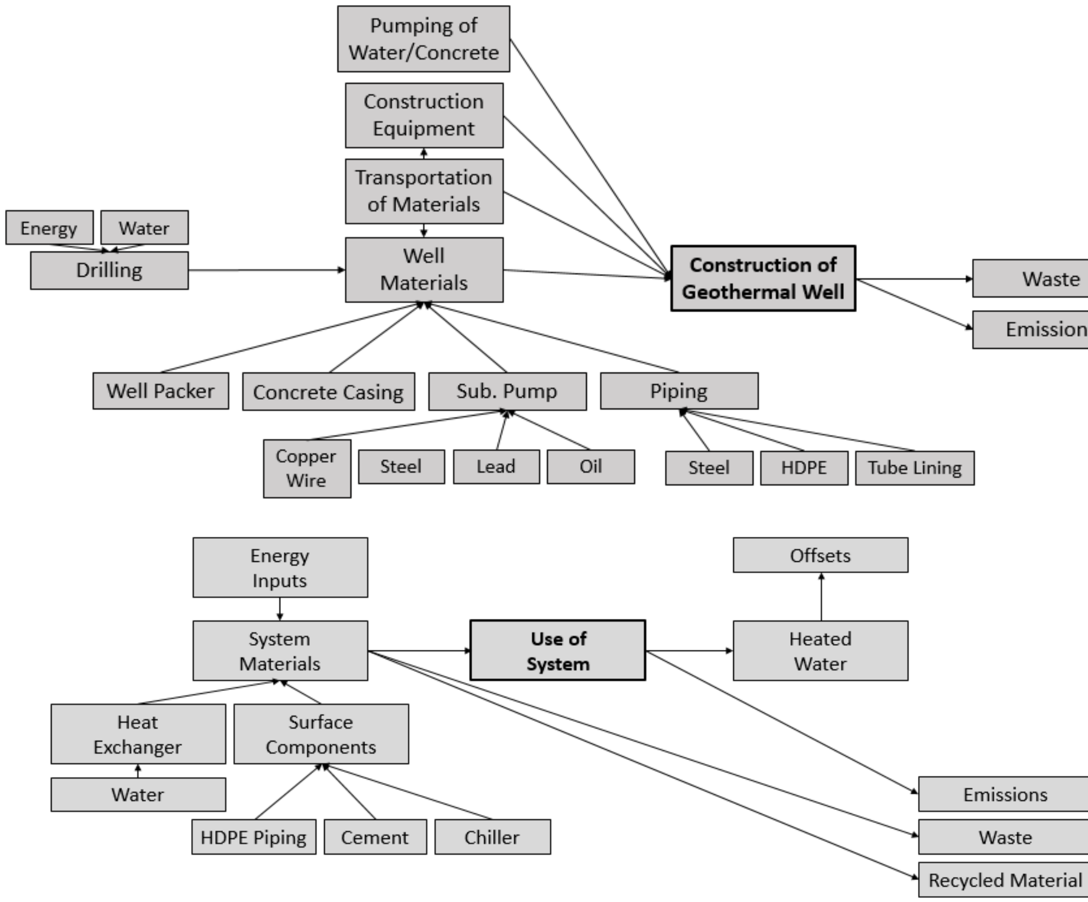


Figure 5: Flow diagram representing the scope of the LCA, including the components that comprise the well design and operation of the GES at the U of IL.

The impact categories that are evaluated within this LCA tool are ozone depletion, 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 and has negative human health risks as well as poses threats to terrestrial and aquatic ecosystems (Solomon 1999). GWP is a measure of 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, which is a reaction of NO_x and VOCs in the atmosphere and has associated human health risks and reductions in air quality. Acidification relates to SO_2 concentrations, which is an acidifying compound with potential groundwater and surface water impacts, including threats to soil and aquatic organisms. Eutrophication quantifies levels of nitrogen, which is a limiting nutrient. Eutrophication causes dense growth of plant life and death of animal life in aquatic bodies due to a lack of oxygen. This issue is particularly important 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, which is defined as the total additional future cost to the global society due to the production of one unit of resource. It is related to future global production, specifically resource extraction cost and recycling rate (Ponsioen 2013). These impact categories are meant to guide a user in evaluation of the overall environmental impacts of a product or service.

The life cycle impacts for the proposed GES were compiled for each of the impact categories. Each individual impact was queried from the SimaPro database as one unit so that the spreadsheet user can adjust the values for the materials accordance to the specific design analyzed. Tables showing the unit impacts for the proposed geothermal system within the ILB can be found in Tables 2 and 3

Table 2. Inventory table showing the unit impacts of the material production phase of the GES, with the impact values compiled using SimaPro software.

Lifecycle Stage, Components & Processes		Impact Categories					
Material Production		Impact Inventory					
Injection Well (IW)	**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**
Casing 1 (surface)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 2 (int.)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 3 (prod.)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Concrete 1 (surface)	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
Concrete 2 (int.)	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
Concrete 3 (prod.)	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
Tubing	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Tube lining	1 kg Tetrafluoroethylene {GLO}| market for | Alloc Def, U	9.42E-03	3.23E+02	6.41E-01	1.03E-01	4.66E-02	1.77E+01
Injection packer insulation	1 kg Polymer foaming {RoW}| processing | Alloc Def, U	4.73E-08	9.51E-01	6.90E-02	5.43E-03	3.27E-03	5.01E-01
Drilling (prod. of fuel)	1 kg Diesel, low-sulfur {RoW}| production	9.20E-07	5.76E-01	4.60E-02	5.53E-03	1.83E-03	8.15E+00
Drilling (water)	1 kg Tap water {RoW}| tap water production, underground water without treatment	1.96E-11	3.07E-04	1.58E-05	1.55E-06	1.28E-06	2.04E-04
Production Well (PW)	**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**
Casing 1 (surface)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 2 (int.)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 3 (long string)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Concrete 1 (surface)	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
Concrete 2 (int.)	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
Concrete 3 (long string)	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
Tubing	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Tube lining	1 kg Tetrafluoroethylene {GLO}| market for | Alloc Def, U	9.42E-03	3.23E+02	6.41E-01	1.03E-01	4.66E-02	1.77E+01
Production packer insulation	Polymer foaming {RoW}| processing | Alloc Def, U	4.73E-08	9.51E-01	6.90E-02	5.43E-03	3.27E-03	5.01E-01
Drilling (prod. of fuel)	1 kg Diesel, low-sulfur {RoW}| production	9.20E-07	5.76E-01	4.60E-02	5.53E-03	1.83E-03	8.15E+00
Drilling (water)	1 kg Tap water {RoW}| tap water production, underground water without treatment	1.96E-11	3.07E-04	1.58E-05	1.55E-06	1.28E-06	2.04E-04
Submersible Pump	**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**
Copper wire	1 kg Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	1.11E-07	7.89E-01	3.89E-02	3.60E-03	2.41E-04	7.48E-01
Steel	1 kg Steel, low-alloyed {GLO}| market for	1.12E-07	1.64E+00	1.02E-01	8.08E-03	1.23E-02	1.04E+00
Lead	1 kg Lead {GLO}| market for | Alloc Def, U	1.27E-07	1.36E+00	1.38E-01	1.90E-02	1.30E-02	1.40E+00
Lubricant oil	1 kg Lubricating oil {RER}| production | Alloc Def, U	1.26E-06	1.00E+00	6.98E-02	8.27E-03	4.09E-03	1.11E+01
Chiller	**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**
Refrigerant	1 kg Refrigerant R134a {RoW}| production | Alloc Def, U	1.04E-02	1.03E+02	7.87E-01	8.98E-02	2.44E-02	1.53E+01
Steel	1 kg Steel, low-alloyed {GLO}| market for	1.12E-07	1.64E+00	1.02E-01	8.08E-03	1.23E-02	1.04E+00
Aluminum							
Copper	1 kg Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	1.11E-07	7.89E-01	3.89E-02	3.60E-03	2.41E-04	7.48E-01
Surface Components	**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**
Heat Exchanger	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
HDPE	1 kg HDPE pipes E	0.00E+00	2.48E+00	1.12E-01	9.46E-03	2.16E-04	1.11E+01

Table 3. Inventory table showing the unit impacts of the construction, use of system, and end of life phases of the GES, with impact values compiled using SimaPro software.

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 concrete	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 steel	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
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 IW (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 IW (comb. of fuel)	1 hr 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 IW (comb. of fuel)	1 hr 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
Drilling PW (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 PW (comb. of fuel)	1 hr 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 PW (comb. of fuel)	1 hr 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 hr 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
Use of System							
Operation 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**
Electricity for pumps	1 kWh from Ameren		6.23E-01				
Operation of chiller	1 kWh from Ameren		6.23E-01				
Operation of heat exchanger	1 kWh from Ameren		6.23E-01				
Maintenance	Maintenance, heat and power co-generation unit, 160kW electrical {GLO}| market for | Alloc Def, U	2.69E-03	3.98E+03	2.07E+03	2.28E+02	1.33E+02	2.22E+04
End of Life							
Deconstruction	**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**
Pump removal	1 hr 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
Surface equip. removal	1 hr 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
Sealing IW	1 m^3 Concrete, sole plate and foundation {RoW}| concrete production, for civil engineering, with cement CEM I | Alloc Def, U	1.80E-05	3.55E+02	1.63E+01	9.15E-01	3.66E-01	1.68E+02
Sealing PW	1 m^3 Concrete, sole plate and foundation {RoW}| concrete production, for civil engineering, with cement CEM I | Alloc Def, U	1.80E-05	3.55E+02	1.63E+01	9.15E-01	3.66E-01	1.68E+02
Waste	1 kg _48 Recycling of concrete, asphalt and other mineral products, DK	0.00E+00	4.81E-03	2.37E-04	2.54E-05	7.42E-07	7.98E-03
Transport of waste	1 tkm Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3	1.20E-07	5.22E-01	7.55E-02	3.01E-03	7.20E-04	1.08E+00

To compare the proposed GES with an existing system that also produces thermal energy, a spider diagram template was created. The methodology of this spider diagram is like that of the AMOEBA graph presented in the previous background section (Lee 2010). This diagram allows the user to compare two systems based on five categories: energy use, global warming potential, water consumption, waste production, and annual heat production. The user can also weight the importance of performance improvement for each of the five categories using a point system. In the assessment, the GES was compared against the current usage at the U of IL. Information was gathered using three main sources: the U of IL Combined College Energy Report, the Illinois Climate Action Plan, and the Energy Corridor Energy Usage Report. More information on these sources can be found in Thomas (2019).

4. RESULTS

The inventories of unit impacts shown in Tables 2 and 3 were used to calculate the life cycle impacts of the proposed GES. Overall, one of the components of the project with a significantly large impact is the material production of the two wells, specifically regarding the use of steel and concrete. These impacts could change noticeably depending on the selected inventory from the database in SimaPro® and should be adjusted if more information about the raw material sourcing is known for the specific project. A table showing the overall lifecycle totals for each impact category is below in Table 4.

As seen in Table 4, operation of the system contributes the most to GWP (kg eCO_2) of the four phases of the life cycle. This is also seen in Figure 6, where the stages are compared. The high emissions associated with operation are likely attributed to the electricity used to run the pumps, heat exchangers, etc. Altering the design of the GES to implement instrumentation with lower electricity use would assist in decreasing the GWP associated with operating the system.

Table 4. Impact totals for each lifecycle stage as well as total lifecycle impacts for the GES.

Stages	Total kg CFC eq	Total kg eCO_2	Total kg eO_3	Total kg eSO_2	Total kg eN	Total energy surplus (MJ)
Material Production	1.25E+01	1.32E+06	6.28E+04	5.12E+03	4.02E+03	1.16E+06
Material Transport/Cons.	2.46E-01	3.78E+06	1.98E+05	1.82E+04	1.60E+04	2.60E+06
Operation	0.00E+00	5.41E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
End of Life	3.36E-03	6.53E+04	3.03E+03	1.69E+02	6.74E+01	3.13E+04
TOTAL	1.28E+01	1.06E+07	2.64E+05	2.35E+04	2.01E+04	3.79E+06

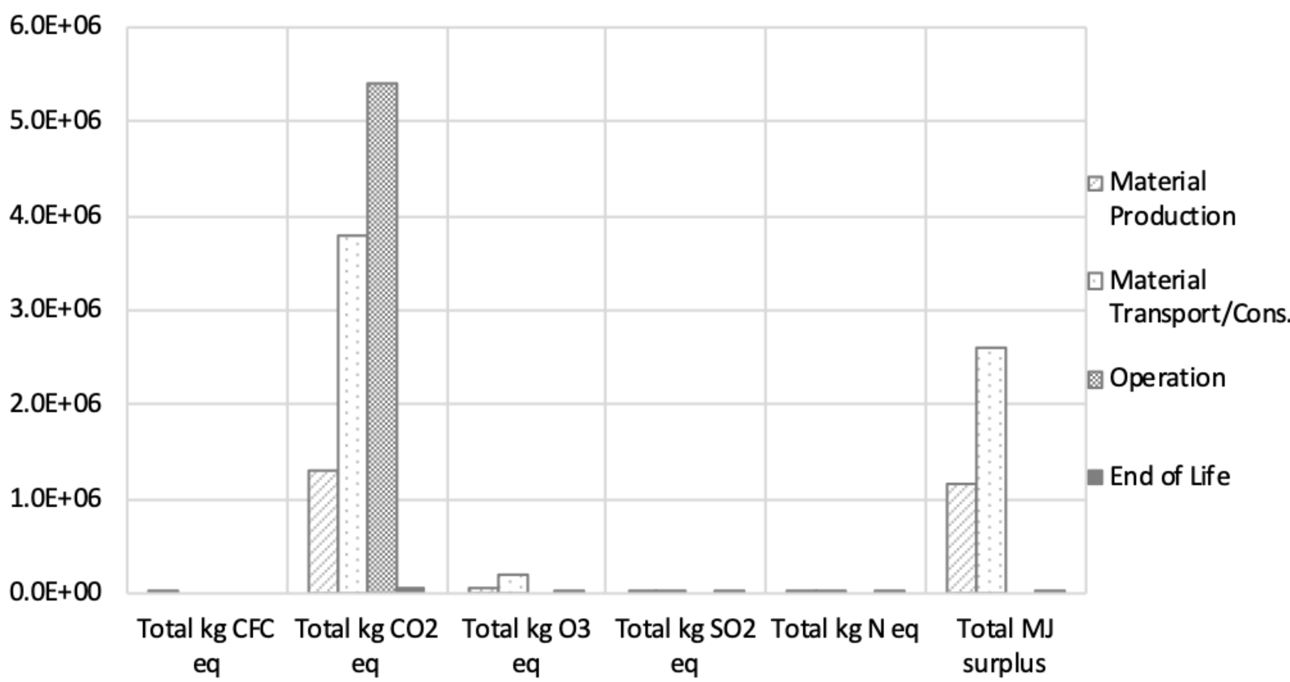


Figure 6: Impact comparison of the four life cycle stages, showing significant GWP associated with the operation of the DDU GES.

Figure 6 also shows the high impacts associated with the material production and material transport and construction phases; i.e., the GWP and fossil fuel depletion impacts. When investigating those impacts further, concrete and steel are the top contributors to these impacts. Figure 7 shows the significant CO_2 emissions associated with the use of steel, totaling to an order of magnitude higher than the other materials. 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.

The depth of the extraction and injection wells requires a significant amount of steel for the well casings, with the deepest casing reaching a depth of 1,981 m. This is likely the explanation for why the steel impacts are higher than the concrete impacts. In many LCAs of geothermal systems, concrete is commonly the top contributor to the overall GWP of the system. This is because concrete has an embodied energy of 12.5 MJ per kilogram, whereas steel has 10.5 MJ per kilogram (Hsu 2010). The amount of steel is higher than that of a low-temperature geothermal exchange system.

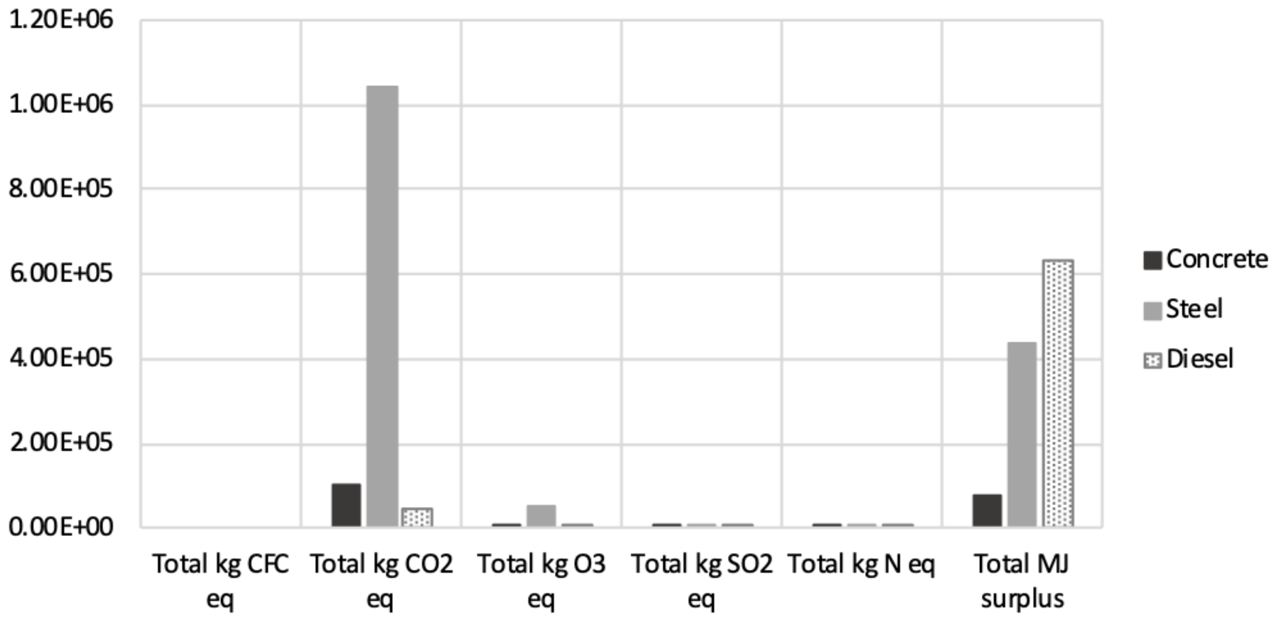


Figure 7: Impacts associated with the use of concrete, steel, and diesel for the DDU project in the ILB. These of these materials comprise the top contributors to the overall environmental impacts of the project.

While there are significant CO_2 emissions associated with the DDU GES system, it still has the potential to offset the environmental impacts associated with the alternative heat option. Currently, the Energy Corridor on the U of IL campus receives energy supply from a combination of propane and natural gas. Using available emissions data for propane and natural gas, the carbon dioxide emissions associated with heating the Energy Corridor were calculated (EIA, 2016). This information is presented in Table 5.

Table 5. Emissions associated with existing heating operations for the buildings along the Energy Corridor.

Energy Corridor Emissions	
Annual NG Use (MMBtu/yr)	5638
Emissions from NG (kg CO2/MMBtu)	53.07
Annual Propane Use (MMBtu/yr)	3814
Emissions from Propane (kg CO2/MMBtu)	63.07
Existing Energy Corridor Emissions (kg CO2/yr)	5.40E+05
Years until DDU emissions offset	10.02

Table 5 shows that the annual emissions associated with the heating of the six buildings along the Energy Corridor total to 539,758 kg CO_2 per year. As stated in Table 1, the Beef and Sheep Laboratory, Poultry Farm, Dairy Farm, and Feed Mill are heated using natural gas, the Energy Farm is fueled by propane, and the Swine Farm utilizes a combination of natural gas and propane. If these facilities were instead heated using the proposed deep direct-use system, the emissions associated with the use of traditional fuels could be offset in approximately 10 years of operation.

The DDU GES system can also be compared to the operations of the Abbott Power Plant, which is the central power plant that serves the university campus. Using available data collected at the Abbott Power Plant, the heat production and associated emissions were calculated. This information is presented in Tables 6 and 7.

Table 6. Heat production data at the Abbott Power Plant on the UIUC campus.

Abbott Power Plant Production	
Hourly Steam Production (lb/hr)	8.00E+05
Annual Steam Production (lb/yr)	7.01E+09
% Steam Used	0.60
Heat in 1 lb of 100 C Steam (Btu/lb)	1112
Hourly Heat Production (MMBtu/hr)	8.90E+02
Daily Heat Production (MMBtu/day)	2.14E+04
Annual Heat Production (MMBtu/yr)	7.79E+06

Table 7. Calculated CO_2 emissions associated with the use of steam on the UIUC campus.

Abbot Power Plant Emissions	
Co-generated steam emissions, 2016 (kg CO_2)	112714860
Annual Steam Production at capacity (lb/yr)	4.20E+09
Emissions from Steam (kg CO_2/lb)	0.0268

As shown in Table 7, approximately 0.0268 kg of CO_2 are emitted per pound of steam used on the UIUC campus, assuming conservatively that only 60% of the total steam produced is used for energy (Lowe 2011). With this information, it is possible to compare the emissions associated with Abbott Power Plant to the emissions associated with the proposed DDU alternative. The CO_2 emissions related to operation of the DDU GES total 5.41E+06 kg CO_2 equivalent. As a result, it will take an estimated 24 years for the DDU emissions to offset the emissions of the Abbott Power Plant alternative. Table 8 summarizes this information below. However, one must note that it would be very cost prohibitive to extend steam lines to the ARF, the costs and LCA impacts for which were not accounted for in this LCA.

Table 8. CO_2 emissions offset by the proposed system on the UIUC campus to replace the existing Abbott Power Plant.

Facility Steam Usage & DDU Offsets	
Annual Steam Usage (lb/yr)	8,500,000
Annual CO_2 emissions offset by DDU (kg)	2.28E+05
Years until DDU emissions offset	23.7

Performance of the proposed GES was also compared to the current impacts for the ARF using a Spider diagram. The results show that the GES is a comparable alternative to help improve campus performance in annual energy use, global warming potential, water consumption, waste production, and especially in annual heat production. Using the estimated low end of heat production estimated for the GES, the DDU technology could produce 2,053% more heat than what is currently being used by the ARF. That equates to heating 14 buildings at maximum monthly energy usage. If the analysis was done using the estimated high-end of the GES heat production, the number of possible buildings heated would increase to a total of 23 buildings. These results show that while there are still notable impacts associated with GES like the DDU technology assessed in this study, there are still tangible benefits that should be considered. Table 9 shows the criteria categories and the associated points assigned to that target performance. Table 10 shows the performance calculation for each of the five categories, and Figure 8 shows the resulting Spider diagram.

Table 9. Points assigned for each of the criteria with respect to the desired performance.

Criteria	Target Improvement	Points
Energy Use (MMBtu)	20%	1
	35%	2
GWP (kg eCO2)	50%	1
	70%	2
Water Consumption (kg)	50%	1
	70%	2
Waste Production (kg)	50%	1
	70%	2
Annual Heat Production (MMBtu)	50%	1
	100%	2

Table 10. Performance comparison of the ARF to the proposed GES.

Criteria	Reference	Strategy	Performance	Points
Annual Energy Use (MMBtu)	9.5E+03	7.0E+03	25%	1
GWP (kg eCO2)	1.1E+08	1.1E+07	91%	2
Water Consumption (kg)	8.0E+06	2.5E+05	97%	2
Waste Production (kg)	1.0E+04	9.0E+02	91%	2
Annual Heat Production (MMBtu)	1.6E+04	3.5E+05	2053%	2

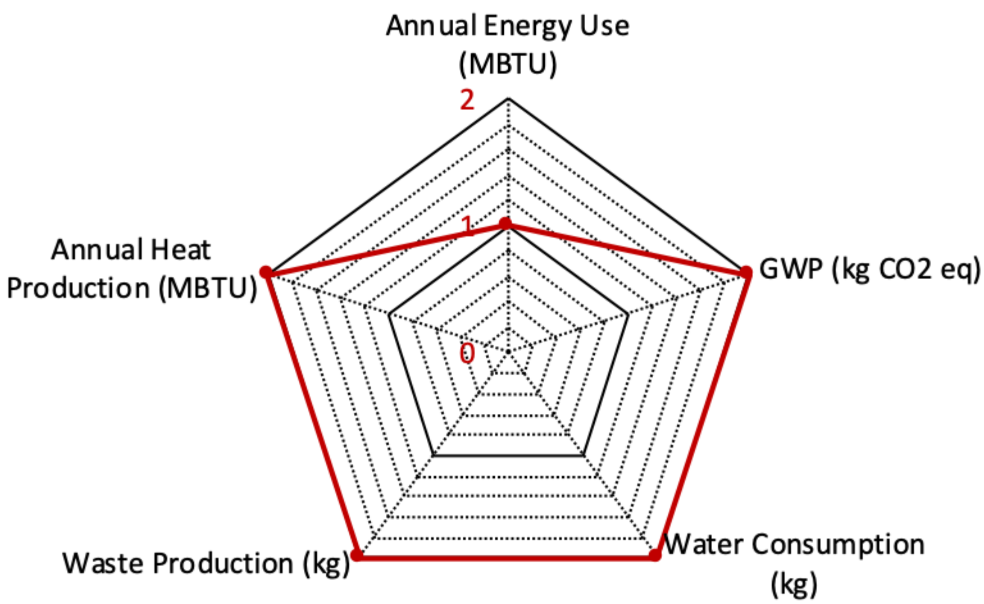


Figure 8. Spider diagram showing how the proposed DDU GES would improve the overall waste production, water consumption, global warming potential, annual energy use, and annual heat production at the ARF.

The LCA results presented above can serve as a procedure to represent other DDU GES using the spreadsheet tool that was developed simultaneously to produce these results. Because a significant portion of the GES at the U of IL is still in the feasibility stage and design parameters are subject to change, it is suggested that the inputs presented here are reviewed as designs are updated.

5. CONCLUSION

DDU GES are low-emission heat source alternatives that have the potential to increase the distribution of geothermal energy usage in areas with lower geothermal gradients that rely on traditional, high-emission fossil fuel sources of heating. While these GES are often considered truly sustainable energy sources, further investigation into the environmental performance of the system reveal that there are quantifiable impacts associated with various components of DDU technologies throughout the operation. A number of the high-impact components of DDU GES come from the electricity required to power external supplements to the system. Sourcing the electricity used for these components from low-emission sources could assist in reducing the environmental impacts of the system. Furthermore, carefully considering the amount of raw material used to construct the system could reduce any unnecessary impacts from material sourcing and transport. In the case of the proposed GES for the U of IL, this assessment shows that the GES can serve as promising alternative source to replace heating provided by propane or natural gas. To truly quantify the total environmental impacts associated with a DDU GES, a full design of the system is required. Once the design is completed, using the developed LCA spreadsheet tool would assist the implementation team with understanding the benefits and drawbacks of moving forward with this type of GES. Furthermore, using the tool while finalizing the design of the system could provide further insight into areas of the system that produce emissions that could be managed or minimized.

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