Heat Beneath Our Feet

The Potential of Geothermal Heat Generation

An evaluation of heat pump technology at Notre Dame

Daniel O'Duffy and Kevin Donkor

Thesis:

In this project we will assess the possibility of utilizing ground-coupled heat pump technology at Notre Dame.

Criterion:

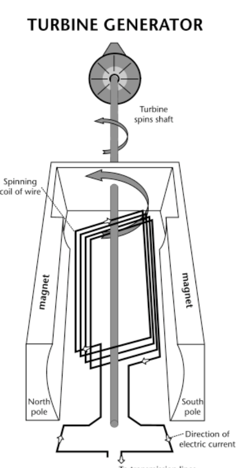
The viability of switching to a ground-coupled heat pump source of heat (as opposed to heat sourced from coal-heated steam, the status quo) will be analyzed according to a few key criterions, contrasting each to the status quo:

- Financial cost.
- Environmental impact.
- Future potential – how the cost might be offset by savings in the future, and other possible ramifications of changing our heat source.

Study Target:

Analyzing the impact of a switch to heat pump heat source on a large, campus-wide scale would be an enormous project. Rather than encourage such a dramatic and wholesale change, this project will instead assess the feasibility of installing a heat pump system in a single building. The construction of one system would serve to illustrate its capabilities, with the system then implemented on a larger scale if it were to be successful. Before this, however, we must find out just what system we intend on replacing.

The Status Quo:



Currently, all buildings on campus are heated predominately by the waste products from the coal-fired power plant here on campus. Nearly half of all of America's electricity generation comes from coal.[i] Coal power plants, like most others, operate by heating water into steam, then using the kinetic energy of that moving steam to turn huge turbines, which induces an electric current (as shown in the diagram[ii]) through Faraday's Law. The steam, after being used to turn the turbines, is 'waste', and is often disposed of, mainly by flushing it down into the sewer system, something that causes the rising steam that we see in major city streets. Here at Notre Dame, we utilize this waste steam in heating our buildings. The waste steam produced by the coal is put into the underground tunnel system that branches throughout the campus, then pumped into the piping system in each building, powering the central heating.

The Usage of Coal

There is a vast supply of coal here in the United States The price of coal is "relatively cheap and fairly stable"[iii], and is "has been the least expensive fossil fuel used to generate electricity"[iv] since 1976, so cost right now is not a concern. In the future, base coal prices are forecast to remain at a similar level to now[v]; however, there are likely to be 'carbon taxes' placed upon coal and other forms of polluting power sources, pushing this price up. Because coal has the highest environmental 'price' of usage, it is likely to bear far higher costs. With climate change and renewable resources increasingly in the public consciousness, highly polluting sources of energy are becoming increasingly unpopular; the future of such fuels is uncertain.

The biggest drawback to coal-fired electricity production – and, by extension, the coal-fired heat production – is undoubtedly its polluting factor. Coal is the dirtiest form of energy that man uses today. The pollution is felt with greenhouse gases and solid matter. A typical coal plant produces 3,700,000 tons of carbon dioxide each year, the equivalent to felling 161 million trees[vi]. Other gases emitted include NOx, CO and SO2. Toxic solid matter, including mercury, is also given off. An average 500-megawatt coal plant produces over 125,000 tons of ash and 193,000 tons of sludge each year.[vii]

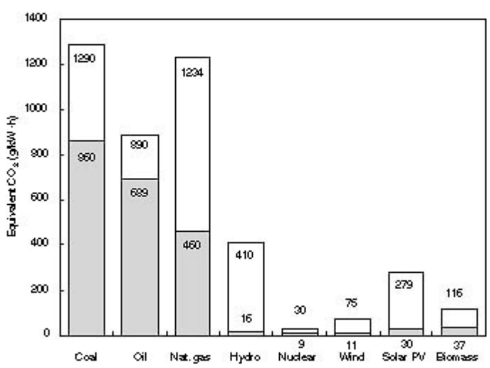


Figure 1 - Full Energy Chain CO2 Equivalent Emission Factors[1]

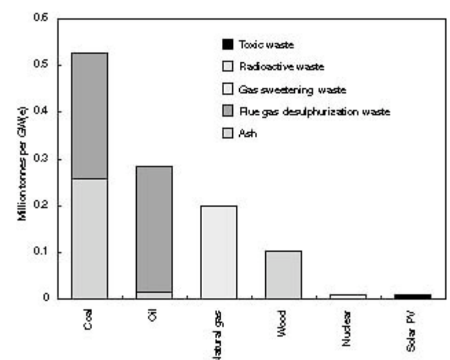


Figure 1 - Waste Generated Annually in Fuel Preparation

Though Notre Dame's power plant is not as large as the larger commercial electricity generation power plants, it still adversely affects the environment, as seen in this summary of the pollution caused by our power plant.[1]

CO	NO2	PB	PM10	PM2.5	SO2	VOC
68.8	652.4	0.034	24.6	9.6	4177.6	4.4

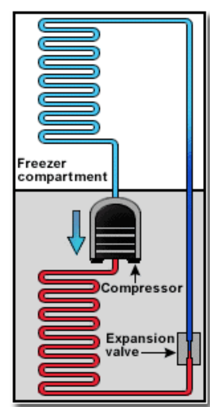
[1] The criteria pollutants are Volatile Organic Compounds (VOC), Carbon Monoxide (CO), Nitrogen Oxides (NO2), Sulfur Dioxide (SO2), and Particulate Matter less than 10 microns in diameter (PM10).

This data puts Notre Dame in the top 100 polluting power plants in the state.[viii] No matter what size the power plant is, burning coal causes "smog, soot, acid rain, global warming, and toxic air emissions", with waste products of "ash, sludge, toxic chemicals, and waste heat" (UCSUSA[ix]). Typical coal power plants use only 33% of the coal's heat to produce electricity[x].

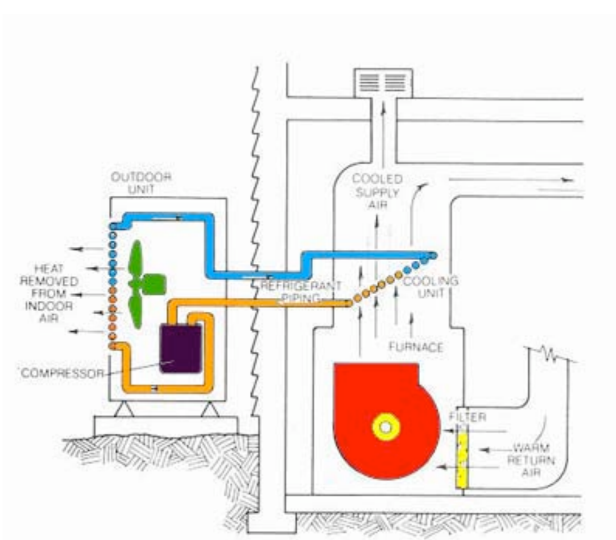
The waste heat from the power plant is sometimes recycled, sometimes flushed into the drainage system – which gives us the rising steam that we see emanating from the drains of city streets – or pumped out into a nearby body of water. At Notre Dame, we use this waste heat to run the heating systems on campus. If we were to refrain from doing this, then the University will have to dispose of that steam differently. This would, probably cause more problems than it would solve, seeing as we will continue to run the coal power plant regardless of how we use the steam, and that steam would have to go somewhere. However, we currently have that problem to some extent currently as coal fired power plants must constantly produce power; the technology does not allow for shut downs during periods in the day or year that exhibit low electricity demand. Thus, when South Bend is warm and we do not need to use the steam energy, we have to dispose of most of the waste steam. This is true in increments throughout the year also.

How the Alternative Works:

Rather than *generating* concentrated heat chemically, a heat pump simply takes existing heat and *moves* it around mechanically. A heat pump works in the same way that a water pump moves water; a water pump doesn't 'create' water but merely moves it around. As heat pumps only *move* heat in or out of a building but they need a source of heat (source temperature) on one end and a place to dump that heat on the other end (sink temperature). One example of a heat pump is a refrigerator (as seen in the diagram[xi]). Fridges pump the heat inside the closed compartment out into the surrounding air, which is why the coils at the back of the fridge (where the heat is dumped) are hot. As the inside of the refrigerator gets colder, so the outside gets hotter. This type of heat pump is so powerful and reliable that it can pump away enough heat to freeze ice, which is exactly what your freezer does.



Graphic courtesy: Science Treasure Trove



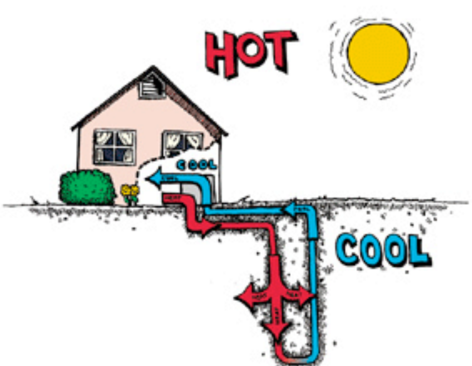
Central Air-Conditioning & Heating System

We only need to grasp two things in order to understand this system. Firstly, a gas cools on expansion; if we use a compressor to liquidize a gas, it will heat up, and vice versa. Secondly, with the Second Law of Thermodynamics, we know that when two things of different temperature are touching or close by, the hotter one will cool and vice versa. Inside the fridge's pipes, a liquid refrigerant carries heat from one area to another. When compressed, the refrigerant gives out heat. When it is expanded, it absorbs heat. Thus, with only a pump and a compressor, you can move heat.

Imagine taking your air conditioner and building it backwards so that the hot coils were inside your home and the cold coils outside. This would have the effect of heating your home. In order to have both a heater and an air conditioner, we don't have to construct a backwards air conditioning unit; all we need is a valve that will switch a single unit from air conditioner to heater. However, if we just made our standard air conditioning units run backwards, the coils would gather ice in the cold outside air, meaning that we would have to fire a furnace to heat the air. The result would look like the diagram on the left[xii].

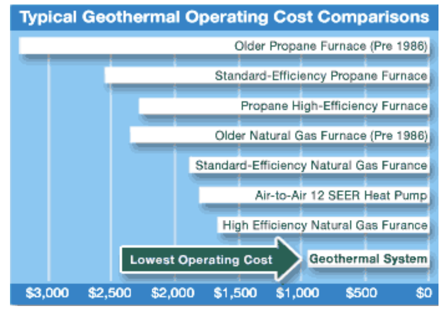
Ground-coupled Heat Pump (GHP, also known as a geoexchange heat pump, or colloquially as a geothermal heat pump) systems are a more efficient heat pump than air conditioners because they use the ground and not the air to heat or cool (hence the name: 'Ground-coupled' Heat Pump). Most air conditioners and heat pumps use the outside air to blow over the coils. This means that in the summer air conditioners try to cool down in 90° or 100°F air. Similarly, in the winter they try to heat up using 20° or 30°F air. The difference with the geothermal system is that the piping is laid outside under the soil or a large body of water. Since the ground absorbs 46% of the Sun's energy that hits the planet (more than 500 times more energy than mankind needs every year)[xiii], the ground just ten feet beneath the surface acts like a solar battery[xiv]. With this, the ground maintains a constant temperature of about 55 degrees (in the U.S.)[xv], making the heat pump far more efficient in both summer and winter. "GHPs take this heat during the heating season at an efficiency approaching or exceeding 400%, and return it during the cooling season."[xvi]

With this roughly constant temperature, we can both heat buildings during the winter and cool buildings during the summer. This is a vast and largely untapped resource, one that we can utilize with the revolutionary heat pump system. With the heat pump, we pump a liquid, usually water or an antifreeze solution, through pipes buried underneath the surface of the earth. In winter, the solution sucks in heat from the ground, carrying it into the building to be used. In summer, the pump system changes direction; this time, the heat is sucked in from inside the building and deposited underground, as shown in the diagram.[xvii] The same technology can also work on an 'open loop' system under a large body of water, operating in a similar fashion with the same results.



Benefits of the Heat Pump

Geothermal heat pumps require little fuel to run once installed, needing only electricity for the pump to run, leading to far lower harmful emissions compared to other heating types, no matter what the source of power. Though the system itself does not pollute, the pump runs on electricity, which may come from any electricity source you like. The GHP system is thus very flexible, whereas the current steam heat usage is wholly dependent upon the operation of the coal power plant. Heat pumps are largely unaffected by changing weather conditions and work continuously throughout the year. Furthermore, we can heat water for free during the summer and at a reduced cost during the winter.



A Heat pump systems offer savings of 25 to 50% on energy consumption[xviii]; they are also very energy efficient, with 70% of the required energy provided by the Earth[xix]. The EPA found that GHP systems are on average 48% more efficient than the best gas furnaces on a source fuel basis, and over 75% more efficient than oil furnaces, even when accounting for *all* of the losses in the fuel cycle, such as power plant electricity generation. "In fact, today's best GeoExchange systems outperform the best gas technology, gas heat pumps, by an average of 36% in heating mode and 43% in cooling mode!"[xx]

The system, once installed, has a very long life expectancy due largely to the fact that it has fewer mechanical components, making it more reliable and less prone to failure. The ground loop has an expected life of over 50 years and requires no maintenance.[xxi] The ground heat exchanger will last for over forty years without maintenance[xxii]. Fossil fuel rivals to GHP units move 3 or 4 times more heat energy than the energy used to run them. In other words, a 1000-watt ground-coupled) heat pump can deliver the same amount of heat as a 3000 or 4000 watt electric heater[xxiii]. The contrast to other forms of heating is stark.

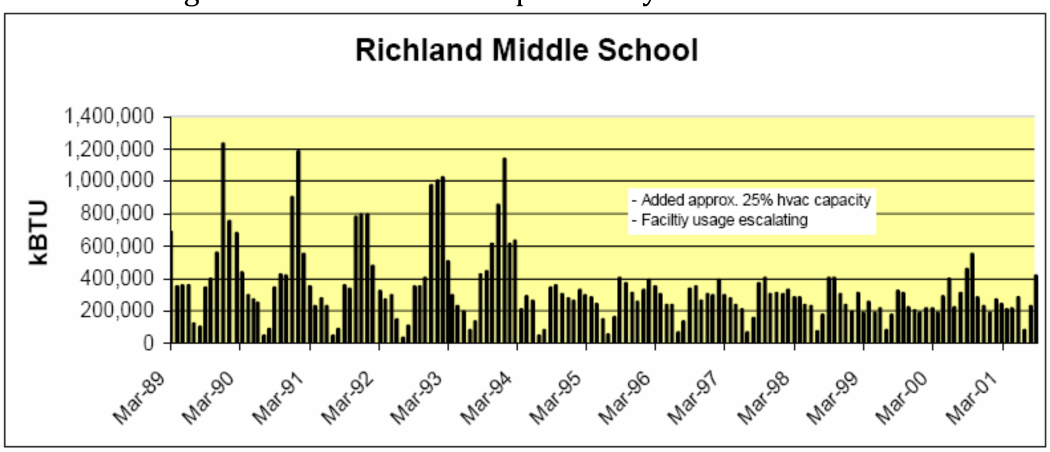
Space-Conditioning System	Heating	Cooling	Hot Water	Installed Cost	Ann. Op. Cost
Electric resistance with elec. A/C	1.00	2.3–2.6	0.90	$5,415–5,615	$871–2,945
Gas furnace with elec. A/C	0.64–0.87	2.3–3.2	0.56–0.60	$5,775–7,200	$461–1,377
Adv. oil furnace with elec. A/C	0.73	3.1–3.2	0.90	$6,515	$1,162–1,370
Air-source heat pump	1.6–2.9	2.3–4.3	0.90–3.1	$5,315–10,295	$353–2,059
Ground-source heat pump	2.7–5.4	2.8–6.0	1.2–3.0	$7,520–10,730	$274–1,179

1. Seasonal performance factors represent seasonal efficiencies for conventional heating and cooling systems and seasonal COPs for heat pumps. Ranges show modeled performance by EPA in different climates.

Source: U.S. Environmental Protection Agency, *Space Conditioning: The Next Frontier*, 1993

Other benefits are numerous, including silent running and decreased machinery, freeing up space through reduced machinery size and removing venting systems outside.[xxiv] "Every kilowatt of electricity used in the process generates more than three units more of heat than a conventional system"[xxv], a dramatic difference; with savings in efficiency and in other areas, building owners can save “25 percent to 65 percent on energy costs”[xxvi]. With this taken into account, “while initial investment is high, yearly energy savings provide a payback in from 5 to 7 years over conventional heating and cooling systems.”[xxvii] Compared to standard air conditioning systems, GHP systems can reduce energy consumption by up to 40%, according to the EPA[xxviii], leading them to conclude that GHP systems are “The most energy efficient, environmentally clean, and cost-effective space conditioning systems available today”[xxix]. The U.S. General Accounting Office estimates that, “if [GHP] systems were installed nationwide, they could save several billion dollars annually in energy costs and reduce pollution."

The Environmental Protection Agency found that GHPs can reduce energy consumption, and thus their corresponding emissions, by “over 40% compared to air source heat pumps and by over 70% compared to electric resistance heating with standard air-conditioning equipment.”[xxx] These savings can be made even greater with the addition of efficiency improvements. The financial savings of GHPs can be seen in several case studies. Richland Middle School installed a GHP system in early 1995. The results of that change can be clearly observed in this graph[xxxi]. There was a massive decline in kBTU, or kilo British Thermal Units, in 1995, when the GHP was installed and the efficiency improvements made. The benefit of examining the effect of GHPs on schools is that their energy usage is very similar to what we can expect buildings in Notre Dame to be. The schools have comparable peak energy times, size of building and yearly usage to Notre Dame. Thus, through examining schools, we can have a fair approximation of how GHPs might affect Notre Dame specifically.



Another very clear comparison of the effect of GHP can be seen between schools that have or do not have GHPs, as the schools without GHPs will act as a control group. In the fall of 1995, the Lincoln, Nebraska, school district opened four new elementary schools—Campbell, Cavett, Maxey, and Roper—served by GHPs. The schools have identical floor plans, each with about 69,000 ft2 of space dedicated to classrooms, offices, meeting rooms, a cafeteria, and a gymnasium. Each school served approximately 500 students. The performance of the GHP installations in the four Lincoln schools is well documented by electric and gas utility data (in 15-min and monthly intervals) and 10-min energy management system (EMS) data. In addition, the situation at Lincoln is unique in that the district maintains records on facility design, energy performance, and maintenance activities for all facilities within the district. This information allows a comprehensive review of the design and performance of the GHP systems in the Lincoln Public Schools and a comparison of the performance of these schools to others within the school district. According to figure below, the four new schools are very low energy users when compared to other schools in the district. In fact, on average, the GHP schools used 26% less source energy per square foot per year than the non-GHP schools. Over a two-year period, energy data collected indicate that the four GHP schools outperformed the other schools in the district. Five schools actually consumed less energy than the GHP schools; however, they cooled less than 10% of their total area, while the GHP schools cool 100% of their floor area.[xxxii] This case study is relevant because these schools are situated in Nebraska, which is along the same range in latitude as Indiana. Based on this study, similar results could be yielded for newer facilities built on the Notre Dame campus that have similar dimensions to older buildings that use conventional systems.

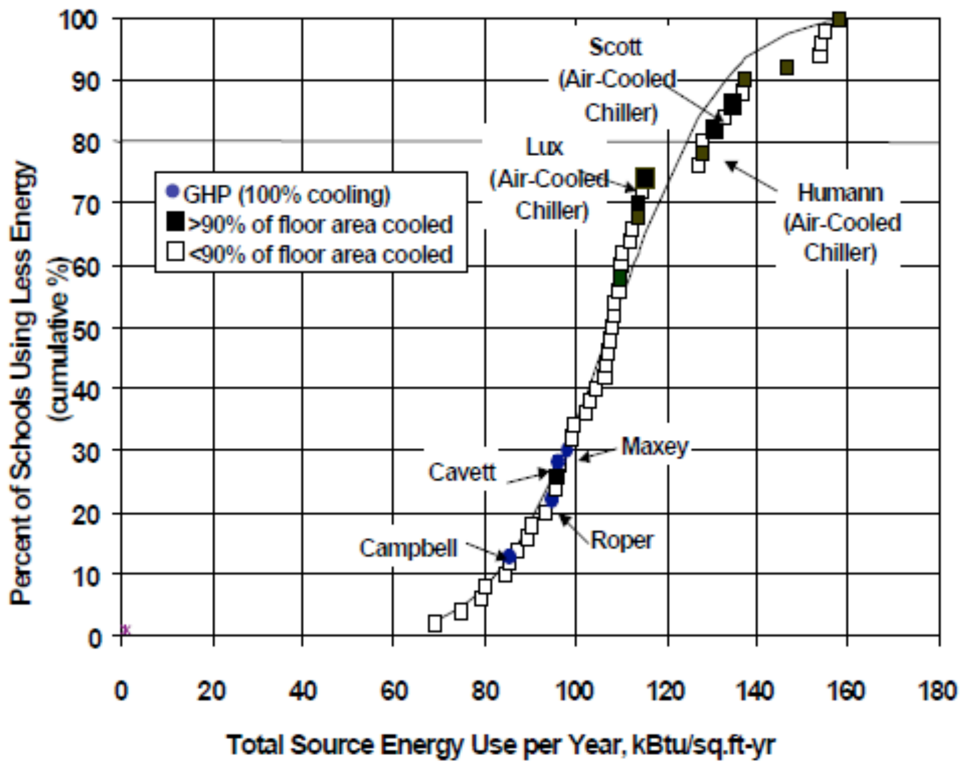
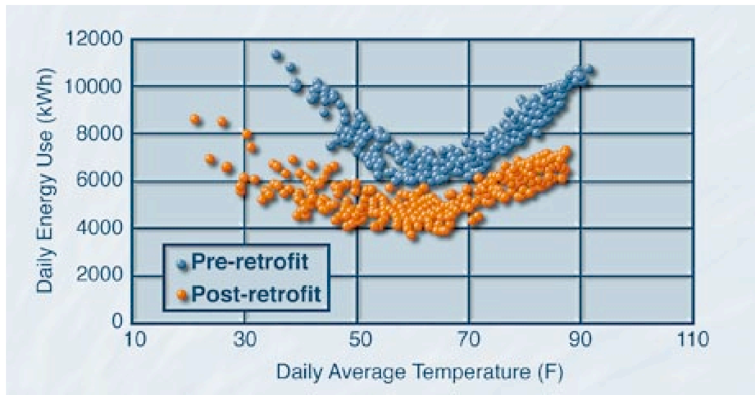


Fig. 2.4. Distribution of average annual source energy consumption for K–12 schools in the Lincoln School District. Solid data markers identify schools that provide space cooling to over 90% of their total floor area. Three schools built in the 1990s with conventional HVAC systems are also identified.

Graphic courtesy: Oak Ridge National Laboratory

The largest geothermal heat pump installation is in Folk Park, Louisiana, where 4,003 homes had their heating and cooling systems renovated, including the installation of GHP systems and a comprehensive energy-efficiency program. As they have such a large sample, we can see the results of the change very clearly. Electrical consumption over the year was reduced by 33%, whilst summer peak electrical demand was reduced by 43%. The direct result of the GHP system's effects can be seen in the diagram to the left, showing a marked decline in energy usage at every temperature, year-round.[xxxiii]



The project at Fort Polk reduced annual electricity use in family housing by about 33%. This plot shows pre- and post-retrofit daily electricity use on Feeder 1, which served housing that was all-electric before the retrofits.

Depending on heating needs, a GHP can supply 80 to 100% of the demand[xxxiv]. In larger systems and in northern climates, there is a larger demand. Increasing the size of the heat pump system to accommodate this increased demand may give benefits when compared to a mixed-source system, but the savings may not offset the higher costs of installation. [xxxv] Nevertheless, any installation would be beneficial in the same ways; the only difference would be the size of the system. Perhaps an ultimate goal would be to make the building 100% sustainable, but a smaller system built this decade can always be expanded upon in the future when the costs of construction naturally drop.

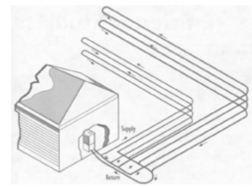
Drawbacks of the Heat Pump

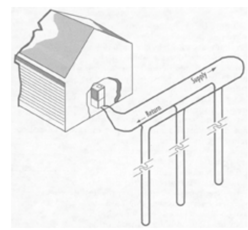
GHP system may need to run alongside a fossil fuel supply, whether as a backup or as a complimentary system, even if the ultimate goal of the system would be to replace the status quo. If, for some reason, the heat pump system were to break down, then fossil fuels could be easily used as a backup. If the heat pump were to be installed on a limited scale, then the job of heating the entire campus could conceivably be split between the two. Any saving in money and emissions is beneficial for the university in several ways, not least with regards to public relations. If Notre Dame were to turn its landmark to sustainable energy to any extent, the University would be seen to be taking the lead on environmental issues, keeping in the theme of the Forum on Sustainability and upholding Catholic social values.

The main drawback for installation of the GHP system is, quite simply, cost of installation. For an average sized home, a GHP system costs about $2,500 per ton of capacity, with a typical tonnage requirement of three tons[xxxvi]. That initial cost is nearly twice the price of a regular heat pump system. On top of this, you must add the cost of drilling to this total amount. That will depend on whether your system will drill vertically deep underground or will put the loops in a horizontal fashion a shorter distance below ground. The cost of drilling can run anywhere from $10,000 to $30,000, with a price for ground looping of $1,000 to $1,500 per ton of capacity[xxxvii]. However, the savings that the system offers would typically cover this outlay in under a decade.

How it may work for Notre Dame:

Pipes for the heat pump system can be laid in several ways. For underground systems, the pipes can be put horizontally or vertically, as shown[xxxviii]. For underwater configurations, we have two possibilities for installation in Notre Dame's two lakes.





Installation costs vary, according to the region and unique requirements that each building would have. Costs may be larger than what most systems would usually cost due to both the size needed and the climate of South Bend. Colder climates may require multiple systems to operate at the same time. Freezing conditions will not affect the system adversely, but the varying soil temperatures would necessitate a larger scale construction. Horizontal heat pump systems are cheaper to install but they require a larger surface area as they are built in trenches. The option of horizontal piping would seem to be closed to us because of the lack of open space on campus, so we are left with two options. One can either build the heat pumps vertically downwards into the soil in small-diameter holes 100 to 400 feet deep, or one could use the lakes to submerge a heat exchanger. Vertical piping is more expensive but is more efficient as the exchanger is buried deeper than otherwise, giving a higher heat source from which to draw. Submerging the exchanger in a lake is cheaper alternative to vertical drilling and would be appropriate given that we already have two lakes. St. Joseph Lake is 27.1 acres in area with a maximum depth of 40 feet, more than enough capacity for the purposes of a GHP system.

Benefits and Drawbacks of Specific Buildings on Campus:

One potential site that comes immediately to mind is Main Building, the center point of Notre Dame's campus. This building, as the administrative heart of the university, would be a great way for the university hierarchy to take the lead on furthering sustainability. What must also be taken into account is the fact that this building, famous for its 'Golden Dome', is the main identifying landmark of the University. We are all 'Domers', after all. What better building to take as an example, then, than the most important, emblematic building in Notre Dame?

However, using Main Building as an example offers unique challenges. Constructed in 1865, Main Building was never created with 21st Century heating systems in mind. The building is constructed in a way that is not conducive to heat conservation. The heating system is relatively antiquated and not best suited to geothermal heat pump sources of power, meaning that it would require extensive retrofitting of a new system. Furthermore, the building is situated in the heart of campus, meaning that there is a limited amount of space for new construction. With all of these factors, Notre Dame's Main Building becomes a less inviting prospect for a case study of the GHP system; indeed, all existing buildings would have this problem to some degree.

The biggest drawback of a GHP system is the initial cost. So for retrofits it may take a long time to realize the savings. However if planned on early — before construction of a facility starts, the economic advantages generally pay back in a very reasonable time. With this in mind, it becomes clear that it would be best to install the GHP in a new building under construction or due to be constructed. Outside construction of the piping would take under a week[xxxix], with the internal systems taking similar time and costs to construct as a conventional heating /cooling system.

For a new building, the costs of construction would be comparable to the installation of traditional forms of heating / cooling systems, just that the geothermal would offer the multitudinous benefits also. With the existing heating system, we are able to heat buildings using the excess waste heat from the power plant. However, our cooling system is run by electric-powered traditional air-conditioning systems. As GHP systems run for both heating and cooling, we would stand to make significant direct cost savings on cooling buildings in the summer, even if the cost for heating (as a recycling of waste steam) is minimal, and savings in the winter. Even if we were to for some reason install the GHP system for use in only cooling buildings, the savings would be significant. If the University is constructing air conditioning systems anyway, why not use a cheaper, more efficient, more environmentally friendly option that will last for decades and avoid future carbon taxing? GHP systems will save 30 to 70% of cost in heating mode, and 20 to 50% in cooling mode compared to conventional systems.[xl] For this reason alone, why not use the GHP?

Conclusion:

By our assessment criterion, the Ground-coupled Heat Pump system is the better option than our current system. This technology offers both financial savings and reduced impact on the environment. The consequences of utilizing such a system is relatively easy to predict.

If the heat pump system were to be implemented on a large scale throughout campus, then the university would most probably have a problem disposing with the waste steam produced by the power plant. Quite simply, the status quo is an efficient and logical method of heating the university. As long as we run our campus through our local coal-fired power plant, utilization of the consequent heat energy is a smart choice, as this steam would have to be disposed of without utilizing its power. We already have this resource as a consequence of our power system.

Though the current way to heat the university is efficient, recycling waste heat energy from the coal-fired power plant, the promise of the geothermal heat pump system is too good to ignore. On a small scale, if we switched the heating source to alternative, renewable systems for a few buildings, we could benefit from the heat source already provided for us as a consequence of our coal-fired electricity generation whilst reducing our carbon footprint and our reliance upon the power plant. Even on such a small scale, this resource would decrease emissions, save money and take a major step towards making the entire university environmentally friendly. Even at a minimum, the technology would offset our heating costs and reduce our reliance upon the coal plant for our heating, a necessary step to take for when the University must inevitably turn to renewable sources of energy. As the piping system will last for approximately fifty years without repair, and will not incur high future carbon taxes, it would be a sound investment to make for the future.

Today, there are over 750,000 GHP systems in operation in the United States.[xli] Why shouldn't Notre Dame have one? Using the geothermal heat pump system on Notre Dame's new constructions would be a marvelous way for Notre Dame to take the lead on this crucial issue, setting an example to the students, staff and alumni of ND and indeed the world. The system might be a first step in making the entire building sustainable, reducing the campus' carbon footprint and it may even start a movement to make the entire campus to 'go green'. The switch to a renewable source would be a publicity coup, showing the University's commitment to sustainability and the fight against climate change. Financially, the system offers the promise of major savings for a long period of time. Finally, geothermal heat pumps pollute drastically less than fossil fuel based alternatives. Thus, for practical, financial, environmental and indeed moral reasons, geothermal heat pump technology has great potential and is worthy of further study.

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[i] 49% of the nation's total 4.16 Trillion Kilowatt Hours, according to the Energy Information Administration. <http://www.eia.doe.gov/kids/infocardnew.html#ELECTRICITY>

[ii] Energy Information Administration <http://www.eia.doe.gov/kids/energyfacts/sources/images/turbinegen.gif>

[iii] A quote from Energy Literacy Advocates <http://www.energyliteracy.org/compare-coal-power.html

[iv] Quote from the Energy Information Administration, <http://www.eia.doe.gov/neic/infosheets/coalprice.html>

[v] Currently, the average minemouth price per short ton is $25.16. In 2030, this will *fall* to $23.45 per short ton. Statistics courtesy of the Energy Information Administration, <http://www.eia.doe.gov/neic/infosheets/coalprice.html>

[vi] http://www.ucsusa.org/clean_energy/coalvswind/c02c.html

[vii] http://www.ucsusa.org/clean_energy/coalvswind/c02d.html

[viii] Data from the Indiana Department of Environmental Management, <http://www.in.gov/idem/4629.htm>

[ix] <http://www.ucsusa.org/clean_energy/coalvswind/c01.html> Is the source of both quotes.

[x] Converting energy to electricity at 33% average. <https://www.healthgoods.com/education/Energy_Information/General_Energy_Information/fossil_fuel%20coal.htm>

[xi] Diagram courtesy of Energy Quest. <http://home.howstuffworks.com/refrigerator4.htm>

[xii] Diagram courtesy of Energy Quest. <http://www.energyquest.ca.gov/how_it_works/air_conditioner.html>

[xiii] http://userpages.umbc.edu/~tokay/chapter2new.html

[xiv] Geo Enterprises, Inc., summarizing the findings of the EPA study on GHP systems http://www.geo-enterprises.com/plain/Benefits.htm

[xv] http://ezinearticles.com/?Using-The-Ground-to-Cut-Your-Utility-Bill&id=134275

[xvi] Geo Enterprises, Inc., summarizing the findings of the EPA study on GHP systems http://www.geo-enterprises.com/plain/Benefits.htm

[xvii] Diagram and quote from http://www.igshpa.okstate.edu/geothermal/geothermal.htm

[xviii] http://rebeeco.com/content/view/15/15/
[xix] http://www.wapa.gov/es/pubs/fctsheet/GHP.pdf
[xx] http://www.geoexchange.org/geothermal/publications/doc_download/10-all-the-comforts-of-home-heating-and-air-conditioning-for-25-to-50-less.html. The data from last two sentences of the paragraph and the quote come from this pdf.
[xxi] Geo Enterprises, Inc., summarizing the findings of the EPA study on GHP systems http://www.geo-enterprises.com/plain/Benefits.htm
[xxii] http://www.igshpa.okstate.edu/geothermal/commercial.htm#3
[xxiii] http://academic.evergreen.edu/g/grossmaz/tromblnr.html#The300to400
[xxiv] All stats in this paragraph from http://www.igshpa.okstate.edu/geothermal/commercial.htm
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