CO_2 EMISSION REDUCTIONS FOR GEOTHERMAL HEAT PUMP SYSTEMS IN THE NORTHEAST AND MID-ATLANTIC UNITED STATES

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ABSTRACT

Geothermal Heat Pump systems developed in the US largely because of the demand for space cooling in single-family houses. About fifteen years ago geothermal heat pump systems with borehole heat exchangers (BHE) were being applied to larger buildings. The motivation to reduce or avoid greenhouse gas emissions has spurred geothermal technologies in the last ten plus years. To estimate the impact of GHP installations on avoidance of CO_2 emissions, nine commercial installations in New Jersey were studied. In all cases emissions were reduced over a conventional system. If high efficiency GHP systems were installed the avoided emissions were between 31% and 50% of a gas boiler/ cooling tower system. These results are extrapolated for other similar climates with different fuel mixtures.

Key Words: ***geothermal heat pumps, carbon dioxide emission reduction, underground thermal energy storage.***

1 INTRODUCTION

A major motivator, at this time, for encouraging Geothermal Heat Pump (GHP) systems in the US is related to greenhouse gas emission concerns. With growing commitment of some state governments to reduce CO_2 emissions, and international encouragement since the Kyoto Protocol Treaty's immanent adoption, there is an interest in encouraging GHP technology. The original motivation to establish a national program to encourage GHP systems was a study supported by the US Environmental Protection Agency ("Space Conditioning: The Next Frontier"), which found that GHP systems were "the" viable technology that could contribute to reduction of greenhouse gases. This led to the establishment of the Geothermal Heat Pump Consortium (GHPC) - a partnership of electric utilities, GHP manufacturers, design engineers and geologists, and the US government (US Department of Energy (US DOE) and US Department of Environmental Protection (US EPA). The GHPC has as its goal to promote the use of GHP systems so that the technology moves from the niche market to the mainstream market. The recent (registered) name for this technology is GeoExchange®, which seams to better fit the overall applications including Underground Thermal Energy Storage (UTES). Nine realized buildings in New Jersey were modeled. In addition, a large system at Richard Stockton College was studied for emission reduction and is presented here.

1.1 Large BTES project—Richard Stockton College of New Jersey

The Richard Stockton College of New Jersey GHP system is described here was the motivator to the following study. The lessons learned from this system suggest that there are environmental impacts on the ground, and the efficiency of these systems can degrade over time due to thermal buildup in the ground.

Richard Stockton College of New Jersey has one of the largest single BTES (u-tube closed-loop) well fields, encompassing over 1.2 million cubic meters with 400 boreholes to 135 m depth penetrating three aquifers within saturated sands and clays. It is calculated that less than 2% of the thermal energy stored in the first summer of operation, for example, moved outside the well field within the first six months. In this case the HVAC design (including over 5000 kWc of HPs) does not balance the thermal load on the field, as a well-designed UTES system should. There is about twice the heat stored in the field during the cooling season (April - October 15) as cold stored during the heating season (Oct 15 – March). Thus the field is slowly heating. The three aquifers are moving heat from the field so that most engineers involved with the project expected that the aquifers would stabilize the temperature before the field overheated. In the original design it was decided a cooling tower could be added later if there was too much heat buildup (over approximately 6 degrees C). While this system is not an optimal design, in excess of $300,000 per year has been saved in energy costs. These cost savings translate to a payback period, of additional investment costs compared with a retrofit with a conventional system, of 8 to 12 years, without considering utility incentives. As shown in Table 1, the reduced electrical and natural gas demand results in substantial reductions of onsite and offsite emissions as summarized in terms of equivalent of taking American automobiles off the road permanently.

The serpentine set of buildings that are being heated and cooled by the geothermal system can be seen in figure 1. The well field is under the parking lot in the middle bottom of figure 1. Figure 2 illustrates the energy flow for both heating and cooling where all inputs are primary energy. This shows that with an input of 84 units of primary energy, 100 units of heat and cold are delivered to the complex. The result is that the project reduces its demand on primary energy and therefore is responsible for avoiding emissions. Table 3 summarizes the avoided emissions in equivalent American automobiles in 1992.

Fig. 1. Aerial view of Stockton campus

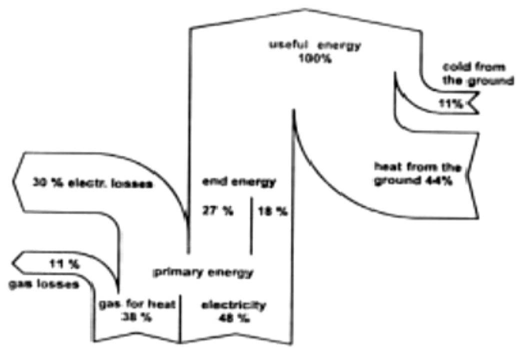

Fig. 2. Energy Flow diagram for Stockton geothermal system

Table 1. Environmental Benefit of Stockton College Geothermal Installation

	Reduced emissions (t/a)	Equivalent cars
CO_2	2207	459
NO_X	5.4	186
SO_X	10.9	3395

The GHP system at Stockton is not an optimum design for several reasons. Firstly, it was a retrofit that necessitated utilizing the existing air distribution system. As a result the HP units were specially manufactured for a roof top installation. Secondly, the HP units are not nearly as efficient as current design. If the Stockton system were designed today, the savings and avoided emissions would be much greater.

During the design phase, the prediction was the borehole field would increase in temperature about 0.5^{o}C (1 ^{o}F) per year almost indefinitely provided the aquifers did not affect the thermal energy flow. The plan was to put a cooling tower on the water loop and operate it in the winter to thermally balance the field. Note that typical hybrid systems would use the cooling tower in the summer to handle the peak demand. This design utilizes the ground as a seasonal thermal store and is called Underground Thermal Energy Storage (UTES). Thermally balancing the field over a year's period of time is critical for two reasons. First the system is primarily operating in the cooling mode and the efficiency of the heat pumps diminishes with higher water loop temperatures. Second, the heat buildup changes the underground ecology. The cooling tower was not initially installed but rather planned for the future. In the meanwhile we have been measuring this thermal buildup as part of the research program. The cooling tower is being added this winter (2005) and will be in operation in the following winter. The temperature of the ground will be steadily reduced, over several years time, to bring the temperature to the original value.

2 MODELED AVOIDED CO_2 EMISSIONS

Energy savings (and related emissions reductions) are only indirectly related to installed heat pump capacity. They are highly dependent on patterns of use. For example, a 500-kWc installation at an elderly care facility might save more energy than 700 kWc at an office building open only 40 hours per week. In addition, heat pump installations are sized to deal with extremes of climate and operating conditions. A building must be comfortable in the hottest and coldest weather, and under conditions of maximum use, such as when an auditorium is filled to capacity and spotlights and other electrical equipment are being operated. Hence, much of the time heat pumps are cycling off and on to meet more moderate levels of demand. Some buildings, as a result have a higher cooling capacity for the average load than others.

The ideal research approach would be to monitor energy use in identical, adjacent buildings, one using a conventional HVAC system and the other equipped with geothermal heat pumps to determine avoided energy consumption. A situation approximating this arose in 1995 in Washington County, Tennessee, when two high schools built in the early 1970s were retrofitted with contrasting systems. According to a Geothermal Heat Pump Consortium case study, the conventional system showed an operating cost reduction of about 20% over the previous installation, and the heat pump system accomplished about a 35% improvement. Savings at the geothermal school (compared to the conventional school) for 1998 were about \$35,000 including ~\$8000 in reduced maintenance costs. (GHPC, 1999) Unfortunately, energy savings expressed in term of cost cannot be directly converted to carbon dioxide emissions reduction figures.

Another approach to measuring the energy savings associated with heat pump installations is to use computer building simulation modeling. A building design and use pattern can be specified and energy use determined through use of a mathematical model incorporating climate data appropriate to New Jersey. This yields a result that is entirely hypothetical. Both the building and its energy use are artificially generated.

Our chosen research approach is a hybrid, involving application of a mathematical model to actual buildings. The micro-AXCESS Energy Analysis Program, Version 10.01 with Vinokur-Pace modifications was applied to real buildings for which complete design information was available. Seven buildings were selected for modeling. They fall into several categories - commercial offices (2), college classroom buildings (3), college cluster housing (modeled for both ten and twelve month occupancy), a middle school, and an elderly care facility. Additionally, a single-family residence was studied by using metered data and making assumptions about the efficiencies of the available heating/cooling options. Information on the buildings studied is summarized in Table 2. New Jersey climate data was used, based on Atlantic City TMY (typical mean year) with solar data. The buildings studied are listed in Table 2.

Energy use figures were generated for three HVAC options, namely conventional or typical systems (natural gas heat and electrical air conditioning and cooling towers) and both medium and high efficiency heat pumps. (Lower efficiency GHP systems are available but their use seems increasingly unlikely.)

Table 2. Buildings studied

Project ID	Cooling capacity	Floor Area	Category and use
	(in kWc)	(m^2)	
1	88	517	Commercial office
2	1755	15630	Five story office building*
3a	105	2286	College cluster housing (10 mo. use)
3b	105	2286	College cluster housing (12 mo. use)
4	263	1791	Two story college classroom building
5	1053	7509	Two story college classroom building
6	352	2326	Two story college classroom building
7	1232	13023	Middle school
8	632	5390	Elderly care facility, 3 stories, 120 beds
9	23	195	Single family residence
* Includes small area of 24-hour use offices.			

From the energy profiles, monthly and annual carbon dioxide emissions were calculated so that the relative "greenhouse" impact of each option could be compared.

2.1 Methodology of emissions avoidance calculations

When heat pumps are used, natural gas consumption drops to zero unless gas is used for cooking or domestic hot water, and electrical demand changes. A standard emission factor can be used to determine the air pollution from combustion of natural gas. The emission factor for gas combustion used in this project was 1.85 kg/m^3 (11.5 lbs/ccf). (AP-42, 5^{th} edition.)

It is more difficult to determine the emissions associated with electricity. This is because the electrical generating mix varies and is usually unknown. Various sources suggest emissions factors ranging from .35 to 1.1 kg (0.77 to 2.40 lb.) of carbon dioxide emitted per kilowatt-hour of electricity generated. The lower value reflects documentation accepted by the Department of Energy Climatewise Program (Voluntary Reporting of Greenhouse Gases) for the State of New Jersey. The value of 0.35 kg/kWh was promulgated in 1992 and has not been revised since. It reflects the substantial contribution of nuclear generating plants in New Jersey and also reflects the Climatewise Program's caution about excessive claims. The values for adjacent states are higher - 0.58 for Pennsylvania and 0.62 for Maryland.

Another source of emissions factors is the Natural Resources Defense Council, which has abstracted data from the EPA Acid Rain Database to create an emissions profile for each of the fifty largest electric utilities in the country. Two of New Jersey's three major utilities are included in the report, which dates from 1995. General Public Utilities was listed as emitting 0.63 kg/kWh of carbon dioxide and Public Service Electric and Gas 0.36 kg/kWh, one of the lowest values in the group studied. (NRDC, 1997)

The highest value found (1.1 kg/kWh) dates from 1990 and pertains to generation by coal combustion only. It may not represent current coal burning technology. For this work, we selected a value based on the national average and being used by the NJ DEP in its proposed carbon dioxide emissions trading rule (Open Market Emissions Trading, 1999). This value is 0.59 kg (1.29 lbs) CO_2 emitted per kilowatt-hour of electricity generated. Determining a more accurate emission factor for this work would require use of specific power plant dispatch data for marginal power generation.

2.2 Results of Study in New Jersey

The results for buildings analyzed using the AXCESS model and for the single-family residence are summarized in Table 3. The emissions ranges indicated reflect calculations for both medium and high efficiency heat pumps.

Table 3. Comparison of typical systems with medium and high efficiency GHP

Project type	CO_2 reduction	CO_2 reduction
		(kg/kWc)
1 - Commercial office	19% - 34%	156-255
2 - Commercial office	41% - 46%	177-201
3a - College cluster housing	38% - 45%	75-91
(10 month occupancy)		
3b - College cluster housing	43% - 50%	167-198
(12 month occupancy)		
4 - College classrooms	19% - 26%	63-87
5 - College classrooms	18% - 26%	51-73
6 - College classrooms	17% - 32%	85-159
7 - Middle school (ages 11-13)	29% - 42%	136-192
8 - Elderly care facility	28%-42%	120-144
9 - Single family residence	48%	186

* Ranges indicate use of medium and high efficiency heat pumps.

The highest annual carbon dioxide savings suggested by Axcess modeling for high efficiency heat pumps is 255 kg/kWc for project 1, a small commercial office building. The lowest was 73 kg/kWc, for project 5, one of the college classroom buildings.

Project 3 (college cluster housing evaluated on a ten and twelve month bases) is of particular interest because it shows the value associated with use of heat pumps for air conditioning. Summer use of the facility roughly doubles the avoided CO_2 emissions. The middle school (project 7) likewise shows increased savings in summer. It is to be anticipated that all future school construction (and most renovation) will include air conditioning to allow for twelve-month community use of facilities and to protect the public's investment in computers and associated equipment that require secure buildings.

2.3 Application to Other States and Regions

There is concern that the use of heat pumps shifts energy-use patterns, reducing electrical consumption in the summer and increasing it in the winter, without net improvement in terms of environmental impact. Evaluating air quality impact is complicated by the difficulty (discussed above) of assigning an emission factor when electrical generating mix is unknown. Using a range of emission factors, this study shows that heat pumps are responsible for smaller releases of carbon dioxide annually than conventional systems in the nine buildings studied for the New Jersey climate.

However, these calculations do not consider which power plants are dispatched on the margin during the periods of electrical demand. If, for example, more fossil fuel plants were generating, on the margin, during the winter and cleaner gas turbines in the summer as peak generators, then the shift of electrical demand from GHPs from summer to winter may not have the same benefit of CO_2 reduction, even if the total electrical demand is reduced. This effect is not captured in any of these calculations. On the other hand, if nuclear power is the base load generator and fossil fuel power plants are used as peak generating plants, then the reverse may be true. This effect was beyond the scope of this study.

To understand the implications of these results to other locations and climates, it seems likely that CO_2 emissions will be reduced if the total electrical use is reduced as well as natural gas use, assuming there isn't some drastic difference in summer and winter emission factors. This is especially the case in the above buildings if the comparison is with the higher efficiency GHP. The New Jersey climate is fairly similar to other Mid-Atlantic states, the coastal region of New England states, and Midwestern states in the median latitudes. These regions are characterized by moderate winters and humid warm summers. Other Mid-Atlantic states and the coastal region of New England have a similar fuel mix to the one used in the New Jersey study. This suggests that the results here can be applied to the Mid-Atlantic and coastal region of New England. The results are summarized in Table 4. The Midwestern states use mostly coal-burning power plants. To understand the implications of this different emission factor, the emissions were recalculated for a coal-only scenario and summarized in Table 5. This shows that the fraction or reduced emission is less than for New Jersey, but the actual reduction in emissions is typically larger. This is because most buildings with GHPs actually demand fewer kWh of electricity and no natural gas. So fewer kWh of electricity generated by coal has a larger absolute reduction in emissions, even if the reduction fraction is smaller.

Table 4. Summary of CO_2 reduction calculation for emissions factor in New Jersey and for high efficiency GHPs

Project ID	Total reduction emissions (kg CO_2)	Original emissions (kg CO_2)	HVAC fraction	percentage of total	percentage of HVAC
1	22508	112546	0.59	20	34
2	352754	2849183	0.27	12	46
3a	9349	52726	0.39	18	45
3b	20807	87967	0.47	24	50
4	22753	179497	0.48	13	26
5	76640	634297	0.46	12	26
6	55643	326233	0.54	17	32
7	235642	872366	0.65	27	42
8	129365	785430	0.39	16	42

Table 5. Summary of CO_2 reduction calculation for emissions factor assuming all coal generation and for high efficiency GHPs in New Jersey

Project ID	Total reduction emissions (kg CO_2)	Original emissions (kg CO_2)	HVAC fraction	percentage of total	percentage of HVAC
1	21010	174564	0.59	12	20
2	462287	4719764	0.27	10	36
3a	8690	82667	0.39	11	27
3b	28231	142768	0.47	20	42
4	20868	288183	0.48	7	15
5	97997	1049040	0.46	9	20
6	55767	517240	0.54	11	20
7	301786	1387672	0.65	22	33
8	146873	1265744	0.39	12	30

The southern states with warmer climates will see an even larger benefit in emission reductions, since there will be an even larger reduction in electrical use. This is due to the larger cooling demand and smaller heating demand. The largest benefit comes in the much higher efficiency of GHP systems in the cooling mode compared with a standard chiller.

It is not as obvious if there is as large a benefit in regions with colder climates. Caneta Research (1999) found that for all regions of Canada, GHP systems result in lower CO_2 emissions for a single-family house, an elementary school and a small multi-unit residential building. The smallest reduction, 15%, was in Regina where the electricity was generated solely from coal plants.

3 CONCLUSION

Studies reported here show that geothermal systems result in lower CO_2 emissions. While there is a large range of realized savings, all buildings studied benefited the goal of reduced CO_2 emissions. It appears that these findings can be applied to other regions and climates in the US. The only possible exception may be in cold climates with little cooling and larger heating demands that are utilizing coal generated electricity. With the commitment to the Kyoto Agreement increasing, GHP systems can play a substantial role in helping the US meet its commitments.

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www.geoexchange .org (projects on members' only page)

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