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Hybrid Ground-Source Heat Pumps for Cooling Cellular Tower Shelters: from Campus Living Laboratory to Nationwide Deployment

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ABSTRACT

Tens of thousands of cellular towers are in operation across the U.S. Most of the cell towers are accompanied by a small shelter that houses electrical equipment continuously generating around 8 kW_{th} of heat. The annual electricity bill for cooling these shelters with conventional air-source heat pump (ASHP) systems and their corresponding carbon footprint are significant. This paper presents methodology and results of techno-economic and environmental modeling of five different cooling configurations for shelters located across various states with different climates. The five configurations include: case 1: ground-source heat pumps (GSHP)-only; case 2: GSHP + air economizer (AE); case 3: GSHP + dry-cooler (DC); case 4: ASHP-only (business as usual – BAU); and case 5: ASHP + AE. With no consideration of incentives or rebates, base case results show that the total cost of ownership (TCO) for all configurations is the lowest for states located in cooler climatic regions (e.g., Maine, Minnesota, Colorado), and the highest for states located in warmer climatic regions (e.g., California, Florida). The configuration with the lowest overall TCO is case 5: ASHP + AE, and the highest is case 1: GSHP-only. Furthermore, the configuration with the lowest lifetime electricity consumption and CO_2e emissions is case 2: GSHP + AE, and the highest is case 4: ASHP-only. With the use of energy-efficient GSHP systems, regions with high electricity prices and consumption will experience lower costs and environmental impacts from a reduction in operating conditions over the lifetime of the system (20 years). It is expected that the prospect of GSHP systems will be more favorable in the future than in today's economy when incentives and rebates, increasing electricity prices, and carbon taxes are considered.

1. INTRODUCTION

In 2010, a multi-year study at Cornell University began investigating the technical performance and economic attractiveness of ground-source (geothermal) heat pump (GSHP) systems providing cooling to cellular tower shelters nationwide. A proof-of-concept study conducted by LaBrozzi et al. (2010) in collaboration with Verizon Wireless showed that GSHPs in combination with air economizers (AE) ("hybrid GSHP") present a cost-effective and energy-efficient alternative to conventional air-source heat pump (ASHP) units. Subsequently, a full-scale and fully-monitored hybrid GSHP system was designed and built in 2014 at a Verizon Wireless cellular tower site in the Cornell University Plantations (Varna, NY). The demonstration system has 6 boreholes (with almost 560 m total borehole depth) and has been operating reliably and efficiently since installation (Beckers, 2016). In the Spring of 2016, thermodynamic and heat transfer models of hybrid GSHP and ASHP systems were developed using the transient energy simulation software TRNSYS (Klein et al., 2010) to investigate and optimize system configuration for different operating conditions. Design and validation of the simulation models were summarized in Beckers (2016) using data collected both at Varna, NY and from literature sources. The validated models became a major component in the development of a Systems Engineering Model (SEM) to analyze the techno-economic and environmental performance of hybrid GSHPs and ASHPs for cooling of cellular tower shelter sites nationwide. The SEM characterized the U.S. with consideration of various climatic regions, hydrogeological regions, estimated population and cell tower densities, capital expenditure and operating costs, and environmental emissions. The SEM architecture used ArcGIS (ESRI, 2016) for spatial analyses and models developed in TRNSYS and MATLAB (MathWorks, 2009) software to perform technical and economic analysis, as shown in Figure 1. As part of the SEM analyses, five cooling configurations were considered: case 1: GSHP-only; case 2: GSHP + AE; case 3: GSHP + dry cooler (DC); case 4: ASHP-only (BAU); and case 5: ASHP + AE.

This study summarizes collaborative work between Cornell University and Verizon Wireless involving modeling, validation, and nationwide analysis of hybrid GSHP and ASHP systems for cooling cellular tower shelters. The objectives of the study are fourfold: 1) monitor and analyze the performance of the hybrid GSHP cooling system at the Cornell-Verizon cell tower site ("Varna site"); 2) develop computer models and validate the models using data from the Varna site and literature, and simulate hybrid GSHP systems providing cooling to cellular tower shelters; 3) using the validated computer models, optimize the GSHP system configuration, geometry of borehole heat exchangers, borehole field layout, and operating strategy; and 4) investigate the technical, economic, and environmental performance of cellular towers equipped with hybrid GSHP and ASHP systems at a nationwide scale. This paper briefly discusses the methodology for addressing objectives 1 through 3 in sections 2 and 3, and focuses on methodology and results of objective 4 in sections 4 and 5. Additional documentation for objectives 1 through 4 is provided in Beckers (2016) and Beckers et al. (2016).

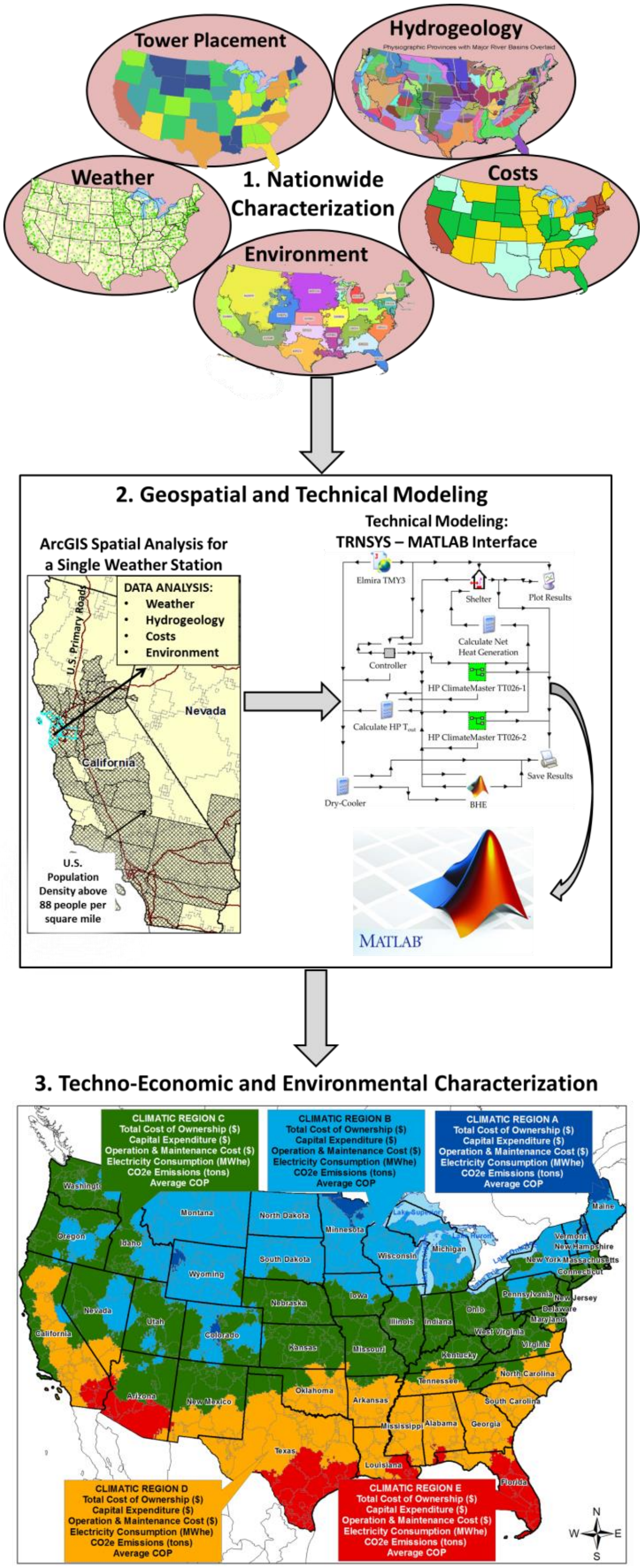

Figure 1: Schematic of the Systems Engineering Model (SEM) incorporating ArcGIS, TRNSYS, and MATLAB software to perform techno-economic and environmental analysis of hybrid GSHP and ASHP systems for cooling cellular tower shelters.

2. HYBRID GROUND-SOURCE HEAT PUMP (GSHP) SYSTEM AT THE CORNELL-VERIZON CELL TOWER SITE

A full-scale and fully-equipped hybrid GSHP was designed and built during the period 2011-2013 to provide cooling for a newly-built Verizon Wireless cellular tower shelter in the Cornell University Plantations (Varna, NY). The system start-up phase was completed by the end of 2013 and by the beginning of 2014, all telecommunication, cooling system, and data acquisition equipment were in full operation.

Due to relatively cold winters in Upstate New York, the hybrid system includes an air economizer (AE) and a dry-cooler (DC). The AE brings cold outside air into the shelter when the ambient temperature drops below the set-point temperature of 10°C. When the AE is running, the heat pump system shuts down, which allows the geothermal reservoir to thermally recover as no heat rejection from the shelter into the ground is taking place. The use of an AE requires replacing the air filters on a regular basis, which increases maintenance costs. In addition, there is an increased risk for dust particles entering the shelter and potentially negatively affecting the electronics when using AEs. The DC is an air-cooled heat exchanger, located outside of the cellular shelter and connected to the borehole heat exchangers (BHEs). Circulating the glycol solution between BHEs and DC during cold days provides active cooling of the reservoir ("recharging"), which offsets the thermal imbalance in heat exchange during warmer months and enhances the long-term performance of the GSHP in a cooling-dominated application. In addition, the DC can be utilized as a pre-cooler in series with the geothermal reservoir (Beckers et al., 2014; Beckers, 2016).

In Figure 2, the BHE field consists of 4 single-U (1-U) heat exchangers (81 m depth each) and 2 double-U (2-U) heat exchangers (117 m depth each; pipes within BHE are in parallel with each other) with each BHE individually controlled by a valve. The site includes a wide array of sensors to monitor the performance of the hybrid GSHP system and to provide data needed for validation of numerical models.

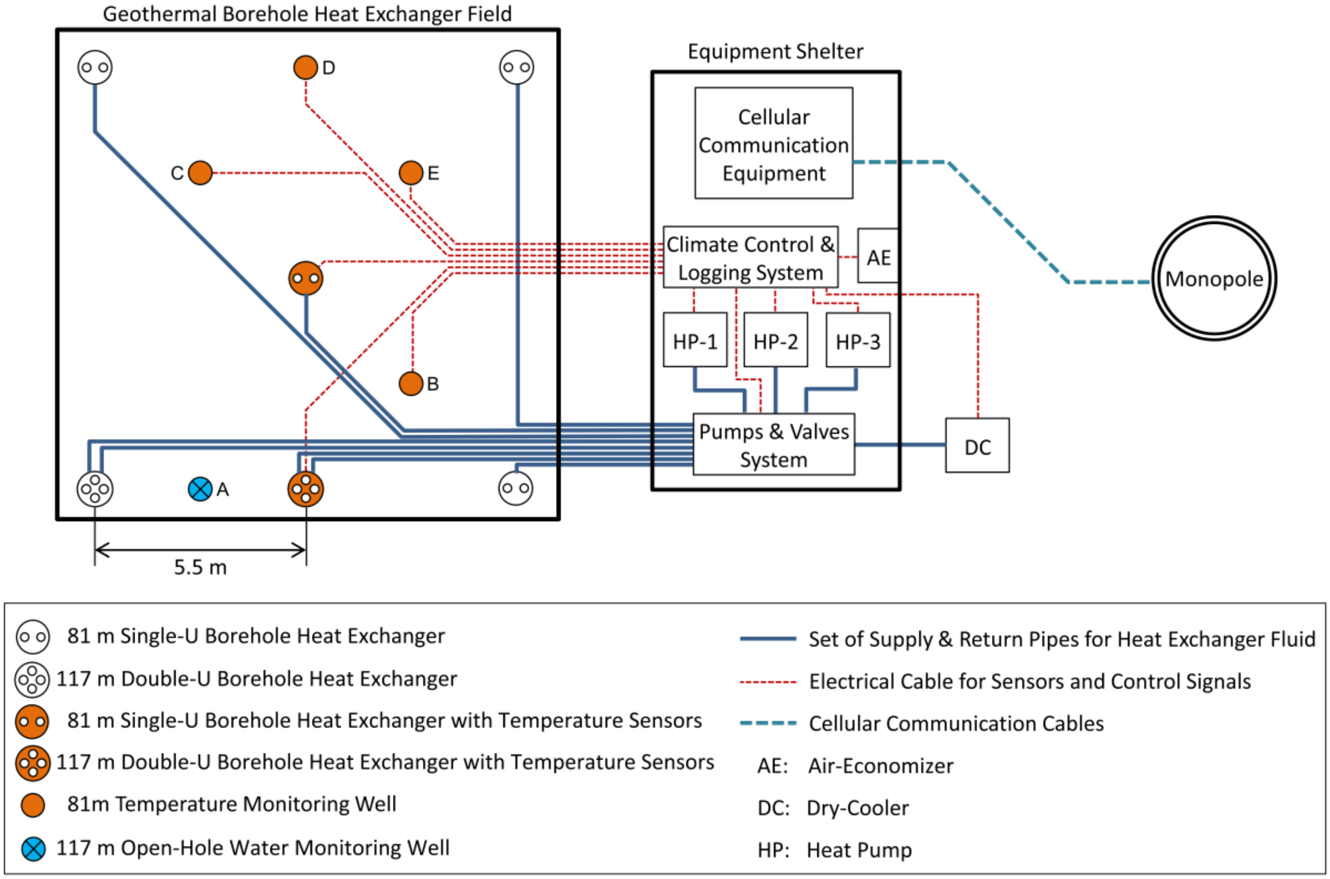

Figure 2: Layout of the Verizon hybrid ground-source heat pump (GSHP) project at Varna, NY including borehole heat exchanger field, equipment shelter, and cellular tower monopole.

3. TRNSYS SYSTEM MODELING AND VALIDATION

The simulation software TRNSYS was used to develop a model of the hybrid GSHP system for cooling cellular tower shelters (Klein et al., 2010). Figure 3 shows a schematic of the TRNSYS model. Ambient temperature data, either from local measurements or from an existing weather database, is incorporated using the TMY3 data format (Wilcox and Marion, 2008). The shelter is represented by a single-zone lumped capacitance building model in TRNSYS, with parameter values such as thermal capacitance derived from measured data. The GSHP, AE, and DC units are modeled using correlations based on the manufacturers' datasheets. The BHE is represented using transient heat transfer models based on g-functions outside the BHE and a finite difference model within the BHE. Descriptions of specific TRNSYS components and correlations used to describe them are documented in Beckers (2016). The models of many individual components (e.g., GSHP, BHE) have been validated or are directly based on experimental measurements at the Varna site (e.g., cell tower shelter) (Beckers, 2016). For model validation purposes, the TRNSYS simulation incorporates the actual ambient temperature, heat pump inlet temperature, and the equipment heat generation measured at the site. The circulating fluid supply temperature is not simulated, but is directly based on the Varna site measurements because the BHE model does not include groundwater advection due to lack of data on the local groundwater flow.

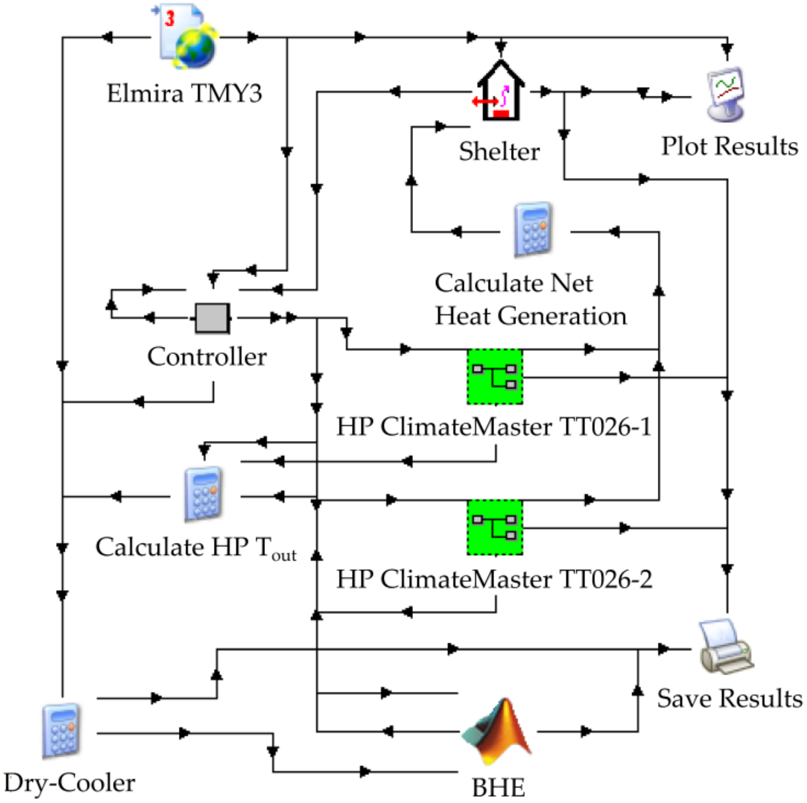

Figure 3: Schematic of the TRNSYS model of hybrid GSHP for cooling of cellular tower shelters.

4. ANALYSIS OF A NATIONWIDE IMPLEMENTATION OF HYBRID GROUND-SOURCE HEAT PUMPS (GSHP) AND AIR-SOURCE HEAT PUMPS (ASHP) IN CELLULAR TOWER SHELTERS

The fourth objective of this study involves a nationwide analysis of the techno-economic and environmental performance of hybrid GSHP and conventional ASHP systems for cooling cellular tower shelters. The feasibility assessment of nationwide deployment is a multidisciplinary study based on various climatic regions, hydrogeological regions, estimated population and cell tower densities, capital expenditure and operating costs, and environmental emissions from electricity generation. The analysis uses the numerical models developed for the Varna, NY site (see sections 2 and 3) and a Systems Engineering Model (SEM) developed for a set of representative, regionally-located cellular tower shelters (Beckers, 2016; Beckers et al., 2016).

4.1 Overview of the Systems Engineering Model (SEM)

The SEM multidisciplinary approach consists of nationwide characterization of six subsystems: 1) technical data modeling (GSHP, AE, DC, ASHP); 2) weather data modeling; 3) tower placement factors and location; 4) hydrogeological characterization; 5) cost modeling; and 6) environmental modeling.

The output of the SEM is a set of case studies for five cooling configurations (see section 1) that describe the total cost of ownership (TCO), lifetime electricity consumption (LEC), and environmental emissions (LCO_2e) in various geographic locations within the contiguous 48 U.S. states. The techno-economic and environmental performance of the cooling configurations are summarized nationwide by using climatic subdivisions based on the Typical Meteorological Year (TMY3) weather boundaries of annual mean surface temperature as shown in Figure 4 (Wilcox and Marion, 2008).

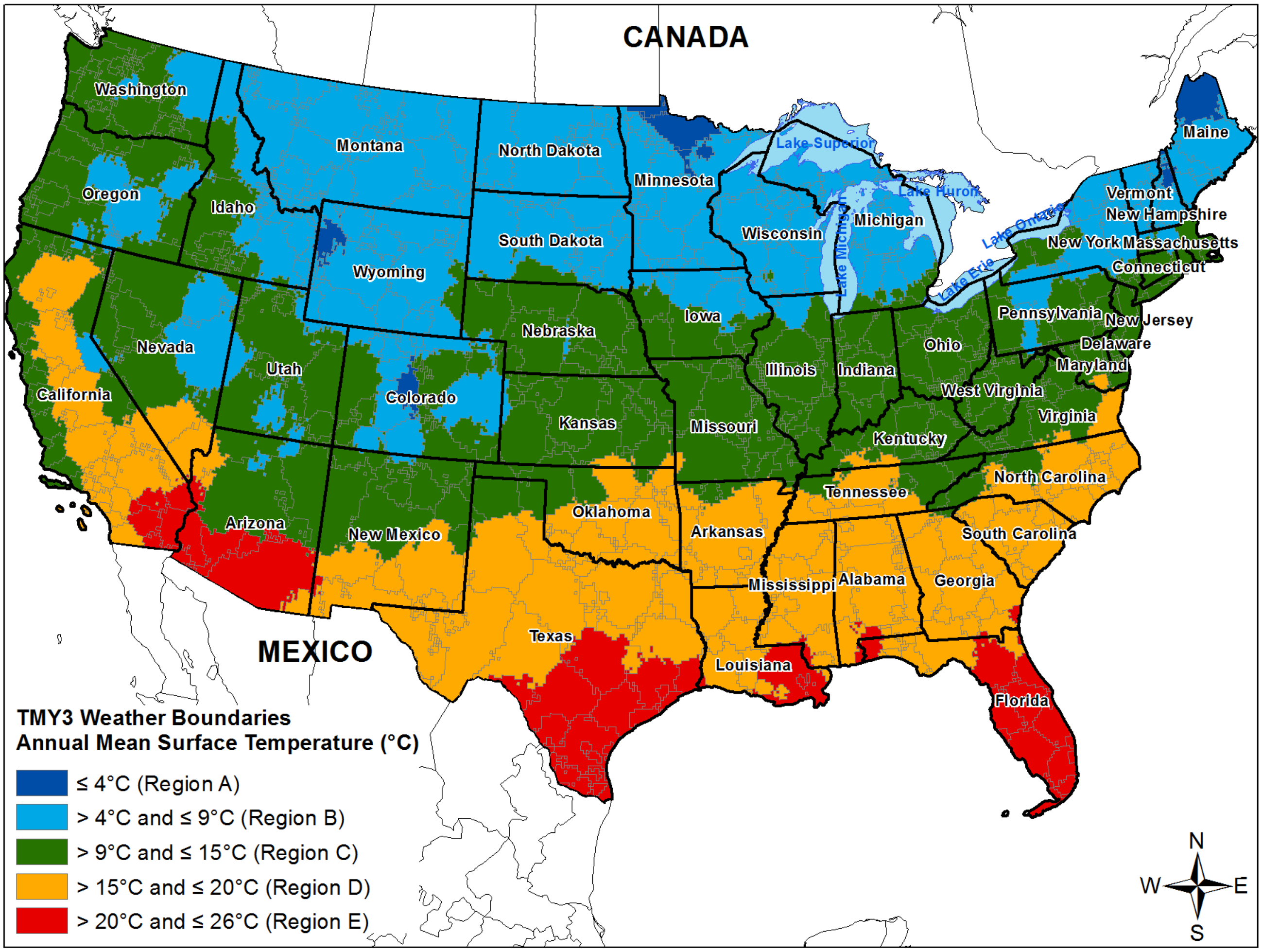

Figure 4: Nationwide climatic subdivisions based on the Typical Meteorological Year (TMY3) weather boundaries of annual mean surface temperature (Wilcox and Marion, 2008).

4.1.1 Technical Data Subsystem

The technical data subsystem includes the TRNSYS model validated using results from the Cornell-Verizon experimental site in Varna, NY to assess the performance of the GSHP field (see sections 2 and 3). The model uses site-specific parameters including thermal properties of the soil/rock and grout, borehole installation criteria, and the coefficient of performance (COP) of the heat pump, among other parameters (Beckers et al., 2014; Beckers, 2016). A representative heat generation for cellular tower shelters across the nation was set at 8 kW_{th} (Feeney, 2015; 2016).

4.1.2 Weather Data Subsystem

Performance of the GSHP, AE, DC, and ASHP units depend on the weather conditions at the site, including dry-bulb temperature and relative humidity, among others. To reflect the weather conditions, the Typical Meteorological Year (TMY3) database was employed. The TMY3 dataset contains hourly meteorological values for the most typical months of the year over a time period spanning from 1976 – 2005 (Wilcox and Marion, 2008). A total of 925 TMY3 weather stations with different uncertainty classifications and data pool years (> 10 years) were used to characterize the U.S. climate. Along with the 925 weather stations, a total of 545 TMY3 weather boundaries are included in the dataset to identify areas that share similar climatic conditions based on the location of the stations. Often, the weather boundaries include more than one station. Therefore, the station with the lowest uncertainty (Class I and II) was used to represent each of the 545 TMY3 boundaries.

4.1.3 Tower Placement Factors Subsystem

Verizon Wireless estimates that over 18,000 cell tower shelter sites across the nation could benefit from replacing their conventional ASHP units with energy efficient GSHPs. The estimates provided by Verizon do not include cabinet sites located outdoors which utilize heat exchangers instead of ASHPs for cooling, and other lower cooling load sites that would not benefit from retrofitting GSHPs (Feeney, 2015; 2016). State-level estimates of cellular shelters from Verizon and spatial analyses indicate that the number of cellular tower shelters is expected to be higher where major roads and high population clusters are collocated.

4.1.4 Hydrogeological Data Subsystem

Hydrogeological characterization enables the identification of rock types and provides estimates of their thermal conductivity. Thermal conductivity is a measure of how effective soil/rock units will conduct heat to/from the circulating fluid in the GSHP borehole. In addition to the characterization of thermal properties of soils and rocks, hydrogeological studies permit the classification of groundwater bearing units. The presence of groundwater has an influence on the heat transfer because groundwater could carry heat in/out of the GSHP system.

To estimate the hydrogeological conditions across the nation, groundwater regions were established based on twelve classifications by Thomas (1952) and Heath (1984). Each region contains information on expected geological settings and aquifer characteristics. To estimate the thermal regime of each of the twelve hydrogeological regions, surficial and bedrock geological maps were used (Schruben et al., 1997; Soller et al., 2009). The surficial (unconsolidated material) and bedrock units were classified into five subtopics: 1) unconsolidated materials; 2) sedimentary rocks; 3) volcanic rocks; 4) plutonic rocks; and 5) metamorphic rocks according to the U.S. Geological Survey Earth Material website (USGS, 2014).

For conduction-dominated systems, thermal properties for the geological subtopic classifications were assigned based on a range of thermal conductivities from literature compilations by Čermák and Rybach (1982) and Clauser and Huenges (1995). An average estimated thermal conductivity characteristic of each hydrogeologic region was then assigned to each geographic location analyzed.

4.1.5 Cost Data Subsystem

To determine the total cost of ownership (TCO) for the five cooling configurations, several factors were considered including: the current national market for GSHP installations, average retail price of electricity for the commercial sector, and available incentives offered to energy-efficient technologies. The TCO includes capital expenditures for each cooling configuration plus operation and maintenance costs, including electricity purchased over the expected lifetime of the system (20 years).

In 2013, Battocletti and Glassley summarized data from surveys on the costs and benefits of GSHP deployment nationwide, including estimated drilling costs across census regions. As part of the capital expenditure of installing GSHPs, regional drilling cost variations could have a significant impact on the TCO nationwide. The average retail price of electricity for the commercial sector is an important factor in the determination of the operating costs included in the TCO because the considered technologies consume electricity to provide cooling.

For the base case scenario presented in this study, no consideration of incentives or rebates was included in the economic analysis. Existing and potential sources of incentives or rebates could result in a favorable impact on the feasibility of financing GSHP systems for commercial installations. The Database of State Incentives for Renewables and Efficiency (DSIRE) operated by the North Carolina Clean Energy Technology Center at North Carolina State University lists a number of existing incentives in both commercial and residential settings for the implementation of energy-efficient systems (DSIRE, 2015). At the federal level, a corporate depreciation has been offered to energy-efficient technology, including GSHP units, through the five-year Modified Accelerated Cost Recovery System (MACRS). This depreciation method is an annual tax deductible that allows accelerated recovery of the cost of the technology over the first few years of its lifetime. Recently, the federal government offered “bonus” depreciation for energy property placed in service from 2008 to 2013 in the amount of 50%. The remaining basis can then be depreciated in accordance to the five-year MACRS (ClimateMaster, 2014; DSIRE, 2015; IRS 2015). Because incentives and rebates might vary from year-to-year, it is recommended to search for any relevant opportunities in the databases previously mentioned before the installation of energy-efficient systems.

4.1.6 Environmental Data Subsystem

Verizon’s current greenhouse gas (GHG) reporting standards are defined by “The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard” (WRI, 2015). The three scopes under the reporting standards include: 1) direct sources of emissions owned or controlled by Verizon; 2) indirect emission sources generated off-site, but purchased by Verizon; and 3) business travel by air and rail. In this study, scope 2 of the reporting standards was evaluated because it considers electricity purchases from the grid to power and provide cooling to Verizon’s cellular tower shelters (WRI, 2015; Sotos, 2015). The Emissions & Generation Resource Integrated Database (eGRID) from the U.S. Environmental Protection Agency (EPA) was used to estimate indirect emissions from electricity consumption by using EPA subregions (EPA, 2015). EPA subregions represent a portion of the U.S. power grid contained within a single North American Electric Reliability Corporation (NERC). Individual NERC regions might have similar GHG emissions and electricity generation resource mix characteristics, as well as similar transmission losses. The annual CO_2 equivalent (CO_2e) total output emission rates were used in this analysis to assess the lifetime greenhouse gas emissions for each cooling configuration. The subregion with the highest annual CO_2e emission rate (832 g/kWh$_e$) is the Western Electric Coordinating Council/Rockies (RMPA), which comprises much of the state of Colorado and parts of Wyoming and Nebraska. The electricity generation resource mix of the RMPA subregion is primarily coal (~70%) and natural gas (~16%). The subregion with the lowest annual CO_2e emission rate (186 g/kWh$_e$) is the Northeast Power Coordinating Council/Upstate New York (NYUP), which comprises much of the state of New York. The electricity generation resource mix of the NYUP subregion is primarily natural gas (~30%), followed by hydro (~29%) and nuclear (~29%) (EPA, 2015). The lifetime CO_2e estimates for the cooling configurations provided in this study depend on the estimated lifetime electricity consumption as well as the CO_2e emission rates. Therefore, regions with low lifetime electricity consumption but high CO_2e emission rates (per unit of electricity consumed) could produce higher lifetime CO_2e emissions than regions with high electricity consumption but low CO_2e emission rates.

5. RESULTS AND DISCUSSION

Results of applying the SEM to estimate the techno-economic and environmental performance of the five cooling configurations are presented in this section by using nationwide climatic divisions (see Figure 4). Table 1 summarizes the base case parameters implemented in the study.

		Cooling Configuration				
Parameter	**Metric**	**Case 1: GSHP-only**	**Case 2: GSHP + AE**	**Case 3: GSHP + DC**	**Case 4: ASHP-only (BAU)**	**Case 5: ASHP + AE**
Shelter Heat Generation	Technical	8 kW_{th}				
Weather Data	Technical	based on specific TMY3 weather stations and boundaries				
Hydrogeologic Data	Technical	mean conduction-only thermal conductivity estimates based on surficial and bedrock geologic maps for the U.S.				
AE Setpoint	Technical		10°C			10°C
DC Setpoint	Technical			5°C above mean annual surface temperature		
System Lifetime	Technical	20 years				
Net Discount Rate	Economic	3%				
Electricity Rate	Economic	based on EIA 3-year average (2012 - 2014) for the commercial sector				
Drilling Capital Cost	Economic	based on national market analysis median price per length of geothermal loop installed				
GSHP Unit Capital Cost	Economic	$5,000 (two units for redundancy)				
GSHP capital cost for pumps, piping & installation	Economic	$5,000				
ASHP Unit Capital Cost	Economic				$2,500 (two units for redundancy)	
AE Capital Cost	Economic		$1,000			$1,000
DC Capital Cost	Economic			$1,000		
GSHP Maintenance Cost	Economic	$200/year				
ASHP Maintenance Cost	Economic				$580/year	
AE Maintenance Cost	Economic		$200/year			$200/year
Incentives	Economic	None				
Environmental Emissions	Environmental	based on EPA eGRID year 2012 tables and maps				

Table 1: Summary of the base case technical, economic, and environmental parameters implemented in the five cooling configuration case studies.

Major findings from the SEM for the five cooling configurations are summarized in Table 2 and figures 5, 6, and 7 for six geographic locations in the U.S. representative of various climatic regions (see Figure 4). The illustrated results are based on a shelter heat generation of 8 kW_{th}, an expected system lifetime of 20 years, and costs conditions that do not consider incentives, subsidies, or rebates.

In Figure 5, the total cost of ownership (TCO) for all configurations is the lowest for states located in cooler climatic regions (e.g., Maine, Minnesota, Colorado). In these states, the total lifetime electricity consumption is expected to be lower, and in the case of the GSHP system, less total borehole length is required (under 270 m for some regions). For example, Caribou, ME has the lowest TCO for case 2: GSHP + AE because its cold climate allows for frequent use of air economizers (AE) during the year. The use of AE reduces capital and operating expenditure due to lower total borehole length of the GSHP system and lower lifetime electricity consumption, respectively.

As shown in Figure 5, the TCO for all configurations are the highest for states located in warmer climatic regions (e.g., California, Florida). In order to provide continuous cooling in warmer climatic states, more electricity is consumed over the lifetime of the system, and the GSHP system requires larger total borehole lengths (up to 1080 m for some regions). In regions requiring significant total borehole lengths, the capital expenditures of installing GSHPs can be as high as eight times the cost of business as usual (BAU) ASHPs. The operation and maintenance (O&M) costs depend on the lifetime electricity consumption of the cooling configuration, and vary depending on the state's electricity prices. The O&M costs for ASHPs can be twice as high as the costs of energy-efficient technologies (GSHPs). In warmer climatic states (e.g., Florida), installing AEs is not recommended because the small fraction of the year when the AE can be used does not justify the added costs of installation, operation, and maintenance. With the exception of Miami, FL, the configuration with the lowest overall TCO is case 5: ASHP + AE followed by case 2: GSHP + AE. The configuration with the highest overall TCO is case 1: GSHP-only followed closely by case 3: GSHP + DC and case 4: ASHP-only.

In Figure 6, the configuration with the lowest lifetime electricity consumption is case 2: GSHP + AE followed by case 5: ASHP + AE. The configuration with the highest overall lifetime electricity consumption is case 4: ASHP-only followed by case 3: GSHP + DC and case 1: GSHP-only. Similarly, the lifetime CO_2e emissions are the lowest for case 2: GSHP + AE, and the highest for case 4: ASHP-only. For example, Figure 7 shows that the lifetime CO_2e emissions in Colorado for case 4: ASHP-only are almost a factor of three greater than for case 2: GSHP+AE. Overall, Colorado has higher lifetime CO_2e emissions for most configurations because its electricity generation resource mix is primarily coal (~70%) (see section 4.1.6). Even though all five cooling configurations located in Florida consume the highest amount of electricity of all the considered geographic locations, their environmental impacts are lower than those of states that consume less electricity because Florida's electricity generation mix is primarily natural gas (~68%). As expected, upstate New York results in the lowest lifetime CO_2e emissions for all configurations and geographic locations because its electricity generation resource mix is based on low CO_2 emitting energy sources.

The electricity consumption of the GSHP systems varies depending on the coefficient of performance (COP). In this study, a representative total borehole length was chosen for each climatic region to provide a COP of at least 3.5. Typical GSHP COP's can range from 3 to 6, which means that for each unit of electricity input, the GSHP provides 3 to 6 units of cooling capacity (Glassley, 2010; Beckers, 2016). Lower lifetime electricity consumption and environmental emissions for GSHP systems can be achieved by increasing the total borehole length, which improves the COP of the system (Beckers, 2016).

The base case results of the five cooling configurations summarized in this section represent an approximation of the expected regional values based on the available data. To improve the accuracy and increase the spatial resolution at any particular location, it is necessary to perform detailed hydrogeologic and climatic analyses, as well as establish economic and environmental metrics that are representative of that exact geographic location. To assess the impact of parameter variations on the performance of the five cooling technologies, a sensitivity analysis of the parameters discussed in Table 1 is currently being undertaken by our group.

			Cooling Configuration				
Climatic Region	**City, State**	**Metric**	**Case 1: GSHP-only**	**Case 2: GSHP + AE**	**Case 3: GSHP + DC**	**Case 4: ASHP-only (BAU)**	**Case 5: ASHP + AE**
Experimental Site	Varna, NY (Experimental site)	TCO ($)	61,300	45,800	58,500	54,700	41,200
		LEC (MWhe)	348	157	366	403	214
		LCO_2e (tons)	65	29	68	75	40
A	Caribou, ME	TCO ($)	56,100	38,500	57,100	51,300	35,400
		LEC (MWhe)	354	127	385	379	157
		LCO_2e (tons)	103	37	112	110	46
B	Minneapolis, MN	TCO ($)	48,100	39,300	49,200	47,100	37,200
		LEC (MWhe)	282	131	344	400	213
		LCO_2e (tons)	183	85	224	260	139
C	Denver, CO	TCO ($)	52,300	43,600	49,400	47,600	39,000
		LEC (MWhe)	296	160	326	416	243
		LCO_2e (tons)	246	133	271	346	202
D	Sacramento, CA	TCO ($)	69,400	62,400	65,300	64,600	58,500
		LEC (MWhe)	322	232	325	441	347
		LCO_2e (tons)	95	69	96	131	103
E	Miami, FL	TCO ($)	96,900	100,700	78,500	53,700	57,500
		LEC (MWhe)	362	359	469	501	499
		LCO_2e (tons)	185	184	241	257	256

Table 2: Total cost of ownership (TCO, $), lifetime electricity consumption (LEC, MWhe), and lifetime CO_2e emissions (LCO_2e, tons) by cooling configuration for six geographic locations nationwide in different climatic regions.

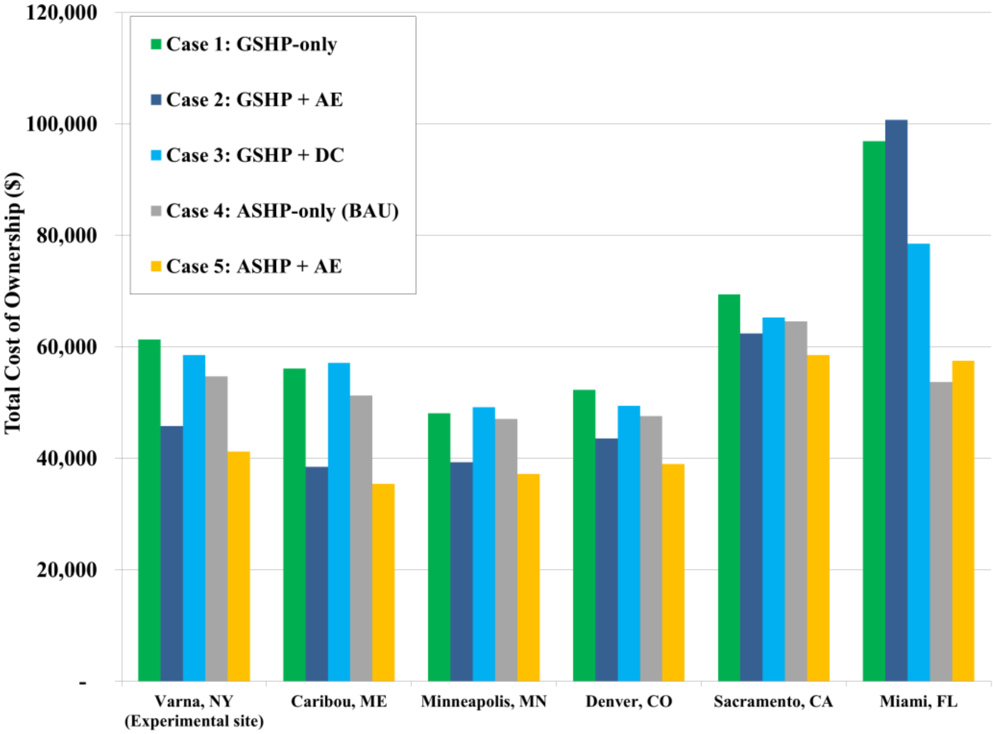

Figure 5: Total cost of ownership (TCO, $) for five cooling configurations by geographic locations nationwide in different climatic regions.

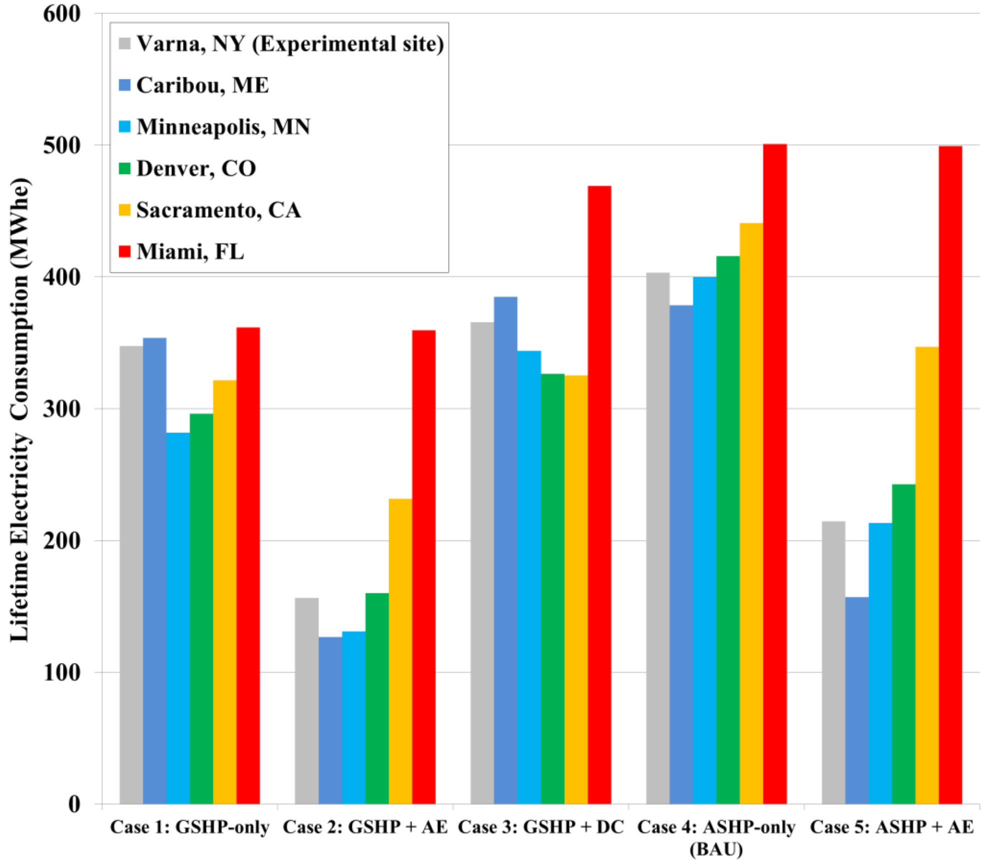

Figure 6: Lifetime Electricity Consumption (LEC, MWhe) for six geographic locations nationwide in different climatic regions by cooling configuration.

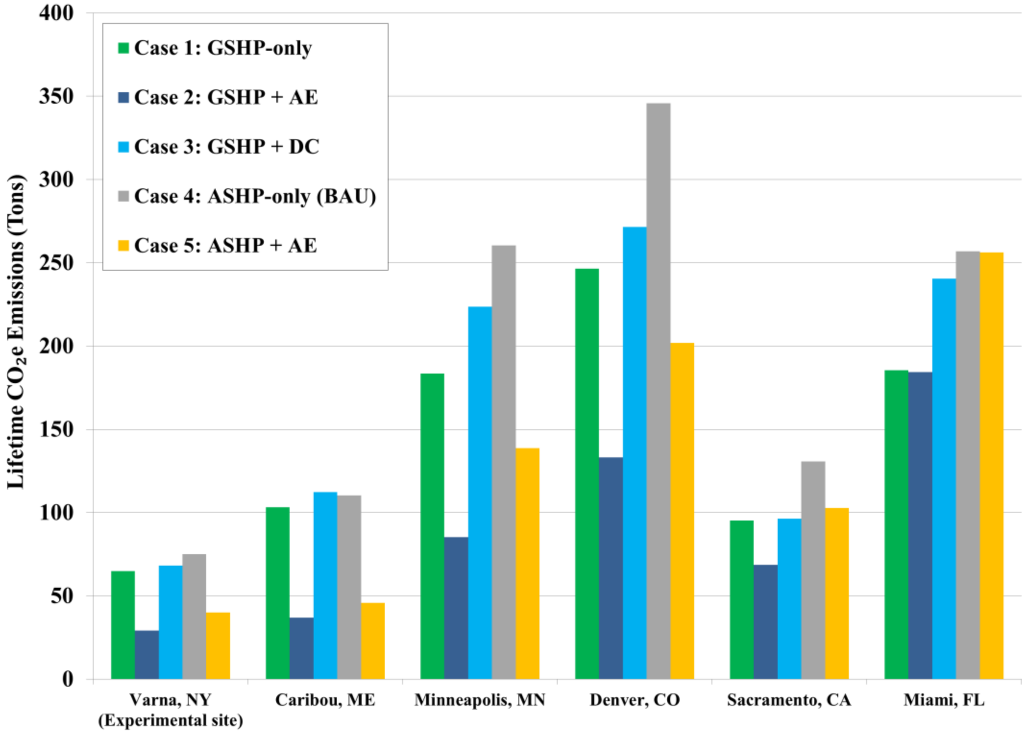

Figure 7: Lifetime CO_2e Emissions (LCO_2e, Tons) for five cooling configurations by geographic locations nationwide in different climatic regions.

6. SUMMARY AND CONCLUSIONS

This study summarized a multi-year project undertaken by Cornell University and Verizon Wireless to investigate the techno-economic and environmental performance of hybrid ground-source heat pump (GSHP) and air-source heat pump (ASHP) systems for cooling of cellular tower shelters nationwide. A hybrid GSHP demonstration site was built in 2014 at a Verizon Wireless cellular tower site in the Cornell University Plantations (Varna, NY). By 2016, simulation and validation models of hybrid GSHPs and ASHPs were developed, tested, and validated to investigate and optimize various system configurations using transient energy simulation models (TRNSYS). The validated models were incorporated into a Systems Engineering Model (SEM) for nationwide analysis of cellular tower cooling systems. This paper described the methodology and results of implementing the SEM in six geographic locations with varying climates within the contiguous 48 U.S. states. The performance of five cooling configurations was evaluated: case 1: GSHP-only; case 2: GSHP + AE; case 3: GSHP + DC; case 4: ASHP-only (business as usual – BAU); and case 5: ASHP + AE.

Major findings from the SEM show that the total cost of ownership (TCO) for all configurations is the lowest for states in cooler climatic regions (e.g., Maine, Minnesota, Colorado) because of lower lifetime electricity consumption and, in the case of the GSHP systems, lower total borehole length (under 270 m in some regions). Similarly, the TCO is the highest for states in warmer climatic regions (e.g., California, Florida) because of high lifetime electricity consumption, and significant required total borehole length for GSHP systems (up to 1080 m in some regions). The configuration with the lowest overall TCO is case 5: ASHP + AE followed by case 2: GSHP + AE. The configuration with the highest overall TCO is case 1: GSHP-only followed closely by case 3: GSHP + DC and case 4: ASHP-only. Furthermore, the configuration with the lowest lifetime electricity consumption and CO_2e emissions is case 2: GSHP + AE, and the highest is case 4: ASHP-only. In some states (e.g., Colorado), the lifetime CO_2e emissions for case 4: ASHP-only are almost a factor of three greater than the emissions for case 2: GSHP+AE because the electricity generation resource mix is primarily from non-renewable sources (e.g., coal, natural gas). With the use of energy-efficient GSHP systems, regions with high electricity prices and consumption will experience lower costs and environmental impacts from a reduction in operating conditions over the lifetime of the system (20 years).

The base case results presented in this study provide an approximate evaluation of the performance of five cooling configurations in various locations across the U.S. To increase the accuracy and the spatial resolution at a particular location, it is recommended to perform a detailed hydrogeologic and climatic analysis and consider available incentives and rebates for energy-efficient technologies. Future work includes a sensitivity analysis of the parameters discussed in Table 1 to assess the cost, energy, and environmental performance of the cooling configurations given varying parameters. It is expected that with consideration of incentives and rebates, increasing electricity rates, and possible carbon taxes, the investment in GSHP systems will be more favorable in the future than in today’s economy.

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REFERENCES

Battocletti, E.C., and Glassley, W. E.: Measuring the Costs and Benefits of Nationwide Geothermal Heat Pump Deployment, U.S. Department of Energy, Geothermal Technologies Program under Award Number DE-EE0002741, (2013).

Beckers, K.J.H.F.: Low-Temperature Geothermal Energy: Systems Modeling, Reservoir Simulation and Economic Analysis, A Dissertation Presented to the Faculty of the Graduate School of Cornell University, Cornell University, Ithaca, NY, (2016).

Beckers, K. F., Aguirre, G.A., Lukawski, M., and Tester, J.W.: Hybrid Geothermal Heat Pump for Cooling Cellular Tower Shelters: from Campus Living Laboratory to Nationwide Deployment, Verizon Wireless Final Project Report for Phase 3 in CY 2015-2016, Unpublished Internal Report, Cornell University, Ithaca, NY, (2016).

Beckers, K. F., Yavuzturk, C.C., and Tester, J.W.: Techno-Economic Modeling and Monitoring of Hybrid Ground-Source Heat Pump System with Borehole Heat Exchangers for Cooling-Dominated Cellular Tower Application, Poster Presentation, P.1.8, 11th IEA Heat Pump Conference, May 12-16, 2014, Montreal (Quebec), Canada, (2014).

Čermák, V., and Rybach, L.: Thermal conductivity and specific heat of minerals and rocks, Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology, New Series, Group V (Geophysics and Space Research), Volume 1a (Physical Properties of Rocks), edited by G. Angenheister, Springer, Berlin-Heidelberg, (1982), 305-343.

Clauser, C., and Huenges, E.: Thermal Conductivity of Rocks and Minerals, Rock Physics and Phase Relations: A Handbook of Physical Constants, AGU Reference Shelf 3, American Geophysical Union, (1995), 105-126.

ClimateMaster, Inc.: Guide to Federal Tax Incentives for Commercial Geothermal Heat Pumps, Federal Tax Incentives, ClimateMaster Geothermal Heating & Cooling, (2014).

DSIRE (Database of State Incentives for Renewables & Efficiency): U.S. Department of Energy: Energy Efficiency & Renewable Energy, North Carolina Clean Energy Technology Center, North Carolina State University, Information Available Online at: http://www.dsireusa.org/, (2015).

EIA (U.S. Energy Information Administration): Table 5.6.A.: Average Price of Electricity to Ultimate Customers by End-Use Sector, by State, Electric Power Monthly, Form EIA-826, Monthly Electric Sales and Revenue Report with State Distributions Report, Independent Statistics & Analysis U.S. Energy Information Administration, Information Available Online at: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a, (2015).

EPA (Environmental Protection Agency): The Emissions & Generation Resource Integrated Database: Technical Support Document for eGRID with Year 2012 Data, Office of Atmospheric Programs Clean Air Markets Division, Contract #EP-W-11-003, Work Assignment No. 4-88, United States Environmental Protection Agency, Available online at: https://www.epa.gov/energy/egrid, (2015).

ESRI (Environmental Systems Research Institute): ArcGIS Desktop: Release 10.4.1, Redlands, CA, Environmental Systems Research Institute, (2016).

Feeney, J.: Personal Communication, Verizon Wireless: Engineering and Operations Support, (2015; 2016).

Glassley, W.E.: Geothermal Energy: Renewable Energy and the Environment, Energy and the Environment, Abbas Ghassemi, Series Editor, CRC Press, Taylor & Francis Group, Boca Raton, FL, (2010), 187.

Heath, R.C.: Ground-Water Regions of the United States, Geological Survey Water-Supply Paper 2242, Unites States Geological Survey (USGS) Science for a Changing World, (1984).

IRS (Internal Revenue Service): How to Depreciate Property, Publication 946, Cat. No. 13081F, Department of the Treasury Internal Revenue Service, (2015).

Klein, S.A., Duffie, J.A., Mitchell, J.C., Kummer, J.P., Thorton, J.W., Bradley, D.E., Arias, D.A., Beckman, W.A., Duffie, N.A., Braun, J.E., Urban, R.E., Blair, N.J., McDowell, T.P., Duffy, M.J., Mitchell, J.W., Freeman, T.L., Evans, B.L., Fiksel, A., Williams, P.M., and Kummert, M.: TRNSYS 17: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA, Information Available Online at: http://sel.me.wisc.edu/trnsys, (2010).

LaBrozzi, B., Dodge, E., and Tester, J.: Utilization of Closed Loop Geothermal Heat Pumps at Verizon Wireless Cellular Towers, Final Project Report for Verizon Wireless, Cornell School of Chemical and Biomolecular Engineering and Cornell Energy Institute, CEI-2010-1, (2010).

MathWorks: MATLAB The Language of Technical Computing, Release 2009a, The MathWorks, Inc., Natick, MA, (2009).

Schruben, P.G., Arndt, R.E., and Bawiec, W.J.: Geology of the Conterminous United States at 1:2,500,000 Scale –A Digital Representation of the 1974 P.B. King and H.M. Beikman Map, United States Geological Survey, Digital Data Series DDS-11, Release 2, (1997).

Soller, D.R., Reheis, M.C., Garrity, C.P., and Van Sistine, D.R.: Map Database for Surficial Materials in the Conterminous Unites States, United States Geological Survey, Data Series 425, United States Department of the Interior, United States Geological Survey, (2009).

Sotos, M.: The Greenhouse Gas Protocol: Scope 2 Guidance, An Amendment to the GHG Protocol Corporate Standard, Greenhouse Gas Protocol, World Resources Institute (WRI), (2015).

Thomas, H.E.: Ground-Water Regions of the United States – Their Storage Facilities, U.S. 83rd Cong., House Interior and Insular Affairs Comm., The Physical and Economic Foundation of Natural Resources, v.3, (1952).

USGS (United States Geological Survey): Geologic Units Containing Earth Material, Mineral Resources On-Line Spatial Data, United States Geological Survey Science for a Changing World, Information Available Online at: http://mrdata.usgs.gov/geology/state/sgmc-lith.php?code=root, (2014).

Wilcox, S., and Marion, W.: User's Manual for TMY3 Data Sets, National Renewable Energy Laboratory (NREL) Innovation for Our Energy Future, Technical Report NREL/TP-581-43156, Contract No. DE-AC36-99-GO10337, (2008).

WRI (World Resources Institute): The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard, Revised Edition, Greenhouse Gas Protocol, World Resources Institute, World Business Council for Sustainable Development, (2015).