Characterizing the Effect of an Off-Peak Ground Pre-Cool Control Strategy on Hybrid Ground Source Heat Pump Systems

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Abstract

Geo-exchange systems are a sustainable alternative to conventional space conditioning systems due to their high operating efficiency, resulting in reduced energy consumption and greenhouse gas emissions. However, geo-exchange's ability to penetrate the market has been throttled by large capital investments, resulting in undesirable payback periods. Optimized hybrid ground source heat pump systems (HGSHP) systems have been introduced as a remedy to overcome the current economic hurtles associated to the installation of geo-exchange systems. In both the literature, as well as in practice, there still remains potential for increased economic feasibility of this technology through integration of intelligent operational strategies. This paper presents a novel control methodology referred to as an off-peak ground pre-cool strategy, employing a time-of-use conscious operating logic which artificially pre-condition the system's bore-field. Reducing peak power consumption is achieved by creating improved thermal characteristics during mid-peak/peak time-of-use operating brackets. A comprehensive numerical model was developed to characterize the operation of HGSHP systems for three real case studies. The model implemented a base case set-point control scheme, used as a reference to assess the operational benefit of the proposed off-peak ground pre-cool control strategy. The preliminary analyses indicated operational cost savings of up to 16.4%, under specific pre-cool scheduling. The strategy indicated reductions in both carbon emission and peak power consumption of up to 15.0% and 58.5%, respectively. In all cases increasing cooling supplied by the hybrid geo-exchange system was indicated, with a maximum observed capacity increase of 43.7%.

Keywords: Hybrid Ground Source Heat Pumps, Geo-Exchange, Peak Power Reduction, TOU Control, Load Leveling

1. Introduction

With building energy consumption on the rise, power conservation strategies have become a global priority in many energy usage policies. Space heating and cooling contributes to a large portion of a building's net energy consumption, typically accounting for 50% of a building's annual usage [1, 2]. According to the U.S. energy Information Administration (EIA), the building sector consumed 47.6% of the total energy in the United States, as of 2012 [3]. With environmental awareness and potential resource shortages progressing to the forefront of our concerns, an amplified need for sustainable alternatives will arise.

Geo-exchange is a term utilized in industry to describe a sustainable alternative to conventional HVAC systems [4]. A geo-exchange system is also referred to as a Ground-Source Heat Pump (GSHP); interchangeable terms used to describe this high efficiency earth energy technology. A critical component of GSHP systems are the circulation pumps, which facilitate heat exchange to/from the dwelling. Geo-exchange systems utilize ancient pumping techniques through the application of modernized historical water-lifting technology [5]. By circulating a working fluid through a network of piping, geo-exchange systems utilize the ground as a low temperature thermal reservoir. Taking advantage of the ground's stable temperature characteristics, high efficiency space heating/cooling can be accomplished. The literature clearly indicates that geo-exchange should be urgently sought as a renewable energy system, stressing implementation as frequently as possible [6, 7].

The current economic viability of GSHPs and associated knowledge gaps rely on several factors such as: geographical location (weather patterns and soil conditions), control methodologies, utility rates, and inflation rates [8]. There is great potential for GSHP systems, but due to high upfront costs and long payback periods, their ability to penetrate the market has been throttled.

As a result, GSHP systems are best suited for large buildings with high thermal demands in order to overcome the associated capital investment [9]. The economics of geo-exchange systems (compared to conventional HVAC units) depend heavily on the utility rates of natural gas and electricity. The study performed by Nguyen *et al.* [10] highlighted that the variability in the utility rates in North America have a substantial effect on the size of the resulting ground-loop for a GSHP system. As a result of incremental inflation of electricity rates, GSHP systems are a favourable sustainable alternative for cooling dominant buildings (those requiring more energy for cooling than heating). GSHP systems show less financial incentive for heating dominant buildings due to the comparatively low cost of natural gas [11, 12]. Current rules-of-thumb utilized in industry for system sizing do not correspond to an optimized design, as outlined by Alavy *et al.,* [9] and Nguyen *et al.,* [10]. Optimized hybridization is a remedy that can be implemented to alleviate the high upfront costs and long payback periods associated to this technology. This method couples a GSHP system with an auxiliary heating and cooling unit, or in the case of a retrofitted installation, the existing conventional heating and cooling systems are utilized [8, 9, 10]. HGSHP systems operate in a manner wherein the GSHP unit is sized to meet a percentage of the peak heating/cooling load. In hours of peak demand, the auxiliary systems provide supplementary heating/cooling to meet the building's thermal comfort requirements [13, 14].

In addition to geo-exchange hybridization, an increase in operating efficiency can be obtained through the integration of an improved control paradigm; resulting in the potential for a reduction in energy usage, operating costs, and green-house gas (GHG) emissions [15, 16, 17, 18]. Solar assisted ground source heat pump (SAGSHP) systems have been proposed in the literature as an alternative hybrid system configuration, allowing for improved system efficiency.

Geo-exchange system performance is heavily dependent on soil temperature, SAGSHP systems allow for improved system efficiency in heating mode by a controlled increase in soil temperature. Nam *et al.* [19] simulated the performance benefits of a SAGSHP system with a predicted 28.1% and 9.3% increase in bore-field heat exchange rate and system COP, respectively. Esen *et al.,* [20] conducted a modeling and experimental performance analysis of a solar-assisted GSHP utilizing a 'slinky' ground-loop configuration. Utilizing artificial neural networking and adaptive neuro-fuzzy inference systems, the research indicated successful application of higher level control resulting in improved hybrid solar system performance.

A performance assessment study [21], presented valuable insight on various research areas to further the potential of geo-exchange. It highlighted time-of-use (TOU) based control strategies as an area for further research and development, indicating a potential to reduce electricity costs from 20-25% (excluding regulatory and distribution charges). Aside from the cost savings associated to TOU control, additional benefits are provided to utilities in the form of electrical load leveling, which helps alleviate the pressure placed on the grid during peak hours [21]. The study presented by Carvalho *et al.,* [22] proposed a TOU-conscious strategy; using a GSHP as a flexible load to artificially consume energy in off-peak periods to pre-heat a service building. The building pre-heat method allowed for a portion of the GSHP's operating cycles to be isolated within off-peak brackets, taking advantage of lower electricity rates; resulting in a 34% reduction in electricity costs [22].

The aim of this paper is to propose the preliminary analysis of a new and innovative control strategy for operation of HGSHP systems. Referred to as the off-peak ground pre-cool (OGPC) control strategy, this technique utilizes the auxiliary cooling system as a flexible load to artificially consume electricity during off-peak TOU brackets when energy costs are most economical. This analysis aims to demonstrate that a HGSHP system operated with an OGPC strategy can exploit the bore-field's thermal mass with a pre-cool, creating improved thermal characteristics during mid-peak/peak TOU brackets. With the additional benefit of peak power reduction, introducing a pre-conditioned bore-field helps reduce peak energy consumption by allowing the GSHP to supply more cooling with a higher degree of efficiency. With a TOU-conscious operating strategy, the proposed methodology will not only address improving system economics through an increase in operating efficiency, but also presents a multifaceted approach that intends to concurrently aid the balancing of the electrical grid.

The presented study utilizes two software platforms to evaluate the impact of the operational strategy. During the building energy simulation stage of this research the building thermal loads were determined using eQuest [23], with the remaining design and numerical modeling being carried out using MATLAB [24]. A MATLAB platform was selected to numerically simulate the hybrid geo-exchange system due its successful application in similar research presented in the literature [25, 26, 27, 28, 29]. Numerical simulations were conducted to predict the impact the proposed strategy has on electrical energy consumption, annual operating cost, carbon emissions, and peak power reduction for three pre-cool operating schedules; shoulder, peak, and full season. A comparative analysis was performed for nine real buildings located in Toronto, Canada.

In the literature as well as in practice there still remains potential for improved hybrid geo-exchange system performance through the application of alternate control strategies. With a significant portion of research and industry applications still relying on classical control methods, there is a pressing need for the development of alternative operational prospective [2]. In addition, further research and development for TOU-conscious control is stressed for geo-exchange applications [21]. The objective of this study is to present and quantify the impact of a new and novel control methodology; intending to address and fill the knowledge gaps of the two aforementioned voids in the literature.

2. Methodology

The methodology applied in this paper primarily consists of a three-part procedure, which is illustrated in flowchart diagram presented in Figure 1. First, building energy simulations (BES) were conducted to generate estimates of various buildings annual hourly heating and cooling loads. The annual thermal loads are used as an input variable to design an optimally sized HGSHP system, following the rigorous computational approached outlined in Alavy *et al.* [9]. Numerical simulations are then conducted with the aid of a performance prediction model that has been newly developed to quantify the proposed off-peak ground pre-cool (OGPC) control strategy's effect on the hybrid system's performance.

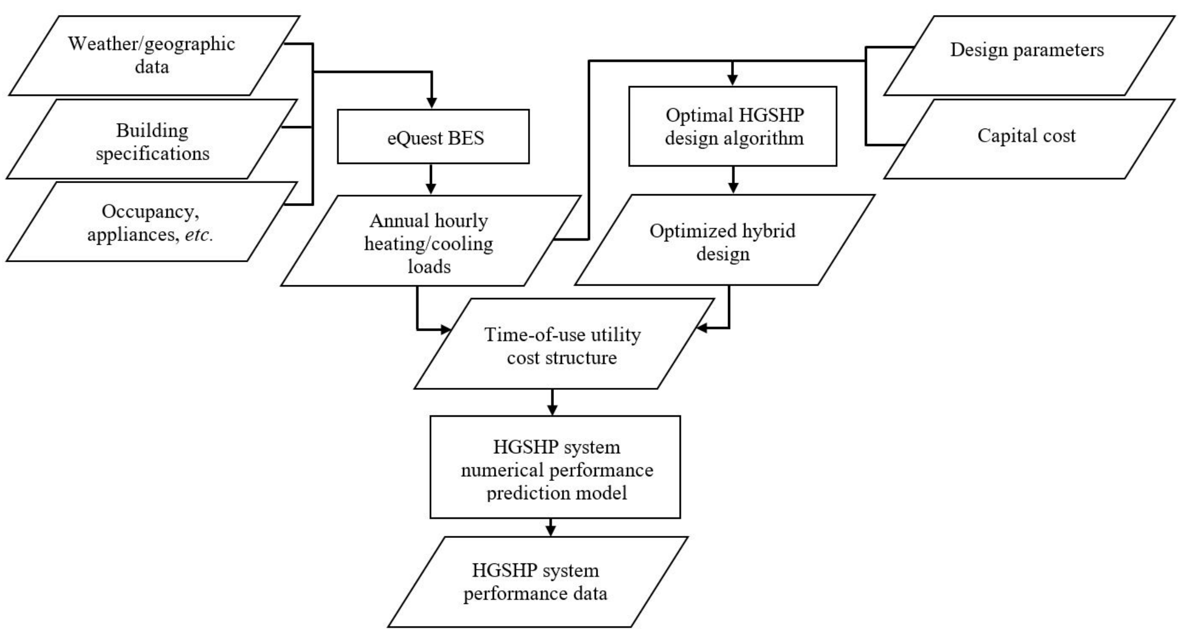

Figure 1: Flowchart of proposed methodology

2.1. Building Loads and Hybrid System Design

In this paper, annual hourly thermal loads associated the various buildings cases where generated in building energy simulations using eQuest. The energy simulation initially allows for both heating and cooling to be supplied in a simultaneous fashion during each time interval. However, the heating and cooling loads are corrected under the assumption that each buildings internal demand can be satisfied with an internal mechanisms before relying on the compensation from the geo-exchange system. In our analysis a common water loop distribution system has been assumed, allowing for internal load compensation to occur. For example, if an operating time step has a large cooling demand and a small heating demand, the heating demand can be met by removing heat from the zone requiring cooling and into the zone requiring heating. By neglecting the power consumption of the internal mechanisms, the net demand will be provided by the HGSHP to/from the common water loop distribution system. For the purpose of this analysis, the three real buildings highlighted in Table 1 are evaluated in detail in this study. An additional 6 building case computations were conducted, with the results summarized in Section 3.3.4.

Table 1: Building information

Building	Sector	Usable Area (m^2)	Conditioned Zones
Mid-rise, multi-residential	Residential	15139.4	105
High-rise, multi-residential	Residential	16824.2	317
School	Educational	4525.3	52

The parameters used in the HGSHP optimal design process were held constant with the analysis conducted in [9, 10]. The configuration of the ground-loop used is a closed-loop system with a single U-tube vertically oriented heat exchanger per borehole, with a bore-field aspect ratio of 11 across by 4 down. The following Table 2 provides a summary of the parameters utilized in the design process.

Table 2: Design parameter summary

Parameters	Value
Cooling design entering sink temperature	25.1 °C
Heating design entering source temperature	1.7 °C
Heat Pump	ClimateMaster Tranquility TT
Soil thermal conductivity	2.94 W/m K
Soil thermal diffusivity	0.072 m^2/day
Duration of operation	20 years
Borehole thermal resistance	0.136 m K/W
Pipe resistance	0.06 m K/W
Pipe size	32 mm
Borehole diameter	127 mm
Grout thermal conductivity	1.47 W/m K
Number boreholes across	11
Number of boreholes down	4
Inflation rate	4%
Interest rate	8%

The heat pump selected for the hybrid system is the ClimateMaster Tranquility Series TT with an assumed fixed COP of 3.1 and EER of 13.6. For the HGSHP system design the ClimateMaster Tranquility TT heat pump (HP) is considered, were the heat pump is a dual stage unit capable of full load and 67% part load operation. A dual stage HP was selected in this study after consulting with GeoSource Energy Inc. personnel [30], stating that this is the most commonly encountered HP configuration in the Southern Ontario, Canada market.

The auxiliary cooling system selected is a non-reversible air-source heat pump (water-air) with an assumed fixed EER of 10.8 [31]. The auxiliary heating system is a natural gas furnace, with an assumed fixed efficiency of 78%, held constant with the design specifications outlined in [10].

The following capital cost parameters were held constant with [9, 10] and is summarized in Table 3.

Table 3: General capital cost of hybrid system components

Item	Cost
Ground heat exchanger (install and materials)	$65.5/m
Auxiliary cooling system, plate heat exchanger including controls and auxiliary equipment	$14/kW of auxiliary cooling design capacity
Auxiliary heating system	$20/kW of auxiliary heating design capacity

2.2. Numerical Model

In this study, in order to simulate and analyze the off-peak ground pre-cool control strategy, a numerical model was developed using MATLAB to characterize the operation of a HGSHP system. The model was developed in a modular manner allowing for simple manipulation of the systems control algorithms, providing flexibility for modification and study of the proposed control techniques.

The numerical model was developed to simulate the operation of HGSHP system (GSHP and auxiliary HVAC systems) in working conditions for a year long duration. A yearly operational analysis was selected over a commonly used 20 year life cycle because the annual savings of the proposed control scheme was being assessed, which was more clearly realized with the selected time frame. The numerical model simulates a load based analysis determining which mechanical system has operational authority in each simulated time step. The model runs a yearly simulation with a time-step of a third of an hour for a total of 26,280 iterations.

The procedure that the numerical model follows is presented in the flowchart schematic in the following Figure 2. When the algorithm is initiated, all input parameters are specified, such as annual hourly heating/cooling loads (eQuest BES), optimal HGSHP system specifications (design procedure from [9]), and time-of-use electrical cost structure. The input data is then processed to determine important characteristics of the buildings thermal requirements, such as total heating/cooling demand required, peak heating/cooling loads, and whether the building under consideration is heating or cooling dominant. The capacities of the GSHP and auxiliary systems are then determined based of the optimal shave factor ($\propto$), defined as the percentage of peak cooling demand met by the geo-exchange system, with the remaining load $(1-\propto)$ being supplemented by the auxiliary systems. A numerical simulation of an optimally sized HGSHP system operating for one year is then initiated, with a set-point control algorithm fitted to the model to determine the operational authority of the sub-systems depending on the buildings thermal requirement in the current time-step. For every time-step of the numerical simulation the portion of demand supplied by the geo-exchange system and the auxiliary systems are determined; the variation in the GSHP COP, and bore-field/entering source fluid thermal response are predicted simultaneously, with this function being explained later. Once the simulation expires, a data post-processing procedure is carried out to determine the resulting performance of the HGSHP system over a year of operation, upon completion of this process the program is terminated.

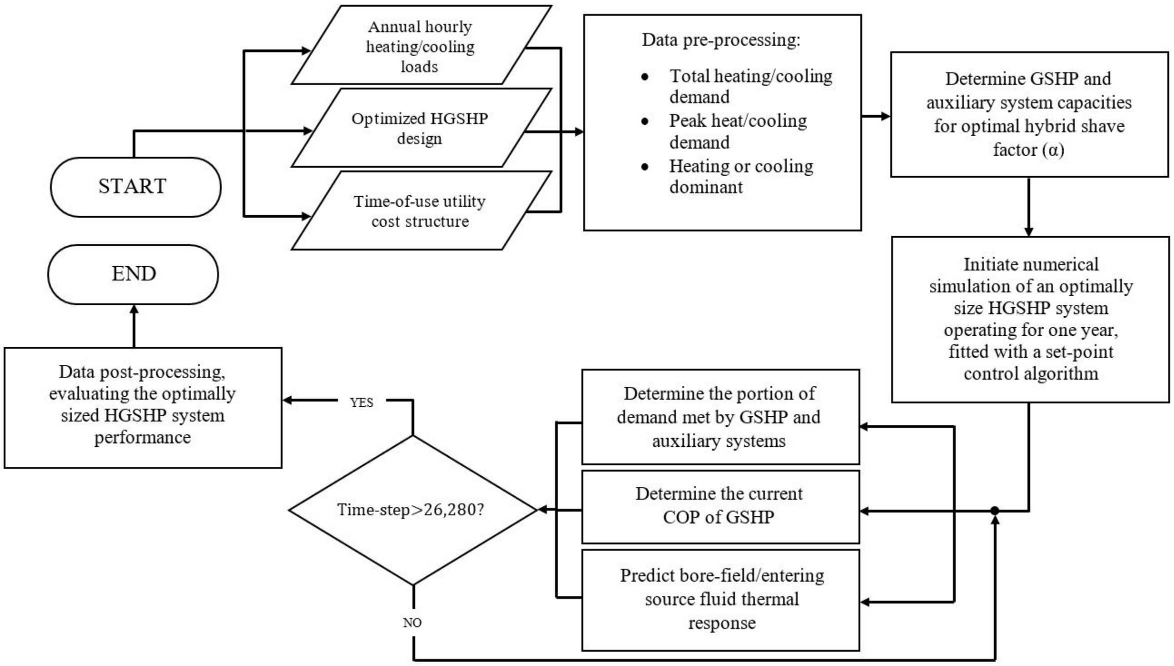

Figure 2: Process flowchart of the numerical performance prediction model

2.2.1. Variable COP Characterization

In [32], Alzahrani conducted a detailed experimental performance analysis of a GSHP system coupled to both a vertical and horizontal ground-loop at the TRCA Archetype Sustainable Twin Houses located in Vaughan, Canada. An observation made in this study highlighted that a heat pumps COP varies substantially with respect to system cycle time. From the raw data collected, a clear correlation was represented; as the cycle on-time increases, the heat pump COP decreases, observing that the GSHP experiences peak COPs during the early transient portion of the on cycle [32]. This occurrence is attributed to the ground-loop working fluid, as well as the soil having a large thermal inertia when the two media have thermally equilibrated. For example, in cooling mode operation in the early transient stage of an on cycle, assuming the ground-loop working fluid has equilibrated with the soil temperature, results in a low inlet source temperature to the heat pump. As the cooling cycle progresses the local ground temperatures rise, as heat is being injected into the ground, resulting in an increasing inlet source temperature. In cooling mode operation as the cycle duration increases, local ground temperature increases and consequently inlet source temperature increases. This results in and increase in GSHP system's compressor power consumption, resulting in a decrease in system COP [32].

A GSHPs cycle time plays a vital role in system performance; as the cooling cycle duration increases and entering source temperature increases, resulting in greater HP compensation to maintain load requirements. Utilizing the experimental data collected by Alzahrani in [32], a variable COP correlation was developed to characterize the GSHP systems COP as a function of the on cycle duration. The following Figure **3** is an illustration of the correlations utilized to characterize the geo-exchange systems COP with cycle time.

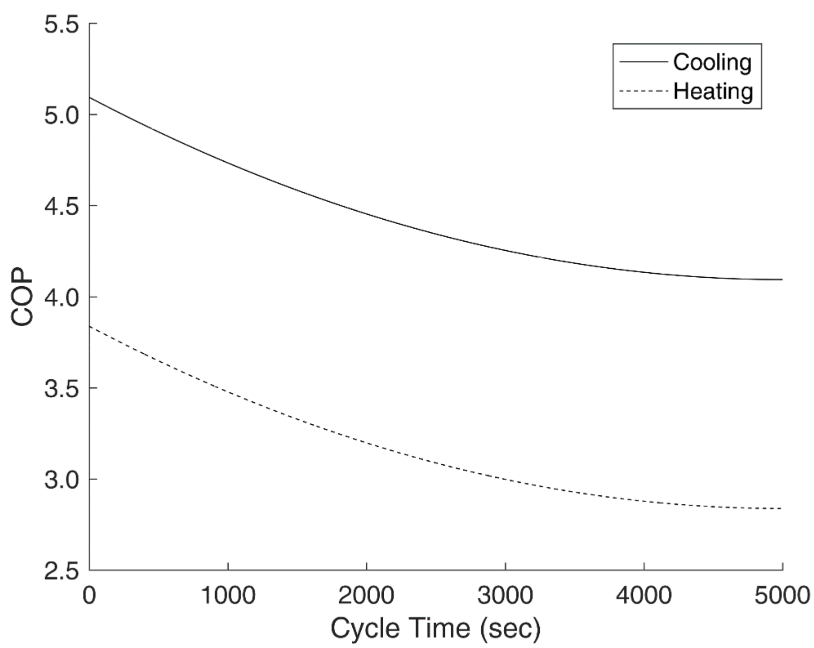

Figure 3: COP variation with respect to GSHP system cycle time

The variable COP output ranges from 5.07-4.09 in cooling mode and 3.84-2.83 in heating mode, following a descending polynomial regression with coefficients of determination exceeding 0.8.

As evident from the COP ranges, the GSHP system is more efficient in cooling mode operation when compared to heating mode. The higher efficiency is due to smaller temperature difference requirements between entering load and sink temperatures to meet thermal demands.

A thermal continuity condition was assumed upon integration of the presented performance correlations. This continuity assumption implies that the ground-loop fluid has a thermal recharge time that is equal to the previous on-cycle duration. For example, if the GSHP is operating for one on-cycle time-step, it takes one off-cycle time-step for the two media to reach steady-state. Thus when the heat pump's on-time is equal to the systems off-time the ground and ground-loop working fluid is assumed to have thermally equilibrated.

2.2.2. Time-of-Use Rates

The 2015 TOU utility structure from Toronto, Canada was adopted as a means to estimate the cost savings associated with the application of the OGPC control technique. TOU brackets are used as a primary control variable in the OGPC algorithm in an attempt to reduce peak power consumption to ease pressure on the grid during high-demand hours, reduce GHG emissions, and decrease annual operating cost in cooling mode. The following Table 4 presents the TOU brackets and electricity rates used in the numerical simulations presented in this paper.

Table 4: TOU electricity rates Ontario 2015 [33]

Period Type	Rate (¢/kWh)	Summer Periods	Winter Periods
Peak	16.1	11a.m. – 5 p.m.	7 a.m. – 11 a.m. 5 p.m. – 7 p.m.
Mid-Peak	12.2	7 a.m. – 11 a.m. 5 p.m. – 7 p.m.	11a.m. – 5 p.m.
Off-Peak	8.0	7 p.m. – 7 a.m.	7 p.m. – 7 a.m.

The Ontario Energy Board (OEB) classifies two peak seasons; summer weekdays ranging from May 1st to October 31st, and winter weekdays ranging from November 1st to April 30th. For weekends and holidays, an off-peak rate is designated for the full day [33].

2.2.3. CO_2 Emissions

The total annual CO_2 emissions associated to the operation of a HGSHP system are dependent on the electricity consumed by the GSHP, the auxiliary systems, and the CO_2 emissions factors for the local electricity supply mix. The electricity supply mix breakdown used in this analysis corresponds to Ontario's power generation data for 2015. Over the 2015 year, Ontario, Canada's average supply mix is categorized into the following sources: 60.56% from nuclear, 23.28% form hydroelectricity, 9.96% from natural gas, 5.77% from wind, 0.10% from solar, and 0.23% from biofuel [34].

In this analysis, the 2015 hourly electricity supply mix for Ontario is used to produce an average hourly CO_2 emissions factor. In each numerical time-step, the supply mix factors for the aforementioned energy sources are determined. The product of each supply mix factor and their corresponding fuel type emissions factor is computed. The summation of the product of each supply mix factor and corresponding fuel type emissions factor produces an average hourly CO_2 emissions factor. This process is iterated 8760 times, corresponding to each of the 8760 hours in

2015. The result of this computation is used to predict the amount of CO_2 emitted (kg), for the operation of the HGSHP system. Utilizing an hourly average CO_2 emissions factor in the computation allows for the ability to evaluate the potential impact that the proposed peak power shaving strategy poses on annual emissions for the three building cases.

In the present study, the CO_2 emissions factors are in terms of kg-CO_2 per kWh (kg-CO_2/kWh) of electricity consumed. The emissions factors used in this analysis are 0.002 kg-CO_2/kWh for nuclear power [35], 0.023 kg-CO_2/kWh for hydroelectricity [35], 0.553 kg-CO_2/kWh for natural gas [36], 0.002 kg-CO_2/kWh for wind power [35], 0.035 kg-CO_2/kWh for solar power [37], and 0.0261 kg-CO_2/kWh for biofuel [38]. The biofuel emissions factor is determined by taking the average for wood chips (0.0149 kg-CO_2/kWh) and wood pellets (0.0373 kg-CO_2/kWh), assuming equal mix of the two sources [38].

2.2.4. Off-Peak Ground Pre-Cool (OGPC) Control Strategy

HGSHP systems are commonly connected either in a parallel or series configuration, depending on system operational requirements [39]. The proposed physical system orientation required to implement a ground pre-cool is illustrated in a system schematic in Figure 4.

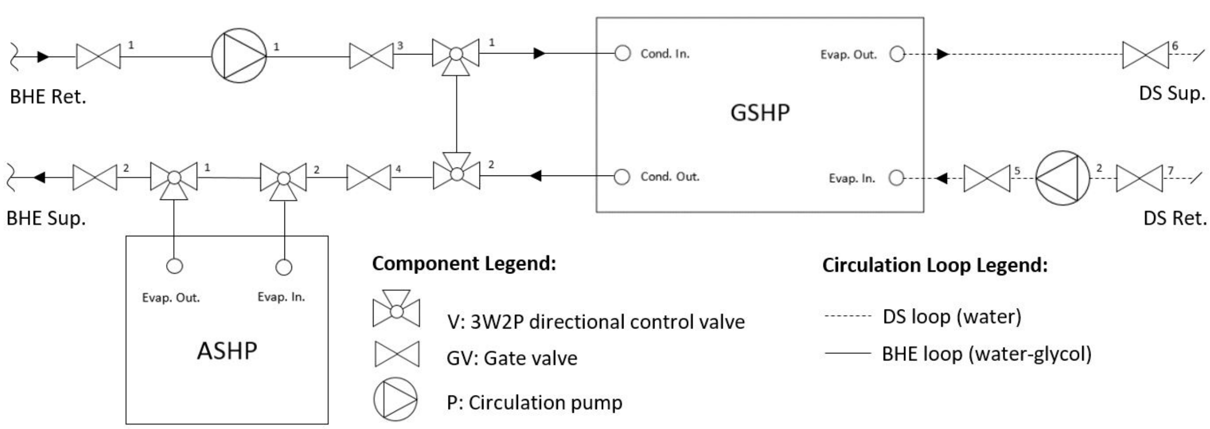

Figure 4: Hybrid ground source heat pump system schematic

The hybrid geo-exchange system uses a series connection of the ASHP with the ground-loop. Utilizing this configuration allows for three operating loops, through the manipulation of four three-way-two-position directional control valves (V1 – V4). Loop one is activated under base load operating conditions, where the GSHP unit is the only active load coupled to the bore-field heat exchanger (BHE). Loop one is the primary circulation loop, accomplished when V1 – V4 are in their rest state. Loop two is activated under peak operating conditions, when the GSHP and ASHP are both active loads, interacting with the BHE to supply the building's thermal demand. Loop two is accomplished by actuating V1 and V2 into their flow diverting state, allowing for the BHE fluid to be circulated through the auxiliary ASHP's evaporator. Loop three is activated for OGPC operation, resulting in the ASHP being the only active load interacting with the BHE. Loop 3 circulation is accomplished by actuating V1 – V4 into their flow diverting state, decoupling the GSHP from the BHE circuit.

The primary control technique used in the operation of the HGSHP system is a conventional set-point control scheme. A set-point control strategy is utilized as a base case scheme to compare system performance benefits that an OGPC has on the operation of a HGSHP system. The OGPC algorithm's operational authority is restricted to the control of only the ASHP, under the condition that specific logic indicators are satisfied.

The OGPC strategy utilizes two control variables to determine the beginning of an OGPC cycle, the control variables being: time of the year and TOU operating bracket. The time of year was utilized as a control variable in the OGPC algorithm to permit flexibility in pre-cool operation, allowing for time spans of various cooling load densities to be targeted by the algorithm. In this study, three operating durations were analyzed; shoulder season (SS) operation schedule (April 1st – May 31st), peak season (PS) operation schedule (July 1st – August 31st), and full season (FS) operation schedule (April 1st – August 31st). The TOU control variable is used in the OGPC algorithm to restrict pre-cooling to off-peak TOU brackets, taking full advantage of low electrical energy prices.

The following Figure 5 presents a flowchart diagram outlining the OGPC control logic. For every iteration of the numerical model, the OGPC algorithm evaluates the state of the two control variables. First the algorithm considers the time of year, attempting to classify the current time-step into one of the three proposed pre-cool schedules; represented by the first three decision blocks (FS, SS, and PS schedule) illustrated in Figure 5. If none of the three decision blocks are satisfied, the HGSHP system maintains primary operation. Once the algorithm determines that the current time-step satisfies the requirements of one of the three proposed schedules, the next control variable is evaluated. The second control variable considers the hour of operation, attempting to classify the current time-step into one of the three TOU operating brackets; represented by the fourth decision block in the logic flowchart presented in Figure 5. The fourth decision block in Figure 5 indicates a time range from 19:00-7:00 hours, which refers to an off-peak TOU bracket for the adopted utility rate structure presented in Table 4. When both logic conditions are satisfied, a pre-cool cycle is initiated. First the bore-field circulation loop 3 is activated, represented by the first process block in Figure 5; resulting in the GSHP being decoupled form the ground-loop, with the only active load being the ASHP. The ASHP is then initiated to operate at full load for a pre-cool cycle; represented by the second process block in Figure 5.

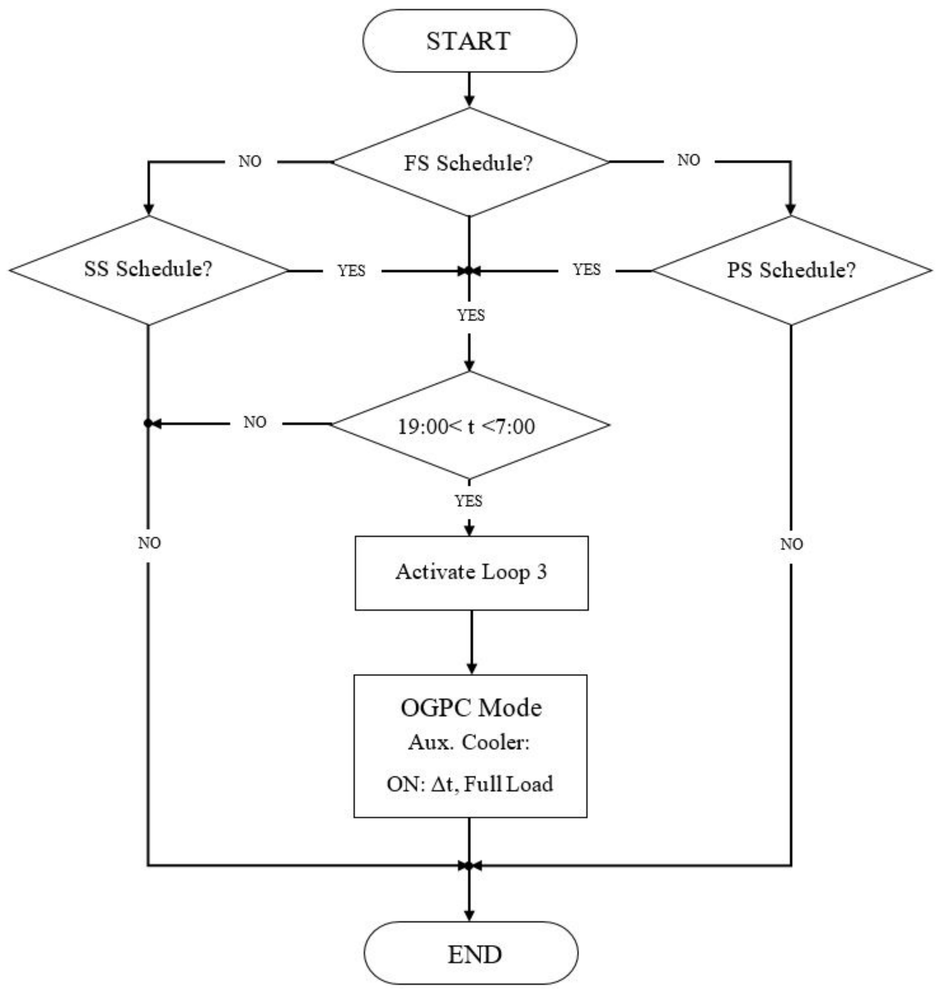

Figure 5: Flowchart diagram of simplified pre-cool control logic

To characterize the bore-field/ground's thermal response to an OGPC, the results presented in the study conducted by Nam *et al.* [19] were used. In [19], a performance predication model was developed to analyze a solar-assisted GSHP (SAGSHP), using TRNSYS [40]. In [19], a solar thermal collector was used to implement a ground pre-heat thermal storage strategy to enhance the performance of the GSHP system. The numerical model for the vertical U-tube ground exchanger (DST model) that were used in [19]. From the results presented in [19], four correlations were developed to characterize the bore-field thermal response to injection/extraction, cooling output and COP variation in response to inlet source temperature change. The correlations were developed in the form of linear regressions, with this assumption being validated based off of the experimental correlations presented in [32].

The present model simulates two assumed physical responses to the thermal benefit resulting from the OGPC; an increase in the rate of heat injection to the ground during cooling operation (increase in cooling output) and an increase in the GSHP system COP. The increase in cooling output is due to the reduction in the sink temperature, resulting in an average increase in heat injection per meter length of the ground-loop. The increase in heat pump COP in cooling mode is a result of a reduction in inlet source temperature, resulting in the reduction compressor power consumption. These assumptions were validated by the studies presented in both [19] and [32], which provide both an experimental and numerical confirmation.

The presented numerical model predicts the GSHP system's performance by means of Eq. 1 and Eq. 2; in which Q_{GSHP} and COP_{GSHP} are the resulting heat output and system efficiency, respectively. In Eq. 1, the product of $\propto$ and CL_{max} represents the base load supplied by the GSHP (system's cooling capacity), where CL_{max} is the peak cooling load and α is defined as the shave factor, which is the percentage of the peak load met by the GSHP. The ΔQ_{out} term is the incremental increase in the system's heat injection to the ground when exposed to a pre-cooled bore-field. The magnitude of the thermal capacity increase is predicted by the aforementioned cooling output correlation generated from the results presented in [19].

$$Q_{GSHP} = \propto \cdot CL_{max} + \Delta Q_{out} \qquad \text{(Eq. 1)}$$

In Eq. 2, the $COP_{\Delta t}$ terms represent the variation of the HP efficiency during transient operation, which is characterized by the cooling curve presented in Figure **3**. The ΔCOP term represents the incremental increase in system performance when exposed to a pre-cooled bore-field. The magnitude of the ΔCOP term is quantified by the aforementioned COP correlation generated from the results presented in [19].

$$COP_{GSHP} = COP_{\Delta t} + \Delta COP \quad \text{(Eq. 2)}$$

Eq. 3, Eq. 4 and Eq. 5 are used to estimate the operational performance of the auxiliary cooling system, where Q_{AUX} and COP_{AUX} are the resulting heat output and system efficiency, respectively. Eq. 3 defines the auxiliary system's cooling capacity, sized to provide supplementary cooling under peak operating conditions. The proposed model simulates the auxiliary cooling unit as a single-stage fixed capacity system.

$$Q_{AUX} = (1-\propto) \cdot CL_{max} \quad \text{(Eq. 3)}$$

Eq. 4 introduces the variable f_{PC}, which is the auxiliary system performance correction factor. The magnitude of f_{PC} is determined by implementing the step function in Eq. 5. The f_{PC} factor is a value of 1.0 when the simulated system is operating within a mid-peak to peak TOU bracket, or a value of 1.5 when operating within an off-peak TOU bracket. A performance correction factor has been introduced to modify the auxiliary systems performance when operating during an off-peak TOU bracket to account for improved operating conditions. It is assumed that on average there is a 50% improvement in auxiliary system COP when operating in an off-peak TOU bracket, when compared to mid-peak and peak durations. This assumption was justified as the average daily maximum to minimum dry bulb temperature difference for a cooling season in Toronto was 8 °C, the average difference in maximum to minimum relative humidity is approximately 30% [41]. It is noted that in a cooling season, maximum temperature and humidity occur primarily in a peak TOU bracket, while minima occur during off-peak durations.

$$COP_{AUX} = f_{PC} \cdot COP_{AUX} \quad \text{(Eq. 4)}$$

Where,

$$f_{PC} = \begin{cases} 1.0, \ t \rightarrow \ mid - peak \ or \ peak \\ 1.5, \ t \rightarrow \ off - peak \end{cases} \quad \text{(Eq.5)}$$

3. Results

The numerical performance prediction model developed in this research considers full seasonal operation (both heating/cooling). However, only cooling season operating results are presented in this section, as the proposed OGPC strategy's scope is limited to impacting system performance in cooling mode operation. The results from this study are presented as follows: building load characteristics/ hybrid system specifications, base case control strategy, shoulder season operation, peak season operation, and full season operation.

3.1. Building Loads and Hybrid System Specifications

In this study, three buildings were considered: a mid-rise (MR) multi-residential facility, high-rise (HR) multi-residential facility, and a school. Each of the buildings utilized in the research are real, and either had a GSHP installed or considered [9, 10]. The following Figure 6 illustrates the predicted building thermal loads as a result of the BES conducted on eQuest. In Figure 6, the cooling demand is presented as a positive load (light gray lines) and the heating demand is presented as a negative load (dark gray lines). The three presented building cases are all cooling dominant facilities, where the peak demand for cooling is greater than the heating requirement. Both the mid-rise (Figure 6a) and high-rise (Figure 6b) facilities require substantially greater amounts of cooling than heating, where the school's (Figure 6c) total cooling and heating requirements are comparatively even. In Figure 6c, the unique cooling demand distribution is attributed to the specific occupancy pattern distinctive to an educational institution, with a reduction in occupants occurring in peak summer months (end of June to the beginning of September).

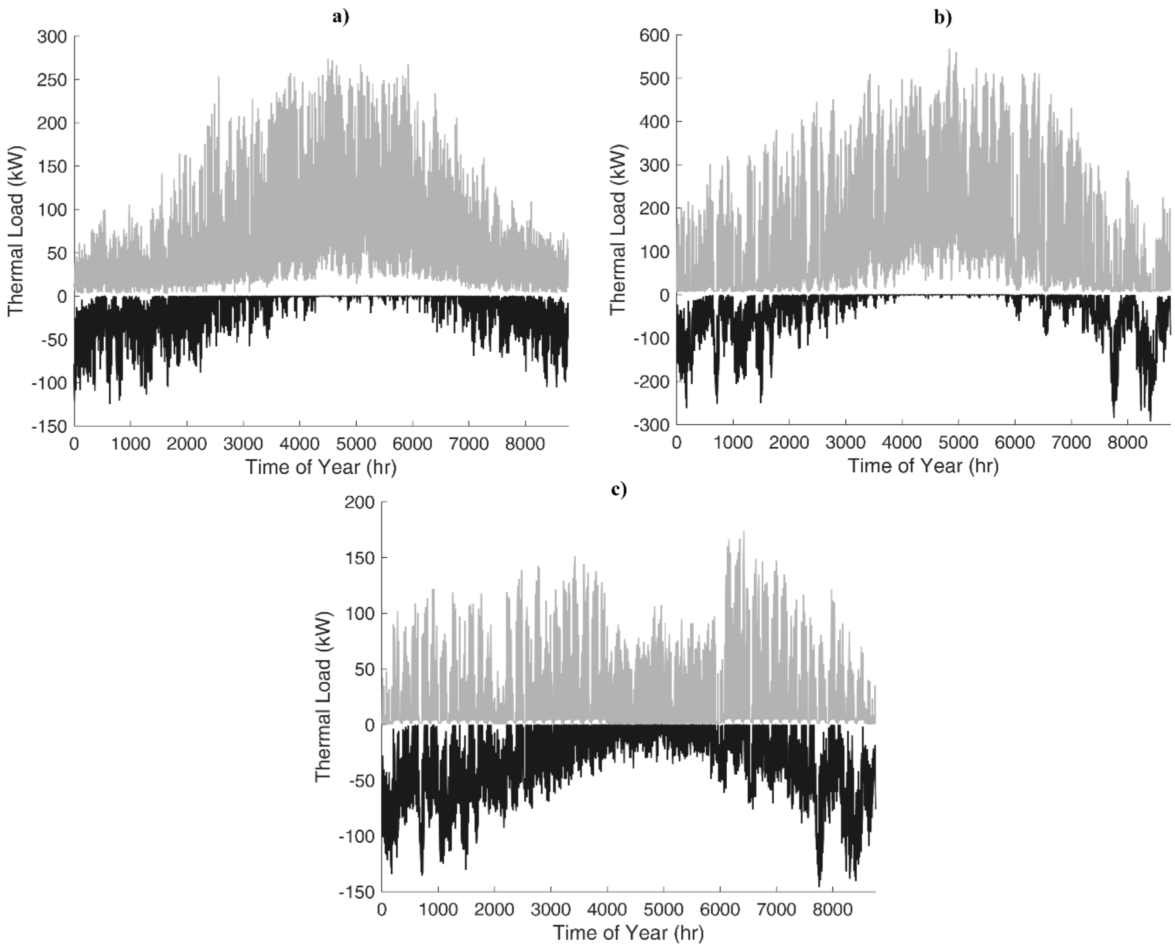

Figure 6: Predicted thermal loads for buildings (a) mid-rise, (b) high-rise, and (c) school

With the hourly loads presented in Figure 6, the design methodology presented in [9] was conducted to optimally size the hybrid geo-exchange systems for the three presented cases. Table 5 presents a summary of important details of the building thermal characteristics and hybrid geo-exchange systems specifications for the mid-rise, high-rise, and school buildings. Referring Table 5, it can be seen the annual total heating demand (THD) to total cooling demand (TCD) ratios reveal both the mid-rise and high-rise buildings are thermally imbalanced requiring four times the amount of cooling as they do heating, with the school being relatively balanced.

Table 5: Summary of building/hybrid system characteristics for a mid-rise, high-rise, and a school building

Building	Peak Cooling Load (kW)	Shave Factor (α)	Ground-Loop Length (m)	THD (MWh)	TCD (MWh)	THD/TCD
Mid-Rise	274.5	0.23	2115.5	143.0	573.7	0.25
High-Rise	568.4	0.21	3920.5	315.7	1212.2	0.26
School	174.0	0.21	791.9	295.9	252.1	1.17

3.2. Base Case Set-Point Control Strategy

The numerical performance prediction model was fitted with a standard set-point control strategy to develop a baseline result in which to compare the proposed OGPC operating strategy. The base case strategy utilizes the GSHP as the primary mechanical system, meeting base load demand and is only assisted by the auxiliary cooling system when the demand exceeds the GSHP systems capacity. Table 6 represents the predicted hybrid system performance over a year of operation when the system is controlled with a standard set-point control scheme. The annual cooling cost (ACC) is given in Canadian dollars, the annual electrical consumption for cooling (AECC) is presented in terms of megawatt hours, and the annual carbon emissions (ACE) is presented in terms of kilograms of CO_2. The total cooling demand met (TCDM) given in terms of a percentage, representing the portion of cooling load supplied by the GSHP system. In Table 6 it can be seen that the under-sized hybrid systems are still capable of meeting a large portion of the total cooling requirement of each of the three presented buildings.

Table 6: Hybrid system performance for a year of operation with a set-point control strategy

Building	ACC ($)	AECC (MWh)	ACE (kg-CO_2)	TCDM (%)
Mid-Rise	20381	185.4	12694	41.7
High-Rise	48127	423.3	29231	35.9
School	8791	75.8	5374	34.5

In Table 7, a summary of the energy consumption distributed over the TOU operating brackets is presented for the three building cases operated with a set-point control strategy. It can be seen that the mid-peak and peak hours of consumption account for a 48.53%, 55.49%, and 58.66% of total yearly energy consumption from space cooling for the mid-rise, high-rise, and school, respectively. It is noted that the higher consumption occurring in the off-peak TOU bracket is attributed to inclusion of weekend/holiday operation, which is categorized in the off-peak cost bracket.

Table 7: Summary of power consumption in TOU brackets, for a year of cooling operation with a set-point control strategy

Building	Off-Peak (MWh)	Mid-Peak (MWh)	Peak (MWh)
Mid-Rise	95.4	44.6	45.3
High-Rise	188.4	122.1	112.8
School	31.3	22.5	22.9

3.3 OGPC Control Strategy

To characterize the effect of the OGPC control strategy on the presented hybrid geo-exchange systems, a primary analysis was conducted where 36 different annual simulations were carried out, with only the pre-cool duration being varied. The simulations where conducted with 20 minute increments of pre-cool time, up to a maximum of 12 hours (full off-peak operating bracket). Upon completion of this study, the OGPC strategy was analyzed to determine the peak power reduction capability, resulting from the thermal benefit of the pre-conditioned bore-field.

3.3.1 Shoulder Season Operation

The simulated results for OGPC control strategy restricted to SS operation are presented in Figure 7. Figure 7 presents the variation in AECC and ACC with respect to pre-cool duration. Each data point represents an annual cooling season simulation, with the horizontal line acting as a datum reference for the same system operating without an OGPC scheme. Note that the fluctuation in the simulated data for both AECC and ACC occurs because of the simplicity of the set-point control algorithm operating the hybrid geo-exchange, resulting in set-point overshoot.

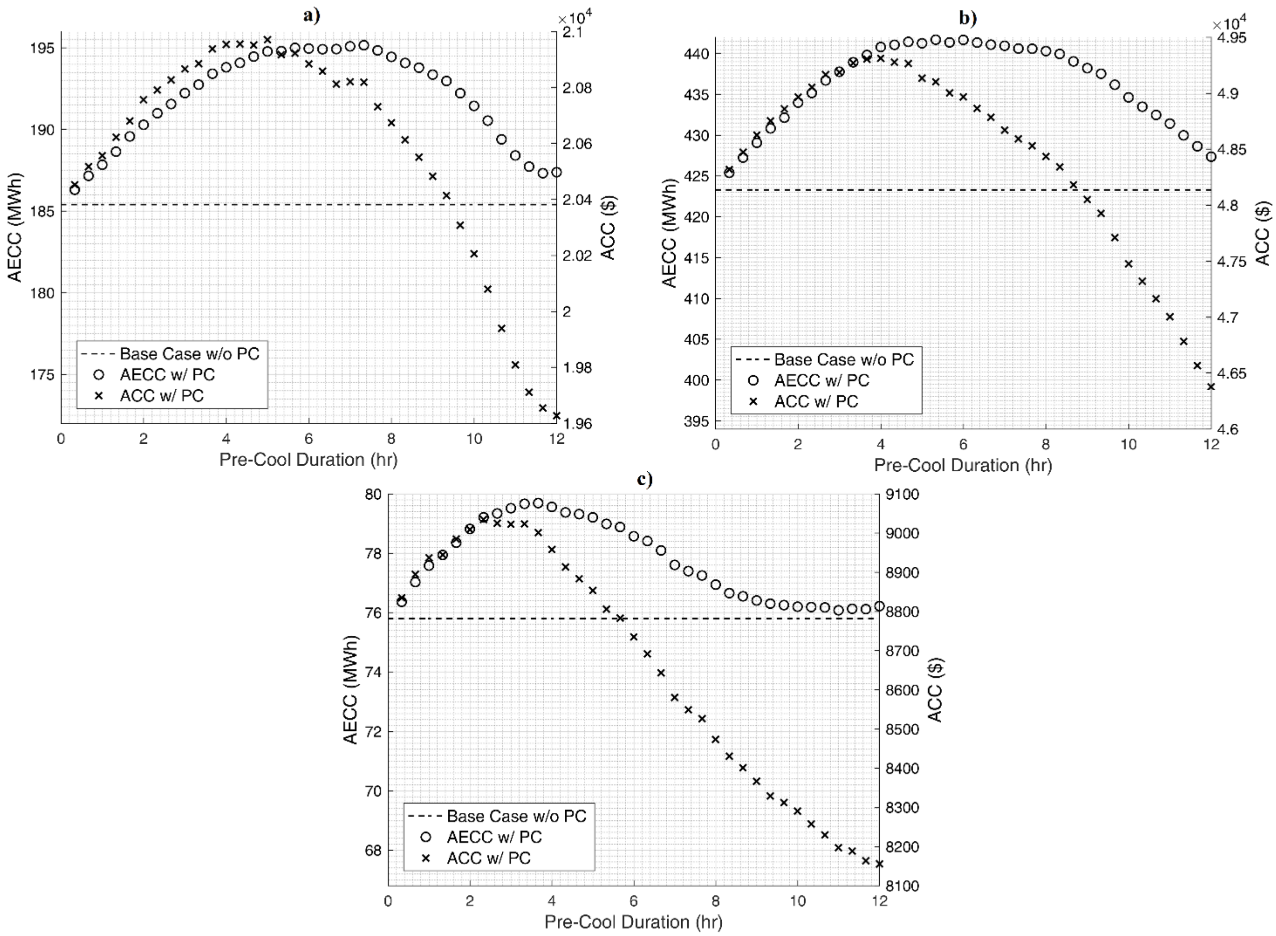

Figure 7: AECC and ACC for SS operation versus pre-cool duration for buildings (a) mid-rise, (b) high-rise, and (c) school

The impact the OGPC strategy has on the three present cases is clearly characterized in Figure 7. All three cases depict a similar trend, in which energy consumption increases for small periods of bore-field pre-conditioning. After reaching a peak in annual energy consumption, all three systems begin to experience the thermal benefit imposed by longer periods of pre-cool. The mid-rise (Figure 7a) and high-rise (Figure 7b), required longer periods of pre-conditioning before a positive impact was realized on system energy consumption; approximately seven and six hours, respectively. When analyzing Figure 7c it can be seen that the school required approximately three hours of pre-cool before the systems operation conditions where improved enough to reduce energy consumption. For all three cases, the greatest impact on energy consumption occurs at approximately 12 hours (maximum pre-cool duration), resulting in minor increases in AECC: 1.0%, 0.9%, and 0.3% for the mid-rise, high-rise, and school, respectively.

Implementing the TOU structure presented in Section 2.2.2, the annual cooling cost was determined for the three presented cases operating within a shoulder season period. Both the mid-rise (Figure **7**a) and high-rise (Figure **7**b) required a minimum pre-cool duration of approximately nine hours to break even with the operating cost associated with the base case control scheme. The school (**Error! Reference source not found.**Figure **7**c) showed financial gain for a pre-cool duration of only five hours. The largest ACC savings accomplished for all three buildings were realized for a full 12 hour pre-cool, accomplishing ACC savings of: 3.7%, 3.6%, and 7.2% for the mid-rise, high-rise, and school, respectively.

The potential for cost savings is accomplished by the proposed methodology's ability to shift a percentage of mid-peak/peak power consumption into off-peak TOU brackets, taking advantage of the low electricity cost. Table 8 summarizes the mid-peak/peak power reduction potential for the shoulder season pre-cool schedule. All three buildings show significant mid-peak/peak reduction potential, resulting in 16.6% / 16.3%, 14.9% / 14.4%, and 24.7% / 24.4%, for the mid-rise, high-rise, and school, respectively. The school indicates a greater benefit from a peak power reduction prospective because is has a smaller hybrid system compared to the mid-rise and high-rise buildings. With a smaller hybrid system (smaller bore-field/soil volumes) the thermal impact of the pre-cool strategy is active for longer durations, allowing for the school to realize a greater peak shaving benefit. This point is illustrated further in the TCDM by the geo-exchange systems, resulting in an additional: 11.9%, 12.2%, and 21.8% of the total cooling demand being met by GSHP for the mid-rise, high-rise, and school, respectively. The increase in TCDM is a result of the geo-exchange system's artificially inflated cooling capacity, due to a pre-cooled bore-field. The school's TCDM is nearly double that of the mid-rise and high-rise, as a result of the school's smaller hybrid system size (smaller bore-field/soil volume).When evaluating the ACE for each building case, there is a negligible impact observed from an emissions perspective, resulting in a minor increase in annual CO_2 emitted, of just under 1%.

Table 8: Shoulder season summary of mid-peak/peak power reduction potential, ACE increase, and resulting TCDM for the mid-rise, high-rise, and school buildings

Building	Peak Power Reduction (%)	Mid-Peak Power Reduction (%)	ACE Increase (%)	TCDM (%)
Mid-Rise	16.3	16.6	0.5	53.7
High-Rise	14.4	14.9	0.9	48.2
School	24.4	24.7	0.4	56.4

3.3.2 Peak Season Operation

The same analysis was repeated for a peak season operating bracket to determine how the bore-field pre-conditioning affects the hybrid system dynamics in a period of typically high cooling load density. It can be seen in Figure 8 that pre-cool strategy impact on the systems annual energy consumption is sensitive to time of month. Both the mid-rise (Figure 8a) and high-rise (Figure 8b) exhibit a similar trend which resulted from the shoulder season operating bracket, where energy consumption increases for lower pre-cool durations and begins to decrease for longer periods. What differs from peak season results is that both the mid-rise and high-rise AECC is greater than the shoulder season simulation, resulting in an AECC increase of 8.0% and 6.5% for the mid-rise and high-rise, respectively. This consumption increase is a result of the high cooling load density during the peak season time bracket, degrading the thermal impact the pre-cool has on the bore-field due to a greater amount of heat being injected into the ground to satisfy cooling demands.

The school (Figure 8c) shows a positive impact for a peak season pre-cool, showing a degrading energy consumption trend for pre-cool durations greater than four hours, resulting in a minor AECC increase of 0.7%. The school is able to benefit from peak season operation due to lower cooling load density in this time frame (illustrated in Figure 6c), due to the unique occupancy pattern attributed to the educational facility. With the reduced thermal demand and the integration of an OGPC strategy the geo-exchange system was able to supply a larger percentage of cooling demand in a more efficient manner.

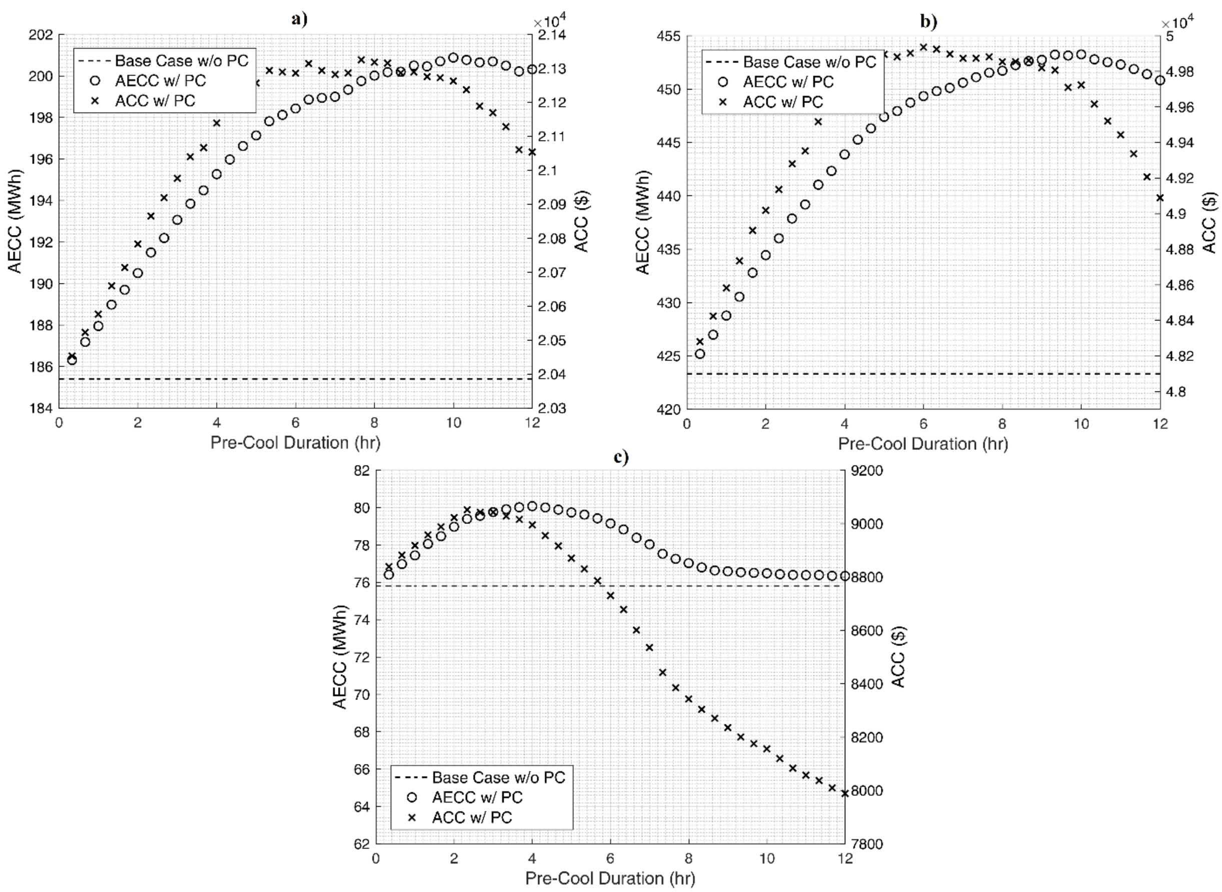

Figure 8: AECC and ACC for PS operation versus pre-cool duration for buildings (a) mid-rise, (b) high-rise, and (c) school

For both the mid-rise (Figure 8a) and high-rise (Figure 8b), peak season pre-conditioning provides no economic benefit in the form of a reduction in operating costs when the TOU structure in Section 2.2.2 is implemented. The school (Figure 8c) shows a significant cost reduction for off-peak pre-conditioning with a minimum pre-cool duration of approximately five hours to break even with the operating cost associated with base case control scheme. The HGSHP system shows the greatest cost savings at a full 12 hour pre-cool, with an ACC reduction of 9.1%. The ability to generate operational cost savings is limited by the energy prices associated to the TOU structure utilized in the cost computation. Although the potential savings are limited for the mid-rise and high-rise, the proposed operating strategy still provides potential for load leveling capabilities for all three building cases.

Table 9 summarizes the results for the mid-peak/peak power reduction potential for the peak season pre-cool operating schedule. The results show a positive impact from a mid-peak/peak power shaving perspective for all three building cases; resulting in reductions of 10.4% / 8.8%, 8.8% / 8.7%, and 25.5% / 33.9% for the mid-rise, high-rise, and school, respectively. However, the mid-rise and high-rise suggest a mid-peak/peak reduction approximately half that of a shoulder season pre-cool schedule (Table 8, Section 3.3.1). This result is attributed to an increase in the frequency of cooling requirements during peak season. With an increase in cooling demand, the thermal benefit provided by the OGPC strategy is degraded due to the increased rate of heat rejection to the building's bore-field. This occurrence is further illustrated in the TCDM increase for the three buildings; resulting in an additional 8.8%, 9.0%, and 21.9% for the mid-rise, high-rise, and school, respectively. The mid-rise and high-rise building's TCDM increase is approximately 25% less when compared to a shoulder season pre-cool schedule.

Table 9: Peak season summary of mid-peak/peak power reduction potential, ACE increase, and resulting TCDM for the mid-rise, high-rise, and school buildings

Building	Peak Power Reduction (%)	Mid-Peak Power Reduction (%)	ACE Increase (%)	TCDM (%)
Mid-Rise	8.8	10.4	4.4	50.5
High-Rise	8.7	8.8	3.1	44.9
School	33.9	25.5	-15.0	56.4

When considering the ACE, the mid-rise and high-rise show minor increases in total CO_2 emitted; 4.4% and 3.1%, respectively. This result stems from the degraded pre-cool benefit caused by higher cooling load density in peak season. When evaluating the school, the simulations indicate a potential 15% reduction in total CO_2 emitted. The school shows a 15% savings in CO_2 emitted due to the reduced cooling demand in peak season (lower building occupancy). In addition, there is a greater difference between the off-peak/peak emissions factors during the peak season timeframe, generating a more significant carbon emissions reduction for each kilowatt of electricity consumption deferred to an off-peak operating bracket.

3.3.3 Full Season Operation

The control algorithm was modified to restrict the OGPC operating strategy to a full season period, where the predicted results for AECC and ACC with respect to the variation in pre-cool duration are presented in Figure 9. It can be seen from Figure 9 that all three buildings show a positive impact in energy consumption for a pre-cool duration greater than eight, nine, and four hours for the mid-rise, high-rise and school, respectively. Both the mid-rise (Figure 9a) and high-rise (Figure 9b) show a positive impact for full season operation but still result in a more substantial AECC for a 12 hour pre-cool, with a 9.1% and 7.4% increase, respectively. The school (Figure 9c) results in a minor 1.2% increase in AECC for a maximum pre-cool duration.

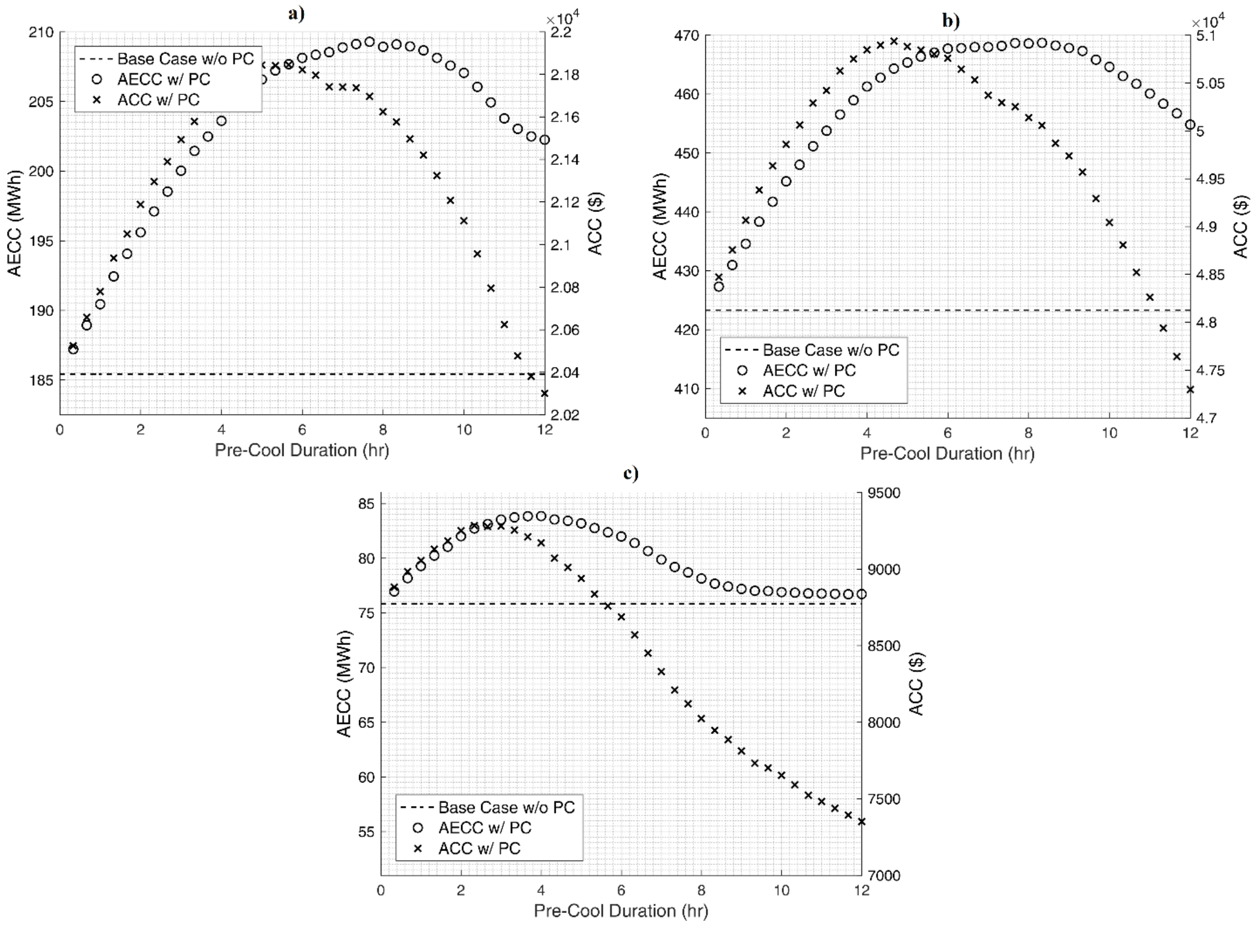

Figure 9: AECC and ACC for FS operation versus pre-cool duration for buildings (a) mid-rise, (b) high-rise, and (c) school

The mid-rise (Figure 9a) and high-rise (Figure 9b) buildings require close to the maximum pre-cool duration to obtain any operational cost savings, resulting in the largest ACC reduction of 0.4% and 1.7%, respectively. The lower magnitude of annual cooling cost savings are a result of the inclusion of the peak season operation within the full season timeframe, previously shown to be less favorable to the mid-rise and high-rise buildings. To elevate the cost savings associated with both of the multi-residential buildings peak season operation should be omitted from the operating schedule, putting precedence on shoulder and mid-season operation. From Figure 9c, it is clear that the school is substantially impacted by a full season operating schedule, with the predicted minimum pre-cool duration being approximately five hours, the system accomplishes a 16.4% savings in operating cost for a pre-cool duration of 12 hours.

Table 10 summarizes the simulation results for the full season operating schedule, indicating great potential from mid-peak/peak power reduction: 26.6% / 25.3%, 23.3% / 23.6%, and 49.8% / 58.5% for the mid-rise, high-rise, and school, respectively. The school model indicates approximately double the mid-peak/peak reduction potential (compared to the mid-rise and high-rise) as a result of its unique cooling demand profile and ideally sized hybrid system (smaller bore-field/soil volumes). The combination of these two factors allows the school to exploit the thermal benefit introduced by the pre-conditioning strategy more effectively. This occurrence is further illustrated in the TCDM increase for each building case, resulting in an additional 20.7%, 21.3%, and 43.7% for the mid-rise, high-rise, and school, respectively. The school's TCDM increase is approximately double the simulation results for the mid-rise and high-rise buildings.

Table 10: Full season summary of mid-peak/peak power reduction potential, ACE increase, and resulting TCDM for the mid-rise, high-rise, and school buildings

Building	Peak Power Reduction (%)	Mid-Peak Power Reduction (%)	ACE Increase (%)	TCDM (%)
Mid-Rise	25.3	26.6	4.9	62.5
High-Rise	23.6	23.3	4.1	57.2
School	58.5	49.8	-14.5	78.3

When evaluating the ACE for the three building cases in full season, consistent trends occur when compared to peak season operation. The mid-rise and high-rise indicate minor increases in CO_2 emitted, 4.9% and 4.1%, respectively. With the school model indicating a potential 14.5% reduction in annual carbon emissions. The school with a full season operating schedule shows less potential for CO_2 emissions (compared to peak season) due to the inclusion of the shoulder season pre-cool timeframe.

The economic optimization methodology utilized to size the hybrid geo-exchange systems for all of the building cases indicated a common advantage for the three suggested pre-cool schedules. The optimal hybrid systems resulted in designs that are sized to meet less than 25% of peak cooling demand. These designs physically equate to a reduced ground-loop requirement and reduction in capital cost, compared to a non-hybridized system. Utilizing the OGPC strategy allowed for an augmentation of the GSHP system's cooling capacity. With this augmentation, the resulting optimal hybrid systems are capable of supplying a larger portion of demand over the cooling season. The advantage of this physical response introduced by the pre-cool strategy is that future hybrid designs can be strategically sized to further reduce ground-loop requirements (improving economics by reducing capital cost) while meeting greater portions of total cooling demand; taking full advantage of the potential to reduce operating costs and carbon emissions.

3.3.4 Additional Building Cases

Table 11 presents a summary of six additional building cases that were considered: a private school, high-rise condominium, hospital, transit facility, fast-food restaurant, and restaurant. The private school and the high-rise condominium indicated trends that are consistent with the results discussed above. It can be observed that the building cases that indicate a positive impact from application of an OGPC control strategy are those with hybrid systems sized to meet smaller portions of peak cooling demand. Thus, buildings with small shave factors indicated the greatest potential for a reduction in peak power consumption and operational cost.

The hospital, transit facility, fast-food restaurant, and restaurant show no significant benefit to the integration of an OGPC strategy for the optimally sized HGSHP systems. Both the hospital and transit facility indicate minor benefits (under 5%) with regard to peak power reduction and total cooling supplied by the geo-exchange system. When considering both the fast-food restaurant and restaurant, the proposed control strategy indicates no benefit at all. This result is due to the hybrid systems for the aforementioned buildings being sized to meet a greater portion of peak cooling demand (lager shave factor design parameter). As the shave factor parameter is increased, the ground-loop length increases, GSHP system capacity increases, and the auxiliary ASHP capacity decreases. Thus hybrid systems sized to meet larger portions of peak demand (smaller auxiliary cooling capacity and larger ground-loop lengths) result in excessive energy consumption with insignificant GSHP operating benefit; resulting from the negligible thermal impact on the bore-field, due to large bore-field/soil volumes.

The results presented in Table 11 clearly indicate the benefits associated to the OGPC strategy are sensitive to the hybrid system proportions. This trend provides valuable insight to the hybrid optimization process; systems sized to meet smaller portions of peak cooling demand indicate strong potential for a reduction in ACC, ACE, and peak power consumption. This information can be further utilized by feeding back into the economic optimization methodology presented in [9]. Incorporating the pre-cool control strategy into the hybrid design procedure introduces the advantage of allowing for additional dimensions of optimization. With this addition, the optimization process can be expanded to maximize the operational cost savings. Moreover, the OGPC strategy incorporated into the hybrid optimization design introduces the advantage of further improving the economic appeal of a hybrid geo-exchange system as a sustainable energy alternative.

Table 11: Summary of results for additional building case studies

Building		AECC (MWh)	ACC ($)	ACE (kg-CO_2)	Peak Power (MWh)	Mid-Peak Power (MWh)	TCDM (%)
Private School α = 0.29 168.2 kW peak	BC	67.2	8341.3	4790.2	23.7	25.1	59.6
	SS	+0.8%	-5.6%	-9.2%	-22.0%	-20.7%	71.6
	PS	+4.6%	-3.3%	+1.1%	-20.2%	-15.3%	68.8
	FS	+5.5%	-9.1%	-8.8%	-41.9%	-36.2%	80.9
High-Rise Condominium α = 0.30 314.4 kW peak	BC	248.1	26813.0	16414.2	57.3	55.4	57.0
	SS	+5.3%	-2.3%	+0.3%	-12.1%	-12.6%	68.2
	PS	+10.1%	+1.2%	+5.1%	-1.8%	-2.1%	59.4
	FS	+17.4%	-0.9%	+5.9%	-15.4%	-17.1%	71.6
Hospital α = 0.36 375.0 kW peak	BC	324.2	34815.4	21145.9	73.0	70.6	60.3
	SS	+14.3%	+10.0%	+9.7%	-2.5%	-3.1%	62.0
	PS	+15.9%	+11.6%	+13.0%	-1.0%	-1.3%	61.4
	FS	+30.0%	+21.3%	+22.7%	-3.1%	-4.3%	63.2
Transit Facility α = 0.42 239.4 kW peak	BC	187.7	24047.1	13688.3	74.1	72.2	64.6
	SS	+15.3%	+9.1%	+9.3%	-1.5%	-0.3%	65.7
	PS	+16.3%	+10.0%	+12.0%	-0.4%	-0.4%	65.2
	FS	+31.3%	+19.2%	+21.3%	-1.7%	-1.2%	66.3
Fast-Food Restaurant α = 0.60 104.0 kW peak	BC	123.7	12744.7	8194.1	22.3	24.7	87.0
	SS	+7.5%	+5.8%	+5.0%	0.0%	0.0%	87.0
	PS	+7.7%	+6.0%	+6.3%	0.0%	0.0%	87.0
	FS	+14.9%	+11.8%	+11.3%	0.0%	0.0%	87.0
Restaurant α = 0.65 92.6 kW peak	BC	106.0	10784.9	6845.5	17.9	20.2	91.4
	SS	+6.8%	+5.4%	+4.7%	0.0%	0.0%	91.4
	PS	+7.0%	+5.6%	+5.8%	0.0%	0.0%	91.4
	FS	+14.1%	+10.9%	+10.5%	0.0%	0.0%	91.4

4. Conclusions

The scope of this paper is to provide a preliminary analysis of a novel control strategy for the application of hybrid geo-exchange systems. The analysis aimed to demonstrate the positive impact that proactive pre-conditioning of a bore-field can have on system performance. Employing both a thermal pre-conditioning scheme in tandem with TOU conscious control, this study proposes a multifaceted methodology to address system economics through improved operating efficiency and aid in the balancing of the electrical grid, at negligible capital investment.

In this study, a numerical performance prediction model was developed using MATLAB to characterize the performance of HGSHP systems associated to nine real building cases. The model was used to simulate the hybrid geo-exchange systems response when controlled by the proposed OGPC control strategy for shoulder, peak, and full season operating schedules. The following is a summary of the significant findings and conclusions determined from this analysis:

<u>Shoulder Season Operation:</u>

- The mid-rise and high-rise buildings showed their largest financial benefit, obtaining an annual cooling cost savings of just under 4% for less than a 1% increase in energy consumption.
- Reductions ranging from 17% to 25% of mid-peak/peak power consumption were accomplished, with an increase total cooling demand met by the GSHP of approximately 12% for the mid-rise/high-rise, and 22% for the school.
- Simulations indicate no potential for emissions savings, resulting in minor increase of just under 1% of CO_2 emitted for all three building cases.

Peak Season Operation:

- The impact the OGPC has on the hybrid geo-exchange systems performance is extremely sensitive to the buildings thermal load characteristics.
- The mid-rise and high-rise showed no financial incentive due to the high load density in the operating time frame resulting in the degradation of the pre-cool thermal benefit, as a result of an increase of heat injection to the bore-field.
- Although the mid-rise and high-rise showed no financial gain, a notable mid-peak/peak power reduction and increase in total cooling demand met by the GSHP were observed.
- The school indicates a potential 15% reduction in total CO_2 emitted, due to the combination of reduced cooling demand (lower building occupancy) in addition to there being a greater difference between the off-peak/peak emissions factors, during peak season operation.

Full Season Operation:

- Minor operating cost savings for both the mid-rise and high rise were observed. For further cost improvement, peak season operation should be excluded and additional focus should be placed on shoulder and mid-season operation.
- The school showed a predicted operating cost savings of over 16% with just over a 1% increase in energy consumption, while reducing mid-peak/peak power consumption by approximately 50% - 59% with the GSHP meeting an additional 44% of the total cooling demand.

- The OGPC strategy significantly impacts the school due to the unique thermal load distribution, resulting from the occupancy pattern specific to an educational institution (lower summer loads).

This study demonstrated the potential for improving the economics of geo-exchange through the integration of a TOU-conscious control strategy. In addition, the potential for peak power shaving and a reduction in carbon emissions has been demonstrated.

Further research could be of benefit. A parametric study is recommended to evaluate the sensitivity of the conclusions drawn for the various building cases. Secondly, an experimental analysis should be conducted and compared to the results of this paper; experimentally quantifying the impact of an OGPC strategy. Future work in this research is the integration of higher level control techniques to optimize the operational cost savings, peak power shaving, and carbon emissions reduction potential introduced by an OGPC strategy.

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