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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%.

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

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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 [8–10]. 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 [15–18]. 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 to 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 [25–29]. 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 Fig. 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.

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