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An analysis of the factors affecting hybrid ground-source heat pump installation potential in North America

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HIGHLIGHTS

- Five sensitivity analyses were performed using 10 real buildings.
- Toronto's fixed electricity rate was compared with time-of-use rates.
- Weather (and rates) sensitivity analysis was performed (11 cities).
- Natural gas and electricity inflation analysis was performed.
- A seasonality control strategy was investigated.

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ABSTRACT

Growing demands for space heating and cooling make ground-source heat pump (GSHP) systems a viable renewable alternative. The economic outlook of potential installations can be addressed by hybridizing GSHP systems with an auxiliary system. To better understand optimization factors in sizing hybrid GSHP systems, a series of sensitivity analyses have been performed. Using a rigorous mathematical, computational approach to size hybrid GSHP systems recently published in Alavy et al. (2013), the use of sensitivity analyses has allowed for a better determination of the impact that variations in input parameters have on the performance of GSHPs. A total of five analyses were performed to determine the effects that operating costs, inflation, geographical location within North America, and a seasonality control strategy have on sizing hybrid GSHP systems. The effects inflation of natural gas and/or electricity prices have depends on a building's energy demands. An inflation (deflation) in electricity rates makes hybrid GSHP systems for very cooling (heating) dominant buildings more economical compared to conventional systems. Installations of smaller GSHP systems are more economical when considering time-of-use electricity rates compared to fixed electricity rates, for buildings with long operating hours during off-peak periods. However, downsizing the ground loop system causes an increase in annual operating costs which result in longer payback periods. Similarly, if a building is situated in a location with warmer weather where ground temperatures are thus higher, an optimally designed system will tend to have a shorter ground loop length. By meeting less of the building's peak energy demands (hybrid shave factor) substantially reduces the initial costs of the ground-loop installation.

1. Introduction

Space heating and cooling is responsible for a large portion, over 60% and 50% for Canadian residential and commercial sectors respectively, of a building's total energy demands [1]. Due to increasing environmental concerns and potential resource shortages, there is an ongoing drive to develop and implement sustainable alternatives. Ground-source heat pump (GSHP) systems have shown great success and potential, making them a popular clean renewable alternative to consider [2–6].

GSHPs are versatile, economically preferable to conventional systems, and can be combined with other renewable alternatives [7–12]. Bagdanavicius and Jenkins [11] studied the power requirements of GSHP systems for space and domestic hot water heating in a residential area in Wales, United Kingdom. Through simulations, they determined that if 50% of the residents used heat pumps for space and domestic hot water heating, the total peak in electric

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power would be 49–63 GW [11]. In [12], an underground water-source loop heat-pump air-conditioning system was applied in a residential building in Beijing. Chen et al. [12] estimated the system's ability to save energy, and determined that space conditioning (heating and cooling) was most economical (per square foot) for units with large square footage.

Since 2005, the total installed capacity of GSHPs has increased by 78.9% [13]. Qi et al. [13] emphasizes the importance of addressing the problem of imbalance between heating and cooling loads, especially for buildings situated in extreme hot and cold climate, which in turn affects system performance and economics [13]. Implementing proper control strategies is important in optimizing GSHP system performance [14–17]. High upfront costs and long payback periods are currently presenting obstacles to significant market penetration. In many cases, market penetration impedance for GSHP systems can be alleviated with the use of appropriate computational tools for design analyses. Improving the economic outlook of potential installations can be addressed by hybridizing GSHP systems with an auxiliary system [18–24]; a building's base load energy demands are met by the GSHP system and any excessive peaks are met by an auxiliary system.

Using a hypothetical sample building situated in Hong Kong, Man et al. [23] studied the economics of a hybrid GSHP system, with a cooling tower being used as the auxiliary cooling system. The simulated results indicate that hybrid GSHP systems, with proper design, can be economical for hot-weather areas like Hong Kong. On the contrary, Ozyurt and Ekinci [24] presented an experimental study of vertical GSHP system performance in a cold climate in Turkey. The GSHP system operated in non-design conditions, which resulted in lower than expected heat pump performance. Wu et al. [25] proposed using ground source absorption heat pumps (GSAHPs) as a potential solution to the thermal imbalance of GSHP systems in cold regions.

Due to the highly variable nature of sizing GSHP systems, general standards currently used by the industry do not always correspond to an optimized design [18,26]. Alavy et al. [18] developed a new computational approach, replacing the rule-of-thumb method of sizing GSHPs. The methodology, showed that rough standards currently used by the industry do not always correspond to an optimized design [18]. For example, in Sagia et al.'s study [27], the cooling tower (auxiliary cooling system) was sized to meet 20%, 30%, and 50% of a particular building's cooling load [27], with the balance met by a GSHP. By contrast, the methodology proposed by Alavy et al., [18] automatically sizes the heating and cooling systems, meeting the building's peak cooling and heating loads, with continuously variable auxiliary system capacity. The most economical design is selected based on the lowest net present value of capital and operating costs. Since this methodology was developed recently and is still poorly understood, a significant knowledge gap exists on how best to apply these new techniques. Furthermore, Alavy et al. [18], limited their study to ten buildings in the region of Southern Ontario, Canada. As such, sensitivity analyses to a variety of design parameters remain valuable to explore as a way of increasing the knowledge base of automatically sizing GSHPs as a component of a hybrid system. By using this methodology, the present work investigates the effects that geographical location (weather patterns and utility costs) has on the sizing of hybrid GSHP systems in North America.

The ten real buildings in [18], were analyzed using Toronto Canada's weather patterns, natural gas and fixed electricity rates. However, the paper focused on explaining and validating the methodology. To address the existing knowledge gap, using the proposed methodology, five sensitivity analyses were performed and will be described and discussed in this paper. Toronto's weather patterns, natural gas and fixed electricity rates will be used as the base case for the five analyses. This paper will begin by outlining the analyzed parameters in Section 2, followed by a brief explanation of the base case in Section 3. The sensitivity analyses, Analyses #1–5, will be covered in Sections 4-8 of this paper.

Time-of-use electricity rates were introduced as an incentive for consumers to save by using power during off-peak hours. This system reduces strain on the electricity grid and helps reduce carbon emissions by moderating the reliance of fossil fuel power plants during peak hours. In Analysis #1, using the ten real buildings from [18], Toronto's fixed electricity rate and an operating duration of 20 years (the base case) will be compared with time-of-use rates. This sensitivity analysis will provide insight on whether fixed or time-of-use electricity rates will be more economical for a particular building equipped with a hybrid system and how the varying rate structures affect optimal hybridization.

In Analysis #2, a weather sensitivity analysis will be performed. Toronto's weather patterns (base case) will be compared with weather patterns from 11 US cities (focusing on weather extremities). This analysis will determine how different weather patterns affect the design and performance of hybrid GSHP systems. In Analysis #3, the most recent electricity and natural gas rates for the cities tested (weather patterns) will be compared to the base case. The results will be used to determine which cities are most economical for hybrid GSHP installations.

Analysis #4 will study the effects of electricity and natural gas inflation. By using historical data of electricity and natural gas costs, a worst case scenario inflation value can be determined and used. The implications of inflation on the economics will be investigated.

In Analyses #1–4, and in [18], the hybrid GSHP systems were sized to provide heating and cooling for all 8760 hourly loads of one calendar year. In Analysis #5, a simple control strategy will be implemented such that during the winter months, all cooling demands (building cooling loads) will be set to zero. Similarly, during the summer months all heating demands (building heating loads) will set to zero. This control strategy assumes the building will obtain free cooling (heating) during winter (summer) from outdoor air. The results will be compared to the base case where a seasonality control system is not considered.

2. Sensitivity analyses: parameters used

The literature on environmental modeling supports the need for sensitivity analysis when undertaking a model-based study [28]. In particular, the application of sensitivity analyses is useful when the parameters employed in the model are impacted by uncertainties related to the parameter data [29] and can provide for a better understanding of the impact of changes in input data on a model's results. Decisions arising from performance modeling are better informed by the results of sensitivity analyses. Otherwise, a risk of misunderstanding the behaviors suggested by the model may result in inferences leading to improper choices [30].

When evaluating performance modeling of GSHP and hybrid-GSHP energy systems, the more recent literature has recognized the need for the use of sensitivity analyses related to model parameters such as electricity and natural gas pricing, interest rates, annual operating hours and ground temperatures when presenting the results of modeled outcomes [31–35].

For the purpose of sensitivity analyses, ten real buildings ranging from large multi-residential to commercial were analyzed as detailed in Table 1, data courtesy of CleanEnergy™. Based on these buildings a total of five sensitivity cases are investigated using the parameters, such as heat pump inlet temperature, boiler cost, interest and inflation rates, listed in Tables 2 and 3. The criteria in determining the optimal GSHP size is based on one which