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Research Paper

Financial optimization and design of hybrid ground-coupled heat pump systems

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HIGHLIGHTS

- Optimization-based design improves the net present value of Hy-GCHP systems.
- The approach integrates six design and operation parameters.
- Fine tuning some parameters can significantly improve financial performances.
- Hybrid systems can reduce significantly energy consumption and peak electrical load.

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ABSTRACT

A strategy to optimize the net present value of a hybrid ground-coupled heat pump system is presented. The method relies on a spectral-based simulation tool that predicts the heat pump performance on an hourly basis and on a optimization algorithm. The approach considers the project financial parameters, the hourly thermal load of the building, the pumping energy, the control strategy, the design fluid temperature of the heat pumps, the ground thermal properties, the footprint available for the ground heat exchanger, the local construction and equipment costs as well as complex electricity rates such as demand charges and energy. The proposed method gives the optimal number and location of the vertical boreholes, the number of required heat pumps and their operating temperature limits as well as the optimal energy savings generated by the ground-coupled heat pump system. Results indicate that fine tuning some design parameters such as the number of boreholes and installed heat pumps or the temperature limit in heating mode can significantly improve the financial performance of a project. Additionally, results confirm that use of hybrid systems could reduce significantly the electrical consumption and peak electrical load of a building.

1. Introduction

Hybrid ground-coupled heat pump (Hy-GCHP) systems are one of the most attractive energy saving measures for commercial and institutional buildings since they provide most of the energy savings generated by GCHP systems designed for peak demand while reducing the capital cost associated with the ground heat exchanger (GHE). The underlying strategy of hybrid system consists in using GCHPs (and its associated GHE) to supply the building's base thermal demand, and to use auxiliary backup systems to cover the additional demand during peak periods.

Designing a Hy-GCHP system is however a complex task involving many design parameters such as the installed capacity of each subsystem, the number and location of geoexchange wells and the heat pumps' temperature setpoints. Although it is possible to design Hy-GCHP systems through standard sizing approaches [1,2], recent works indicate that standard design equations can lead to improperly sized GHEs, with sizing errors in the range of –21% to 167% [3]. In this context, optimization-based design approaches are interesting alternatives since they allow assessing the impact of purely technical decisions on the construction and operation costs of a system. The general idea consists in simulating numerically the energy consumption of a hybrid system to assess its operation costs and identify, through optimization algorithms, the design parameters improving its economic performance. The economic indicator

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used to quantify the system's financial outcome is usually chosen to fulfill the requirements of a specific geoexchange project and may include the net present value of the total cost [4,5], the total revenue requirement [6], the total cost minimization [7,8] and the system's first cost [9].

Finding the global optimum may however be difficult and numerically intensive since the design parameters may include a combination of constrained continuous and integer variables, which can lead to an objective function containing many local optima. A wide variety of optimization methods have been used. Recent attempts in the field of geoexchange have used the branch and bound method [7], evolutionary algorithm [6,7], particle swarm optimization [5], gradient-based approach [8], Taguchi method [10], heuristic combining local and global methods [7] and sweeping techniques [11].

This paper presents a methodology to optimize the net present value generated by the operation of Hy-GCHP systems subject to complex electricity rates such as demand charges and energy. This paper shows, through two numerical experiments, that using water-to-water heat pumps (in conjunction with water-to-air heat pump) to provide space heating at an acceptable cost when natural gas is not available could result in a significant reduction of the energy bill, and that fine tuning some design parameters can significantly improve the financial performance of a project.

2. Hybrid ground-coupled heat pump system specifications

The analysis described in this work is relevant for buildings having a primary water loop as shown in Fig. 1. In this system, geothermal water-to-water heat pumps (GHP) are connected to a GHE on the source side and to a water loop on the load side. The GHPs provide base heating and cooling to the water loop, which is connected to water-to-air heat pumps located in the various building zones. This configuration enables energy transfer between the various building zones through the primary loop, which is used as thermal reservoir. With a proper selection of loop temperature setpoints and equipment, it is then possible to operate water-to-air heat pumps in different operation modes and, for example, use a given heat pump to provide cooling in a central zone while providing heating in peripheral zones.

The various heat fluxes between the system components are summarized in Fig. 2 for a case with 14 borehole, 4 GHPs and 4 building zones. The GHPs add or remove energy to the water loop to maintain its temperature within the operation range of the water-to-air heat pumps. To reduce the system's initial cost, it is frequent for commercial systems designers to undersize the GHE and the GHP capacity and to rely on auxiliary backup systems to cover part of the total thermal demand transmitted to the water loop ($\dot{Q}_L$). For Hy-GCHP systems, it is expected that at some point the entering water temperature on the source side (*EST*) will reach the GHPs' temperature limits (EST_{min} or EST_{max}). During these events, a control sequence will decide whether a GHP is on, off, or in cycling mode. Deactivating one of the N_{GHP} installed GHPs will reduce the GHP total capacity ($\dot{Q}_{GHP}$) and require to increase the energy delivered by the auxiliary backup heating ($\dot{Q}_H^a$) or cooling ($\dot{Q}_C^a$) system to the water loop.

3. Simulation approach

Simulation of a Hy-GCHP system allows the evaluation of the energy consumption of the GHPs and auxiliary systems over time. Due to its high computational efficiency, a spectral method [12,13] is used to simulate the system described previously and to provide the necessary inputs to the objective function computation. The approach provides the energy delivered to the water loop by the GHPs and auxiliary backup systems and integrates the various

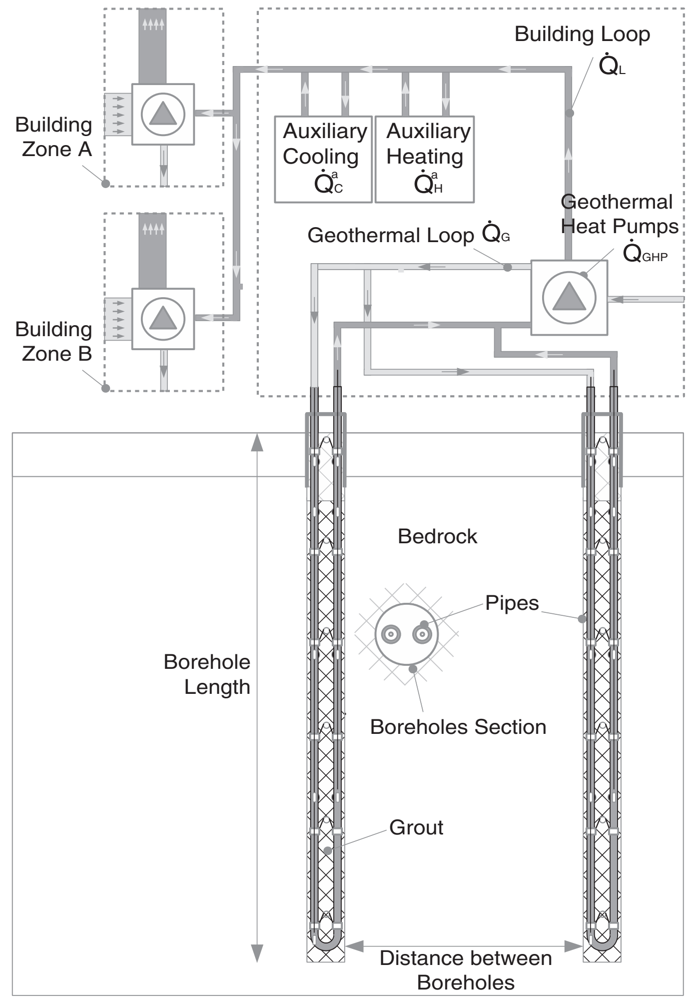

Fig. 1. Typical hybrid ground-coupled heat pump system.

features of the GHPs (performance and capacity curves) and GHE (ground and grout thermal conductivity, borehole length and spacing, burial depth, pipe spacing, borehole diameter, etc.). This section presents only the main features of the simulation tool used in this work and the interested reader is referred to the original papers for a complete description of the algorithm. However, for the sake of completeness, a derivation of the main equations follows.

The simulation approach used here relies on the widely used standard model, which provides the mean fluid temperature in the GHE ($\bar{T}_f(t)$) through:

$$\bar{T}_f(t) = T_G + \frac{\dot{Q}_G(t)}{L} \cdot R_b + \frac{\dot{Q}_G}{2\pi kL} \cdot g(t, k, \alpha, r_b, D, H) \quad (1)$$

where t is the time, T_G is the undisturbed ground temperature, $\dot{Q}_G$ is the total ground thermal load, L is the total GHE length, R_b is the equivalent borehole thermal resistance, k is the ground thermal conductivity and g is the transfer function of the GHE (Eskilson's g-function [14]). In Eq. (1), g describes the thermal behavior of the GHE and integrates the length H, radius r_b, burial depth D and coordinates of each borehole as well as the ground thermal properties such as thermal conductivity k and diffusivity α. Since function g is specific to a given GHE geometry, g must be recomputed every time the location of the boreholes is modified. Note that the