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## Non-Topical Article

# Reducing Capital Cost for Geothermal Heat Pump Systems Through Dynamic Borefield Sizing

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***Geothermal heat pump systems offer a sustainable solution for heating and cooling of buildings, significantly contributing to climate goals by reducing greenhouse gas emissions and achieving carbon neutrality. However, the higher initial costs associated with the borefield pose a barrier to widespread adoption. This article explores how dynamic borehole modeling can optimize borefield sizing, achieving up to a 35% size reduction in the investigated cases, thereby making these systems more cost-effective.***

### Introduction

The building HVAC sector's energy use has garnered increasing attention as a critical component in achieving environmental, energy, and climate goals. Geothermal heat pump systems (GHPS) are gaining prominence due to their potential for significant energy use reduction. These systems exploit the ground as a heat source and consist of two main components: the heat pump system and the borefield. Unlike air-to-water heat pump systems, GHPS (if properly sized) benefit from more stable soil temperatures, offering consistently higher efficiency even in very cold climates. However, the higher initial investment due to the borefield remains a barrier to widespread adoption. To reduce capital cost, it is essential to use a borehole model that is sufficiently accurate to predict heat transfer within and around boreholes, preventing oversizing.

### Understanding geothermal heat pumps

GHPS extract heat or cold from the ground (a source of renewable energy) to provide thermal comfort in a building. When heating a building, the GHPS extracts heat from the ground and releases it into the space to be heated. GHPS are most efficient when the temperature difference between the ground and the supply water to the building is small. Therefore, buildings that use a GHPS are usually equipped with a low-temperature (or, for cooling, a high-temperature) emission system such as underfloor heating or Thermally Activated Building Structures (TABS).

GHPS are becoming increasingly important due to their potential to reduce energy use, especially when there is both heat and cold demand. Their high energy efficiency is attributed to three main factors. First, GHPS can provide passive cooling, which requires only circulation pump energy and contributes to the ground thermal balance (when there is heating demand in another season). Second, the coefficient of performance (COP) of the heat pump in GHPS is higher than that of air-to-water heat pump systems because the ground temperature remains relatively constant, resulting in a smaller temperature difference to bridge, especially in time periods when the heat demand is the highest. Finally, this technology also has the advantage of seasonal storage (when the borefield is designed for that purpose), where the stored heat from cooling in summer can be released in winter and vice versa.

Overall, GHPS leverage the earth's temperature to enhance heating and cooling efficiency, making them increasingly attractive for both residential and commercial applications.

### The Importance of borefield sizing

Determining the optimal size of the borefield is one of the biggest challenges in GHPS. Due to the significant investment cost, minimizing the borefield size is crucial for economic feasibility. However, the borefield must be large enough to ensure that the heat transfer fluid (HTF) does not exceed predefined temperature limits: at the upper side to allow passive cooling and at the lower side to avoid freezing.

Accurately predicting the HTF temperatures throughout the entire range of borefield operation is thus essential for designing GHPS. For example, a borefield may be dominated by long-term heat buildup or affected by short-term peak loads. In the latter case, fluid temperatures inside the borefield may rise rapidly, with fluctuations of 5-10°C occurring over one to two hours. This emphasizes the importance of accurately determining fluid temperatures, as they directly influence the required length of the borefield and associated investment costs.

In practice, it often happens that a borefield is oversized, which is a result of sizing with a steady-state model that neglects the dynamic behavior of the fluid, the pipe, and especially the grout. Heat is then transferred immediately (without any delay) from the fluid to the ground, leading to an overestimation of heat injection into (or extraction from) the ground. In contrast, a dynamic model accounts for the thermal mass of the materials between the fluid and the ground, introducing inertia and resulting in transient heat transfer processes. Consequently, the borefield size can be reduced while still meeting the predetermined temperature constraints, significantly lowering investment costs.

**Advancements in dynamic borehole modeling**

Dynamic borehole modeling considers the short-term thermal interactions within the borefield, accounting for the thermal inertia of the fluid, pipes, and grout. By incorporating these transient effects, a more accurate prediction of the system's performance is provided, allowing for a reduction in borefield size without compromising efficiency.

Most software tools currently used, such as EED, GHEtool, and the DTS model used in the TRNSYS sizing tool, rely on Finite Line Source (FLS)-generated g-functions for heat transfer outside the borehole combined with an equivalent thermal resistance method for heat transfer inside the borehole. These methods represent the boreholes as finite lines and assume steady-state heat transfer inside, neglecting the thermal capacities of the materials making up the borehole. As a result, these sizing tools are not accurate for short-term heat transfer estimation and often lead to oversizing.

This article presents the impact of incorporating short-term dynamic effects into the basic model and examines whether the relevance of these effects depends on the chosen load profile. Two main improvements are made to the basic model to better describe heat transfer in borefields. First, the finite line is transformed into an infinite hollow cylinder, introducing a realistic borehole geometry and incorporating an accurate heat exchange surface between the borehole and the ground. Second, a dynamic model is introduced to replace the steady-state equivalent thermal resistance method, accounting for the transient heat transfer inside the borehole. These effects are modeled in GHEtool, an open-source Python package that includes all functionalities needed for borefield sizing and temperature evolution evaluation [1]. A comparison between the basic model and the newly introduced model, including the two short-term dynamic effects, has shown a significant impact on sizing [2].

**Relationship between load profiles and borefield size reduction**

To understand the impact of different load profiles on borefield sizing, three load profiles with varying characteristics were carefully selected. The two main load characteristics considered were the variability in peak load and the imbalance between heating and cooling demands. These profiles enabled the evaluation of the relevance of including the short-term dynamic effects under different scenarios. Table 1 gives the yearly demand and peak demand for the three investigated buildings. The hourly building loads employed for sizing are converted to primary geothermal loads using a SCOP of 4 and a SEER of 20 and are shown in Figures 1-3.

*Table 1: Yearly demand [MWh] and peak demand [kW] for the three different buildings*

| | | Auditorium | Office | Swimming pool |
|---|---|---|---|---|
| Yearly | Heating | 38.3 | 117.6 | 1965 |
| | Cooling | 3.86 | 118.3 | 41.89 |
| Peak | Heating | 32 | 214 | 540 |
| | Cooling | 90 | 371 | 106 |

***Profile 1: High Variability in Peak Load***

The first load profile represents an auditorium building with significant fluctuations in heating and cooling demand throughout the day. This high variability in peak load makes it an ideal candidate for dynamic borehole modeling. Traditional steady-state models tend to oversize the borefield for such buildings, as they do not account for the short-term thermal capacity of the system, which will flatten out the depicted load peaks.

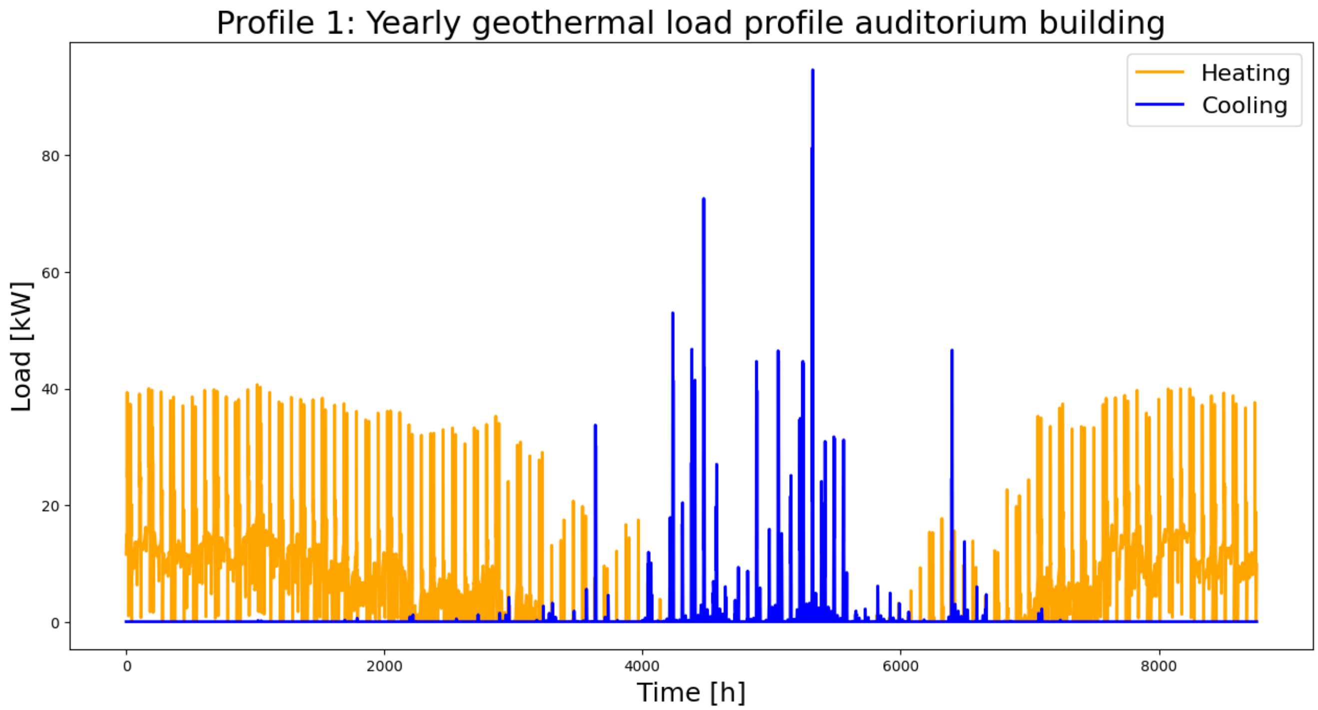


*Figure 1: Yearly primary geothermal load profile of the auditorium building in kW.*

Dynamic borehole modeling for this profile showed a substantial reduction in borefield size, as the model accurately captured the thermal inertia effects, allowing the system to handle peak loads more efficiently. Figure 4 illustrates that the required borehole length can be reduced by 35% for this building, achieved through dynamic borehole modeling.

***Profile 2: Balanced Load with Moderate Variability in Peak Load***

The second load profile pertains to an office building characterized by a balanced heating and cooling demand with moderate peak load variability.

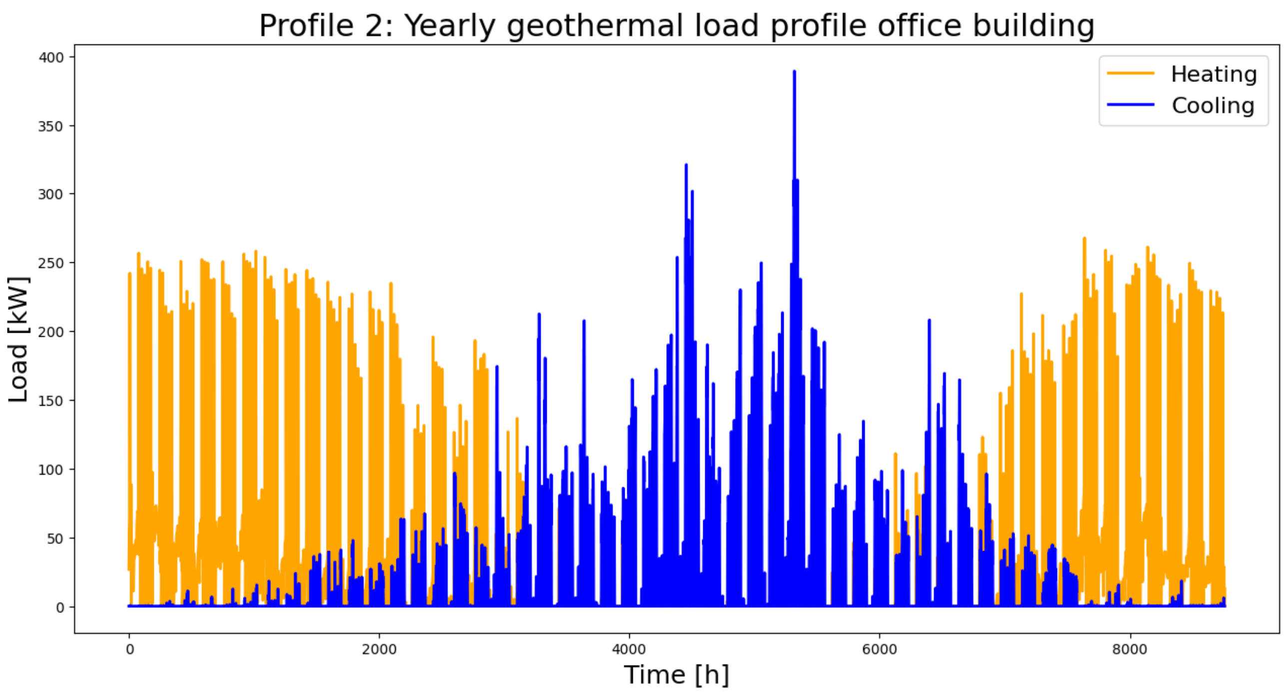


*Figure 2: Yearly primary geothermal load profile of the office building in* kW.

The results indicate that even with moderate peak load variability, dynamic borehole modeling can achieve significant cost savings. The sizing is primarily influenced by temperature peaks because there is no significant imbalance between heating and cooling demands over the year. Accurate estimation of the HTF temperature during peak hours results in a more precise borefield size. For this specific case, the required borefield size can be reduced by 11%, as shown in Figure 4.

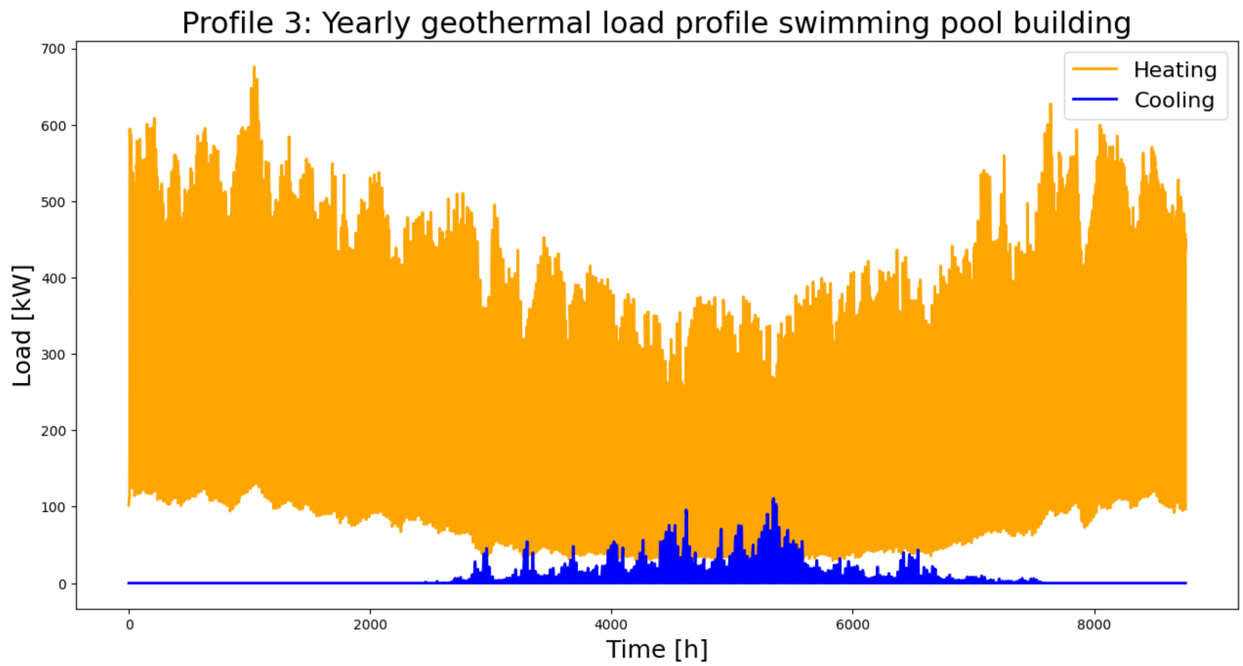


*Figure 3: Yearly primary geothermal load profile of the swimming pool building in kW.*

***Profile 3: Highly Imbalanced Stable Load***

The third load profile focuses on a swimming pool building, which has stable heating and cooling demands but a significant imbalance between both. This imbalance means that the building requires more heating than cooling, or vice versa, over the course of the year, as shown in Figure 3. This substantial load imbalance causes the ground temperature around the borefield to cool down year after year since more heat is extracted than injected. Consequently, the HTF temperature decreases annually until it hits the lower temperature limit at the end of the exploitation period. This constraint is considered during the sizing process, and thus, the sizing is dominated by this large imbalance. The dynamic borehole model, which accounts for short-term effects, does not alter the steady-state behavior in the long term. This explains why, for this specific case, incorporating short-term dynamic effects does not offer the potential for size reduction.

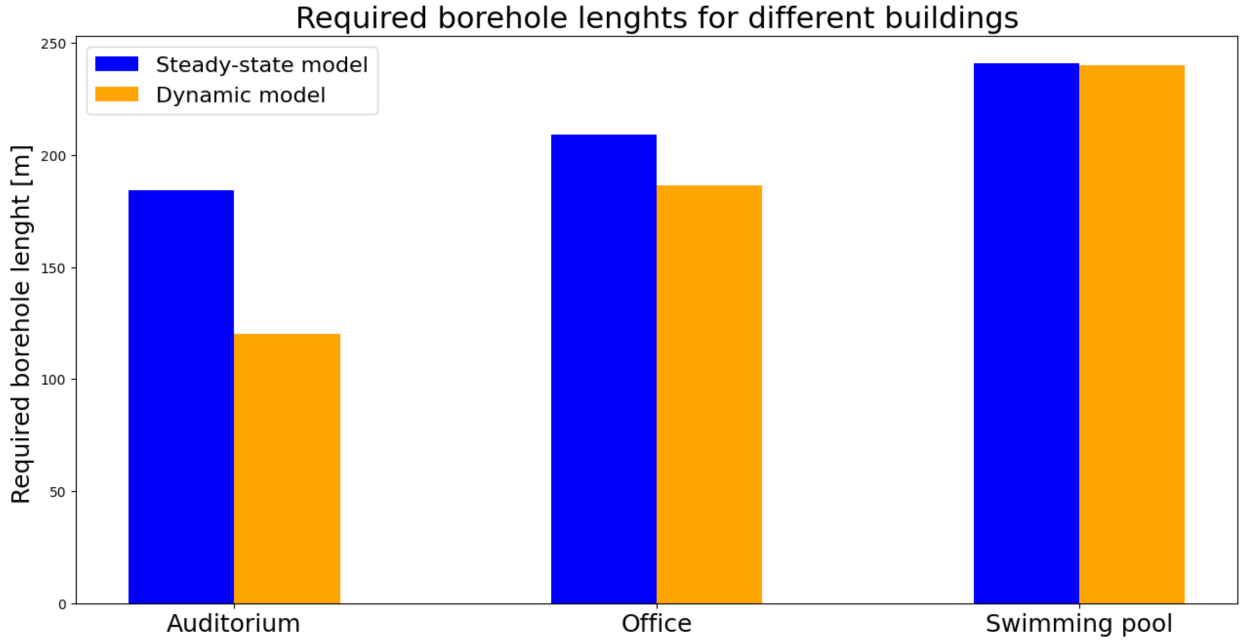


*Figure 4: Required borehole lengths for the different buildings and different borehole models*

**Benefits for Reaching Climate Goals**

The enhanced efficiency and reduced costs of GHPS directly contribute to global climate goals. By decreasing reliance on fossil fuels for heating and cooling, GHPS reduce greenhouse gas emissions. Additionally, their long lifespan and low maintenance requirements make them a sustainable choice for the future.

The International Energy Agency's (IEA) Tracking Clean Energy Progress 2023 report highlights the crucial role of geothermal energy in the transition to a net-zero emissions world [3]. GHPS, being a mature and reliable technology, are well-positioned to aid this transition by offering a renewable and efficient alternative to conventional heating and cooling systems.

By optimizing borefield sizing through dynamic borehole modeling, GHPS become more cost-effective, encouraging broader adoption. This not only makes the technology more accessible to a wider range of users but also accelerates its impact on reducing carbon footprints and advancing energy sustainability.

**Conclusions**

Geothermal heat pump systems are a powerful technology in the fight against climate change. By optimizing borefield sizing through dynamic borehole modeling, these systems can become more accessible and cost-effective, thus accelerating their adoption. As the world transitions towards a sustainable energy future, GHPS will play a crucial role in reducing emissions and promoting energy efficiency.

This article describes a method to enhance the commonly used steady-state borehole models for borefield sizing by incorporating short-term dynamic effects. These improvements introduce a more realistic cylindrical geometry and consider the thermal capacities of the borehole components. This approach flattens out the heat transfer peaks, allowing for a smaller borefield size while still meeting the predefined temperature constraints of the HTF. For buildings with high variations in peak thermal demand, dynamic borehole modeling can significantly reduce borefield size and installation costs. The investigated cases demonstrated a size reduction of up to 35%.

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