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Integrating Temperature and Part-Load Dependent COP in Shallow Geothermal Borefield Design

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Abstract

In conventional shallow geothermal borefield design, both the building demand and a predefined seasonal coefficient of performance (SCOP) are used as inputs. The SCOP serves to convert building loads into ground loads. However, this method introduces two key inaccuracies: (1) both peak power and total energy demand are scaled equally, often leading to an overestimation of peak extraction power; and (2) the SCOP is typically based on standard conditions (B0/W35), whereas actual system temperatures are often higher, resulting in an underestimation of seasonal imbalance and an oversized borefield.

Furthermore, because the SCOP is used as a fixed input, the borefield design process itself does not influence the efficiency of the ground source heat pump (GSHP), which is contrary to reality.

This paper demonstrates the benefits of incorporating both temperature-dependent and part-load-dependent COP curves into the design process. Simulation results show that by accounting for the true operational behavior of the GSHP, seasonal efficiencies exceeding 7 can be achieved, significantly higher than the standard B0/W35 SCOP values, which are often below 5. On the other hand, including only the temperature dependency does not lead to a significant difference in SCOP. This results not only leads to more accurate and cost-effective borefield designs but also highlights the critical role of system design in the actual efficiency of GSHP installations.

1. Introduction

The building sector is responsible for 26% of global CO_2 emissions attributed to energy usage (IEA, 2023). The majority of these emissions can be attributed to the heating and cooling demand of these buildings. In order to meet the climate goals, it is necessary to decarbonise this demand.

One promising technology that has been around for over 50 years is the use of ground source heat pumps (GSHP) connected to shallow geothermal borefields. Not only does this technology have a very high seasonal efficiency for heating, it can also provide our buildings with free (or passive) cooling, whereby no compression step is needed.

The biggest challenge for the wide acceptance of this geothermal solution is the high investment cost on the one hand and the increasing efficiency of air source heat pumps (at a lower investment cost) on the other, making the business case for GSHP very difficult. Within this discussion lies the importance of correct borefield design, since, for sustainability and comfort reasons, we cannot risk undersizing our borefields, but oversizing them would make them economically infeasible.

The essence of the simulation of borefields lies in the concept of *g*-functions, which are non-dimensional functions that govern the thermal interaction between different boreholes in a borefield and the interaction between the borefield and the neighbouring ground. After the introduction of this concept in the PhD of Eskilson in 1987, quite a lot of research has been done on how to calculate these *g*-functions as fast and efficiently as possible. One of the latest methodological innovations has been the research of Prieto & Cimmino (2021), where they introduced the concept of ‘equivalent boreholes’. These equivalent boreholes share similar temperatures and heat extraction rates and could hence be modelled as a single borehole, speeding up the simulation significantly. Recently, artificial neural networks have been used to further speed up the calculation of these *g*-functions by Dusseault & Pasquier (2019), Blanke et al. (2024) and Rose et al. (2025).

All the advancements related to the calculation of *g*-functions and the thermal simulations of borefields govern the actual injection and extraction load of the borefield, whereas typically a building load is known (or estimated). This means that a conversion from the building load towards the ground load is needed in order to simulate the borefield.

Typically, a constant SCOP is used to model this conversion, as in the software EED (Hellström & Sanner, 1994) or GEO-HANDlight (Van de Ven & Koeningsdorff, 2019). This is, of course, a very important assumption, since the efficiency of a heat pump depends on both temperature and part-load operation. Making this an input leads to the counterintuitive result that your geothermal design has no impact on the real efficiency of the heat pump. Therefore, other design tools such as GHLEpro (Spitler, 2000) and GLD (Gaia Geothermal, 2019) have added the option to work with a quadratic GSHP efficiency curve to take into account the temperature dependency of the heat pump. However, they also make abstraction of the part-load operation of the heat pump and how this impacts the final efficiency of the system and the borefield design.

This paper aims to fill that gap and show the importance of taking, besides the temperature dependency of the coefficient of performance (COP) of the heat pump, also the part-load dependency into account. This part-load-dependent efficiency is implemented in GHEtool (Peere & Blanke, 2021).

2. Methodology

The importance of the efficiency assumption (constant, temperature dependent, or temperature and part-load-dependent) of the heat pump was investigated based on three different case studies. For these three cases, the borefield was sized for a minimum average fluid temperature of 0°C and 3°C. This shows the importance of the efficiency assumption on the required borehole length of the borefield (and hence the investment cost). As a second measure, the average SCOP was calculated for these three cases for a fixed borefield size to obtain an indication of the real efficiency of a GSHP and the corresponding operational cost.

The sizing and simulation were carried out with an hourly resolution using GHEtool v2.3.4 (Peere & Blanke, 2021). The viscosity, Reynolds number, and effective borehole thermal resistance were calculated at every timestep to obtain the most accurate result (Peere, 2026). The simulation parameters that are identical for all simulations are given in Table 1.

Ground thermal conductivity	2.1 W/(mK)
Average surface temperature	10°C
Geothermal flux	0.07 W/m^2
Fluid	25 v/v% MPG
Flow rate	0.25 kg/s/borehole
Double DN32 PN16	
Grout thermal conductivity	1.5 W/(mK)
Pipe-to-borehole-center	35 mm
Borehole diameter	150 mm
Buried depth	1 m

Borehole spacing	6 m
Minimum average fluid temperature	0°C / 3°C
Maximum average fluid temperature	25°C
Simulation period	20 years

Tab. 1: Simulation settings.

All systems were simulated using the detailed part-load efficiency data of the SV62 heat pump from Alpha Innotec.

3. Cases

For the simulation, three different buildings were investigated: a multi-family residential building, an office building, and a multi-utility building. The first two buildings were dynamically simulated using IESVE. For the last building, only the peak loads and yearly energy demands were available, and these were upscaled to an hourly load profile based on the weather data of Kleine Brogel in Belgium. Some general information on the building demands is provided in Table 2. The case-specific simulation parameters are given in Table 3.

	Peak heating	Peak cooling	Yearly heating	Yearly cooling
Residential building	66 kW	97 kW	152 563 kWh	24 083 kWh
Office building	214 kW	371 kW	117 509 kWh	118 276 kWh
Multi-utility building	535 kW	676 kW	643 017 kWh	267 744 kWh

Tab. 2: Peak powers and yearly energy demands for the different cases.

	Borehole configuration	Efficiency cooling (SEER)
Residential building	5 x 8	20 (passive)
Office building	8 x 9	7 (active)
Multi-utility building	10 x 12	20 (passive)

Tab. 3: Case specific simulation settings.

4. Results and discussion

First, the required borehole depths were simulated using the different efficiency assumptions. The results are shown in Table 4 and Figure 1.

	Constant SCOP	Temperature dependent	Temperature & part-load-dependent
	Residential building		
0°C	68.05 m (4.86)	65.88 m (4.71)	67.66 m (5.33)
3°C	95.44 m (4.86)	94.84 m (4.94)	97.36 m (5.74)
	Office building		
0°C	99.98 m (4.86)	99.26 m (5.38)	97.46 m (7.20)
3°C	99.98 m (4.86)	99.26 m (5.38)	97.46 m (7.20)
	Multi-utility building		
0°C	135.99 m (4.86)	132.76 m (4.85)	136.53 m (5.60)
3°C	176.65 m (4.86)	176.43 m (5.07)	181.91 m (6.06)

Tab. 4: Required borehole depths for the different efficiency assumptions. The resulting average SCOP's are given between brackets.

Since both the residential and multi-utility buildings are limited by the minimum average fluid temperature, increasing the minimum temperature threshold from 0°C to 3°C leads to an increased required borehole depth. For these cases, using a temperature and part-load-dependent COP results in a slightly larger borehole depth. This is because (as can be seen in Table 4) the SCOP is higher in this case than the B0/W35 SCOP of 4.86, putting more emphasis on the imbalance. As both cases are heating and extraction dominated, this increases the required borehole depth slightly, with a maximum of 3%.

Having only a temperature-dependent COP does not change the design much for these cases and gives just a slightly lower borehole length. This can be explained by the fact that the COP during peak heating is slightly lower than the average SCOP, minimising the effect of peak power on the final design while the SCOP remains very close to (and sometimes even lower than) the B0/W35 SCOP, resulting in an identical imbalance.

For the office building, the situation is slightly different. Since this borefield is limited by the maximum average fluid temperature, the required borehole depth does not change when switching from 0°C to 3°C. In this case, using the temperature- and part-load-dependent COP has a positive effect on the required borehole depth. This is because the COP is significantly higher (7.2 compared to the official 4.86), which counteracts the injection-dominated imbalance.

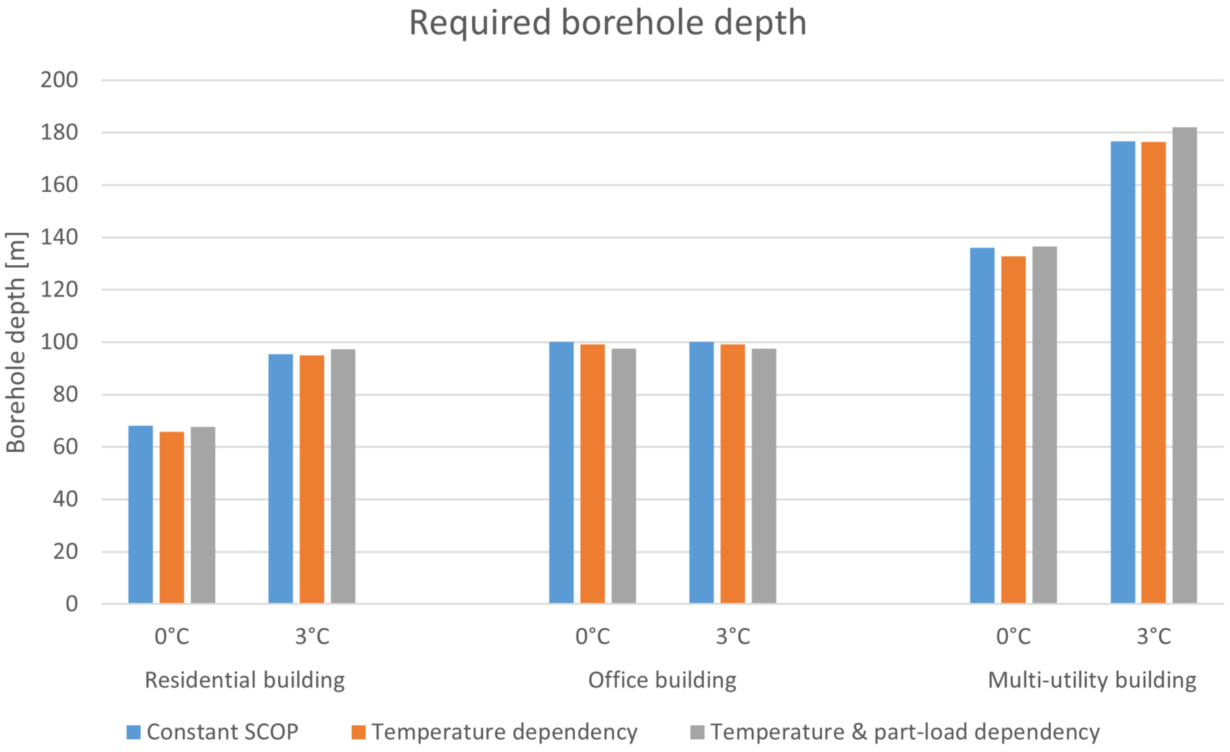

Fig. 1: Required borehole depths for the different efficiency assumptions.

As a second evaluation of the importance of the efficiency assumptions, the largest borehole depth for each case (Table 4) was selected, and the average SCOP over a period of 20 years was calculated for the different COP assumptions. The results can be seen in Table 5 and Figure 2.

	Constant SCOP	Temperature dependent	Temperature & part-load-dependent
	Residential building		
0°C	4.86	4.76	5.38
3°C	4.86	4.98	5.78
	Office building		
0°C	4.86	5.38	7.22
3°C	4.86	5.38	7.22
	Multi-utility building		
0°C	4.86	4.91	5.67
3°C	4.86	5.13	6.13

Tab. 5: Average SCOP in heating over a period of 20 years.

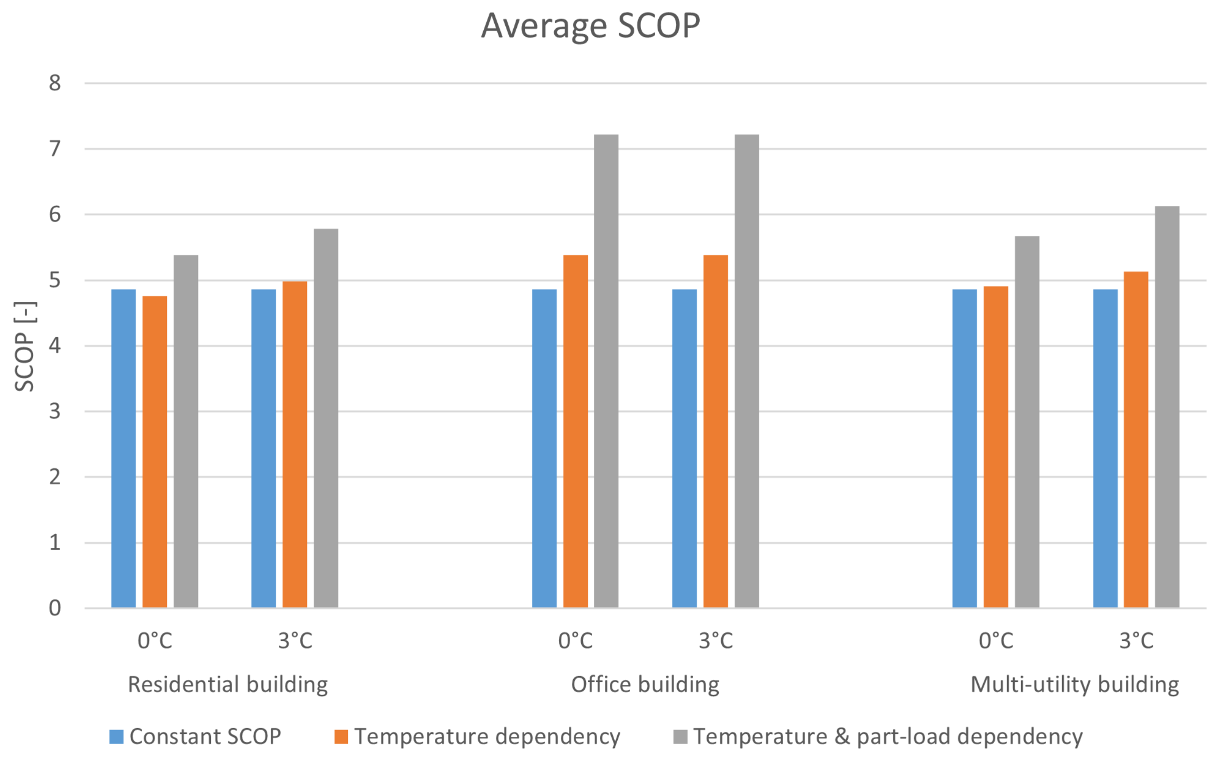

Fig. 2: Average SCOP in heating over a period of 20 years.

It is clear that the SCOP difference between the official B0/W35 value and the temperature-dependent COP is almost non-existent. Only in the case of the office building is a clear difference visible, since the average fluid temperatures are higher. When both the temperature and part-load dependencies are taken into account, the resulting difference becomes quite significant, reaching up to 7.2 in the case of the office building. Overall, an increase in SCOP of around 10–50% can be observed when the part-load dependency is considered, showing that the real SCOP differs from the official documentation.

In Figure 3, the temperature evolution of the multi-utility building is shown, where a clear imbalance is visible, cooling down the borefield year after year. This imbalance translates into a yearly decrease in the SCOP, as visible in Figure 4. Here it is clear that both the temperature-dependent and the temperature- and part-load-dependent SCOP curves decrease over time due to this imbalance. The temperature-dependent COP even leads, after year 10, to a lower SCOP than the official B0/W35 value. This is because, in the final years, the temperatures are often close to B0/W35, and since the temperature-dependent COP accounts only for full-load behaviour, it leads to an underestimation of the efficiency.

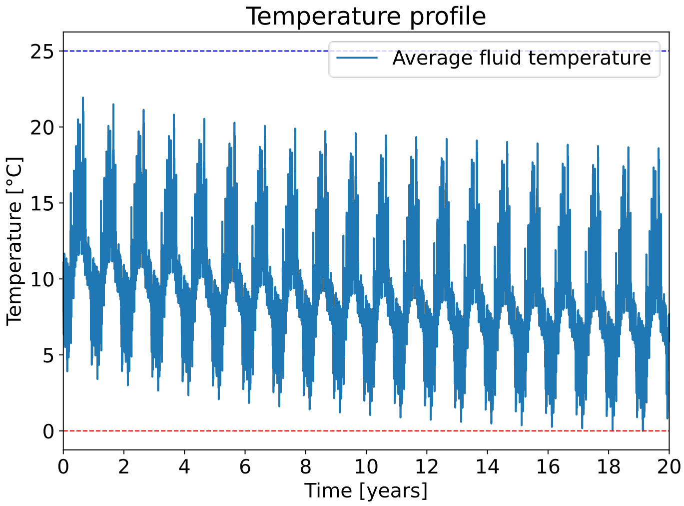

Fig. 3: Temperature profile for the multi-utility building.

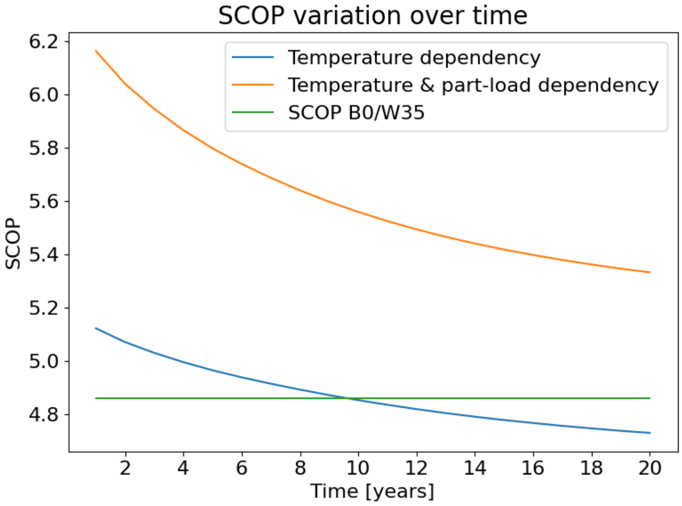

Fig. 4: SCOP variation over time for the three different assumptions.

Figure 4 also shows a large difference between the temperature-dependent and the temperature- and part-load-dependent COP, which can be further explained by looking at Figure 5. In this close-up, it is clearly visible that the variation in COP is greater when the part-load efficiency is included in addition to the temperature dependency alone. It is also clear that for peak powers, the efficiencies overlap, since here the heat pump works at full load and there is no part-load behaviour.

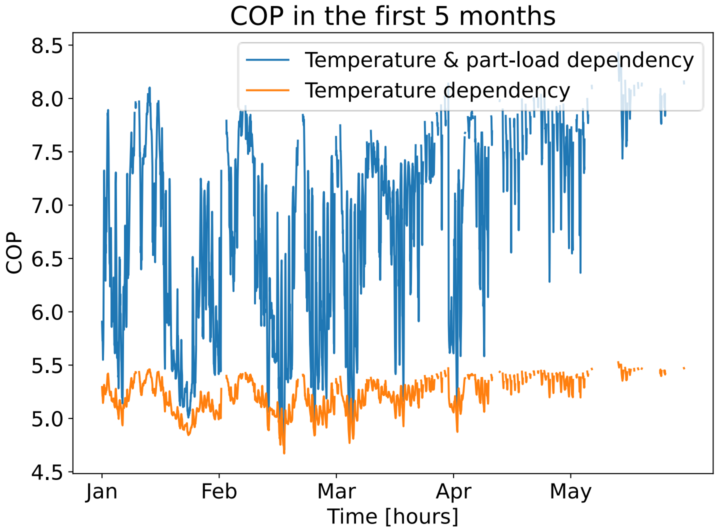

Fig. 5: Close-up of the first 5 months of the multi-utility building.

5. Further research

This article stressed the importance of using both temperature- and part-load-dependent data for the simulation and design of borefields, but this is not the end of the story.

First, in this research a constant mass flow rate was still used. Typically, when the heat pump modulates, the mass flow rate also fluctuates, which has an impact on the Reynolds number, the effective borehole thermal resistance, and ultimately the fluid temperature. In follow-up research, it is therefore suggested that a variable flow rate be taken into account.

Secondly, it was now assumed that when only 80% of the peak heating demand was required, all heat pumps operated at 80% part-load. However, in cases where hundreds of heat pumps are present, it could be that 80% of them operate at full load while 20% are switched off. This would result in a lower efficiency, since the heating would not be delivered by heat pumps operating under part-load conditions. Further research should therefore consider this sensitivity, examining factors such as simultaneity in more detail.

6. Conclusion

In this research, the effect of assumptions related to heat pump efficiency was investigated. It is shown through three different case studies that taking into account only the temperature dependency of the COP has a negligible effect on the design and efficiency of the system. Only in the case where the borefield was injection dominated did this lead to a slight improvement. When, in addition to the temperature dependency, the part-load efficiency was also considered, the required borefield size increased slightly (up to 3%) due to a significantly higher SCOP (10–50%).

This research therefore highlights the importance of considering the real operation of the heat pump when designing geothermal systems to reveal the true efficiency of a GSHP, thereby making these systems more economically viable.

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