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FACULTY OF
ENGINEERING SCIENCE

Cost-efficient Cooling of Buildings by means of Borefields with Active and Passive Cooling

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Thesis voorgedragen tot het behalen
van de graad van Master of Science
in de ingenieurswetenschappen:
energie

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Academiejaar 2021 – 2022

Preface

This master thesis is the final step towards our engineering degree, something we both worked hard for and are extremely proud of. Our shared passion for energy, sustainability and teamwork is the main ingredient for the work you are reading at this moment. We have added generous amounts of determination and persistence, and have finished it off with a healthy portion of strong friendship. Finally, we seasoned to taste with some late-night *Python* programming. We most likely won't receive a Michelin star for this dish, but an engineering degree is fine with us too!

This master thesis has given us the wonderful opportunity to get to know the academic world of research and be part of an amazing research team, the Thermal Systems Simulation team of KU Leuven. Besides that, we improved our *Python* skills, reporting and academic writing skills and now have an very solid understanding of borefields and building operations. By working as a team, close cooperation and clear communication was key, something we got significantly better at over time. We are grateful for this opportunity and will undoubtedly benefit from all the lessons learned in our future careers.

This work is more than the research conducted by us, it is a combination of inspiration, insights and guidance from multiple people who supported us in the process. Without them, it would not have been possible to achieve this result. First of all, we would like to thank our promotors Prof. Helsen and Prof. Boydens for guiding us through this research and sharing with us their expertise on the topic. Special thanks go to our daily supervisors Wouter and Louis for positively challenging our thinking and helping us both contribute to our fullest potential. Furthermore, we would like to thank Jelger and Siebe for helping us through the simulations in the Modelica environment. Final thanks go to our Jury members for taking their time to read our text and evaluate our work.

Probably this text won't be the shortest master thesis text you will ever read, for which our sincere apologies, but we did our very best to provide an interesting read in the wonderful world of borefields.

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Abstract

The building sector is responsible for 25% of global CO_2 emissions dominated by the energy use for heating and cooling [1]. The Paris Agreement pledges to limit global warming well below 2 °C by decarbonizing the economy, with a major role to play for the building sector. This stimulates the development and deployment of high efficiency and low emission heating and cooling solutions. Geothermal borefields using passive cooling, i.e. without a heat pump, are an attractive solution to reduce the emissions related to building operations in moderate climates. The investment cost for a borefield designed for passive cooling only is high which can hold back wide-scale deployment. This work aims to investigate the most economical way to cool buildings by means of borefields with active and passive cooling.

A new borefield sizing algorithm is developed that combines active and passive cooling with an hourly time resolution. The borefield size is determined such that the fluid temperature profile remains between its predetermined minimum and maximum limit. The high temporal resolution results in significant computational complexity which is reduced by using the Fast Fourier Transform and the convolution operator. The range of interesting borefield sizes is bounded by both the minimal size using combined active and passive cooling and the maximal size using passive cooling only. The economical optimal borefield size within this range is determined using Bayesian optimization.

It is found that the load profile strongly influences the potential of combined active and passive cooling to reduce the total cost of ownership (TCO). A load profile that imposes a minimal borefield size due to the maximum fluid temperature indicates a high potential for combined active and passive cooling. Furthermore, it is found that large intra-day load variations within the load profile maximize this potential. Load profiles that impose a minimum borefield size due to the minimum fluid temperature show no potential for combined active and passive cooling. Finally, the most influential parameters on the TCO are determined through an extensive sensitivity analysis.

Samenvatting

De gebouwensector is verantwoordelijk voor 25 % van de globale CO_2-emissies, voornamelijk te wijten aan het energiegebruik tijdens het verwarmen en koelen van gebouwen [1]. Het klimaatakkoord van Parijs omvat de belofte om de opwarming van de aarde onder de 2 °C te houden. Dit kan door in te zetten op een koofstofneutrale economie, waarin een belangrijke rol weggelegd is voor de gebouwensector. Deze beloftes stimuleren de ontwikkeling en uitrol van efficiënte koel- en verwarmingssystemen gekenmerkt door lage emissies. Geothermische boorvelden die passief koelen, i.e. koelen zonder het gebruik van een warmtepomp, zijn een interessante oplossing om emissies gerelateerd aan het koelen van gebouwen in een gematigd klimaat te verminderen. De uitrol op grote schaal wordt tegengehouden door de hoge investeringskost voor dit soort boorvelden. Dit werk onderzoekt de economisch meest voordelige manier om gebouwen te koelen met boorvelden gebruik makend van actieve en passieve koeling.

Een nieuw dimensioneringsalgoritme voor boorvelden is ontwikkeld dat actief en passief koelen combineert en gebruik maakt van een uurlijkse tijdsresolutie. De boorveldgrootte is bepaald zodat het temperatuurprofiel van het fluïdum in het boorveld blijft tussen zijn maximum- en minimumlimiet. De nauwkeurige tijdsstap van één uur brengt een verhoogde rekentijd met zich mee, die verminderd kan worden door gebruik te maken van de Fouriertransformatie en de convolutiebewerking. Het interval aan interessante boorveldgroottes is begrensd door een minimale grootte bij maximaal gebruik van gecombineerd actief en passief koelen en een maximale grootte bij gebruik van enkel passief koelen. De economisch optimale boorveldgrootte binnen dit interval wordt bepaald via een Bayesiaanse optimalisatie.

Een belangrijk resultaat van dit onderzoek is de sterke invloed van het belastingprofiel op het potentieel van gecombineerd actief en passief koelen om de totale kost over de levensduur van het boorveld (TCO) te verlagen. Een belastingprofiel dat een minimum boorveldgrootte oplegt door de maximale fluïdum temperatuur geeft een groot potentieel aan. Verder is bevonden dat belastingprofielen met grote dagelijkse variaties in de belasting dit potentieel vergroten. Belastingprofielen die een minimale boorveldgrootte opleggen door de ondergrens voor de fluïdumtemperaturen tonen geen potentieel voor het gebruik van actief koelen. Tot slot zijn de meest invloedrijke parameters op dit resultaat onderzocht in een uitgebreide sensitiviteitsanalyse.

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Abbreviations

AC	Active cooling
ASHP	Air source heat pump
COP	Coefficient of performance
EER	Energy efficiency ratio
EU ETS	European Union emission trading system
GSHP	Ground sourve heat pump
HEX	Heat exchanger
HP	Heat pump
HTC	High temperature cooling
IC	Investment cost
IDEAS	Integrated district energy assessment simulations
LCA	Life cycle analysis
LT	Lifetime of the borefield
LTH	Low temperature heating
OC	Operating cost
OCc	Operation cost due to cooling
OCh	Operating cost due to heating
PC	Passive cooling
Q1	Quadrant 1
Q2	Quadrant 2
Q3	Quadrant 3
Q4	Quadrant 4
TC	Total cost
TCO	Total cost of ownership
WSHP	Water source heat pump

Symbols

B	Borefield spacing
$C_{abatement}$	Abatement cost
C_{elec}	Electricity price
C_{inv}	Borefield investment cost
C_{op}	Borefield operating cost
DR_{nom}	Nominal discount rate
$g(t)$	G-function evaluated at t
H	Borefield depth
k_s	Ground thermal conductivity
L	Borefield size
$L1$	Smallest possible borefield size corresponding to maximal combined cooling
$L2$	Largest relevant borefield size corresponding to passive cooling only
q	Thermal load
Q_H	Thermal energy injected into the heat sink
Q_L	Thermal energy extracted from the heat source
R_b^*	Equivalent thermal borehole resistance
R_g	Ground thermal resistance
R_i	Inflation rate for electricity
T_b	Borehole wall temperature
T_f	Average fluid temperature in the borefield
T_{fp}	Average fluid temperature in the borefield due to the peak load
T_g	Undisturbed ground temperature
T_{lim}	Limiting temperature in the sizing algorithm
T_{maxA}	Maximum temperature limit for active cooling
T_{maxP}	Maximum temperature for which passive cooling is possible
T_{min}	Minimum temperature limit
W	Electrical energy supplied to the heat pump

Chapter 1

Introduction

1.1 Context and motivation

The building sector's space cooling generates roughly 1 Gt of CO_2 emissions yearly[1][4]. Based on current policy intentions, the cooling demand is estimated to grow 3% per year over the coming three decades. This growth rate is eight times higher than the growth rate of heating demand in the previous three decades [4]. Two of the strongest drivers for this large growth are the average global temperature rise due to climate change and the expansion in buildings floor area. The number of cooling degree days are, according to the IEA [4], expected to increase by 50% by 2050 and 70% by 2070. The buildings floor area is, also according to the IEA [4], expected to double in the coming 40 years. In total, space cooling is expected to be accessible to an additional 5 billion people by 2070. Also building heating (space heating and sanitary hot water) is currently responsible for roughly 4.3 Gt of CO_2 emissions[2].

Although the share of CO_2 emissions related to space cooling is currently smaller compared to the CO_2 emissions related to space heating, the large expected growth of space cooling makes it clear that efficient cooling is an important step towards decarbonisation objectives such as the goals of the EU 2030 Climate and Energy framework or the 2050 Net Zero goals [4].

To this end researchers all over the world are striving towards more efficient means of cooling and heating buildings through hardware and software. New hardware technologies such as floor heating, ceiling cooling and concrete core activation (CCA) all aim to maximize the efficiency of indoor climate control by allowing methods such as high temperature cooling (HTC) and low temperature heating (LTH). New software and algorithms such as model predictive control (MPC) are developed to optimally control the different components that make up the climate control system.

[1] These emissions result from the use of electricity based for cooling in 2019 according to the IEA [4].

[2] This number is according to [4] in 2019 and accounts for emissions from direct fossil fuel combustion as well as from upstream electricity and heat generation.

One specific upcoming way of using the mentioned hardware technologies is in combination with a geothermal heat exchanger (also called a borefield). With the ground temperature below the temperature of the building, it is possible to transfer heat directly from inside the building to the ground using the geothermal heat exchanger. This results in limited operating costs and CO_2 emissions as no additional energy is required for the cooling operation.

By adding a heat pump in between the geothermal heat exchanger and the building, heat can be transferred from the building to the ground even when ground temperatures exceed inside building temperatures. This results in less efficient cooling and is called active cooling. By allowing active cooling, however, the necessary borefield size reduces which strongly reduces investment costs.

Borefields are generally designed using rules of thumb with upfront decisions concerning cooling and heating strategy. This, in some cases, might lead to cost inefficient investment decisions. Additionally there seems to be a gap in the literature concerning the design of borefields using combined active and passive cooling. Therefore there is the need for a methodology that includes the cooling strategies mentioned above in the design process of the borefield to reach a cost-efficient solution.

1.2 Research questions

Based on Section 1.1, the main research question of this thesis is defined as follows:

What is the most economical way to cool buildings by means of geothermal borefields with active and passive cooling?

This main research question is answered by looking at several supporting research questions. These questions aim to break down the broad perspective of this thesis in multiple mutually exclusive topics that are tackled throughout the work. Section 1.3 links these research questions to the general structure of the text. While navigating through this text, the reader can at all times fall back on Section 1.3 to locate themself within this research with respect to the research questions.

The supporting research questions are posed from two different perspectives: the engineering and the scientific perspective. The scientific questions focus on the detailed methodological approach. The engineering perspective on the other hand is more focused on the practical applications of the insights discovered by studying the scientific questions.

The scientific research questions can be summarized as follows:

- **Can the use of combined active and passive cooling lead to a lower Total Cost of Ownership (TCO) compared to the use of passive**

cooling only? If so, how can this contribution of active cooling be modeled correctly in an economic optimization?

- **An increase in time resolution of the optimization leads to an increase in accuracy of the results and an increased computational time and complexity. To what extent are the advantages of the increased time resolution worth the disadvantages when considering active cooling?**

The first scientific research question leads to two interesting research areas. The first one analyzes how to correctly model combined active and passive cooling. The second one leads to an optimization question focused on cost minimization where combined use of active and passive cooling is considered. Both the investment cost and the operating cost are taken into account and the scientific challenge here is to accurately determine the solution to this optimization problem.

The second scientific research question starts with the state of the art borefield sizing and temperature profile modeling techniques and investigates whether an increase in time resolution is worth the increase in complexity it brings with it.

The above-mentioned questions form the backbone of this thesis. The engineering questions link the conclusions hereof to possible applications in industry:

- **Which parameters have the greatest impact on the TCO and to what extent can they be influenced during the design phase of the borefield?**
- **To what extent can the use of the developed tool provide new insights in the design phase of geothermal borefields, potentially changing investment decisions?**

The first engineering research question leads to an extensive sensitivity analysis, in which the influence of both technical and market economic parameters on the TCO is studied. After the most influential parameters are identified, the extent to which these parameters can be influenced in the design phase of the borefield is discussed. The ecological impact of the economic optimal solution is an additional challenging research domain.

The second engineering question calls for a detailed case study where the methodologies developed in this master thesis are applied. Former investment decisions concerning borefield design are compared with the new insights on combined active and passive cooling. This links the developed methodologies directly to current practices in industry.

The framework of this text often falls back on these questions to maintain a clear structure.

1.3 Structure

The following section describes how the scientific and engineering research questions drive the framework of this text. The work consists of an introduction followed by 10 chapters divided into three parts. All chapters end with a conclusion or a summary of the key takeaways, depending on which format is more appropriate.

The first part describes the research framework by diving deeper into relevant technologies and concepts that are used throughout the thesis and visits existing research and literature that has close links with the subject of this text in Chapter 2. Also, the first part guides the reader through the preliminary study that has been conducted in Chapter 3. This preliminary study aims to answer the first part of the first scientific research question.

The second part of the text deals with the developed methodologies for sizing borefields, modeling combined active and passive cooling and determining the economic optimum in borefield design. Chapter 4 presents and compares multiple borefield sizing methodologies which aim to answer the second scientific research question. The most promising of these is then used in Chapter 5 to model combined active and passive cooling in a borefield. Chapter 6 uses the results from Chapter 4 and the methodology of Chapter 5 to construct an economical optimization problem. Chapter 5 and Chapter 6 together aim to answer the second part of the first research question.

The third and last part of the text presents the results of the previous two parts applying the economical optimization problem constructed in Chapter 6 to various different situations. The insights that have been discovered by studying the results in detail are then discussed in Chapter 7. This chapter also provides a short, preliminary ecological assessment on the CO_2 emissions of the economic optimal solution. Next, it presents the results of a detailed sensitivity analysis that examines the effect of various key parameters on the TCO of a borefield in Chapter 8. Chapter 7 and Chapter 8 together aim to answer the first engineering research question. Also, this chapter discusses how these parameters can be influenced in the design phase of the borefield. Following the sensitivity analysis, part three compares the results of the developed methodologies when applied to real-life borefield projects with the actual investment decisions made in Chapter 9. This chapter aims to answer the second engineering research question.

Lastly, a conclusion summarizes the most important insights and takeaway messages from all three parts by answering all four research questions and provides a complete answer to the main research question.

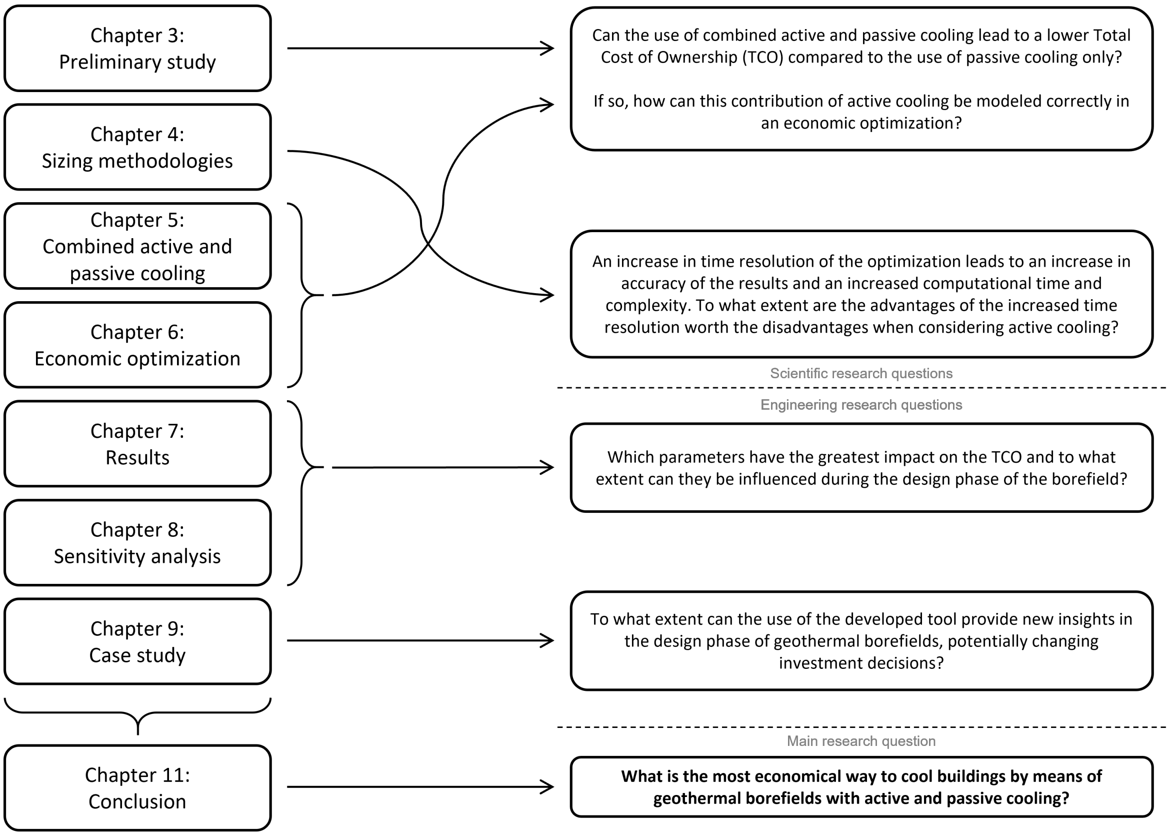


Figure 1.1: Schematic representation of the structure of this work.

All parts are divided into chapters that are linked to a part of or an entire research question as described above. Figure 1.1 schematically represents the links between these chapters and the research questions. On the left hand side of the figure, Chapters 3 to 9 and 11 are listed. On the right-hand side, the four research questions are listed, split into the scientific research questions in the top half of the figure and the engineering research questions in the bottom half. In the middle of the figure, various arrows indicate which chapters provide an answer to each of the research questions. Please note that Chapters 1, 2 and 10 have been excluded from this figure as they are not directly related to a research question.

At all times Figure 1.1 can serve as a guide for the reader throughout the text.

Part I

Research Framework

Chapter 2

Literature review

This chapter aims to give the reader a basic understanding of some of the most frequently used concepts and technologies in this thesis together with an idea of the state of the art in current research concerning active and passive cooling with borefields.

Section 2.1 dives deeper into relevant concepts and technologies of which a good understanding is necessary before continuing to Chapter 3. It discusses the main components of thermal systems and the relevant heating and cooling operations. Section 2.2 shortly describes the state of the art in current research. Finally, Section 2.3 elaborates on the physical background necessary to model the borefield behavior as a response to a thermal load[1].

2.1 Technologies

This section aims to cover the working principle of the main components of a thermal system (Section 2.1.1) and describe the passive cooling, active cooling and heating operation (Section 2.1.2). Furthermore a short description of the concepts low temperature heating (LTH) and high temperature cooling (HTC) is given.

2.1.1 Components of thermal systems

The main components of a thermal system are the heat source, the heat sink, HEXs and optionally a heat pump. In the context of this research, the heat sink and source are the ground and the building respectively or vice versa. The HEXs allow heat transfer between two separate fluid circuits. The HEX coupled to the ground (a

[1] If the reader is familiar with heat pumps, borefields and different modes of heating and cooling, Section 2.1 can be skipped. If the reader is also comfortable and familiar with g-functions, equivalent thermal borehole wall resistances and the link with fluid temperature modeling in a borefield, also Section 2.3 can be skipped. If not, the reader is strongly recommended to go through Chapter 2 entirely as understanding these concepts is necessary before moving to the next chapter.

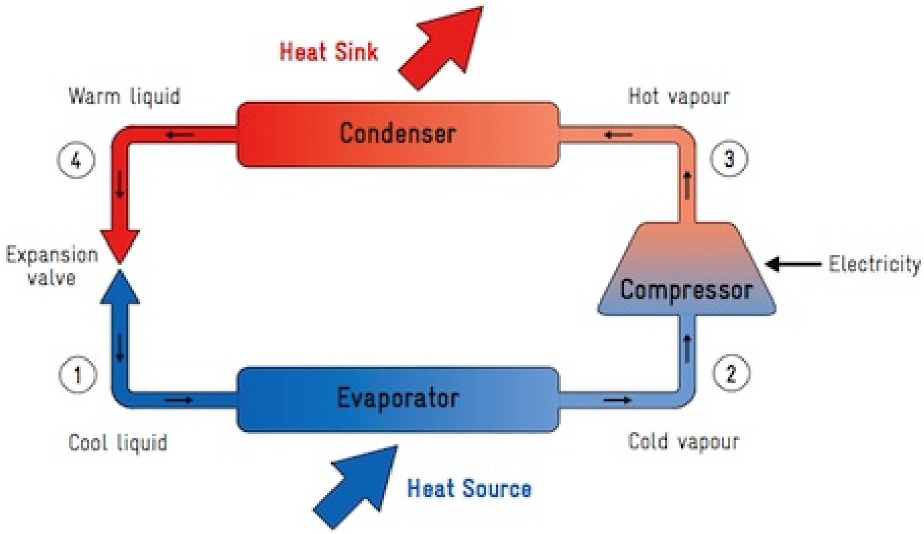


Figure 2.1: Schematic describing the basic operation of a heat pump [5].

geothermal heat exchanger) is often called a borefield. This sections aims to explain the working principle of the heat pump and the borefield.

Heat pumps

Just as water naturally flows downhill from regions of higher elevation to regions of lower elevation due to gravity, heat also naturally flows from regions of higher temperature to regions of lower temperature due to thermal diffusion. To transport water uphill, one has the possibility to use a fluid pump. Similarly, if one wishes to transfer heat opposite to the direction of natural diffusion, a heat pump (HP) is needed. This heat pump uses electrical energy to convert low-quality thermal energy to high-quality thermal energy.

Figure 2.1 represents the basic operation of a heat pump together with its main components: evaporator, compressor, condenser, expansion valve and working liquid. The working liquid is circulated through all four of these components whilst absorbing heat from the heat source and exuding heat to the heat sink in the evaporator and condenser respectively. The source and sink can be, for example, the surrounding outside air and inside air respectively or a flowing river and indoor domestic heat emission system respectively. Using this schematic as a guideline, the working principle of the heat pump can be understood as follows. Inside the evaporator, which acts as a HEX between working fluid and heat source, heat is naturally transferred from the heat source to the working fluid due to their respective temperature difference. This process causes the working liquid to evaporate, hence the name. Next, the vapor exiting the evaporator is compressed using electricity by the compressor. This increases the temperature and pressure of the vapor. This compressed working fluid vapor enters the condenser, where it naturally exudes its heat to the heat sink, which results in condensation of the working fluid. Lastly, the working fluid goes through an expansion valve which reduces the pressure and results in a cool liquid that can enter the evaporator to absorb heat and repeat the process. An adequate temperature difference between the temperature of the working fluid and heat sink in the condenser is important for the proper working of the heat pump. This, similarly, also applies for the evaporator.

A bidirectional heat pump can be used as a heating- or cooling device depending on the working fluid flow direction. In Figure 2.1 the heat pump cools the heat source whilst heating the heat sink. If the direction of working fluid flow would be reversed, the working fluid would evaporate in what was previously called the condenser and condense in what was previously called the evaporator. In this case the heat pump would be cooling what was previously called the heat sink and heating what was previously called the heat source.

The efficiency of a heat pump depends on the difference between the heat source temperature and the heat sink temperature. The smaller this temperature difference, the more efficient the heat pump works, that is the less electrical energy it needs to transfer the same amount of thermal energy. Assuming the maximal theoretical efficiency (Carnot efficiency), the coefficient of performance (COP) of a heat pump in heating operation and cooling operation can be described as seen in Equations (2.1) and (2.2) respectively. Please note that the COP of a heat pump in cooling operation is further referred to as the EER. Here Q_H, Q_L and W represent the thermal energy supplied to the heat sink by the heat pump in heating operation, the thermal energy extracted from the heat source by the heat pump in cooling operation and the electrical energy required herefore respectively.

$$COP = \frac{Q_H}{W} \stackrel{\mathrm{c}}{=} \frac{T_H}{T_H - T_L} \tag{2.1}$$

$$EER = \frac{Q_L}{W} \stackrel{\mathrm{c}}{=} \frac{T_L}{T_H - T_L} \tag{2.2}$$

Three main types of heat pumps are widely used today: the air source heat pump (ASHP), the water source heat pump (WSHP) and the ground source heat pump (GSHP). The first of the three is by far the easiest and cheapest one to install and therefore historically the most used heat pump. This heat pump transfers heat between the outside and the inside of a building by utilizing the outside air as a heat source (sink). The second type of heat pump uses water instead of air to extract (inject) heat from (into). The third type of heat pump uses the ground as a source of (geothermal) heat. The main advantage of the water- and ground source heat pump is the higher efficiency (COP and EER) they can achieve in operation. However, they do require significantly larger investment costs due to more complex heat exchangers and installation processes. The ground source heat pump (also geothermal heat pump) will play a major role in the coming chapters of this work.

Borefields

Ground HEX are used in combination with the ground source heat pump can be divided in two main categories: vertical loop configuration and horizontal loop configuration. Within these categories, designs vary. Figure 2.2 represents the most used designs.

The first, and most important for this work, is the vertical loop configuration and consists of a multitude of bores or wells that are drilled in a vertical fashion anywhere between 50 and 150 meters deep (also called a borefield). These bores are generally spaced roughly 5 to 10 meters apart and contain a U-shaped tube that carries a heat transfer fluid through the ground[2]. In some cases these bores can be integrated in foundation piles when constructing a building and are then called energy piles. As the heat is exchanged at great depth, there is little influence from the seasonal temperature cycle which results in a constant ground temperature across the HEX. It is this configuration that is focused on throughout the text.

The second and third configurations are the horizontal loop and slinky loop, respectively, and consist of horizontal loops or slinky loops that are buried at much smaller depths (1.2-3 meters deep). These configurations do experience delayed influence of the seasonal temperature cycle due to the thermal inertia of the ground. The pond loop configuration can be seen as a water source heat pump configuration but is included here as it often is treated as a ground source heat pump configuration.

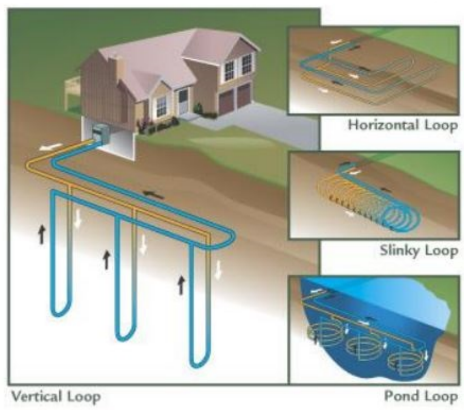


Figure 2.2: Most common configurations of ground HEXs [6].

Next to the different spatial configurations, also the configuration of the borehole itself can be varied. As vertical boreholes are the main focus here, Figure 2.3 present three of the most common borehole configurations. Out of the three configurations presented here, the U-tube configuration is most common due to its simplicity. The coaxial configuration generally ensures the largest heat transfer between fluid and ground but is most intricate to install, leading to high investment costs [7]. Many of the components of the borehole (especially the grout, diameter of the inner pipe and the material of the inner pipe) can be varied to increase heat transfer capabilities.

[2]Please note that the configuration (depth, spacing, geometry...) is decided upon in the design phase of the borefield and can vary greatly depending on the specific use-case

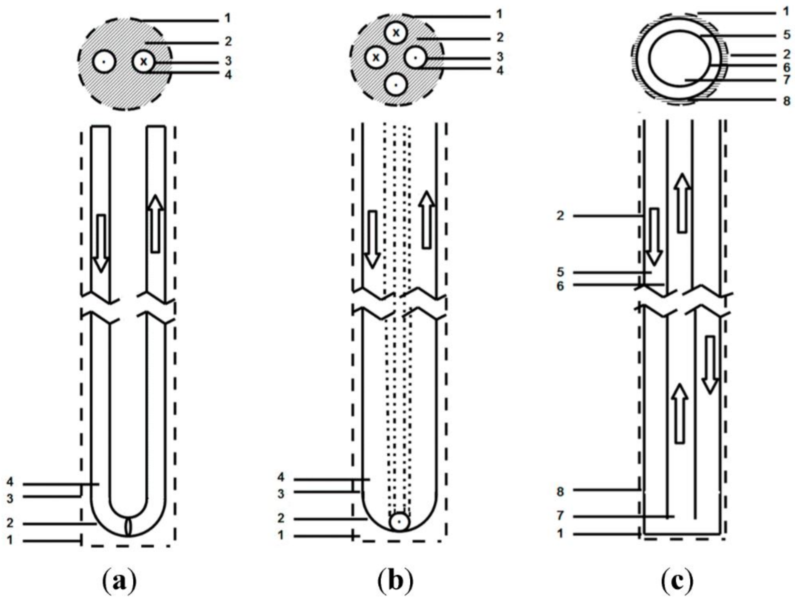


FIGURE 2.3: Schematic representation of three different borehole configurations: (a) single U-tube, (b) double U-tube, (c) coaxial [7]. The components on the figure are numbered as: 1-borehole wall, 2-grout, 3-interior of the U-tube, 4-U-tube wall, 5-annulus space, 6-inner column (pipe), 7-interior of inner column (pipe), 8-external column.

A great advantage of the borefield is its ability to seasonally store thermal energy. Heat that would be transferred to the surroundings when cooling a building using an ASHP in the summer, could be stored in the ground when using a borefield. In this way, due to thermal inertia[3], this heat can be released in the following winter to heat up the building again. This work considers in detail the cooling and heating operation of a borefield in combination with a heat pump.

2.1.2 Heating and cooling operation

When the ground source HEX is used together with a heat pump (also called ground coupled heat pump), it can be used to heat (cool) a building by extracting thermal energy from the ground (building) and injecting it into the building (ground). There are three relevant modes of operation: passive cooling, active cooling and heating. Finally, HTC and LTH are concepts which allow for more efficient heating and cooling operations by aiming for a higher COP and EER of the heat pump.

[3]Naturally the amount of heat that can be stored in the borefield and the period of time after which the heat is lost due to heat diffusion to the surrounding ground is very dependent on all sorts of ground parameters. This work investigates the effects of ground parameters on the operation of a borefield in detail later on.

Passive Cooling This method of cooling refers to the situation where the ground temperature (and as a result also the average fluid temperature in the ground HEX) is significantly lower than the temperature of the to-be-cooled space. In this way, heat can naturally be extracted from the to-be-cooled space and can be transferred to the borefield by using a simple HEX in between the indoor circuit and the borefield circuit. This results in a low operating cost as only a relatively small circulation pump is needed to circulate the fluid through the borefield and there is no need for a heat pump. This method is represented as the middle schematic in Figure 2.4.

Active Cooling If the ground temperature rises (and therefore also the average fluid temperature in the borefield) passive cooling might not be possible anymore as the temperature difference between the fluid in the indoor circuit and the fluid in the borefield circuit reduces, resulting in limited heat transfer. To further inject heat from the to-be-cooled space into the borefield, a heat pump must be used. This method is represented as the rightmost schematic in Figure 2.4. Here a heat pump is located in between the indoor circuit and the borefield fluid circuit and as this heat pump requires electrical power to function properly, this mode of operation is generally more expensive than the passive cooling mode. Important to note is that due to the non-ideal efficiency of the heat pump, more heat will be injected into the borefield that is extracted from the to-be-cooled space.

Heating The heating mode[4] of operation is similar to the active cooling operation except for the direction of heat flow. In the heating mode, also the heat pump is located between the indoor circuit and the borefield fluid circuit but the heat is extracted from the borefield and injected into the indoor circuit instead of the other way around. This also requires electrical power and thus also results in a considerable operation cost. This mode is represented in the leftmost schematic in Figure 2.4.

High Temperature Cooling and Low Temperature Heating Recently, due to the increased importance of efficiency, there has been a strong trend towards Low Temperature Heating (LTH) and High Temperature Cooling (HTC) systems [9]. From Equations (2.1) and (2.2) it is clear that by reducing the temperature difference between source and sink, the COP and EER increase. It is therefore that LTH and HTC systems are attractive. Examples of heat emission systems that are compatible with LTH and or HTC are floor heating, ceiling cooling and concrete core activation which all allow heat carrier fluid temperatures in the range of 16-18 °C for cooling and around 30 °C for heating. An elaborate overview of the different technologies suited for LTH and HTC with their respective temperature ranges is provided in [10].

[4] As this work mostly considers the heating and cooling of residential buildings in the middle and north European region, passive heating is considered impossible due to the ground temperature between 50 and 150 meters being lower than the temperature of the to-be-heated residential building. This means a heat pump is always necessary to extract heat from the borefield and inject it into the to-be-heated space.

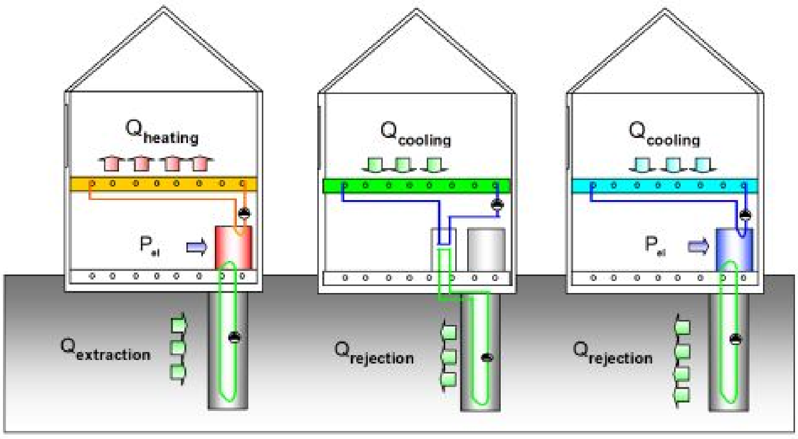


FIGURE 2.4: Schematic representation of the three modes of operation of the ground coupled heat pump [8].

2.2 State of the art

The following section discusses the current state of the art regarding cooling with geothermal borefields. Note that literature regarding the detailed modeling of borefields is revisited in the relevant chapters for the reader's convenience. The specific literature on the g-function and ground response of the borefield is already touched upon in Section 2.3.

The recently proposed method to size geothermal borefields in combination with other technologies in a graphical and insightful way is the starting point of this master thesis. Peere [3] concludes that other technologies in combination with geothermal borefields, described as hybrid systems, lead to significant cost reductions. Peak cooling loads are shifted away from passive geothermal cooling towards technologies with lower initial investment costs. Substituting passive cooling with active cooling in order to reduce investment costs of the geothermal borefields is stated as cost inefficient due to high operating costs arising from the compression step in active cooling but identified it as a topic for future research. The author does not consider the combination of active and passive cooling and accurate temperature computations to achieve a cost minimal solution. This topic is addressed in this work.

A shift from the regular geothermal borefield sizing methods with a focus on meeting the peak demand to a system approach aligns with the global trend towards system approaches in general scientific research. Robert and Goselin [2] size the borefield by solving an optimization problem with a cost minimizing objective. The paper distinguishes itself by also optimizing the percentage of the peak load that is cooled or heated by the ground source heat pump. The reasoning is thus similar to the hybrid system approach proposed by Peere [3].

The costs of a borefield are split into two cost components in the work of Robert and Goselin [2]: initial and operating costs. The former consists of the purchase cost of the heat pump and drilling, excavation and piping costs. The latter is an energy cost, due to the compression step in the heat pump, fluid circulation pump and an eventual backup heating or cooling system. Figure 2.5 provides an overview of the allocation of the aforementioned costs. This is case specific but the main cost drivers can be generalized: the energy cost, drilling cost and heat pump cost. These findings are confirmed in [11], where a detailed economic analysis is made for GSHP systems in Australia. Note that in hot climates, active cooling is assumed to be the standard due to higher ground temperatures.

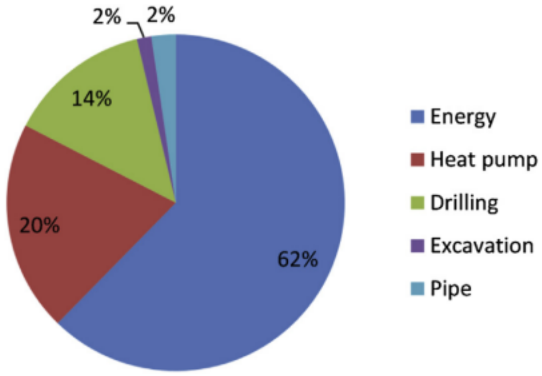


Figure 2.5: Borefield cost distribution for a specific case study in the work of Robert and Goselin [2].

Eicker et al. [12] describe the potential of geothermal borefields for office building climatisation in their work. Both active and passive cooling are discussed as possible cooling methods. The appropriateness of both cooling strategies is determined by the average ground temperature. Although this is a relevant parameter, this does not necessarily result in a cost-efficient cooling strategy. This paper again does not consider the possible combination of both cooling regimes, which confirms the existence of a gap in the literature.

2.3 Physical background for borefield behavior

This section discusses the modeling of a very fundamental concept that is used many times throughout this work being the borefield behavior as a response to a thermal load. This behavior comprises all temperature responses in the borefield. Understanding the fluid temperature response in the borefield on a thermal load is important for two reasons. The first is that the fluid temperature determines the mode(s) of cooling that is (are) possible as explained in Section 2.1.2. Secondly the fluid temperature in the borefield directly influences the necessary borefield size as described in Chapters 3 and 4.

2.3.1 Borefield response

The average fluid temperature of the borefield is determined by the borefield size and the thermal load. All heat that is transferred through the borefield to the ground, must dissipate in the surrounding area. When a constant heat flow is injected into the borefield (for example when cooling a building), the ground in and around the borefield heats up and as a result, the average fluid temperature in the borefield also increases due to this constant heat flow. The average fluid temperature keeps increasing until there is a thermodynamic equilibrium between the injected heat in the borefield and the dissipated heat in the surroundings. A larger borefield therefore can dissipate a larger heat flow than a smaller borefield. The average fluid temperature in a larger borefield will be lower than in a smaller borefield assuming an equal and constant injected heat flow. This same conceptual example can be done with a constant heat flow that is extracted from the borefield (for example when heating a building) leading to a higher average fluid temperature in a larger borefield than in a smaller borefield. It is clear from this conceptual example that the average fluid temperature in the borefield strongly depends on the size of the borefield and the thermal load.

Modeling the relationship between the temperatures inside the borefield and thermal load on the borefield is necessary as explained at the start of Section 2.3. This relationship is built on the concept of the g-function that Eskilson proposed in 1987 [13].

2.3.2 G-function and borehole wall temperature

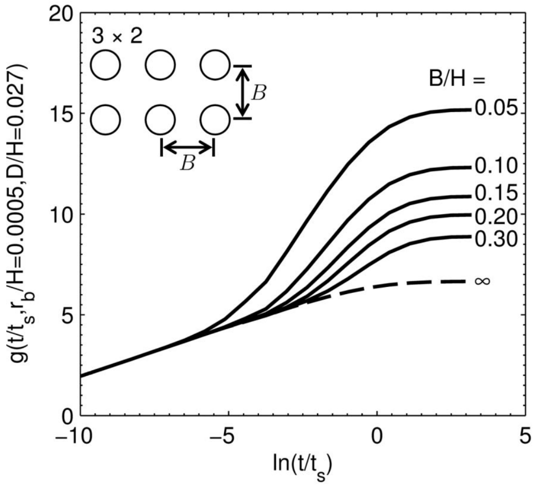
The g-function is touched upon many times throughout Chapter 4. Therefore, this section aims to give the reader insight in how the g-function is used in this particular context. The origins, mathematical and physical derivations and in-depth insights concerning the g-function are not considered as essential understanding for the reader of this work. [13, 14, 15] are good starting points for a reader looking for detailed works regarding this topic.

The g-function, proposed by Eskilson in his original work [13], returns a normalised borehole wall temperature response factor in function of the normalised duration of a constant thermal load q per unit length, given ground parameters and a given borefield geometry [15]. A range of g-functions were presented in [13] for different borefield geometries. An example of such a g-function is presented graphically in Figure 2.6a.

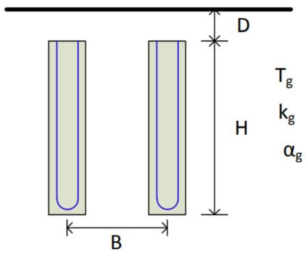
The value of the temperature response factor returned by the g-function depends on one non-dimensional time parameter and three non-dimensional geometrical parameters as can be seen in Equation (2.3) [16].

$$g = f(t/t_s, r_b/H, D/H, B/H) \tag{2.3}$$

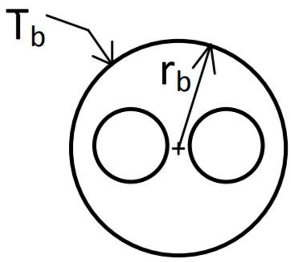
As clarified in Figure 2.6b and Figure 2.6c; B, H, D, r_b, T_b and T_g represent the borehole spacing, the borefield depth, the depth at which the boreholes are positioned under the ground surface, the borehole radius, the borehole wall temperature and the undisturbed ground temperature respectively. The non-dimensional time parameter t/t_s describes the duration of the constant thermal load q per unit length applied to the borefield. Here $t_s = \frac{H^2}{9\alpha_g}$ where α_g represents the thermal diffusivity of the ground.



(A) An example of g-functions for various ratio's of the borehole spacing to the borehole depth ($r_b/H = 0.0005$ and $D/H = 0.027$) [14].



(B) Diagram of a simple borefield representing the parameters used in the g-function [14].



(C) Diagram of a single U-tube borehole clarifying the borehole wall temperature and the borehole radius [14].

Figure 2.6: Examples of g-functions with clarifying diagrams representing key parameters.

A basic example of the use of a g-function is represented in Equation (2.4). Here a constant thermal load q is applied to the borefield for a duration equal to t_q with a ground thermal conductivity equal to k_s. The borehole wall temperature T_b is equated as the undisturbed ground temperature T_g plus the borehole wall temperature change due to the thermal load per unit length q[5]. This temperature change is equal to the thermal load per unit length multiplied by a thermal response factor $\frac{g(t_q)}{2\pi k_s}$ in which $g(t_q)$ represents the g-function evaluated at t_q.

$$T_b = T_g + \frac{q}{2\pi k_s} \cdot g(t_q) \tag{2.4}$$

2.3.3 Temporal superposition and fluid temperature

Previous section describes how the change in borehole wall temperature can be linked with the geometric configuration of the borefield and the thermal load that is applied. This section aims to extend this line of thought to a non-constant thermal load as in practice most thermal loads are of this kind. Also this section describes the relationship between the borehole wall temperature and the temperature of the fluid that circulates in the borefield as this is the temperature relevant for the constraints discussed at the start of Section 2.3.

For a varying thermal load applied to the borefield, the borehole wall temperature must be computed as the response to multiple superimposed constant thermal loads as shown in Figure 2.7.

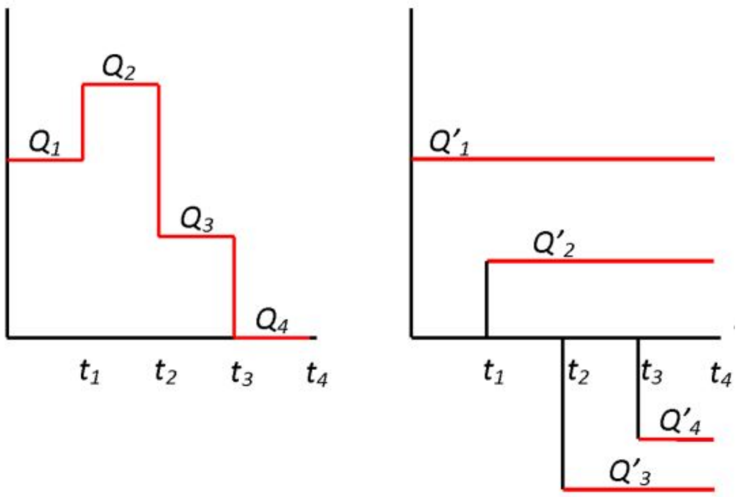


FIGURE 2.7: Schematic representation of a varying thermal load represented as a set of superimposed constant thermal loads [17].

[5]Please note in this example a negative thermal load is considered as the heating operation of the borefield, heat will thus be extracted from the borefield resulting a borehole wall temperature drop.

Expanding the basic example of Equation (2.4), the borehole wall temperature at time t_n can be computed as follows:

$$T_b(t_n) = T_g + \frac{1}{2\pi k_s L} \begin{bmatrix} Q_1 & Q_2 & \dots & Q_i & \dots & Q_n \end{bmatrix} \cdot \begin{bmatrix} g(t_n) - g(t_{n-1}) \\ g(t_{n-1}) - g(t_{n-2}) \\ \vdots \\ g(t_i) - g(t_{i-1}) \\ \vdots \\ g(t_1) \end{bmatrix} \tag{2.5}$$

Please note that in Equation (2.5) the thermal load is considered negative when heat is extracted from the borefield (for example when heating a building). Also note that now Q_i is assumed to be the total thermal load at time t_i, as opposed to the thermal load per unit length in Equation (2.4), hence the addition of L in this equation representing the total borehole length[6].

The term 'ground thermal resistance' is often used to shorten notation. An example of this ground thermal resistance can be seen in Equation (2.6). Please note the unit of this thermal resistance is $\frac{K \cdot m}{W}$.

$$R_g = [g(t_n) - g(t_{n-1})]/2\pi k_s \tag{2.6}$$

To understand the link between the borehole wall temperature and the fluid temperature it is important to understand the concept of an equivalent thermal borehole resistance R_b^*. Johan Claesson and Saqib Javed explain the mathematical origins of this equivalent resistance in great detail in [18]. For the purpose of this work it is sufficient to understand what this resistance represents physically and how it is used to compute the fluid temperature in the borefield.

The equivalent thermal borehole resistance (R_b^*) is defined by Equation (2.7) where T_f, T_b and q_b represent the simple mean of the fluid temperature at the inlet and outlet of the borefield circuit, the average borehole wall temperature and the thermal load per unit length respectively [18]. The unit of this equivalent thermal borehole resistance is thus $\frac{K \cdot m}{W}$. It physically represents the thermal resistance between the center of the tube through which the fluid flows and the borehole wall. Values for this parameter vary between 0.08 and $0.16\frac{K \cdot m}{W}$ in practice.

$$R_b^* = \left| \frac{T_f - T_b}{q_b} \right| \tag{2.7}$$

[6] Borehole size or length (L) and borehole depth (H) are often used interchangeably as they are linked to one another by the fixed borefield geometry. As an example: if the borehole size is computed to be 1200 meters, and the fixed borehole geometry is 10x12, the borehole depth is equal to 10 meters.

Using R_b^*, the average fluid temperature in the borefield for a non-constant thermal load at any time t_n can be found by combining Equation (2.5) and Equation (2.7) as in Equation (2.8). Please note that here again $Q(t_n)$ represents the total thermal load at instance t_n, where extracting heat from the borefield is considered as a negative load, hence the L in the equation.

$$T_f(t_n) = T_b(t_n) + \frac{Q(t_n)R_b^*}{L} \tag{2.8}$$

Key Takeaways

- A borefield is another name for a ground HEX consisting of a multitude of wells through which a fluid flows while exchanging heat with the ground.
- When the average fluid temperature in the borefield is sufficiently low, heat can be directly transferred from the indoor building cooling circuit to the borefield fluid circuit without the need of a heat pump. This results in a low operating cost and is called passive cooling.
- When the average fluid temperature in the borefield exceeds a certain limit, a heat pump is necessary to transfer heat from the building cooling circuit to the borefield fluid circuit. This results in a significant operating cost and is called active cooling.
- There seems to be a significant gap in the research concerning combined active and passive cooling. This gap is addressed in this work.
- The main cost drivers for borefields are the drilling, heat pump investment and energy costs during operation.
- To model the fluid temperature inside the borefield, g-functions, temporal superposition of thermal loads and the concept of an equivalent thermal borehole wall resistance are used.

Chapter 3

Preliminary study

This chapter discusses the preliminary study that has been the first step in the larger research that makes up this thesis. The focus of this preliminary study is to answer the first part of the first scientific research question and create a framework in which further research on this topic can be conducted. First of all the scope of this preliminary study with specific questions to be answered is discussed in Section 3.1. Section 3.2 presents the used methodology. Section 3.3 subsequently interprets the results and provides a guiding discussion. Finally, Section 3.4 wraps up the preliminary study by summarizing the main outcomes and conclusions.

3.1 Scope of the preliminary study

The preliminary study starts with clearly defining the goals and objectives of the preliminary study in Section 3.1.1. In order to achieve these goals, the preliminary study relies on four different load profiles. These load profiles each represent one borefield quadrant. The notion of borefield quadrants is therefore introduced in Section 3.1.2. Lastly, as this is a preliminary study, multiple simplifying assumptions are made to reduce the complexity of the problem in Section 3.1.3.

3.1.1 Objectives

The main objective of this preliminary study is to confirm the need for the additional research in the earlier mentioned topic of borefield cooling. This is done by breaking down the first part of the first scientific research question posed in Section 1.2.

The first part of the first scientific research question 'Can the use of combined active and passive cooling lead to a lower Total Cost of Ownership compared to the use of passive cooling only?' is divided as follows:

- Is it beneficial to use active cooling instead of passive cooling?
- Is there an optimum to be found by only cooling part of the cooling demand actively?

The first question compares the use of active cooling with passive cooling in economic terms. The use of active cooling allows to reduce the borefield size as higher maximum temperatures are allowed. This cost reduction is counteracted by the operating cost associated with the compression step in active cooling. The second question investigates whether there is a cost-efficient solution to be found by combining active and passive cooling.

3.1.2 Case Study: Load Profiles in Four Quadrants

As temperature profiles of borefields are typically grouped in four quadrants, four different cases are required in order to fully understand the potential of active cooling in geothermal borefields. For each case, three situations are compared with each other: active cooling only, passive cooling only and a combination of passive and active cooling optimized for minimal borefield size. The detailed methodology is further explained in Section 3.2.

The four borefield quadrants are categorized by two different criteria: the imbalance (heating or cooling dominated) and the limiting year (first or last year) for passive cooling operation. Note that by considering active cooling, the limiting year of the load might change. The imbalance is defined as the difference between the yearly cooling load and the yearly heating load and expressed in Watts. A positive imbalance, also referred to as cooling dominated, will therefore result in an increasing temperature of the borefield over its lifetime. A negative imbalance or heating dominated borefield is characterized by a declining temperature profile. The limiting year is the second criterion and refers to the year in which the average fluid temperature circulating in the borefield reaches the maximum or minimum temperature limit leading to a constraint in borefield size. These two constraints can be visualized in four quadrants and are depicted in Figure 3.1.

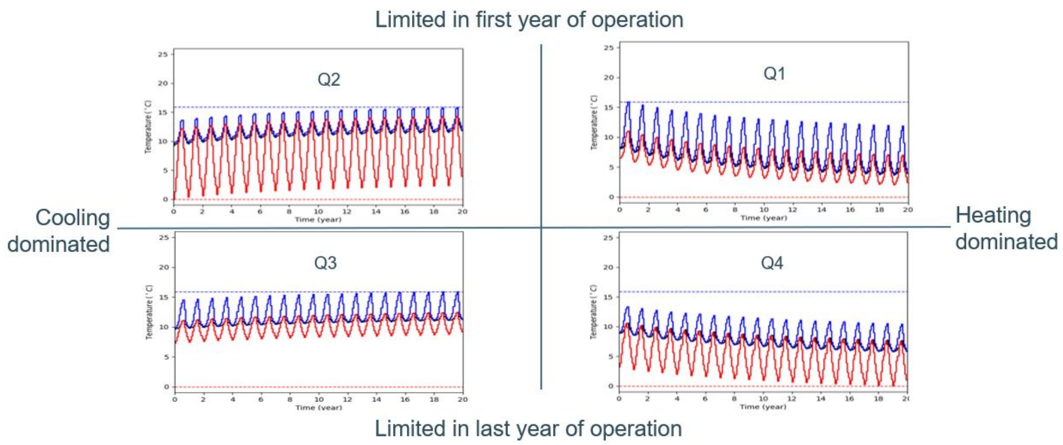


Figure 3.1: Spatial representation of the four borefield quadrants.

The four graphs in Figure 3.1 show the average peak temperature of the fluid circulating in the borefield for each month when taking the full cooling and heating peak load into account in blue (upper oscillating curve) and red (lower oscillating curve), respectively, over the full 20 year simulation period[1]. Based on the temperature profiles for passive cooling only, the load profiles are categorized in their respective quadrant.

This case study uses four load profiles, demonstrated in Figure 3.2, specifically selected to examine all quadrants. Quadrant 1 represents a heating dominated load profile with a first year limitation. The borefield temperature decreases over time due to the larger annual extraction of heat from the borefield than the injection of heat into the borefield. As this load profile is characterized by high cooling peaks, the limitation is in the first year due to the maximum temperature limit of the borefield. Quadrant 4 shows a similar temperature decrease over time compared to quadrant 1 as both are heating dominated load profiles. The higher heating peaks of quadrant 4 make the minimum temperature limiting in the last year of operation. The reasoning behind the temperature profiles of quadrants 2 and 3 is similar to that from quadrants 1 and 4, except quadrants 2 and 3 are cooling dominated. The interpretation above is visualized in the graphs in Figure 3.1.

The load profiles considered in this case study have a monthly time resolution with information on the monthly peak- and base load for both heating and cooling. The base load is defined as the average monthly energy consumption for heating and cooling and the peak load is defined as the maximum load (this would then include the base load)[2].

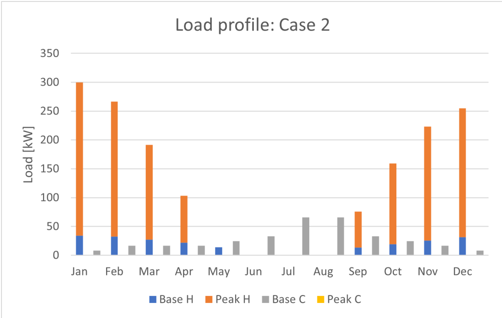
3.1.3 Assumptions

The preliminary study aims to provide an answer on the research questions posed in Section 3.1.1 by using a simplified methodology. The assumptions for this simplified approach are listed in Table 3.1. The preliminary study does not consider a discount rate nor temperature-dependent COP or EER. The heating load is assumed to represent the heating load seen by the borefield, i.e. the electricity use of the heat pump and the effect of the COP is already included. Furthermore, the yearly heating and cooling demand is assumed to be constant over the lifetime of the borefield.

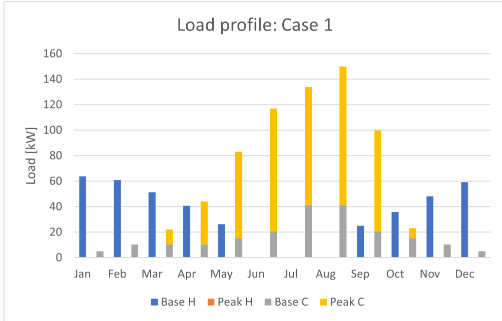
The relevant difference between passive cooling and active cooling is the maximum allowed average peak fluid temperature in the borefield. Passive cooling is characterized by relatively low fluid temperatures in the borefield in order to be able to cool buildings directly. Therefore, the temperature limit is set to 16 °C to ensure a sufficient temperature difference between the fluid and the to-be cooled space. Active cooling uses a compression step in the heat pump which allows higher fluid

[1] These graphs show the average temperature of the circulating fluid as a result of the combined base and peak load. The distinction between base and peak loads will be further elaborated in coming sections and the next chapter.

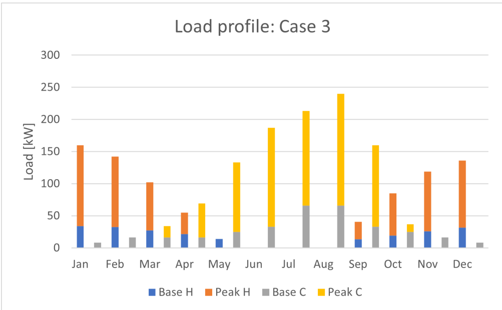
[2] An example: if the base load in a certain month equals $50kW$ and the peak load equals $150kW$, this would mean that on top of the base load there is demand for another $100kW$ extra thermal load.



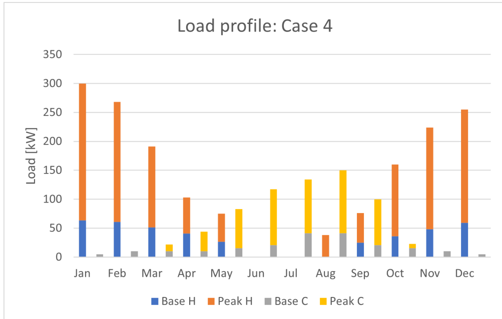
(A) Detailed load profile for case 2: cooling dominated and first year limited.



(B) Detailed load profile for case 1: heating dominated and last year limited.



(C) Detailed load profile for case 3: cooling dominated and last year limited.



(D) Detailed load profile for case 4: heating dominated and last year limited.

Figure 3.2: Detailed load profiles for the cases used in the preliminary study.

temperatures in the borefield. This limit is set at 25 °C. The undisturbed ground temperature is set to 10 °C[3].

3.2 Methodology

The objective of the preliminary study is to provide an answer on the first part of the first scientific research question. The development of a simplified methodology to provide this answer and broaden the understanding of the concept of borefield modeling is explained in this section. This will then serve as a first framework in the development of a more accurate methodology in Chapters 4 to 6. The research questions developed specifically for the preliminary study require an economic comparison of the costs of three cooling strategies: passive cooling only (PC), active cooling only (AC) and combined active and passive cooling (PC+AC).

First, a sizing methodology for borefields making use of only three load pulses with a monthly time resolution is explained in Section 3.2.1. This methodology allows

[3] These values are chosen based on previous research conducted by Peere[3] and will be revisited in Chapter 7.

Variable	Value
Time horizon	20 years
Constant EER for active cooling with GSHP	5
Higher temperature limit of the fluid for passive cooling	16 °C
Higher temperature limit of the fluid for active cooling	25 °C
Lower temperature limit of the fluid	0 °C
Electricity cost	0.25 EUR/kWh
Borefield investment cost	35 EUR/m
Conductivity of the soil	2.1 W/mK
Ground temperature at infinity	10 °C
Equivalent borehole resistance	0.2 K/W
Width of rectangular field	12 boreholes
Length of rectangular field	10 boreholes
Borehole spacing	6 m

TABLE 3.1: Numerical values of the assumptions made in the preliminary study.

borefield sizing when considering active or passive cooling only. Secondly, this sizing methodology is expanded to allow sizing of borefields in case active and passive cooling is combined in Section 3.2.2. Finally, the approach for the comparison between the three cooling strategies is explained in Section 3.2.3.

3.2.1 Borefield sizing: 3 pulse method

This section discusses a sizing algorithm which determines the necessary borefield size for a given monthly load profile consisting of base and peak load information. This is studied in detail with emphasis on the mathematical and physical background of the sizing approach. The sizing methodology combines two well-known sizing algorithms from the literature and is proposed and implemented by Peere [19]. The author also developed an open-source tool in *Python* to size geothermal borefields which will serve as an inspiration for the implementation of the methodologies proposed later in this work [19].

The three pulse sizing method combines two different sizing algorithms: one sizing approach based on the first year of operation developed by Monzo et al. [20], the other one based on the last year of operation and proposed by Bernier et al. [21]. As explained in Section 3.1.2, the load profiles can be divided in four quadrants based on the temperature profile for passive cooling operation. Given only the load profile, it is possible to determine whether the load is heating or cooling dominated and therefore exclude two out of four quadrants. The selection of the right quadrant out of the two remaining ones can not be done a priori as the limiting year is not known in advance. This explains the need for the combination of the two sizing approaches. Each sizing approach calculates the minimal required borefield size for the relevant temperature limit. The approach that returns the largest borefield size indicates

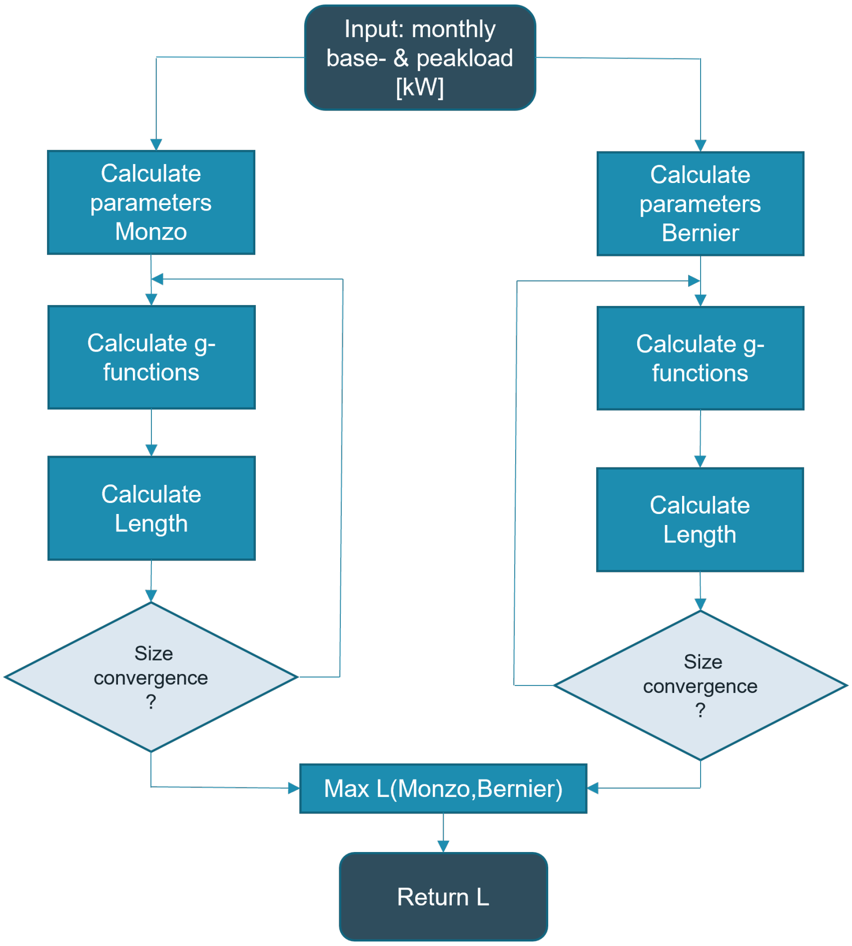


Figure 3.3: Flow chart describing the 3 pulse sizing method based on [3].

which limit will bound the temperature profile and this size is therefore selected as the final borefield size[4]. This approach is visualized in Figure 3.3, the calculation itself is touched upon further in this section.

The following two sections will discuss the sizing methods by Bernier and Monzo in more detail with emphasis on the mathematical and physical background. Both authors use the reformatted ASHRAE equation by Bernier [22] as the starting point of their approach.

[4]Consider for example a cooling dominated profile, pointing to Q2 and Q3 as possible quadrants. The borefield is then sized for these quadrants by using the sizing approach from Monzo and Bernier respectively. The largest borefield size of these two sizes will finally indicate whether the load is limited in the first or final year of operation and thus determine the definitive quadrant.

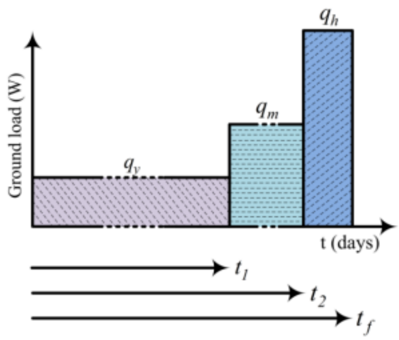


FIGURE 3.4: Graphical representation of three thermal ground pulses [16].

Sizing approach based on last year of operation

The sizing approach based on last year of operation by Bernier is a modification to the general ASHRAE equation where the penalty temperatures are omitted. This is an important step towards the general applicability and ease of implementation of the sizing approach as these penalty temperatures are only documented for specific borefield configurations [21]. The modification to the ASHRAE equation [21] results in following equation for the borefield size:

$$L = \frac{q_y R_{gy,g} + q_m R_{gm,g} + q_h R_{gh,g} + q_h R_b^*}{T_m - T_g} \tag{3.1}$$

with q_a, q_m and q_h as three ground pulses, developed by Bernier et al. [21]. These thermal pulses represent respectively the average load over the lifetime of the borefield, the base peak load of the critical month and the peak load of the critical month in Watts. T_m is the binding temperature limit in the respective quadrant[5] and T_g is the undisturbed ground temperature. The ground thermal resistances $R_{ga,g}$, $R_{gm,g}$ and $R_{gh,g}$ [16] are evaluated as explained in Section 2.3:

$$R_{gy,g} = [g(t_f) - g(t_f - t_1)]/2\pi k_s \tag{3.2}$$

$$R_{gm,g} = [g(t_f - t_1) - g(t_f - t_2)]/2\pi k_s \tag{3.3}$$

$$R_{gh,g} = [g(t_f - t_2)]/2\pi k_s \tag{3.4}$$

The g-functions are evaluated at time instances $t_f = t_y + t_m + t_h$, $t_1 = t_y$ and $t_2 = t_y + t_m$ with t_y 20 years, t_m 1 month and t_h 6 hours in accordance with the literature [20, 21, 22, 23]. The three thermal ground pulses are visualized in Figure 3.4. As the borefield depth L is not known a priori for the calculation of the g-functions, an iterative approach is necessary. This is visualized in Figure 3.3.

Sizing approach based on first year of operation

The sizing based on the first year of operation is developed by Monzo et al. [20] and is also a modification to the ASHRAE equation. The penalty temperatures are

[5]The minimal temperature limit is set at 0 °C, the limit for passive and active cooling at 16 °C and 25 °C respectively in this preliminary study.

omitted in a similar way as in the method proposed by Bernier [21] which results in:

$$L = \frac{q_{pm}R_{pm,g} + q_{cm}R_{cm,g} + q_hR_{gh,g} + q_hR_b^*}{T_m - T_g} \tag{3.5}$$

with q_{pm} the average load of the months before the critical month (as now only the first year is considered)[6], q_{cm} the base load of the critical month[7] and q_h again the peak load of the critical month. T_m is the binding temperature limit in the respective quadrant and T_g is the undisturbed ground temperature. The thermal resistances are calculated in a similar manner to the last year of operation sizing. The dependency on the borefield depth of the g-functions results again in an iterative approach as shown in Figure 3.3.

3.2.2 Sizing of borefields with combined active and passive cooling

The borefield sizing explained in the previous section is only suited when considering passive only. In cases with active cooling only, the load experienced by the borefield is higher than the initial load. This is due to the electricity use associated with the compression step of the heat pump and therefore depends on the EER of the heat pump. For combined active and passive cooling, information on the temperature profile is required to determine whether the borefield fluid temperature is below the limit for passive cooling of 16 °C. The knowledge on when active cooling has to be used is necessary to correctly integrate the electricity use in the load profile. Therefore, a dedicated methodology for combined active and passive cooling is necessary and visualized in Figure 3.5 .

First, the borefield is sized for a maximum temperature limit of 25 °C. Therefore, active cooling is used if the fluid temperatures exceeds the maximum temperature for passive cooling, equal to 16 °C. The borefield is initially sized with the original load profile. In the next step, the temperature profile for the specific load profile is calculated, as explained in Section 2.3. This profile gives the necessary information on when active cooling is applied. For each month with a peak fluid temperature above 16 °C, active cooling is considered as necessary. Therefore, the initial load is modified in each time step in which active cooling is necessary to account for the electricity use by means of the following formula:

$$Q_{c,borefield} = \frac{1 + EER}{EER} \cdot Q_{c,init} \tag{3.6}$$

with $Q_{c,borefield}$ the load experienced by the borefield. This adapted load profile is used to repeat the sizing process until convergence is achieved.

This approach assumes, as mentioned before, a constant EER for cooling and a monthly temporal resolution. Therefore, the methodology is not suited for general conclusions on the potential of combined active and passive cooling due to a lack of

[6] 'pm' stands for previous months, as the months before the critical month are considered.
[7] 'cm' stands for critical month.

accuracy. The method suffices to answer the research questions of the preliminary study and gives a better understanding of the challenge for the larger research questions in this work.

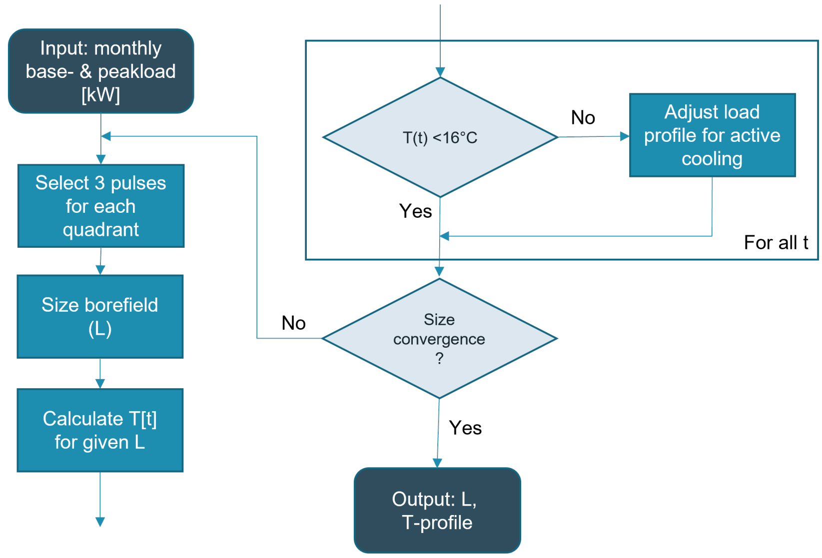


FIGURE 3.5: Flow chart describing the preliminary sizing methodology for combined active and passive cooling.

3.2.3 Economic comparison of cooling strategies

The economic comparison of different cooling strategies aims to compare the total cost of ownership (TCO) associated with passive cooling, active cooling and combined active and passive cooling. The TCO consists of the investment cost of the borefield and an eventual energy cost for the heat pump for active cooling, referred to as operating cost. The operating cost for heating is assumed to be equal for the three different strategies and is therefore not considered in this comparative analysis.

The TCO for passive cooling only consists only of a cost component for the investment of the borefield as no energy costs for the heat pump are present. This is directly calculated from the sizing approach explained in Section 3.2.1 with a maximum temperature limit of 16 °C.

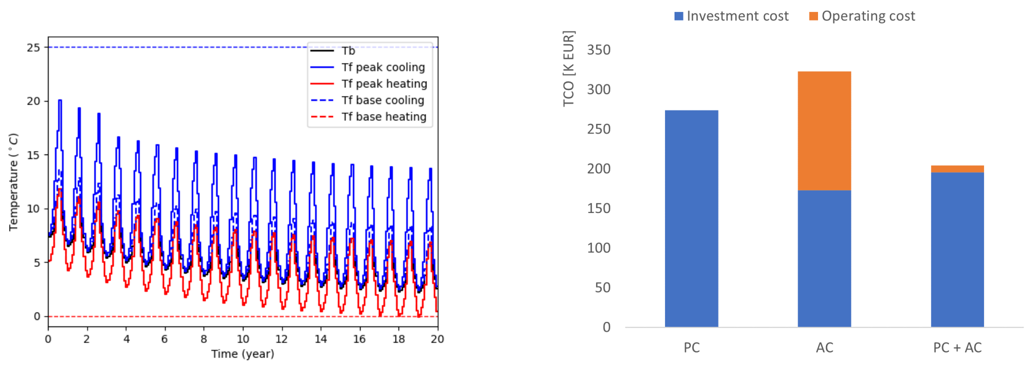
The TCO for active cooling only has both an investment and operating cost component. The investment cost follows from a slightly modified sizing approach compared to the passive cooling case as the temperature limit is now set to 25 °C. The electricity use of the heat pump for active cooling is taken into account by adapting the whole load profile up front. Information on the temperature profile is not necessary as the full load is cooled actively with a constant COP. The operating cost follows from multiplying this adapted load (in kWh) with the electricity price.

Finally, the TCO for combined active and passive cooling is calculated by means of the sizing approach discussed in Section 3.2.2. The investment cost is easily calculated from this borefield size. The operating costs now have to be determined ex post from the output of the sizing algorithm. The adapted load profile is compared to the initial load profile to determine the electricity use for active cooling. This then results in the operating cost.

3.3 Results and discussion

In order to investigate whether the use of combined active and passive cooling in combination with a borefield is economically favorable and thus answering the questions posed at the start of the chapter, a comparison is made between meeting the demand with passive cooling only (PC), active cooling only (AC) and a combination of both passive and active cooling. This combination favors passive cooling for sufficiently low borefield fluid temperatures and uses active cooling if the 16 °C limit is exceeded. A specific case study is conducted in each quadrant separately. The input load profiles are already touched upon in Figure 3.2.

3.3.1 Quadrant 1: Heating Dominated, First Year Limited



(A) Resulting temperature profile in the most cost-efficient scenario: combined active and passive cooling.

(B) Comparison of the Total Cost of Ownership (TCO) when considering passive, active or combined cooling.

Figure 3.6: Case 1: results of the preliminary study.

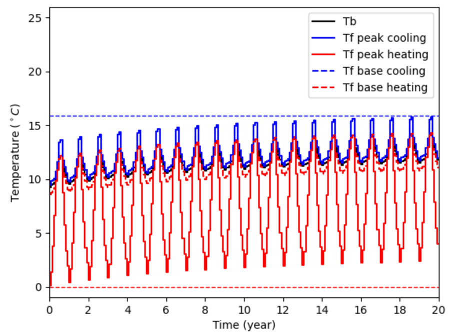
The first case considers a heating dominated load profile with a first year limitation. The load profile is characterized by high cooling peaks causing the maximum temperature to limit the size of the borefield. By using active cooling instead of passive cooling, the depth of the borefield can be reduced from 65.1m to 41.3m. This reduces the investment cost by nearly 40%. The extra compression step for active cooling causes significant operating costs. By only using active cooling if strictly necessary[8], this operating cost can be reduced. Therefore, the total cost can be reduced from 274 kEUR in the passive cooling case to 204 kEUR in the combined active and passive

[8]This is when the temperature exceeds the 16 °C limit.

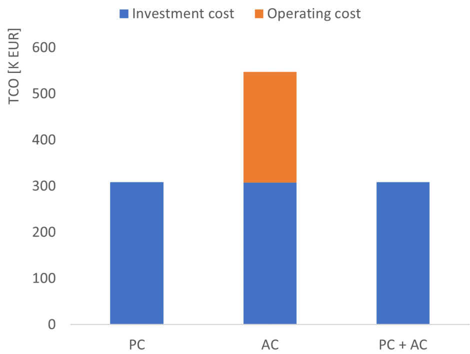
cooling situation. The complete numerical results on the TCO of this case can be found in Figure 3.6b.

The temperature profile of the most promising cooling strategy is depicted in Figure 3.6a with the temperature limit of 25 °C indicated[9]. The heating dominated case is characterized by a declining temperature profile over the years. Therefore, the share of active cooling over the lifetime of the borefield decreases as the fluid temperature exceeds the limit for passive cooling less frequently. Note that the first year maximum temperature limitation in case of passive cooling only is now a final year minimum temperature limitation by using combined active and passive cooling.

3.3.2 Quadrant 2: Cooling Dominated, First Year Limited



(A) Resulting temperature profile in the most cost-efficient scenario: passive cooling



(B) Comparison of the Total Cost of Ownership (TCO) when considering passive, active or combined cooling.

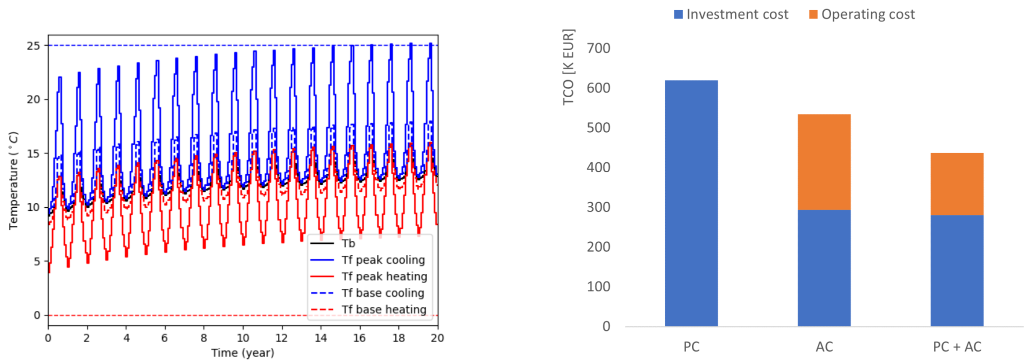
FIGURE 3.7: Case 2: results of the preliminary study.

The second case considers a cooling dominated load profile with a first year limitation. The high heating peaks (that cause the borefield to cool down rapidly) in combination with an increasing temperature profile causes a critical month in the first year of the borefield's lifetime. There is no potential for active cooling in this case as the borefield sizing is limited by the heating peaks and therefore by the minimum temperature. As such, it is impossible to apply any borefield size reduction as the lower boundary of the temperature limit would be exceeded. The fluid temperature does not exceed 16 °C, so passive cooling is always possible. The results of this case study are presented in Figure 3.7.

3.3.3 Quadrant 3: Cooling Dominated, Last Year Limited

The third case considers a cooling dominated load profile with high cooling peaks. Also in this case, there is a high potential for active cooling. By using active cooling

[9]Note that by reducing the borefield size for active cooling, the minimum temperature limit is now binding.



(a) Resulting temperature profile in the most cost-efficient scenario: combined active and passive cooling

(b) Comparison of the Total Cost of Ownership (TCO) when considering passive, active or combined cooling.

Figure 3.8: Case 3: results of the preliminary study.

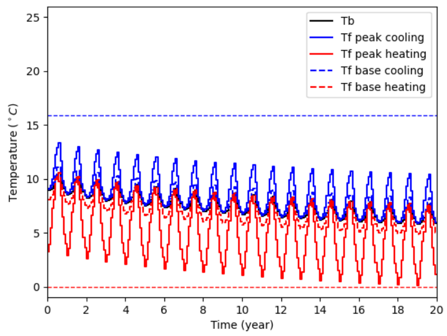
only instead of passive cooling, the borefield depth can be reduced from 147.5m to 69.9m.

An extra reduction in borefield depth to 66.8m is possible when using combined active and passive cooling. This is due to the reduced share of active cooling compared to the active cooling only strategy. The electrical energy from the compression step in active cooling causes additional heating of the borefield. Therefore, active cooling magnifies the effect of the imbalance which results in a larger required borefield size to stay within the temperature limits. This results in an additional investment cost saving for the combined passive and active cooling compared to the full active cooling case. The total cost can be significantly reduced from 534 kEUR in the passive cooling case to 437 kEUR for combined active and passive cooling. The complete numerical results are presented in Figure 3.8b.

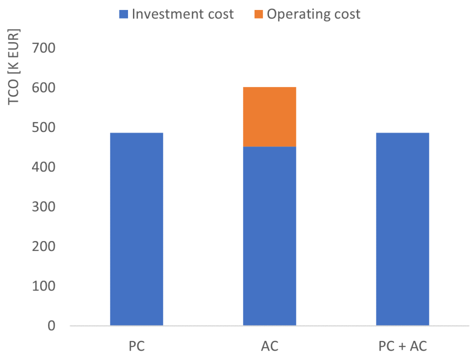
The share of active cooling increases over the years as the borefield heats up year after year due to the positive imbalance. Note that this share of active cooling is the driver for the high operating costs in the TCO.

3.3.4 Quadrant 4: Heating Dominated, Last Year Limited

The fourth case considers a heating dominated load profile with a final year limitation. The use of active cooling is also not beneficial in this case, as is clear from Figure 3.9a. The borefield sizing is again limited by the minimum temperature due to the high cooling peaks, by which an increase in the temperature limit from 16 °C to 25 °C does not impact the TCO. A small borefield size reduction is possible because of the extra heat stored in the borefield due to the active cooling, which can be extracted for heating. This is not financially favorable due to the high extra operating cost caused by the compression step of the active cooling. Figure 3.9 presents the results of this case study.



(A) Resulting temperature profile in the most cost-efficient scenario: passive cooling



(B) Comparison of the Total Cost of Ownership (TCO) when considering passive, active or combined cooling.

FIGURE 3.9: Case 4: results of the preliminary study

3.4 Conclusion

The results described in Section 3.3 clearly answer the questions posed at the start of the chapter. This preliminary study shows that including active cooling in a given cooling problem can be beneficial. The results indicate that advantages of including active cooling are present in cases 1 and 3, representing respectively a heating dominated, first year limited load and a cooling dominated last year limited load. Both cases are limited by the maximum temperature limit, which leaves large potential for methods that increase this temperature limit by allowing higher fluid temperatures in the geothermal borefield. Here, the decrease in investment cost is significantly larger than the increase in working cost. The results also show that including active cooling in cases 2 and 4, representing respectively a cooling dominated, first year limited load and a heating dominated, last year limited load, is not advantageous and results in an increase in total costs as it is the minimum temperature (0 °C) that is limiting. If active cooling were applied here, the maximum temperature limit would increase to 25 °C which increases the operating cost without decreasing the borefield size.

This preliminary study uses a 3 pulse sizing method with a monthly resolution as the core of the sizing algorithm. For the scope of the preliminary study, the trade-off between accuracy and simplicity tends towards the latter. This causes an over-estimation of the operating costs as the monthly resolution can not accurately determine the instances when the fluid temperature exceeds the limit for passive cooling. The need for more accurate sizing methodologies is therefore investigated in Chapter 4.

The preliminary study also makes abstraction of a discount factor for cash flows in future years and a temperature-dependent COP and EER, which would increase the accuracy of the results. These topics are discussed in Chapters 5 and 6.

Part II

Methodology

Chapter 4

Sizing methodologies

The three-pulse method discussed in Chapter 3 is a simple method that requires little computational power to size a borefield when given a monthly load profile but therefore also lacks accuracy in certain situations. Furthermore it does not need knowledge of the full load profile which might prove useful in some applications. Summarizing, it uses three pulses of which two are based on the month with the highest peak load to size the borefield. This might lead to incorrect results for certain types of load profiles[1]. As an example, Figure 4.1 is studied.

Figure 4.1: Example in which the three-pulse method would not succeed in returning a correct result [3].

Using a yearly load profile containing months A and B (as seen in Figure 4.1), the three-pulse method would select the peak load of month B as Q_h, the base load of month B as Q_m and the yearly imbalance as Q_y. The three-pulse method thus assumes the limiting month is always the month that contains the largest peak load, independent of the base load. In the example of Figure 4.1, this is clearly not the case as month A has a higher probability of being the limiting month for the borefield size compared to month B.

Section 4.1 proposes a methodology that overcomes this flaw and makes the sizing of the borefield more accurate and more robust to different kind of load profiles. It takes all the monthly load data into account instead of just three well-chosen pulses.

[1]The load profiles described in Chapter 3 are relatively smoothly varying loads without large sudden peaks in energy requirements. Load profiles that might lead to incorrect results refer to load profiles that include large sudden peaks or highly irregular loads.

Section 4.2 describes several methodologies to size a borefield based on hourly load data. It discusses one aggregated and two non-aggregated methods. Then these three methodologies are compared based on their performance.

Section 4.3 compares the method using a monthly time resolution to the methods using an hourly time resolution. This comparison highlights the benefits of increasing the time resolution and provides the basis on which economical decisions concerning borefield sizing can be made. Finally, the most interesting sizing methodology is validated by using external software in Section 4.4.

Sections 4.1 to 4.4 together aim to answer the second scientific research question described in Section 1.2.

4.1 Method using monthly pulses

This section presents a methodology to size borefields taking into account all monthly load profile data. This approach avoids the issue described in Figure 4.1 which makes this methodology significantly more robust for irregular load profiles.

The sizing methodology starts with the yearly load consisting of 12 base cooling values, 12 base heating values, 12 peak cooling values and 12 peak heating values. Please recall that the peak values represent the maximum total heating or cooling load and thus include the base load as explained in Section 3.1.2[2]. As in the preliminary study, these load values are presented as a thermal power in Watts.

The aim is not to locate the load profile in any quadrant as represented in Figure 3.1. Instead, the aim is to compute the necessary size of the borefield for every time step (month) taking into account the load in all previous time steps. In this way, the methodology sizes the borefield twice for every month (once assuming the heating load is limiting and once assuming the cooling load is limiting).

As stated in Section 2.3, the borehole wall temperature is computed as follows:

$$T_b(t_n) = T_g + \frac{1}{2\pi k_s L} \begin{bmatrix} Q_1 & Q_2 & \dots & Q_i & \dots & Q_n \end{bmatrix} \cdot \begin{bmatrix} g(t_n) - g(t_{n-1}) \\ g(t_{n-1}) - g(t_{n-2}) \\ \vdots \\ g(t_i) - g(t_{i-1}) \\ \vdots \\ g(t_1) \end{bmatrix} \tag{4.1}$$

where T_g and k_s are the undisturbed ground temperature and the ground conductivity respectively. The values for Q_i are the resulting monthly base loads prior to t_n where a cooling load is considered to be positive and a heating load negative (as a cooling

[2]The presentation of peak and base load in Figure 4.1 is thus not representative for the following methodology.

load increases the temperature of the borefield): $Q_i = Q_{bi}^C - Q_{bi}^H$ with Q_{bi}^C and Q_{bi}^H the absolute value of the base cooling and heating load in month i, respectively.

The average temperature of the fluid circulating in the borefield due to the peak load (which is the limiting temperature in operation) for each month is computed as follows using the notion of R_b^* explained in Section 2.3:

$$T_{fp}(t_n) = T_b(t_n) + \frac{1}{L} \cdot \left[(Q_p(t_n) - Q_b(t_n)) \cdot (\frac{g(t_h)}{2\pi k_s} + R_b^*) + Q_b(t_n)R_b^*\right] \tag{4.2}$$

To further clarify Equation (4.2), Figure 4.2 is studied. This figure presents the four main components that contribute to the computation of T_{fp} being the ground temperature T_g and three separate effects that are discussed one by one[3]. The first of these, $\Delta T1$, represents the borehole wall temperature reaction to all previous and current base loads $\frac{D_p}{2\pi k_s L}$ where D_p stands for the matrix product of the resulting monthly loads and the corresponding differences in g-values as shown in Equation (4.1). $\Delta T2$ represents the supplementary borehole wall temperature reaction to the peak load $(Q_p(t_n) - Q_b(t_n))\frac{g(t_h)}{2\pi k_s}$. $\Delta T3$ represents the average fluid temperature reaction to the current peak load $Q_p(t_n)R_b^*$.

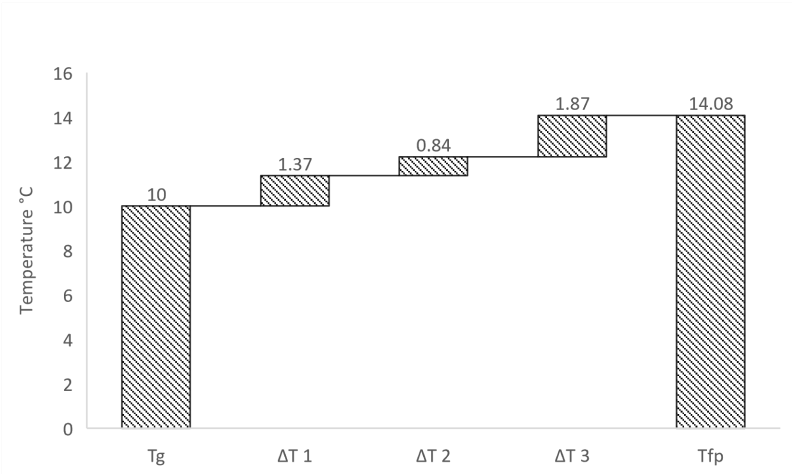


FIGURE 4.2: Breakdown of $T_{fp}(t_n)$ in components following Equation (4.2).

The minimal necessary borefield depth is characterized by the maximal or minimal average peak temperature of the borefield fluid, corresponding to one of the fluid temperature limits. In case a smaller borefield would be used, the temperature would exceed its binding limit. By using the heating loads for $Q_p(t_n)$ and $Q_b(t_n)$ in Equation (4.2) one computes the average fluid temperature due to the momentary heating load and by using the cooling loads for $Q_p(t_n)$ and $Q_b(t_n)$ in Equation (4.2)

[3] Please note that the temperature values in this graph correspond to the month August (cooling dominated) in the first year of a 20 year borefield sizing simulation. Although the actual values are interesting and exact, they are not the main focus of this example. It merely serves as intuitive clarification to Equation (4.2).

one computes the average peak fluid temperature due to the momentary cooling load. To relate this necessary borefield depth to the average peak fluid temperature in the borefield, Equations (4.1) and (4.2) can be combined after which L can be written as in Equation (4.3). $T_{fp}(t_n)$, from Equation (4.2), has been rewritten as T_{lim} to find the minimal allowed borefield depth.

$$L_n = \frac{\frac{D_p}{2\pi k_s} + \left[(Q_p(t_n) - Q_b(t_n)) \cdot \frac{g(t_h)}{2\pi k_s} + Q_p(t_n)R_b^*\right]}{|T_{lim} - T_g|} \tag{4.3}$$

In Equation (4.2), D_p stands for the matrix product of the resulting monthly loads and the corresponding differences in g-values as shown in Equation (4.1) and t_h stands for the assumed duration of the peak load (6 hours as explained in Section 3.2.1). Equation (4.3) is computed twice for every time step, once evaluated for the momentary heating load and once evaluated for the momentary cooling load. T_{lim} stands for the average fluid temperature limit in the borefield which depends on the use of the cooling load or heating load[4]. The largest value of all evaluations of Equation (4.3) is saved as final depth for the borefield in this sizing methodology[5].

Similar to the three-pulse method, the monthly pulse method is a relatively simple method that requires little computational power to size a borefield based on a monthly given load profile. Contrary to the three-pulse method, it does not lead to incorrect results with more specific load profiles as explained at the start of this chapter with the help of Figure 4.1. Furthermore, this method has a higher accuracy in sizing the borefield as it takes into account the whole load information instead of three well-chosen pulses. When sizing borefields for the load profiles used in the preliminary study, the three-pulse method and the monthly pulse method return a borefield size that is between 1.2% and 2.1% difference from each other. The strength of the monthly method comes forth when dealing with more irregular and non-typical residential load profiles.

4.2 Methods using hourly pulses

The monthly pulse method discussed in Section 4.1 is relatively straightforward and uses the full monthly load profile to accurately size the borefield. This monthly method does, however, have a crucial limitation. To understand this limitation, one must understand the implications of using Equation (4.2) to model active cooling[6].

[4] If Equation (4.2) is evaluated for the momentary heating load, T_{lim} represents the lower average fluid temperature limit. If Equation (4.2) is evaluated for the momentary cooling load, T_{lim} represents the higher average fluid temperature limit.

[5] As the g-values in D_p in Equation (4.3) depend on the depth of the borefield, the described sizing process is iterated until L converges. More on this in Chapter 5.

[6] Here an introduction is given to modeling active cooling based on the temperature profile. This is explained in more detail in Chapter 5.

Based on the fluid temperature found in Equation (4.2), the modeling methodology determines if the thermal cooling load in this particular month needs to be cooled actively or can be cooled passively. As described in Section 2.1, passive cooling is only possible up until a certain fluid temperature. Above this temperature, passive cooling is no longer possible due to an insufficient temperature difference between the fluid inside the borefield and the fluid inside the heat emission system of the building. Therefore a heat pump must be used to accommodate this cooling, which is referred to as active cooling.

As the monthly method evaluates the average peak fluid temperature only once for the whole month based on the peak load, the amount of necessary active cooling is largely overestimated. The whole month is considered to be actively cooled when most likely only during certain periods of this month the average fluid temperature surpasses the maximum passive cooling temperature limit. An hourly profile would evaluate the average fluid temperature on an hourly basis, giving a much more accurate estimation of the periods where the fluid temperature surpasses the passive cooling limit.

This section proposes a methodology, based on the one described in Section 4.1, to size borefields starting from hourly thermal load data. Using this hourly time step instead of a monthly one results in a slightly more accurate sizing but most importantly it results in a large increase in accuracy of the computed temperature profile. This in turn gives a much more accurate view on the operational costs that can be expected due to active cooling over the lifetime of the borefield as will be discussed more in detail in Chapter 5 and Chapter 6. It is for this reason that a higher temporal resolution is studied in this work.

The main difference between the previously described methodologies and the hourly methodology is the absence of the breakdown of the load in peak and base load. The hourly load data assumes an average thermal load per hour as initial input, still split up in an average cooling load and an average heating load per hour. Apart from this, the sizing methodology also assumes there is no possibility to extract heat and inject heat into the borefield within the time span of one hour. This thus implies an internal heat exchange if there is a simultaneous heating and cooling load in the load profile.

The borehole wall temperature is computed using Equation (4.1) where now the values for Q_i are the resulting hourly loads prior to t_n where cooling is considered positive and a heating load negative. The average fluid temperature is then found as explained in Section 2.3, shown in Equation (4.4).

$$T_f(t_n) = T_b(t_n) + \frac{Q(t_n)R_b^*}{L} \tag{4.4}$$

From here, again, Equation (4.1) and Equation (4.4) can be combined to determine the borefield depth L, where $T_f(t_n)$ is replaced by T_{lim} to find the minimal allowed borefield depth.

$$L_n = \frac{\frac{D_p}{2\pi k_s} + Q(t_n)R_b^*}{|T_{lim} - T_g|} \tag{4.5}$$

As Equation (4.5) is computed twice every time step[7], it results in a large number of evaluations of this equation. For example, if the lifetime of the borefield would be equal to 20 years, the number of evaluations of the borefield size would be equal to 480 (twice per time step for 20 years) when using the monthly methodology. Using the hourly methodology, 350,400 evaluations must be done. Not only the amount of computations increases, also the computation intensity increases as the hourly method requires the solution of a matrix product with a maximum size of 175,200 by 175,200 twice for every time step. It is clear that increasing the lifetime result in a superlinear increases in the computational intensity of this task. For larger borefield lifetimes this thus becomes extremely time consuming.

The following sections (Sections 4.2.1 and 4.2.2) discuss how this operation can be done in an effective and efficient way concerning computational power by using load aggregation and the convolution operator respectively. Finally, both solution methods are compared to a reference solution in Section 4.2.3 in terms of accuracy and computational speed.

4.2.1 Aggregation

By aggregating past loads, the computational intensity of this sizing can be significantly reduced. Aggregation is based on the fact that thermal loads have a less significant effect on the current borefield temperature the longer ago they were applied to the borefield. For example, the effect seen at time t of a thermal load of $50kW$ applied on the borefield at time $t - 1000$ hours is much smaller than the effect seen at time t of the same thermal load applied at time $t - 1$ hour. Based on this reasoning, it is clear that using the same accuracy in computing the effect of past loads and the effect of more recent loads is not an efficient allocation of computational power. This then gives rise to the idea of aggregating past loads so these effects can be computed quicker with a lower accuracy, leaving the bulk of the computational resources for computing the effects of the recent loads with high accuracy.

Many different aggregation schemes and algorithms have been proposed in literature of which a few are discussed here as done in [24]. Afterwards the most promising one of these is discussed in more detail.

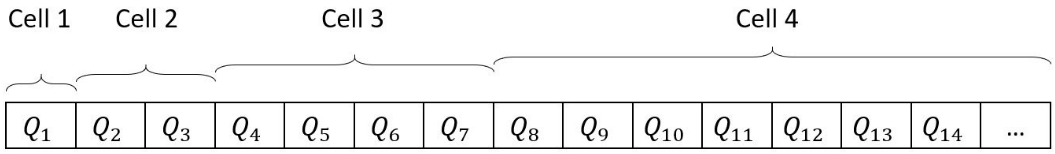
[7]Recall in the monthly methodology Equation (4.3) was also computed twice per time step. Once using the momentary cooling load and once using the momentary heating load. Here Equation (4.5) is evaluated once using the resulting load where heating is considered positive and once with the resulting load where cooling is considered positive. Note that both of these computations use a different value for T_{lim}.

Bernier et al. [25] proposes the Multiple Load Aggregation Algorithm (MLAA) as a revision of the earlier proposed Simple Load Aggregation Algorithm (SLAA). The MLAA categorizes all previous time steps into an 'immediate' and a 'past' time period. The loads in the immediate time period are not aggregated whilst the loads that fall in the 'past' time period are. In this last time period loads are aggregated in blocks of daily (48 hours), weekly (168 hours), monthly (360 hours) and yearly loads [24]. The duration of the immediate time period is taken to be 12 hours. Xiaobing Lui [26] presents aggregation on three levels, each with a respective waiting time. A small block represents aggregation over a period of 24 hours and has a waiting time of 12 hours. A medium block represents aggregation over a period of 5 small blocks, with a waiting time equal to 3 small blocks. A large block represents aggregation over a period of 73 medium blocks and has a waiting time equal to 40 medium blocks. Denis Marcotte and Philippe Pasquier [27] propose a waiting period of 48 hours before starting aggregation. After this period loads are aggregated according to a fixed geometric pattern: 49-50, 51-54, 55-62, 63-78, 79-110, 111-174, 175-302, 303-558, and so on. Johan Claesson and Saqib Javed [24] propose an aggregation scheme that aggregates past loads into cells of which the size varies according to some basic parameters. This method seems most promising for the goal of the thesis at hand and is thus discussed in further detail.

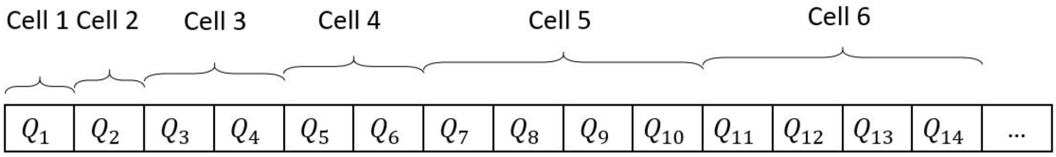
According to [24], loads are placed into cells of varying size based on increasing levels. For the first level $q = 1$, every hourly load is treated as a single cell. For the first level, P_1 cells are used. For the second level $q = 2$, the cell length is increased to 2 hours which means two hourly loads are aggregated into an average load with a duration of 2 hours within this cell. For this second level, P_2 cells are used. For the third level $q = 3$, the cell length is increased to 4 hours and so on. The number of cells with length 2^{q-1} on level q equals P_q. Figures 4.3a and 4.3b show a graphical representation of this aggregation scheme for $P_q = 1$ and $P_q = 2$ respectively. Please note that in these figures no waiting time has been assumed before starting the aggregation algorithm.

This aggregated load, now consisting of a relatively small number of cells, is used as input load profile to the hourly method described in Section 4.2 for sizing of a borefield. As an example, imagine the load profile contains 200,000 hourly load values, corresponding to roughly 22.5 years. By using this load aggregation method with P_q equal to 5, the number of loads is reduced to roughly 80 [24]. Obviously this has an extremely large impact on the computational intensity of the sizing task and therefore thus reduces the time needed.

This method offers many possibilities to vary key parameters such as P_q or the length of the cells at each level. By varying these parameters, the accuracy can be improved at the cost of computational time and vice versa.



(A) Graphical representation of an aggregation proposed by [24] for $P_q = 1$



(B) Graphical representation of an aggregation proposed by [24] for $P_q = 2$

Figure 4.3: Two graphical examples of the aggregation method proposed by Claesson and Javed [24].

4.2.2 Convolution

When carefully analyzing Equation (4.1), a convolution operation can be recognized. Implementing this convolution within the sizing algorithm results in a large reduction in computation time due to the numerical efficiencies that exist within the packages used in *Python*. This section describes in detail the origins of this convolution operation and its implementation.

By evaluating Equation (4.1) for the first few time steps manually, the convolution becomes clear. In particular the matrix product, which is restated in Equation (4.6) for the readers ease, is looked at in detail.

$$D_{pn} = \begin{bmatrix} Q_1 & Q_2 & \dots & Q_i & \dots & Q_n \end{bmatrix} \cdot \begin{bmatrix} g(t_n) - g(t_{n-1}) \\ g(t_{n-1}) - g(t_{n-2}) \\ \vdots \\ g(t_i) - g(t_{i-1}) \\ \vdots \\ g(t_1) \end{bmatrix} \tag{4.6}$$

Table 4.1 shows the manual computation of Equation (4.6) for the first four time steps. Here, t_i is expressed in hours which means g(3) would represent the value of the g-function evaluated at a time equal to 10,800 seconds (= 3 hours).

One might recognize that each of these manual computations is similar to an evaluation of a discrete convolution of Q and g. In this case specific, each of these manual computations corresponds to an evaluation of the discrete convolution of $Q[i]$ and $g'[i]$ where $Q[i]$ represents the hourly load and $g'[i]$ represents the discrete function of g-value differences: $g'[i] = g(t_{i+1}) - g(t_i)$.

Evaluation time (t)	Matrix product
1	$D_{p1} = Q_1 \cdot g(1)$
2	$D_{p2} = Q_1 \cdot (g(2) - g(1)) + Q_2 \cdot g(1)$
3	$D_{p3} = Q_1 \cdot (g(3) - g(2)) + Q_2 \cdot (g(2) - g(1)) + Q_3 \cdot g(1)$
4	$D_{p4} = Q_1 \cdot (g(4) - g(3)) + Q_2 \cdot (g(3) - g(2)) + Q_3 \cdot (g(2) - g(1)) + Q_4 \cdot g(1)$

TABLE 4.1: Manual evaluation of the first four time steps of the matrix product presented in Equation (4.6).

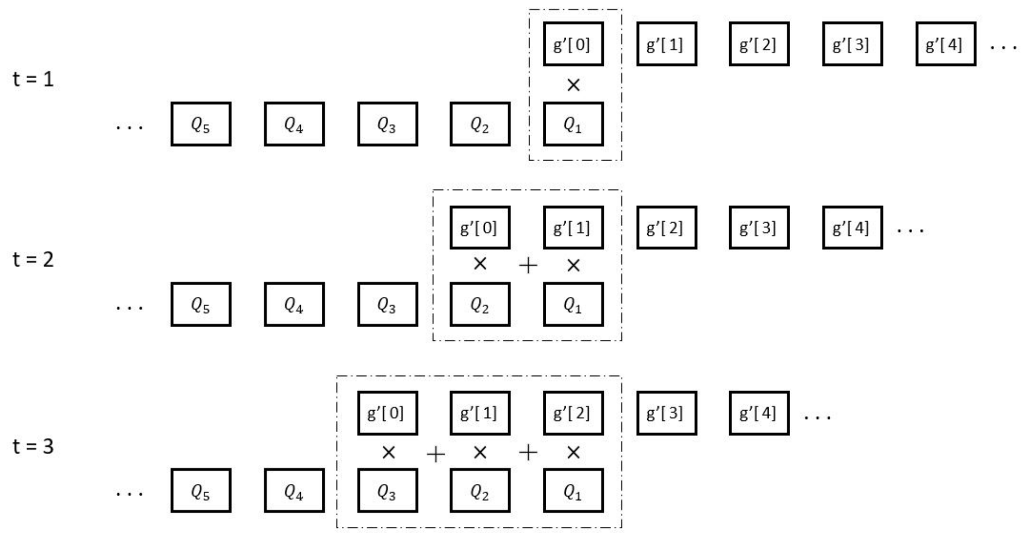


FIGURE 4.4: Graphical representation of the first three evaluations of the convolution function $(Q \circledast g')$.

The discrete convolution is defined as in Equation (4.7) and is used here as in Equation (4.8) where M equals the total amount of hours in the lifetime of the to-be-sized borefield (the total amount of time steps). Please note $g'[i]$ is not defined for negative values of i and thus considered equal to zero if evaluated for a negative i. This convolution operation is shown graphically for the first three evaluations in Figure 4.4. From this figure the resemblance with the continuous convolution function is clear.

$$(u \circledast v)[n] = \sum_{m=-\infty}^{\infty} u[m] \cdot v[n-m] \tag{4.7}$$

$$(Q \circledast g')[n] = \sum_{m=1}^{M} Q[m] \cdot g'[n-m] \tag{4.8}$$

The discrete function in Equation (4.8) can be computed very quickly by taking advantage of the Fourier domain. By transforming the convolution into the Fourier domain it can be solved as a multiplication. The inverse Fourier transform of the result of this multiplication represents the discrete function in the time domain. The hourly pulse sizing algorithm uses the *SciPy* package in *Python* to perform this transformation and multiplication. This method is in accordance with the literature [2, 27].

4.2.3 Performance comparison between hourly methods

Sections 4.2.1 and 4.2.2 describe two variations of computing the matrix product in Equation (4.1) in an attempt to reduce the time needed to do this operation: aggregation and convolution. This section compares their performance, advantages and disadvantages with a reference case executing the time-consuming matrix computation.

To compare both the convolution and the aggregation based on computation speed, a reference is needed. In this section the reference is chosen as the time it takes to run through the sizing for all time steps without using one of the two variations discussed in Sections 4.2.1 and 4.2.2. Furthermore both variations are compared based on accuracy. Again, the accuracy of the sizing without using one of the two variations discussed in Sections 4.2.1 and 4.2.2 is used as a reference and therefore assumed to have an accuracy of 100 %. Table 4.2 summarizes the comparison.

	Reference	Aggregation	Convolution
Sizing duration [s]	35	2.5	0.7
Accuracy [%]	100	<100	100

Table 4.2: Comparison of variations on the expensive matrix product computation for a simulation period of 20 years with an hourly temporal resolution.

As can be seen in Table 4.2, in the reference scenario it takes 35 seconds to complete the full borefield sizing for 175,200 time steps[8]. Comparatively, the aggregation and convolution variations are able to do this same task roughly 14 and 50 times faster, respectively. The aggregation variation is the only one with an accuracy less than 100% compared to the reference case as by aggregating loads a part of the information of the initial load profile is lost. Both the reference scenario and the convolution scenario take into account every single data point in the initial load profile. It is clear that the convolution variation seems to be the most promising one as it is faster and more accurate due to the efficient implementation of the Fourier transform. It is this variation that is used throughout the thesis.

4.3 Summarizing comparison of the sizing methodologies

This section summarizes the advantages and disadvantages of the three previously described methods in Table 4.3. From the previous sections it is clear that the three-

[8] This experiment is executed with a simple load profile for a simulation period of 20 years.

pulse method is the most simple method and requires least computational power. Furthermore it can be used without full knowledge of the monthly load profile[9] and returns a sizing with acceptable accuracy in most cases. However, in some cases the three-pulse method returns incorrect results due to methodological limitations. Also the estimation of the operating cost is inaccurate using the three-pulse method.

The monthly pulse method solves the inaccuracy in the sizing results of the three-pulse method. It is a method that returns an accurate sizing while still being limited in computational complexity. However, the operating costs are estimated inaccurately.

The hourly method tackles the inaccurate operating cost problem of the previous two methods and returns an accurate borefield sizing with an accurate estimation of the operating costs within an acceptable time. A disadvantage of this method is that it requires an hourly load profile as input and is relatively complex computationally.

Due to the academic nature of this thesis and the necessity of accurate working cost estimations, the hourly method using the convolution variation is considered the most suitable. Therefore, this methodology is used further in this work to size borefields.

Methodology	Advantages	Disadvantages
Three-pulse	Limited computational complexity Short computation time Usable with limited load profile data	Inaccurate working costs Possible incorrect results (Figure 4.1)
Monthly pulse	Limited computational complexity Short computation time Accurate sizing	Inaccurate working costs
Hourly pulse	Acceptable computation time Accurate sizing Accurate working costs	Computational complexity Necessity of detailed load profile

Table 4.3: Summary of the comparison of the sizing methodologies discussed in Chapter 4.

4.4 Validation

This section describes the validation of the hourly pulse sizing methodology (Section 4.2) using an external simulation software package called *Dymola*. Section 4.4.1 goes deeper into the objective of this validation. Section 4.4.2 describes how the validation is set up and details which external software packages are used. Section 4.4.3 discusses the results of the validation.

[9] This could prove useful in practical applications where knowledge only exists of the yearly peak and the average base load.

4.4.1 Objective

The goal is to validate the hourly sizing methodology explained in Section 4.2 using external software. This is necessary for the following chapters to be able to confidently build upon and discuss insights based on the methodologies presented in this chapter. For this validation a synthetic hourly load profile is used which is constructed using two superimposed sine waves. One has a 24-hour period representing a daily variation in heating and cooling load which is superimposed on a second sine wave with a yearly period representing the seasonal variation in heating and cooling. This synthetic load profile is discussed in more detail in Section 7.1.2.

The average fluid temperature in the borefield is simulated on an hourly basis using the convolution method (described in Section 4.2.2) and also using an external simulation software package (described in Section 4.4.2). Both consider only passive cooling as it is the sizing methodology that is the subject of the validation[10]. These two temperature profiles are then compared.

4.4.2 Validation software

To perform this validation, the commercial modeling and simulation environment *Dymola* is used. *Dymola* is based on the open *Modelica* modeling language. The validation model, built in *Dymola*, uses models from the Integrated District Energy Assessment Simulations (IDEAS) library. This library was developed by the KU Leuven and is currently maintained by the Thermal Systems Simulation (The SySi) research group [28]. The validation uses models of components contained within this library such as the borefield model, the ideal heater model and the heat pump model.

Important to realise is that the model simulated in the *Dymola* environment is an extremely detailed dynamic simulation. This means effects such as the thermal inertia of the fluid circulating in the borefield are taken into account. In contrast, this effect is not taken into account in the hourly sizing methodology described in this work. Furthermore parameters such as the specific heat capacity of the soil material and density of the soil material are parameters in the IDEAS models but are not taken into account specifically in the hourly sizing methodology. These dissimilarities might result in slight differences when comparing the temperature profiles.

4.4.3 Discussion

Figure 4.5 presents the validation in three different figures. Figure 4.5a shows the temperature profile obtained by using the *Dymola* software together with the temperature profile obtained by using the hourly sizing methodology for a period of 20 years on the top side of the figure. The difference between these two temperature profiles is depicted in the bottom graph of Figure 4.5a.

[10] It is not the aim of this validation to validate any methodologies on combining active and passive cooling. This validation solely aims to validate the hourly sizing methodology. Herefore using only passive cooling is sufficient.

Figures 4.5b and 4.5c show a zoomed-in portion of Figure 4.5a, presenting respectively a period of 1 year and 1 week. From Figure 4.5a it is clear that the maximum temperature difference between the two constructed profiles is slightly more than 0.2 °C and has a periodic nature. This periodic nature can be explained by the periodic nature of the load profile which results in a periodic temperature profile over the 20 years lifetime of the borefield.

When looking into more detail at Figure 4.5b it is clear that the developed methodology follows the external simulation accurately most of the time. The largest deviation can be seen at the transition from a largely heating dominated season to a largely cooling dominated season.

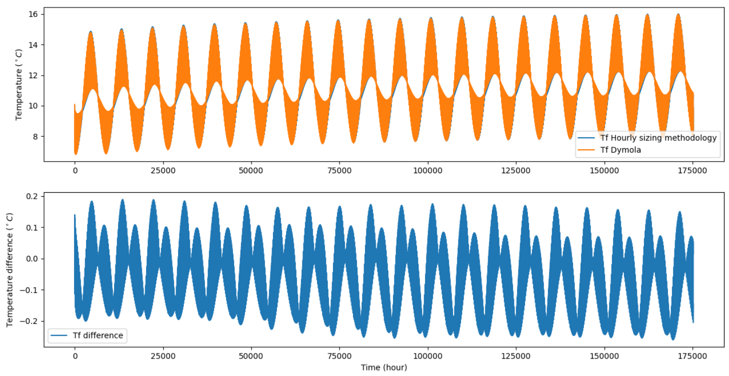
Looking at the daily scale in Figure 4.5c, it is clear the developed methodology follows the external simulation extremely well. The largest deviation between both temperature profiles can be identified as the temperature profile resulting from the *Dymola* simulation lagging slightly behind the temperature profile resulting from the developed methodology. This can be explained due to the fact that the models in *Dymola* take into account the thermal inertia of the fluid circulating in the borefield whereas the developed methodology does not.

Figure 4.5 shows that the temperature difference never exceeds $0.25°C$ which is sufficient to conclude that the methodology developed is validated. The deviation that still exists can be explained by the thermal inertia of the fluid circulating in the borefield and the extra parameters that the model in *Dymola* takes into account.

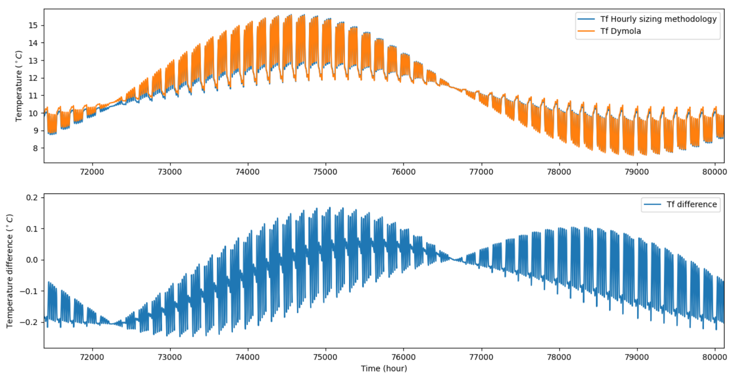
Key Takeaways

The key insights of this chapter are listed below.

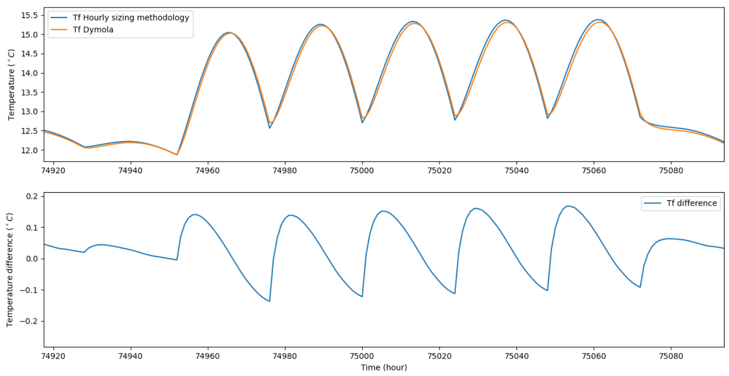
- The three-pulse method leads to incorrect results when dealing with irregular load profiles.
- The monthly pulse method reliably and accurately sizes the borefield but lacks the time resolution to produce an accurate temperature profile.
- The hourly pulse method accurately sizes the borefield and produces a detailed temperature profile which can be used to correctly estimate the operating cost over the lifetime of the borefield.
- Implementing the convolution method strongly decreases the computational time needed for the hourly sizing algorithm without losing out on accuracy.
- The hourly sizing methodology is validated using the external simulation software *Dymola* with the help of the IDEAS library.



(a) Hourly average fluid temperature profiles for a 20 year simulation period (top figure) together with their difference (bottom figure).



(b) Zoomed-in section of Figure 4.5a covering a time period of 1 year.



(c) Zoomed-in section of Figure 4.5b covering a time period of 1 week.

Figure 4.5: Temperature profile comparison between developed hourly sizing methodology and simulation done with *Dymola* software.

Chapter 5

Sizing of borefields with combined active and passive cooling

Chapter 4 explains and compares sizing methodologies with a monthly and hourly time resolution. The main benefit of the hourly method is the increased accuracy of the temperature profile over the lifetime of the borefield. This increase in accuracy results in an increased computational time of the sizing. As described in Chapter 4, this computational time can be reduced by using the fast Fourier transform. The monthly method on the other hand is computationally easier and is less demanding in terms of input data related to the load profile.

This chapter focuses on the development of a methodology to size borefields for combined active and passive cooling, whereas the methodologies explained in Chapter 4 concentrate on passive cooling or active cooling only. These sizing approaches serve now as a backbone for this more complex algorithm. The algorithm is first conceptually explained in Section 5.1. Section 5.2 explains the underlying assumptions of the algorithm and identifies its shortcomings. This chapter concludes by listing a few key takeaway messages.

5.1 Conceptual approach

The general idea to model combined active and passive cooling is already touched upon in the preliminary study, explained in Chapter 3. This approach is now expanded by integrating a temperature-dependent COP in combination with an hourly load profile. This allows for more accurate estimations on the share of active cooling. In case a monthly profile would be used, the entire monthly cooling load would be cooled actively if the maximum average fluid temperature exceeds the temperature limit for passive cooling in that particular month. The hourly method allows to switch from active to passive cooling on an hourly basis which results in a significant increase in accuracy of the operating cost over the lifetime of the borefield. The goal of the algorithm is to compute the minimal required borefield depth for which the temperature never exceeds the predefined limits. In other words, the investment cost is minimized at the cost of an additional operating cost for cooling. This optimization is a necessary step in the economic optimization described in Chapter 6.

The modeling of combined active and passive cooling in the sizing method builds upon two key differences compared to the sizing with passive only. On the one hand, the upper temperature limit is raised as there is no need for a minimal temperature difference to ensure sufficient heat transfer between the fluid in the borefield and the to be cooled space. On the other hand, the compression step in the heat pump will generate additional heat which can be seen as an additional load on the borefield. Although this modeling principle is straightforward, the implementation is more complex and a double iterative approach is necessary as explained in the next paragraphs. Figure 5.1 demonstrates a schematic representation of the implemented algorithm in *Python*.

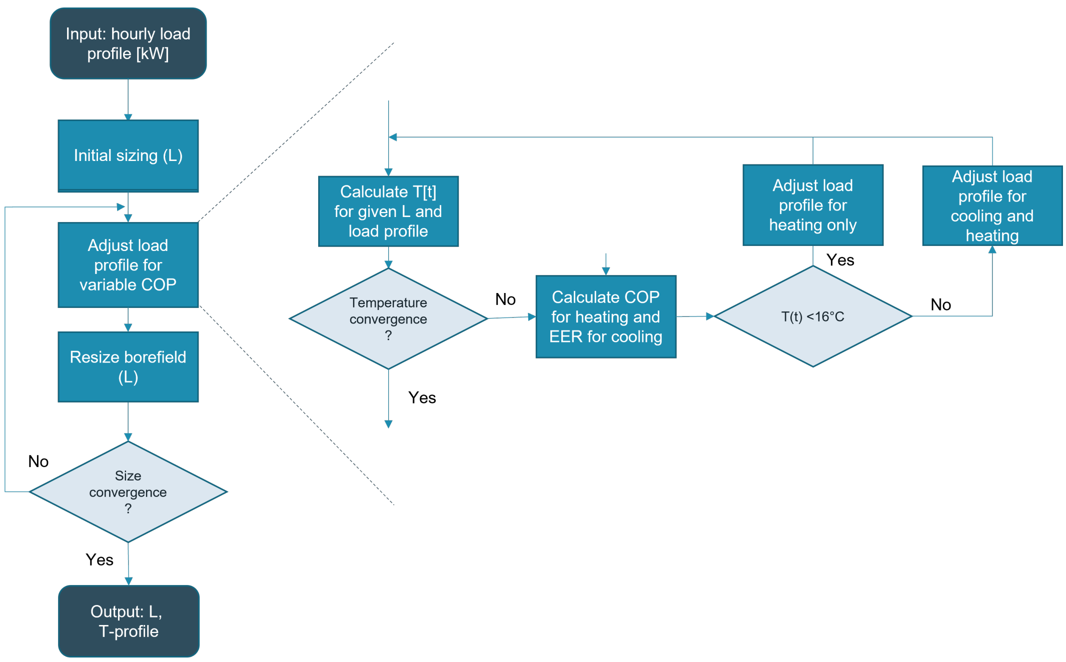


Figure 5.1: Flowchart describing the sizing methodology for combined active and passive cooling consisting of the outer loop (left) and the inner loop (right).

The algorithm starts with an hourly load profile which is required for accurately modeling the borefield behavior and to calculate its temperature profile. From Chapter 3 it is clear that using active cooling only does not lead to a cost efficient solution as active cooling is used at times when passive cooling could be possible[1].

[1]Passive cooling is considered to be possible up until 16 °C whilst the active cooling temperature

The main goal of the algorithm is thus determining when passive cooling is possible and when active cooling is necessary. As active cooling comes with an additional operating cost, passive cooling is preferred when possible.

The first step for the conceptual approach is the sizing of the borefield for the given load profile, as shown in Figure 5.1. The required borefield depth for each hour[2] is calculated as described in Equation (4.5). The largest required depth is chosen as the borefield size. Afterwards, the temperature profile over the total lifetime of the borefield is constructed using this computed borefield size. The load profile is then adapted to account for the additional heat dissipated in the borefield due to the temperature-dependent COP and EER of the heat pump. The new load profile will in turn lead to a different borefield size which makes an iterative approach necessary. This represents the outer loop of the double iterative process required to size the borefield for combined active and passive and is explained extensively in Section 5.1.1.

As mentioned before, the calculation is further refined by using a temperature-dependent COP and EER for heating and cooling. This allows for a more accurate computation of the operating costs of the borefield. An secondary effect of active cooling is also accounted for: the use of electricity for cooling will heat up the borefield additionally which increases the COP for the heating operation and therefore decrease the operating cost for heating.

The hourly COP and EER values are computed starting from the temperature profile for a given borefield size L. By taking these values into account, the additional dissipated heat into the borefield for cooling and diminished extracted heat for heating due to the compression step of the heat pump are represented. The load profile is therefore adapted to represent the actual load experienced by the borefield. The temperature profile is in turn constructed a second time, now using this adapted load profile after which the iteration continues until convergence of COP and EER values. The inner loop in Figure 5.1 represents this approach and is discussed in more detail in Section 5.1.2.

5.1.1 Iterative sizing methodology for combined active and passive cooling

The outer loop of the approach to size borefields with combined active and passive cooling is visualized on the left side of Figure 5.1 and focuses on the iterative sizing methodology. The following paragraphs each discuss a different step in this approach and are represented by a rectangular or diamond-shaped box in the flowchart. The first step sizes the borefield for the initial load profile. Next, the second step adjusts the load profile to account for the heat dissipation and extraction of active cooling

limit is chosen to be 25 °C. The motivation for these specific values is explained in Chapter 7.

[2] Each hour of the studied period is assumed to be the critical hour one by one. The necessary borefield size taking into account the load up until that hour is therefore computed.

and heating respectively. Subsequently, the third step resizes the borefield for the adjusted load profile. Finally, the fourth step verifies whether size convergence is achieved or an additional iteration is required.

First step The initial sizing of the borefield starts with the initial load profile and calculates for each time step t the required borefield size to stay within the temperature limits taking into account all previous loads. This is mathematically represented by Equation (4.5) where T_{lim} represents the relevant temperature limit for the heating or cooling regime. The relevant temperature limit for the heating operation is the lower temperature limit of 0 °C as the borefield cools down by extracting heat whereas the relevant limit for the cooling operation is the upper temperature limit of 25 °C as the borefield heats up by injecting heat. The sizing is therefore executed twice, once for each temperature limit. In order to ensure the temperature limits are not exceeded at any instance, the largest required borefield size over the full lifetime of the borefield is used as the necessary size for the load profile in this first step of the outer loop.

Second step Next, the temperature profile is calculated for the borefield size as explained in Section 4.2 and based on this, the load is modified to take into account the temperature-dependent COP and EER. In case the borefield fluid temperature exceeds the temperature limit for passive cooling, the load should be adapted to account for active cooling. The compression step of the heat pump will result in additional heat dissipated in the borefield in the case of active cooling. For the heating load, the heat pump is always used and therefore the heat injected into the building differs from the extracted heat from the borefield. This is because the additional heat produced by the compression step of the heat pump in heating operation is dissipated in the building and therefore reduces the necessary extracted heat from the borefield. The initial load is thus modified to the load experienced by the borefield.

The efficiency of the heat pump is used as a measure for the additional heat injection in the borefield when cooling or the reduced heat extraction when heating, is expressed in terms of COP for heating and EER for cooling. The COP and EER themselves depend on the temperature of the borefield fluid, which is further explained in Section 5.1.2. The reasoning above results in following formula for the effective load seen by the borefield:

$$Q_{diss}(t) = \frac{EER(t)+1}{EER(t)} Q_{cooling}(t) - \frac{COP(t)-1}{COP(t)} Q_{heating}(t) \tag{5.1}$$

where both the heating and cooling load is considered positive.

Third step In the next step, the iteration process uses the effective load profile from step two. The borefield is subsequently resized for this new load, which will result in a different temperature profile in the next iteration step.

Fourth step The final step in the iterative cycle is checking whether a size convergence has been reached by comparing the two most recent sizing results[3]. If convergence has been reached, the most recently computed borefield size and temperature profile are returned as final output. If not, the algorithm returns to the beginning of step two with the most recent sizing result as borefield size.

5.1.2 Adjust load profile for temperature-dependent COP and EER

Section 5.1.1 described the outer loop of the sizing methodology for combined active and passive cooling presented in Figure 5.1. The right hand side of this figure dives deeper into the way the load profile is adjusted for the temperature-dependent COP and EER. This section guides the reader through this part of the flowchart.

The data for the COP and EER values throughout this thesis are taken from measurements done on a heat pump of Galletti (type: WRE092HSG0) [29]. The in and output temperatures of both sink and source are listed in this data sheet for both heating and cooling operation. The cooling and heating operation of the heat pump assumes a 17°C / 20°C and 30°C/ 35°C regime for the heat emission system in the building. The implementation of the sizing algorithm uses average temperatures for the borefield fluid. Therefore, these values are converted into an average temperature for both sink and source. A linear correlation can then be found between the COP and EER and the fluid temperatures in the borefield, as shown in Figure 5.2.

The use of the temperature-dependent COP and EER is incorporated in the algorithm to model combined active and passive cooling as follows. After the initial sizing (see Figure 5.1), the temperature profile is calculated for that specific borefield size. When the temperature is known, the COP and EER for heating and cooling is easily calculated from the linear relationship shown in Figure 5.2 for each time step t. A change in COP or EER will influence the temperature profile as the effectively dissipated heat in the borefield varies with the COP and EER. To account for this effect, the heating load and cooling load are modified according to the corresponding COP and EER values for every hour to represent the effective load. The total load is thus modified at every time step in a similar manner as Equation (5.1). Note that the heating load is modified for all time steps whereas the cooling load is only modified if the temperature at that specific time instance exceeds the limit for passive cooling. If the temperature is below this limit, passive cooling is possible and no extra heat is dissipated in the borefield. After the modification, the temperature profile is reconstructed for the given borefield size. With this temperature profile,

[3]These two most recent sizing results corresponds to the sizing result of step three in the previous iteration with the sizing result of step three in the current iteration. In case of convergence in the first iteration, these two most recent sizing results correspond to the result of the initial sizing and the result of step three in the current iteration.

again, the COP and EER values at every hour are easily deducted from the linear relationships in Figure 5.2 and the load is again adjusted. This iterative process continues until the temperature profile remains constant[4] in two consecutive iteration steps. This iterative calculation represents the inner loop of the algorithm, which is a part of the larger outer loop of the algorithm.

(a) $COP = 0.122 \cdot T_f + 4.365$ (b) $EER = -0.3916 \cdot T_f + 17.901$

Figure 5.2: Graphical representation of the temperature dependency of the COP and EER [29].

5.2 Assumptions

The reasoning outlined in the previous section is built on four assumptions.

The first assumption is the use of a resulting input load profile in the temperature calculation and borefield sizing. Although the heating and cooling loads are used separately in the algorithm to account for the variable COP, the load seen by the borefield is always the resulting demand between cooling and heating. In case there is a demand for heating and cooling simultaneously, i.e. in the same hour, both are combined and only the resulting load will impact the borefield temperature. This assumption is justified because of the small time step in the modeling approach. If a monthly time resolution would have been used, it would be incorrect to use only the difference between cooling and heating for a particular month as both loads might occur at significant different moments.

The second assumption relates to the practical use of a heat pump. A bidirectional heat pump can both operate in heating and cooling operation, which both have different temperature regimes. Heat pumps used for active cooling usually operate in lower temperature regimes than the cooling regimes used for the COP calculation in Section 5.1.2. Therefore, the assumption is made that the heat pump used for combined active and passive cooling can operate in both of the temperature regimes considered in Section 5.1.2.

The third assumption relates to the high temperature cooling and low temperature heating regimes on the building side. The heat emission system in the building

[4]A maximal difference between two consecutive temperature profiles is used as a convergence criterion.

is assumed to be able to cool and heat the respective demand. Given the low temperature difference with the building, this heat emission system has to be large enough. This is often implemented by floor heating or concrete core activation in practice [9].

The fourth assumption involves the real operation of a heat pump. The algorithm assumes that the heat pump can switch between the heating and cooling regime and the active and passive cooling regime once an hour[5]. An eventual minimal up-time for the heat pump is not accounted for as these are usually well below the considered time step of one hour.

Key Takeaways

The key insights of this chapter are listed below.

- The use of an hourly load profile allows to create a detailed temperature profile over the lifetime of borefield. Herefore, the share of active cooling of the total cooling can be accurately determined.
- A double iterative approach is used to size the borefield with combined active and passive cooling. The outer loop sizes the borefield with an adjusted load every iteration. This adjusted load is constructed by accounting for the temperature-dependent COP and EER iteratively in the inner loop.
- The temperature-dependent COP and EER allow to consider the indirect effects of temperature variations within the borefield in the borefield sizing algorithm.
- The baseline assumptions in this conceptual approach involve the use of a resulting load profile for the borefield sizing, the temperature regimes in which the heat pump operates, the adequacy of the building's heat emission system and the minimal up-time of the heat pump.

[5]Please note that in practice an hourly oscillation between passive and active cooling is extremely rare.

Chapter 6

Economic optimization

The previous chapter developed a sizing approach for combined active and passive cooling by including a temperature-dependent COP and EER. The main research question of this master thesis aims to find the economic optimal share of active and passive cooling. The optimal share can be found by solving an economic optimization problem which uses the algorithm for sizing borefields with combined active and passive cooling as a starting point.

Section 6.1 conceptually explains the approach for the economic optimization. Its subsections elaborate on specific steps of the algorithm: the relevant cost components, the total cost curve and the optimization approach itself. Next, Section 6.2 lists the assumptions and limitations of this approach. Finally, this chapter concludes with a clear overview of the takeaway messages.

Together with Chapter 5, this chapter aims to answer the second part of the first scientific research question.

6.1 Conceptual approach

The economic optimum can be found by using the algorithmic approach proposed in Figure 6.1. The goal is to find the cost-efficient size of the borefield with for an optimal cooling strategy. The cost-efficient solution is defined as the lowest total costs over the full lifetime of the borefield, consisting of an upfront investment cost and an annual energy cost. This Total cost of ownership (TCO) of the borefield is compared for different borefield sizes and serves as the objective function of the optimization. This economic optimization is developed for research purposes and assesses the economical viability of using combined active and passive cooling in borefields. This implemented algorithm in *Python* can also be used as a tool to find the lowest cost solution for a real life borefield sizing.

First step First, the borefield is sized for passive and combined active and passive cooling to determine the two extreme borefield sizes, corresponding to the respective

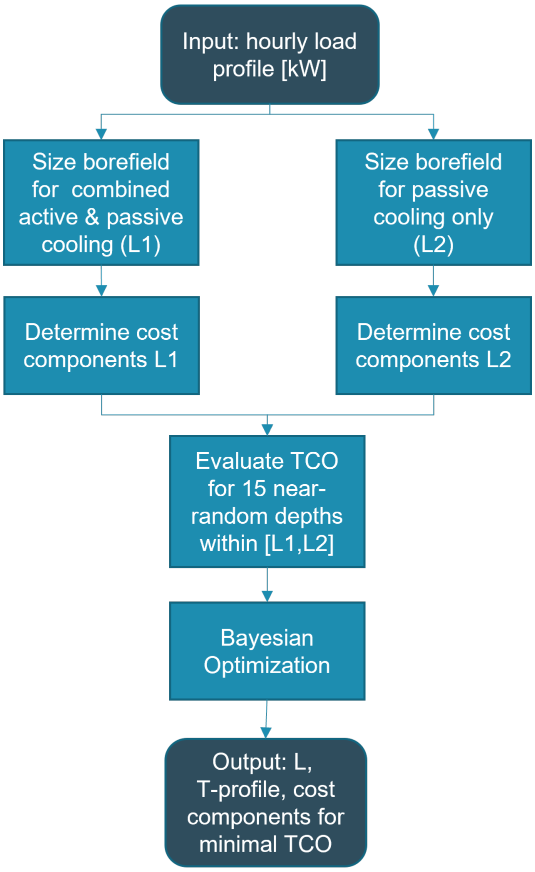


Figure 6.1: Flow chart describing the algorithm for the economic optimization.

maximum and minimum possibly interesting size. The smallest possible interesting borefield size L1 is a borefield optimized for a minimal depth when active cooling is allowed, i.e. if the temperature limit is raised from 16 °C to 25 °C. A smaller borefield is theoretically possible in case of regenerative heating and cooling, but is not considered in this work. An assessment of the potential of regenerative heating and cooling is an interesting follow-up work and further discussed in Chapter 10. The maximum interesting borefield size in economic terms is the classical sizing using passive cooling only, referred to as size L2. An oversized borefield would not be beneficial as the investment costs would rise without any savings in operating costs.

Second step Next, the relevant cost components for the economic optimization are evaluated for borefield sizes L1 and L2. The sizing process computes the temperature profile of the borefield fluid over the lifetime of the borefield with an hourly resolution. This allows to determine the operating costs for both heating and cooling, which are directly related to the COP and EER at each time instance. The investment cost is assumed to be a linear function of the borefield size [29]. A closer look on the calculation of the cost components is provided in Section 6.1.1. The underlying assumptions for this calculation are discussed extensively in Section 6.2.

The optimal borefield size corresponding to the lowest TCO must be one of the extreme values (L1 or L2) or somewhere in between. A conceptual explanation on the possibility of the optimum in between these two extreme values is provided in Section 6.1.2. In other words, the total costs are expressed as a function of the depth of the borefield with a minimum somewhere in between or at the two extreme values L1 and L2.

Third step Finally, the minimum of the TCO function has to be found by solving an optimization problem. The problem can be described as a non-convex optimization problem in two dimensions. Solving this is a mathematically complex task and there is no guarantee to reach the global optimum. This optimization problem is solved by means of Bayesian optimization [30] which starts with an evaluation of a vast amount of borefield depths in the size range between L1 and L2. This is further discussed in Section 6.1.3. The minimum of this function will then result in the most cost-efficient configuration for the given load profile.

6.1.1 Cost components of borefields

The relevant cost components are computed starting from the borefield size and the temperature profile. The Total Cost of Ownership (TCO) consists of all costs over the lifetime of the borefield: the investment costs and the yearly operation costs related to heating and cooling. This section focuses on these components. The main assumptions and neglected cost components are discussed in Section 6.2. In order to account for future cash flows, a discount rate r is considered. An example of the TCO computation for a borefield with a 50 year lifetime is presented in Equation (6.1).

$$TCO = C_{inv} + \sum_{i=1}^{50} \frac{C_{op,cool} + C_{op,heat}}{(1+r)^i} \tag{6.1}$$

The first cost component C_{inv} is the upfront investment cost of the borefield and consists of the costs for drilling, excavating, piping and the purchase costs of the heat pump [2]. The computation of this cost is rather straightforward as a direct relationship with the borefield depth is assumed. Additionally, a reversible heat pump is required in the case of active cooling that provides both heating and cooling opposed to the heat pump in the passive cooling case that is only used for heating. The cost of this heat pump is further discussed in Section 6.2.

The operating cost C_{op} related to heating is indirectly influenced by the use of active cooling. The use of active cooling will drive the heating costs both up- and downwards. On the one hand, by using active cooling more heat will dissipate in the borefield causing a higher fluid temperature. The COP for heating will be higher, as can be seen in Figure 5.2a. The electricity use is then smaller and therefore lower heating costs can be expected. On the other hand, borefields can be smaller when active cooling is used, which will drive down the borefield fluid temperatures during the heating period. A discussion on which effect is dominant is provided in Chapter 7. The energy cost does however not only consist of the electricity use for the compression step in the heat pump, also a cost for pumping the fluid through the borefield is present. This last cost is neglected as is further explained in Section 6.2.

The operating costs for cooling consist of energy costs for the compression in the heat pump and pumping costs. In case of passive cooling, only the cost for pumping the fluid through the borefield is present, which is again neglected.

The total energy costs related to heating and cooling P_{tot} are calculated by the following formula:

$$Q_{heat,el} = \frac{1}{COP} \cdot Q_{heat,load} \tag{6.2}$$

$$Q_{cool,el} = \frac{1}{EER} \cdot Q_{cool,load} \tag{6.3}$$

$$P_{tot,t} = P_{elec} \cdot (Q_{heat,el} + Q_{cool,el}) \tag{6.4}$$

where $Q_{heat,load}$ and $Q_{cool,load}$ represent the initial demand profiles, not the effective dissipated load into the borefield[1]. The electricity price is represented by P_{elec}. Equation (6.4) is evaluated at each time step and is summed for all t to find the total energy costs for heating and cooling.

6.1.2 Conceptual understanding of the cost-optimal solution

In order to find the cost-optimal solution for cooling of buildings with borefields, a good conceptual understanding of the problem is necessary. The algorithm shown in Figure 6.1 first calculates the two boundary depths L1 and L2 of the borefield before looking for the optimum. At first sight, the reader might conclude that optimizing active and passive cooling together for a minimal depth would yield the best solution, as the investment costs are minimized. But, as the cost-optimal solution refers to the case where the total costs (the investment and operating costs combined) are minimized, a dedicated optimization approach is necessary. The motivation for the approach is elaborated in this section, Section 6.1.3 discusses the technical approach to solve the problem.

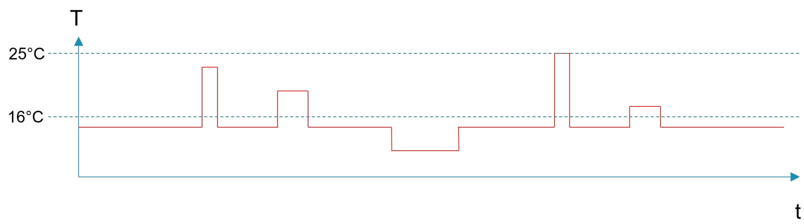
The minimum of the total cost function lies either in one of two extreme borefield depths L1 and L2 or somewhere in between. The minimal borefield size is found when active cooling is used at every instance the fluid temperature exceeds 16 °C. By increasing the borefield size slightly, the temperature profile gets compressed vertically[2] towards the undisturbed ground temperature. The share of active cooling

[1] Here both $Q_{heat,load}$ and $Q_{cool,load}$ are considered positive.

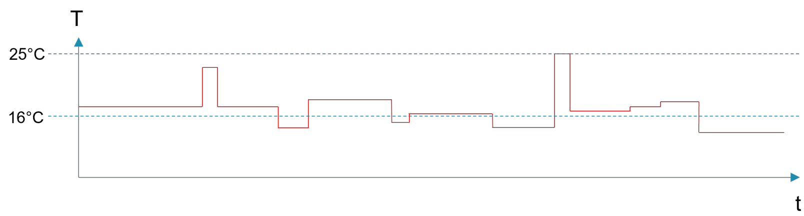
[2] The temperatures are pushed towards the current ground temperature of the borefield, i.e. all temperatures move away from their closest temperature limit. Visually, this corresponds to a vertical compression.

might decrease significantly if active cooling occurs frequently for an average fluid temperature just above the 16 °C boundary. Therefore, a small increase in borefield size could result in a relatively large decrease in share of active cooling. The small increase in investment costs is then compensated by a larger operation cost saving. By constructing the total cost curve, the eventual existence of this optimum between the two extreme values is identified.

The reasoning above also indicates that the shape of the load profile, and therefore the temperature profile, gives a clear indication on the potential of combined active and passive cooling. If the profile is characterized by large peaks in the demand, the potential for combined active and passive cooling is larger as the borefield size is mainly determined by these peaks and to a lesser extent by the average load. By increasing the borefield size and thus the investment costs, a limited operating cost reduction is achieved as only the peaks are cooled in an active way (see Figure 6.2a). For load profiles with smaller peaks and a larger average load, the operation costs are much higher and a larger share of the active cooling demand can be mitigated by the same increase in borefield size (see Figure 6.2b). The potential of active and passive cooling might be determined by using a few rules of thumb following from the insights developed in this master thesis. This is further discussed in Chapter 10.



(A) Hypothetical temperature profile with high potential for active cooling.



(B) Hypothetical temperature profile with low potential for active cooling.

FIGURE 6.2: Graphical representation of hypothetical temperature profiles with high potential and low potential for active cooling.

6.1.3 Bayesian Optimization

The total cost function is typically a non-convex function which makes it difficult to find the global optimum. Additionally, a function evaluation consists of the construction of the whole temperature profile with an hourly temporal resolution, making them computationally expensive. The use of Bayesian optimization allows to

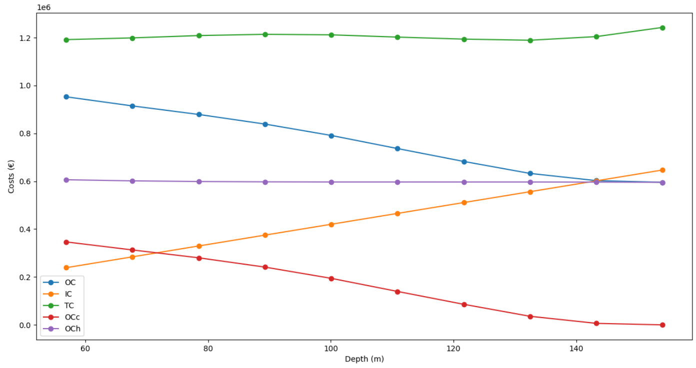


Figure 6.3: Figure showing a situation where an advanced optimization strategy is needed to find the minimum of the total cost curve. An unlucky choice of equidistant evaluations might miss the actual minimum.

find the global minimum with a high certainty in a computationally efficient manner. Note that finding the global minimum of a non convex function with a 100% certainty is mathematically impossible. The optimization approach is explained conceptually without a rigorous mathematical description in this work. The reader can, if desired, consult [30] for a deeper mathematical understanding of the Bayesian optimization approach.

Naturally the shape of the total cost function is not known a priori. And its function values can only be found by using expensive function evaluations. One, relatively simple, search strategy for the minimum of the TCO would be to evaluate the total cost function for multiple equidistant values of borefield size. This approach may result in significantly wrong conclusions. To understand this, Figure 6.3 is studied. When looking more carefully at the total cost (TC) curve, it is not immediately clear whether the minimum is located around 130 meters or it at the leftmost point of the TC curve (which corresponds to the minimal borefield size possible for that particular load profile). The actual minimum is located around 130 meters. As the TCO at these two potential minima is nearly equal, an unlucky choice of the equidistant evaluations might miss the actual minimum around 130 meters.

The aforementioned problem can be avoided by increasing the amount of evaluations, but this will result in a large increase in computational time. By using an optimization method for global optimization like Bayesian optimization, this issue is avoided.

The conceptual principle of Bayesian optimization is shown in Figure 6.4 [31]. As mentioned before, the expensive to evaluate TC function increases the complexity of the optimization. Therefore, a surrogate model of the objective function which is easy to evaluate is created [32]. The optimization approach starts with a set amount of near-random function evaluations of the TC function (called observations) between

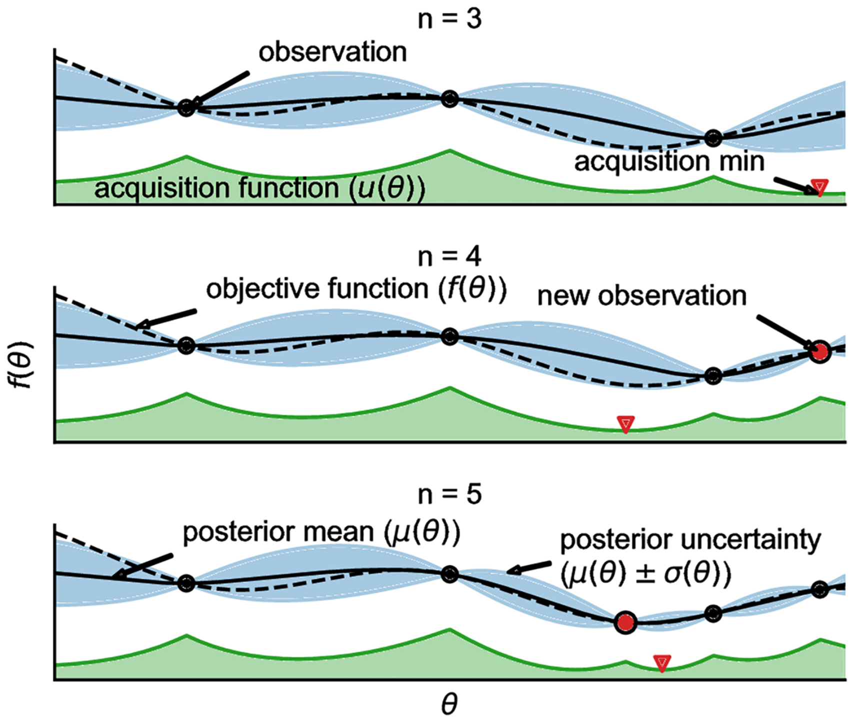


FIGURE 6.4: Graphical representation of the Bayesian optimization strategy [31].

L1 and L2 to create this surrogate model. These near-random evaluations use Latin Hypercube Sampling, which divides the interval into equally probable sub-intervals. In each of these sub-intervals, one random sample is taken [33]. The probabilistic surrogate model is built from these observations by using Gaussian processes. This model is represented by the shaded area in Figure 6.4. The lower boundary of this area is called the acquisition function. As this function is easy to evaluate, the minimum of this function can be easily found. The argument corresponding to the minimum of this function is then chosen as the next depth to evaluate the TC function and added as an additional observation. The process where a surrogate model is constructed is now repeated with this additional data point, which improves the accuracy of the model. In other words, the Bayesian optimization selects its costly function evaluations in an efficient way. This iterative process is repeated for a fixed amount of steps and finally results in a very good approximation of the global minimum of the TC function.

The Bayesian optimization is implemented in the *Python* tool using a *Python* package developed by Scikit [34]. The approach explained in this section has major applications in determining the hyperparameters of neural networks and other black box functions[35] in other research.

6.2 Assumptions

The investment costs of the borefield consists of the costs for drilling, excavating and piping. These are grouped together in a constant cost per meter borefield length. The purchase costs of the heat pump is omitted in the optimization given the assumption that this cost is the same with and without active cooling. This assumption is made because the heat pump for heating can be used bidirectionally, which makes the purchase of an additional heat pump unnecessary. This reasoning does not represent real-life situations in all cases correctly as, depending on the load profile, the size of the heat pump might differ. Furthermore, the price of this bidirectional heat pump is in general higher than its more traditional counterpart.

The operating costs consist of the energy costs for the compression step and the pumping of the borefield fluid. The latter is often negligible compared to the electricity costs for the compression in the heat pump. The calculation is further simplified by assuming a constant electricity price, apart from the inflation rate.

For the economic analysis, reasonable assumptions on the discount rate and the inflation rate for the electricity price have to be made. The nominal discount rate is assumed to be 5%, the inflation rate for electricity use is calculated from Eurostat for the period 2012-2021. The Harmonised Index of Consumer Prices (HICP) for electricity increased from 99.85 to 156.36 between 2012 and 2021 resulting in a yearly 5.11 % inflation for electricity in Belgium, which is higher compared to other member states[36]. The real discount rate is then computed by using Fishers formula:

$$DR_{real} = DR_{nom} - R_i = 5.00\% - 5.11\% \approx -0.11\% \tag{6.5}$$

Key Takeaways

The key insights of this chapter are listed below.

- The total cost of ownership of a borefield is driven by two main cost components: the investment costs and the operating costs related to energy use.
- The minimal relevant borefield size L1 corresponds to combined active and passive cooling operation optimized to minimal investment costs. The maximal relevant borefield size L2 corresponds to passive cooling only.
- The minimal TCO could be located at the two extreme values (L1 or L2) or in between these depths.
- Bayesian optimization is used to determine an eventual optimum in between the two extreme borefield sizes L1 and L2.
- Heat pump investment and pumping costs are neglected as they are assumed to be the same in active and passive cooling operation.

Part III

Insights

Chapter 7

Results

The methodology to assess the potential of combined active and passive cooling is conceptually elaborated and discussed in detail in Chapters 4 to 6. The conclusions of the preliminary study are revisited with a more accurate calculation tool due to the hourly time resolution and temperature-dependent COP and EER incorporated in the algorithm. This chapter, together with Chapter 8, aims to provide an answer to the first engineering research question. Also, it forms the basis on which Chapter 11 answers the main research question of the thesis.

The developed methodology is now applied to different cases for all four borefield quadrants while keeping in mind the conclusions of the preliminary study. The approach to get to the final results is discussed in Section 7.1. The results are then shown in Section 7.2 with a short discussion for each borefield quadrant separately. Finally, these results are interpreted and general conclusions are drawn in Section 7.3.

7.1 Approach for assessing the potential of combined active and passive cooling

The approach to assess the potential of combined active and passive cooling consists of four steps, each discussed separately. The first step revisits the preliminary study and the concept of the four borefield quadrants in Section 7.1.1. This allows the reader to understand the results discussed in this chapter in a more insightful way. The results are obtained by conducting multiple case studies which make use of synthetic load profiles that are introduced in Section 7.1.2. The third step introduces a preliminary calculation of the CO_2 emissions associated with active cooling and links these with the cost savings compared to passive cooling via the abatement cost in Section 7.1.3. Finally, the input values and assumptions for the optimization approach are listed and explained in Section 7.1.4.

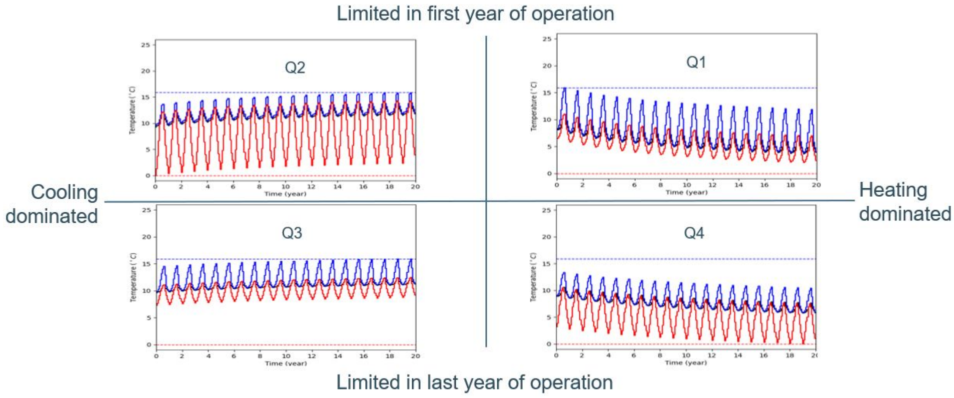


Figure 7.1: Spatial representation of the four borefield quadrants from Chapter 3.

7.1.1 Recap preliminary study: conclusions on four borefield quadrants

The preliminary study introduced four borefield quadrants that categorize the load profiles in terms of dominating load and limiting year of operation. These quadrants are presented visually in Figure 7.1. Note that the temperature profiles when including active cooling operation for the same load might point towards other quadrants as the limiting year might change[1]. Therefore, a load is assigned to a quadrant based on its temperature profile when considering passive cooling only, independent of the behavior of the temperature profile when active cooling is considered.

The first borefield quadrant describes a heating dominated load profile with a limitation in the first year of operation for passive cooling due to its high cooling peaks. The high cooling peaks make the maximum temperature limit binding. By allowing a higher fluid temperature, the borefield size is reduced. Load profiles in this quadrant indicate a large potential for combined active and passive cooling, as is extensively discussed during the preliminary study.

The second borefield quadrant is characterized by a cooling dominated load profile with a limitation in the first year of operation. The high heating peaks associated with load profiles in this quadrant cause sharp declines in the average fluid temperature. Therefore, the minimum temperature limit is binding. The benefit of active cooling, i.e. raising the maximum temperature limit, does not influence the sizing and temperature of the borefield. The preliminary study concluded that there is no potential for active cooling in this quadrant.

The third borefield quadrant comprises cooling dominated load profiles with a limitation in the final year. The dominant cooling peaks in combination with a rising average borefield temperature over the lifetime of the borefield will cause the

[1] The limit of 16 °C for passive cooling used in this thesis is thus raised to 25 °C for active cooling.

temperature profile to reach the maximum temperature limit in the final year. The preliminary study already indicated that load profiles in this quadrant have a high potential for using combined active and passive cooling.

Finally, the fourth borefield quadrant describes heating dominated load profiles with a final year limitation. The minimum temperature limit is binding, which means there is no potential for active cooling. This was already concluded in the preliminary study.

The preliminary conclusions made in Chapter 3 summarized above will now be revisited with the newly developed methodology. The more accurate calculation with the hourly load profiles and temperature-dependent COP and EER allows to confirm or discard these conclusions and provide additional insights and conclusions.

7.1.2 Construction of synthetic load profiles

The economic optimization methodology developed in Chapter 6 is applied to specific load profiles with the objective of evaluating the potential for combined active and passive cooling. Three types of synthetic load profiles are used for each quadrant to draw conclusions based on the shape of the load profile. This results in a set of profiles with high and low expected potential for using active in combination with passive cooling. This section will elaborate on the mathematical description of these load profiles. The shape of the load profiles is described with continuous sinusoidal functions and converted into discrete functions for the case-specific loads.

Profile A The first load profile describes a sinusoidal load, mimicking seasonal variations in heating and cooling load. No periodic daily variations are included in this load profile. Therefore, the borefield does not have the opportunity to cool down which will result in a large share of active cooling and a high operating cost.

The shape of the load profile is described as

$$Q_{heat} = A \cdot sin^{+}\left(2\pi f_0(t - t_0)\right) \tag{7.1}$$
$$Q_{cool} = B \cdot sin^{+}\left(2\pi f_0(t - t_0)\right) \tag{7.2}$$

with t the time expressed in hours. A and B represent the amplitude of the heating and cooling load respectively in kW, f_0 the frequency of the load and t_0 the phase shift indicating when the load starts. The choice for t_0 depends on the instance the borefield is used for the first time. If hour 0 corresponds to January first, t_0 will be positive for the cooling load and negative for the heating load. Note that only the positive values of the sine function are used, negative values are set to zero (indicated by sin^{+}).

Profile B1 The second synthetic load profile to assess the economic potential of combined active and passive cooling is constructed by combining two sinusoidal shapes. This is mathematically represented by a multiplication of two sine functions, one for the seasonal variations, the other for the daily fluctuations as can be seen in Equations (7.3) and (7.4).

$$Q_{heat} = A \cdot \left| sin\left(\frac{2\pi t}{48}\right)\right| \cdot sin^{+}(2\pi f_0(t-t_0)) \tag{7.3}$$

$$Q_{cool} = B \cdot \left| sin\left(\frac{2\pi t}{48}\right)\right| \cdot sin^{+}(2\pi f_0(t-t_0)) \tag{7.4}$$

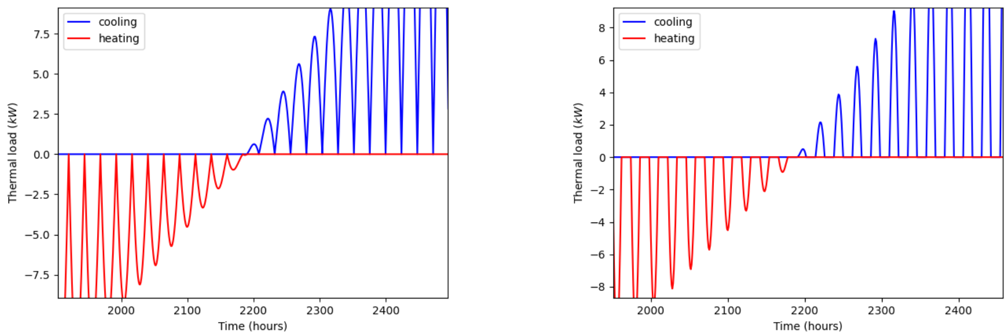
These equations assume a frequency of $\frac{1}{48h}$ for the daily fluctuations. Taking the absolute value of this sinusoidal shape allows to construct a recurring daily load with the duration of a half period. Therefore, the load is present 24 hours a day.

Profile B2 The third synthetic load profile is a variation on the previous load profile. The daily load consists now of 12 hours of load during the day and no load during night time. This load profile aims to represent a realistic load profile in, for example, office buildings:

$$Q_{heat} = A \cdot sin^{+}\left(\frac{2\pi}{24}(t-6h)\right) \cdot sin^{+}(2\pi f_0(t-t_0)) \tag{7.5}$$

$$Q_{cool} = B \cdot sin^{+}\left(\frac{2\pi}{24}(t-6h)\right) \cdot sin^{+}(2\pi f_0(t-t_0)) \tag{7.6}$$

The difference between Profile B1 and B2 is shown in Figure 7.2. Both have a daily load variation but in profile B1, there is a load 24 hours a day opposed to only 12 hours in profile B2. The seasonal variation is also visible in both figures as the amplitude of the daily sinusoidal variation increases.



(A) Load profile B1 (B) Load profile B2

Figure 7.2: Comparison of the daily variations of load profile B1 and B2.

The frequency and phase shift of these load profiles are adapted to correspond to a typical load profile for one of the four borefield quadrants. The complete formulations are shown in the relevant sections.

7.1.3 CO_2 emissions associated with the use of active cooling

Passive cooling of buildings by means of borefields avoids CO_2 emissions from the electricity use of the heat pump. The emissions related to the fluid circulation pump energy are neglected in this work (Section 6.2). Using active cooling in combination with passive cooling has the advantage to reduce investment costs for borefields, but is characterized by significant operation costs related to electricity use. This also results in additional CO_2 emissions, which are shortly touched upon in the discussion of the results. An in-depth research on the additional emissions for active cooling and a life cycle analysis of borefields is a potential topic for future work (Chapter 10).

The CO_2 emissions related to the share of active cooling in the optimal solution are computed directly from the electricity consumption for cooling[2]. The total emissions are then calculated by multiplication with the average emissions per kWh in Belgium, equal to 127 g/kWh in 2021 [37]. Note that these emissions are different around the world and Belgium traditionally has a low carbon intensity for its electricity production due to its nuclear capacity. It is important to keep in mind that these emissions show a declining trend towards the future, in accordance with the climate targets [38].

The additional emissions from active cooling have to be compared with the cost savings over the lifetime of the borefield. Therefore, the concept of abatement cost is introduced.

$$C_{abatement} = \frac{\Delta TCO}{\Delta E} \tag{7.7}$$

In Equation (7.7), ΔTCO represents the change in total costs over the lifetime of the borefield and ΔE represents the change in emissions. In other words, the abatement cost represents the cost to avoid 1 ton of CO_2 emissions emitted indirectly by the heat pump due to active cooling. CO_2 reductions with lower abatement costs can therefore be seen as a more efficient allocation of financial resources, which makes abatement costs a useful tool to compare the effectiveness of different technologies [39]. This abatement cost is calculated for the optimal solution compared to the passive cooling baseline case and provides a link between CO_2 and cost savings[3]. This abatement cost can be compared to the EU ETS allowances price, which is currently equal to roughly 80 EUR/ton CO_2 [40].

This preliminary calculation of the CO_2 emissions serves merely to give the reader the full picture of the advantages and disadvantages of using active cooling and to put the associated emissions in perspective. Furthermore, this abatement cost is used as a way to link the cost savings to its emissions but can not be used as a sole decision mechanism on which investment should be prioritized. This is due to the

[2]By using active cooling, the emissions related to heating will slightly decrease as the average COP increases due to higher borefield temperatures. This change in emissions from heating is considered as a second order effect and neglected in this initial estimation.

[3]The reasoning is thus turned around: the use of passive cooling only is seen as an additional investment compared to combined active and passive cooling which reduces the emissions.

discrepancy between short and long term CO_2 targets and potential gains of learning by doing, which is not accounted for in the abatement cost [39].

7.1.4 Assumptions

Variable	Value
Lifetime of the borefield	50 years
Temperature dependent COP	-0.3916T_{fluid} + 17.901
Temperature dependent EER	0.122T_{fluid} + 4.365
Maximum temperature limit for the fluid for passive cooling	16 °C
Maximum temperature limit for the fluid for active cooling	25 °C
Minimum temperature limit of the fluid	0 °C
Electricity price	0.2159 EUR/kWh
Borefield investment cost	35 EUR/m
Real discount rate	-0.11%
Carbon intensity electricity production	127 g/kWh
Conductivity of the soil	2.1 W/mK
Undisturbed ground temperature	11 °C
Equivalent borehole resistance	0.12 K/W
Width of borefield	8 boreholes
Length of borefield	8 boreholes
Borehole spacing	6 m

Table 7.1: Numerical values of the assumptions made in Chapter 7.

The assumptions to assess the potential of combined active and passive cooling are adapted compared to the preliminary study, as more research on the specific parameters was conducted. This section focuses on the numerical assumptions and the assumptions for the conceptual approach. The limitations of the model are already touched upon in Sections 5.2 and 6.2.

The lifetime of a borefield is assumed to be 50 years in accordance with the requirements for materials used in borefields of the technical guidance published by WTCB [41]. The maximal fluid temperature allowed in the borefield is set at 25 °C, again according to the WTCB guidelines. The minimal temperature of 0 °C is set to avoid freezing. This value varies in practice depending on the type of fluid used. The maximum temperature for passive cooling is set at 16 °C to ensure a minimal temperature difference between the fluid in the borefield and the fluid in the circuit in the building.

The electricity prices are set for non-household consumers with an annual consumption between 20 MWh and 50 MWh with taxes and levies included. This price was 0.2159 EUR/kWh on average in 2021 in Belgium according to Eurostat [42]. The real discount rate is set at -0.11% and is a combination of the market interest rate and inflation for energy prices. A clear explanation on the methodology to calculate this discount rate is provided in Section 6.2. The investment costs for the borefield are set at 35 EUR/m. [29].

The physical parameters are also listed in Table 7.1. The conductivity of the soil is set at 2.1W/mK and lies in the range for typical values for different soil types in Belgium. The undisturbed ground temperature is set at 11 °C, as this is on average between 10 °C and 12 °C in Belgium. The equivalent borehole resistance is set at 0.12K/W. These physical parameters are discussed extensively in [41] and chosen based on this information.

The borefield configuration is for all cases in this chapter set at a square configuration with 8 x 8 boreholes and 6m spacing between different boreholes.

7.2 Results

The potential of combined active and passive cooling is assessed by applying different synthetic load profiles, outlined in Section 7.1.2, to each borefield quadrant separately. This section presents the results of these case studies. An insightful discussion and the interpretation of the results of this section is provided in the next section (Section 7.3).

7.2.1 Quadrant 1: Heating Dominated and First Year Limited

The first borefield quadrant represents a heating dominated and first year limited load profile for passive cooling operation. This quadrant is characterized by high cooling peaks, that cause a maximum temperature limitation for passive cooling.

Profile A

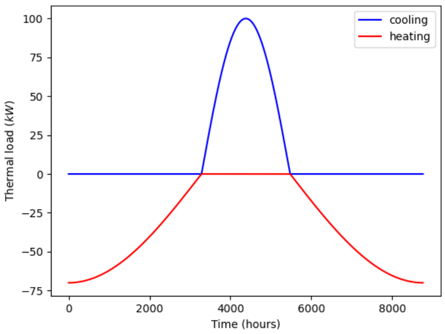
The first case corresponds to a load profile with only a seasonal variation, shown in Figure 7.3a. The mathematical description of this load profile is as follows:

$$Q_{heat}[t] = 70kW \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t + 3 \cdot 8760/8]\right) \quad \forall t \in [0, 3285] \tag{7.8}$$

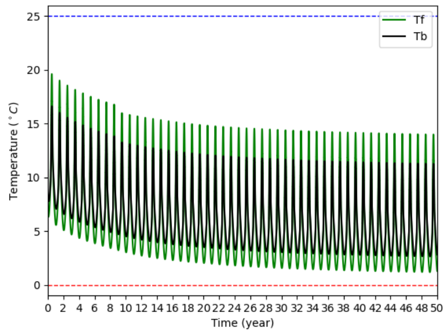
$$Q_{cool}[t] = 100kW \cdot sin\left(\frac{2\pi}{0.5 \cdot 8760} \cdot [t - 3 \cdot 8760/8]\right) \quad \forall t \in [3285, 5475] \tag{7.9}$$

$$Q_{heat}[t] = 70kW \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t - 5 \cdot 8760/8]\right) \quad \forall t \in [5475, 8760] \tag{7.10}$$

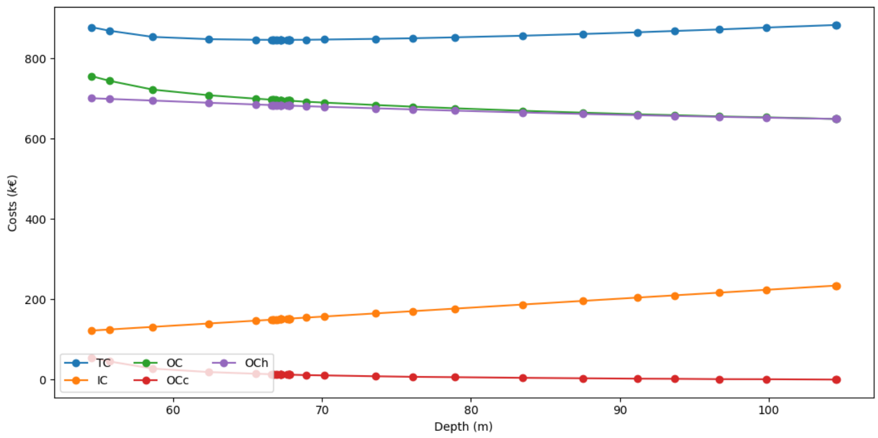
The shift in phase angle corresponds to a short but intense cooling period of only 3 months with a maximum amplitude of 100kW. The heating period lasts 9 months and has a maximum amplitude of 70kW. Therefore, the heating load dominates and results in a negative imbalance. The temperature profile thus shows a declining course over the lifetime of the borefield due to this heating dominated load, as shown in Figure 7.3b. Here, T_f represents the average fluid temperature in the borefield whereas T_b represents the borehole wall temperature.



(A) Load profile used for case A in quadrant 1.



(B) Resulting temperature profile over the lifetime of the borefield.



(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 67.2m.

Figure 7.3: Results for case A in borefield quadrant 1: heating dominated and first year limited profile with seasonal load variations.

All the cost curves relevant for the economic optimization are shown in Figure 7.3c. The TC function has a U-shape with an optimum in between the two extreme borefield sizes. The OC curve declines for an increasing borefield depth mainly due to the decrease in operating costs for cooling (OCc), as the share of active cooling decreases to zero. The operation cost for heating (OCh) is constant at first sight over the borefield depth interval but shows in reality a slightly declining behavior due to the temperature-dependent COP[4].

[4]Smaller borefields are characterized by larger temperature variations, both upwards en downwards. Therefore, the minimal temperatures are lower and these are most relevant for the heating regime. The COP for heating is lower for these lower borefield fluid temperatures which causes the

The optimal borefield depth for load profile A is 67.2m with a total cost of 846 kEUR. This is a cost saving of 37.2 kEUR compared to the use of passive cooling only. This is in between the two extreme borefield depths of 54.5m and 104.6m. Note that the temperature does not reach its upper and lower limit as the optimum is located between the two extreme borefield sizes. These extreme sizes are, per definition, bounded by their relevant temperature limit. The share of active cooling in this economic optimum is 9.1%, which explains the relatively low operating costs for cooling compared to the operating costs for heating. It is also clear from the figure that Bayesian optimization focuses its function evaluations close to the optimum.

The CO_2 emissions for the cooling operation in this optimum over the 50 year lifetime of the borefield are equal to 7.4 tons of CO_2. The abatement cost for using passive cooling instead of combined active and passive cooling is equal to 5054 EUR/ton CO_2.

Load profile B1

The second case adds daily variations to the load profile of the first case. The daily load has a sinusoidal shape with a duration of 24 hours. The mathematical description of the load profile is represented by following equations

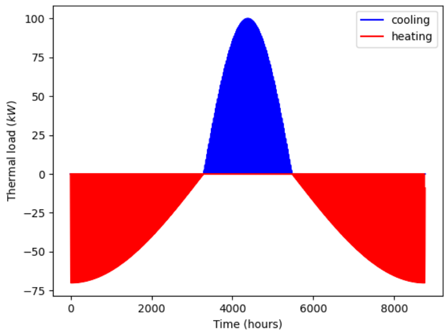
$$Q_{heat}[t] = 70kW \cdot \left| sin\left(\frac{2\pi}{48}[t]\right)\right| \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t + 3 \cdot 8760/8]\right) \quad (7.11)$$
$$\forall t \in [0, 3285]$$
$$Q_{cool}[t] = 100kW \cdot \left| sin\left(\frac{2\pi}{48}[t]\right)\right| \cdot sin\left(\frac{2\pi}{0.5 \cdot 8760} \cdot [t - 3 \cdot 8760/8]\right) \quad (7.12)$$
$$\forall t \in [3285, 5475]$$
$$Q_{heat}[t] = 70kW \cdot \left| sin\left(\frac{2\pi}{48}[t]\right)\right| \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t - 5 \cdot 8760/8]\right) \quad (7.13)$$
$$\forall t \in [5475, 8760]$$

The only difference compared to the first case is the multiplication with an additional sinusoidal term representing the daily variations.

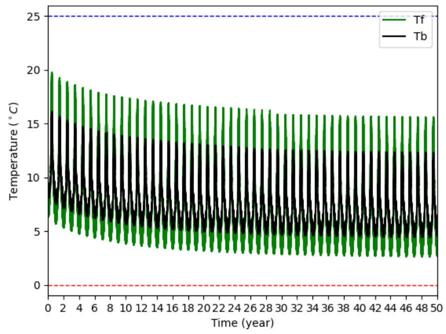
The costs curves for the second case are shown in Figure 7.4c. The various cost components of the TCO as a function of the borefield depth are similar to the cost components in case A. A clear difference is the ratio of the total costs for the two extreme borefield sizes: the TC for the maximum borefield size compared to the TC for the minimum borefield size is smaller in case A than in case B1. Therefore, using combined active and passive cooling is comparatively more interesting for the load profile with daily variations.

The optimal borefield size for the second case is 54.3m with a TC of 548 kEUR. This optimum lies in between the two extreme borefield sizes of 34.9m and 86.4m. By

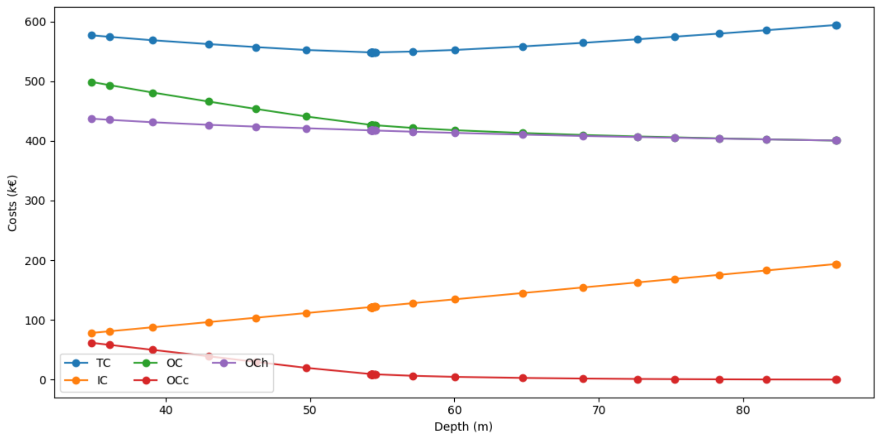
slightly declining operating costs for heating for increasing borefield depth



(A) Load profile used for case B1 in quadrant 1.



(B) Resulting temperature profile over the lifetime of the borefield.

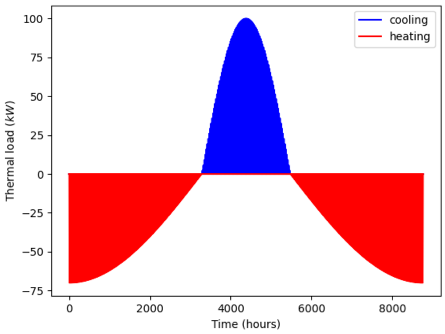


(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 54.3m.

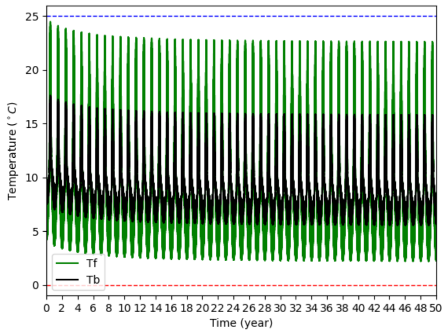
Figure 7.4: Results for case B1 in quadrant 1: heating dominated and first year limited profile with seasonal and 24-hour daily load variations.

using combined active and passive cooling instead of passive cooling only, a cost saving of 45.9 kEUR is achieved. The temperature limits are therefore again not binding. The share of active cooling is 10.6% which is in the same order of magnitude as the first case.

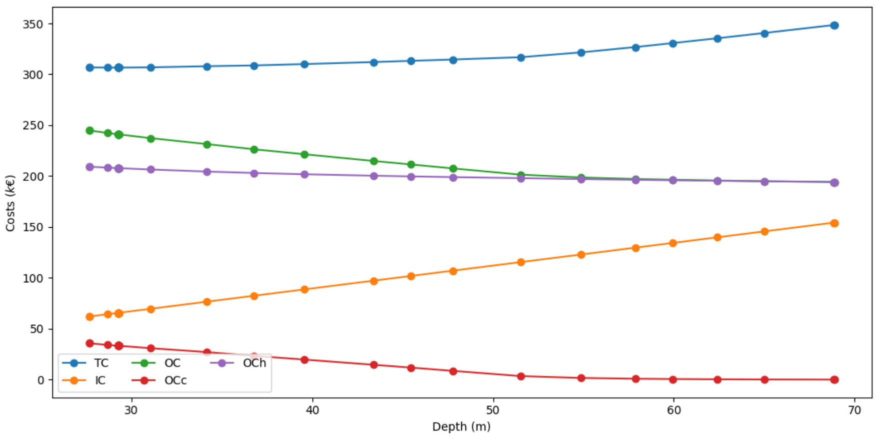
The CO_2 emissions for a borefield with a depth of 54.3m and a share of 10.6% active cooling are 5.3 tons of CO_2 in 50 years. This corresponds to an abatement costs of 8597 EUR/ton CO_2, which is higher compared to the first case.



(A) Load profile used for case B2 in quadrant 1.



(B) Resulting temperature profile over the lifetime of the borefield.



(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal depth is 28.7m

FIGURE 7.5: Results for case B2 in quadrant 1: heating dominated and first year limited profile with seasonal and 12-hour daily load variations.

Load profile B2

The third case for Q1 is very similar to case B1 with only daily loads of 12 hours instead of 24 hours as shown in Figure 7.2. This is mathematically shown by:

$$Q_{heat}[t] = 70kW \cdot sin^{+}\left(\frac{2\pi}{24}[t-6]\right) \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t + 3 \cdot 8760/8]\right) \quad \forall t \in [0, 3285] \tag{7.14}$$

$$Q_{cool}[t] = 100kW \cdot sin^{+}\left(\frac{2\pi}{24}[t-6]\right) \cdot sin\left(\frac{2\pi}{0.5 \cdot 8760} \cdot [t - 3 \cdot 8760/8]\right) \quad \forall t \in [3285, 5475] \tag{7.15}$$

$$Q_{heat}[t] = 70kW \cdot sin^{+}\left(\frac{2\pi}{24}[t-6]\right) \cdot sin\left(\frac{2\pi}{1.5 \cdot 8760} \cdot [t - 5 \cdot 8760/8]\right) \qquad (7.16)$$
$$\forall t \in [5475, 8760]$$

The cost curves shown in Figure 7.5c clearly differ from case A and B1. The difference in TC between the maximum borefield size and the minimum borefield size is smaller in case A and B1 than in case B2. Therefore, using combined active and passive cooling is comparatively more interesting for the load profile B2 than for B1 and A.

Although the optimal depth of 28.7m is still in between the two extreme borefield depths, it is very close to the maximal combined active and passive cooling depth L1 of 27.7m. This results in a TC of 307 kEUR and a cost saving of 41.9 kEUR compared to passive cooling only. The share of active cooling in this optimum is equal to 69.9 %, which is clearly higher compared to profile A and B1. Note that the total yearly load in this case is much smaller compared to previous cases as there are 12 hours a day without any load.

The CO_2 emissions for the economic optimal borefield are 19.5 tons of CO_2, which is clearly higher than for load profile A en B1. This can be explained by the larger share of active cooling and thus the larger electricity consumption. The abatement cost is 2152 EUR/ton CO_2, which is lower than for profile A and B1.

Conclusions on Q1

The three different load profiles all indicate that there is large potential for using combined active and passive cooling. The optima are in between the two extreme borefield sizes L1 and L2, with an optimum closer to maximal combined active and passive cooling depending on the load profile.

Although there is clear potential, it is incorrect to state that using combined active and passive cooling is always useful in this quadrant. This has to be verified for each load profile separately because the load profile itself clearly influences the cost curves. More varying load profiles, like profile B2, tend to have a higher potential for using combined active and passive cooling in Q1 because this gives the borefield the opportunity to cool down and operate more in the cheaper passive cooling regime.

The share of active cooling in case B2 is higher compared to case A and B1. This can be explained by the location of the economic optimum on the TC curve. For case A and B1, this optimum is not located close to borefield size L1, therefore the maximal temperature limit of active cooling is not reached which reduces the average fluid temperature over the lifetime of the borefield. The optimum in case B2 is close the borefield size L1, therefore the average fluid temperature is very close to the maximum temperature limit which results in an increased share of active cooling.

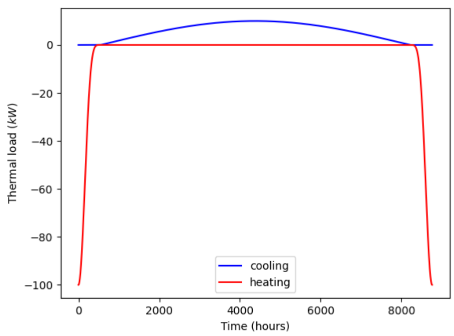
This quadrant is characterized by a heating dominated load profile which translates into low operation costs for cooling because of three reasons. Firstly, the absolute cooling demand is per definition smaller than the absolute heating demand. Secondly, due to the declining yearly fluid temperatures over the lifetime of the borefield, the yearly share of active cooling declines also[5]. Thirdly, the EER for cooling is in general higher than the COP for heating, which is not case specific. Therefore, the additional costs for active cooling (OCc-curve) are limited in respect to the total costs.

A decrease in borefield size starting from L2 causes the cooling load in the first few years to switch from passive cooling to active cooling. Due to the downward-curving shape of the temperature profile in quadrant 1 (higher temperature in the first years), the operating cost increase remains modest whilst a large reduction in the investment cost can be realized up until the optimal borefield size.

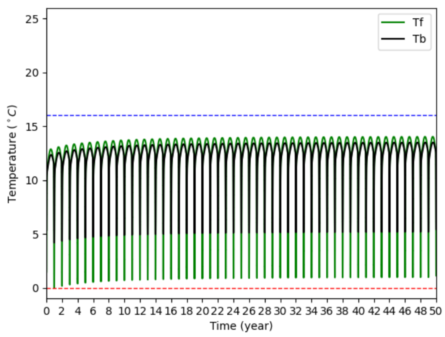
An advantage of having the optimal borefield size in between the two extreme borefield sizes (L1 and L2) is that the average fluid temperature at the end of the lifetime of the borefield does not coincide with a temperature limit. This means the borefield can still be used for heating and cooling after year 50.

The abatement costs for the different load profiles are all in the range of 2000-9000 EUR/ton CO_2, which is high compared to the benchmark price of 80 EUR/ton CO_2 of the EU ETS allowances. This high abatement cost is due to the large costs savings by using combined active and passive cooling and the relatively low additional emissions. Therefore, this is an additional confirmation of the potential for combined active and passive cooling: large cost savings can be achieved without a large impact on emissions.

7.2.2 Quadrant 2: Cooling Dominated and First Year Limited



(A) Load profile used for case A in quadrant 2.



(B) Resulting temperature profile over the lifetime of the borefield.

FIGURE 7.6: Results for case A in borefield quadrant 2: cooling dominated and first year limited profile with seasonal variations.

[5]Due to declining fluid temperatures, the passive cooling temperature limit of 16 °C is exceeded less frequently.

The second quadrant represents a cooling dominated load profile with large heating peaks, resulting in a first year limitation for passive cooling operation.

Profile A

The load profile is shown in Figure 7.6a. This case is rather exceptional for the temperature limitations used in this study. The undisturbed ground temperature is 11 °C. This temperature is the temperature at the first time step, so the load profile requires a very sharp peak in the heating load to reach the lower temperature limit of 0 °C in the first year. Another requirement for the load profile to be in this quadrant is a small imbalance to avoid reaching the maximum temperature limit, as this would make it a load profile in Q3 instead of Q2. Therefore, the mathematical description deviates from the other cases:

$$Q_{heat}[t] = 100kW \cdot sin^5\left(\frac{2\pi}{0.25 \cdot 8760} \cdot [t + 8760/16]\right) \quad (7.17)$$
$$\forall t \in [0, 547] \cup [8213, 8760]$$
$$Q_{cool}[t] = 10kW \cdot sin\left(\frac{2\pi}{1.75 \cdot 8760} \cdot [t - 8760/16]\right) \quad \forall t \in [547, 8213] \quad (7.18)$$

The amplitude of the heating load is much larger compared to cooling, with 100 kW and 10 kW respectively. This is necessary to obtain the large heating peaks to reach a first year limitation. To avoid the case becoming heating dominated, the sine shape of the heating load is made sharper by using a power of 5. The cooling load is assumed to last for 10.5 months whereas the heating load only lasts for 1.5 months, which might not be realistic in building applications in Belgium.

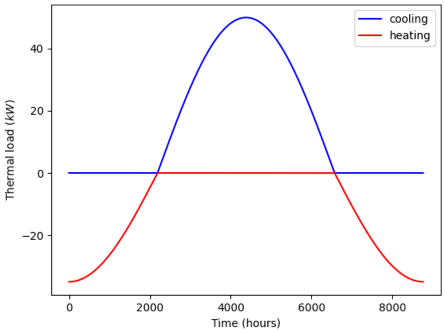
As explained in Section 6.1, the economic optimization starts with sizing the borefield for its two extreme depths L1 and L2. In this case, L1 and L2 are equal to each other because the share of active cooling equals 0% for all depths. Active cooling is never applied because the lower temperature limit is already binding and active cooling is only beneficial for a binding maximum temperature limit. Therefore, the final borefield size is 33.88m with a share of 0% of active cooling and a TC of 162 kEUR.

Conclusions on Q2

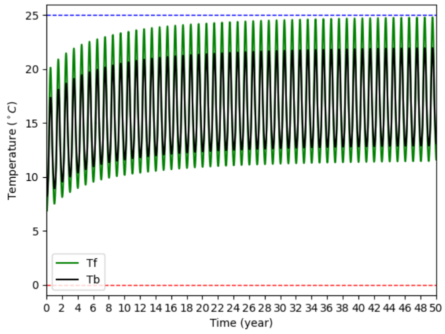
The conclusion of the preliminary study attributed no potential for combined active and passive cooling to this quadrant. This conclusion is hereby confirmed. Passive cooling is the only interesting choice as the temperature limit is impacted by the heating load.

7.2.3 Quadrant 3: Cooling Dominated and Last Year Limited

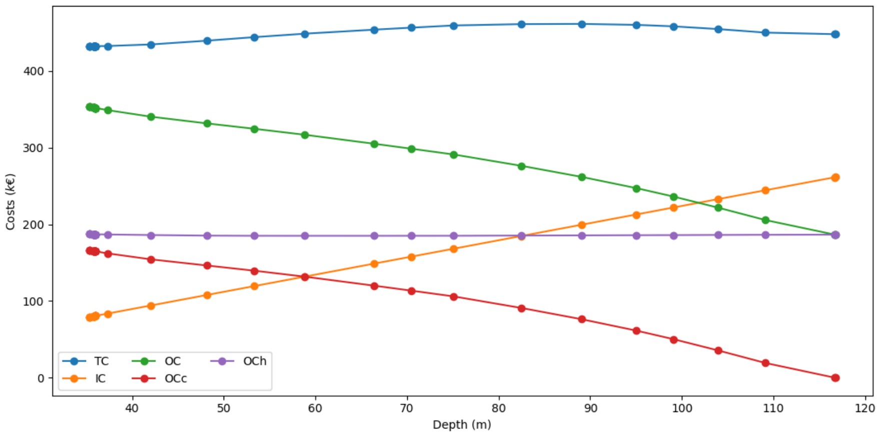
Quadrant three represents a cooling dominated load profile characterized by high cooling peaks which causes a final year limitation for passive cooling operation.



(A) Load profile used for case A in quadrant 3.



(B) Resulting temperature profile over the lifetime of the borefield.



(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 36.0m

FIGURE 7.7: Results for case A in borefield quadrant 3: cooling dominated and last year limited profile with seasonal load variations.

Load profile A

This load profile is very similar to load profile A used in Q1 with again only a seasonal variation (Figure 7.7a). This is mathematically presented by:

$$Q_{heat}[t] = 35kW \cdot sin\left(\frac{2\pi}{8760} \cdot [t + 8760/4]\right) \quad \forall t \in [0, 2190] \cup [6570, 8760] \quad (7.19)$$

$$Q_{cool}[t] = 50kW \cdot sin\left(\frac{2\pi}{8760} \cdot [t - 8760/4]\right) \quad \forall t \in [2190, 6570] \quad (7.20)$$

The amplitude of the sinusoidal function is 35 kW for heating and 50 kW for cooling. The heating and cooling period are assumed to both last for 6 months. This cooling dominated load profile causes an increasing temperature profile as can be seen in Figure 7.7b.

The cost curves are shown in Figure 7.7c. The TC curve shows increasing total costs for larger borefield depths but this changes into a decline close to the borefield depth for passive cooling only. This is due to a sharp decrease in operation cost for cooling closer to the maximal useful borefield depth. The heating operation costs are rather constant as only small COP variations result in differences in this cost component. The investment cost increases linearly due to the constant investment cost per meter borefield depth.

The optimal borefield size for this load profile is 36.0m close to the minimal borefield size for maximal combined active and passive cooling of 35.4m. The maximum temperature of the borefield fluid is therefore slightly below the maximal temperature limit of 25 °C. In this optimum, 97.4% of the total cooling load is cooled in an active way. This can be explained by the temperature profile being mainly above the 16 °C boundary for passive cooling. The total cost in the optimum is 432 kEUR over the full lifetime of the borefield, equal to 50 years in this study. This a cost saving of 15.7 kEUR compared to passive cooling with a borefield depth of 116.8m.

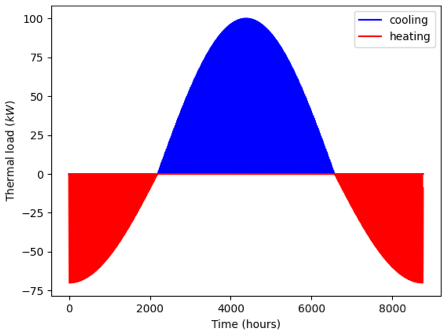
The CO_2 emissions for the cooling operation in this optimum over the 50 year lifetime of the borefield are equal to 94.1 tons of CO_2. The abatement cost for using passive cooling instead of combined active and passive cooling is equal to 116.7 EUR/ton CO_2. This abatement cost is an order of magnitude lower compared to the abatement costs of Q1 and is close to the benchmark of 80 EUR/ton, which indicates the relatively high emissions compared to the cost savings. Therefore, its ecological justification might be questioned.

Load Profile B1

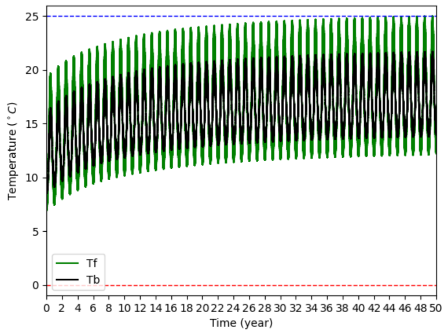
The second synthetic load profile aims to mimic a more realistic heating and cooling demand and is shown in Figure 7.8a. This is done by including daily loads of 24 hours each in the demand, opposed to the first case discussed in this section. The mathematical representation of this case is:

$$Q_{heat}[t] = 70kW \cdot \left| sin\left(\frac{2\pi}{48}[t]\right)\right| \cdot sin\left(\frac{2\pi}{8760} \cdot [t + 8760/4]\right) \quad (7.21)$$
$$\forall t \in [0, 2190] \cup [6570, 8760]$$
$$Q_{cool}[t] = 100kW \cdot \left| sin\left(\frac{2\pi}{48}[t]\right)\right| \cdot sin\left(\frac{2\pi}{8760} \cdot [t - 8760/4]\right) \quad (7.22)$$
$$\forall t \in [2190, 6570]$$

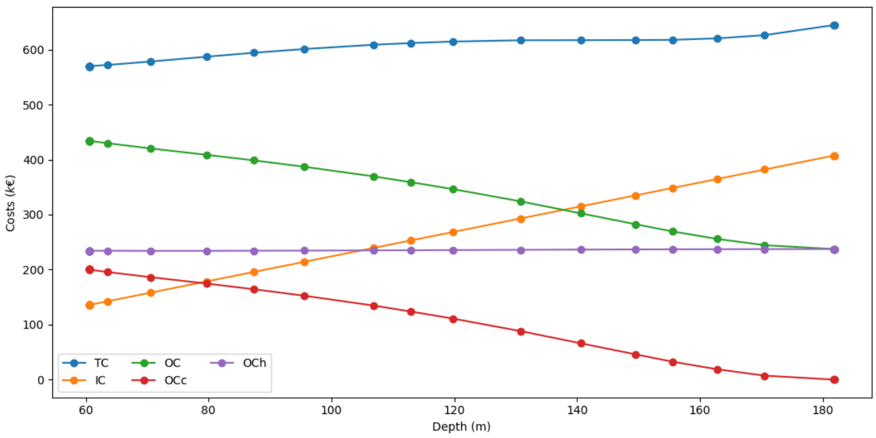
The cost curves for the second case are depicted in Figure 7.8c. The TC curve shows increasing total costs for larger borefield sizes. The optimum of this curve is exactly at the extreme borefield depth L1 for maximal combined active and passive cooling,



(A) Load profile used for case A in quadrant 3.



(B) Resulting temperature profile over the lifetime of the borefield.

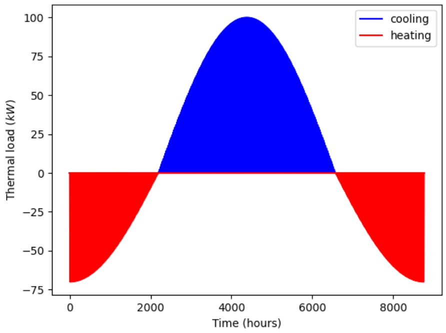


(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 60.6m.

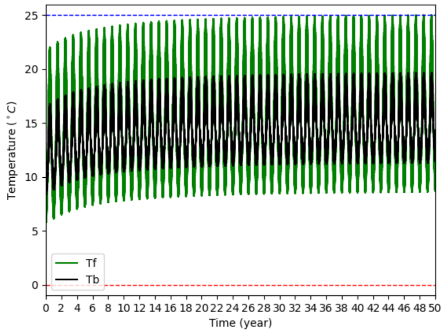
FIGURE 7.8: Results for case B1 in quadrant 3: cooling dominated and last year limited profile with seasonal and 24-hour daily load variations.

which corresponds to a borefield depth of 60.6m for a TC of 570 kEUR. The share of the load that is cooled in an active way is therefore maximal, equal to 96.6% for this specific case. The cost saving compared to passive cooling is 74.9 kEUR or a cost saving of 11.6%.

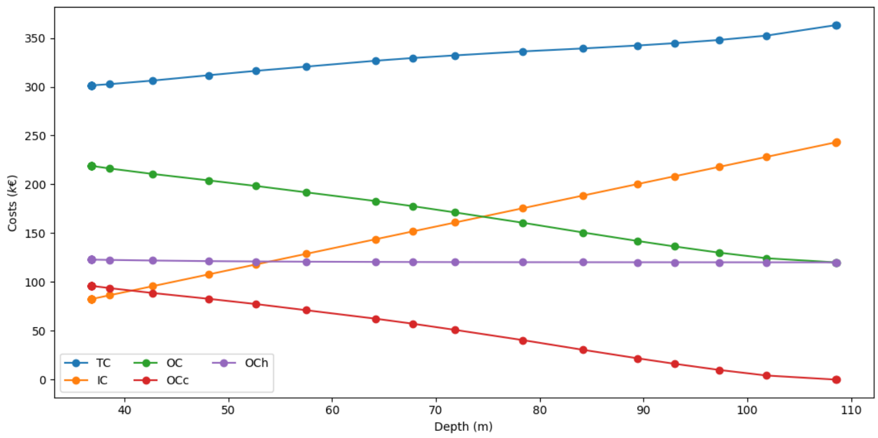
The CO_2 emissions for a borefield with a depth of 60.6m and a share of 96.6% active cooling are 114.2 tons of CO_2 in 50 years. This corresponds to an abatement cost of 656 EUR/ton CO_2, which is higher compared to profile A.



(a) Load profile used in case B2 in quadrant 3.



(b) Resulting temperature profile over the lifetime of the borefield.



(c) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 36.8m.

Figure 7.9: Results for case B2 in quadrant 3: cooling dominated and last year limited profile with seasonal and 12-hour daily load variations.

Load profile B2

Similar as in Q1, a variation on the previous load profile is also investigated. The daily variation only lasts for 12 hours and a period of 12 hour per day without load is introduced. This is mathematically translated into:

$$Q_{heat}[t] = 70kW \cdot sin^{+}\left(\frac{2\pi}{24}[t-6h]\right) \cdot sin\left(\frac{2\pi}{8760} \cdot [t+8760/4]\right) \qquad (7.23)$$
$$\forall t \in [0, 2190] \cup [6570, 8760]$$

$$Q_{cool}[t] = 100kW \cdot sin^{+}\left(\frac{2\pi}{24}[t-6h]\right) \cdot sin\left(\frac{2\pi}{8760}\cdot[t-8760/4]\right) \qquad (7.24)$$
$$\forall t \in [2190, 6570]$$

The TC function of this case is very similar to the TC curve for case B2. The optimum can be found again at extreme borefield depth L1 equal to 36.8m. This results in a TC of 301 kEUR over the lifetime of the borefield. Extreme borefield depth L2 for passive cooling only results in a total cost of 363 kEUR. The share of active cooling is 93.7% for this final load profile in Q3. The cost curves for this case can be seen in Figure 7.9.

The CO_2 emissions for the economic optimal borefield are 54.9 tons of CO_2. These additional emissions are counteracted by a large economic cost saving. The abatement cost is 1128 EUR/ton CO_2, which is high compared to the baseline cost of 80 EUR/ton.

This high abatement cost is due to the large costs savings by using combined active and passive cooling and the relatively low additional emissions. Therefore, this is an additional confirmation of the potential for combined active and passive cooling: large cost savings can be achieved without a large impact on its emissions.

Conclusions on Q3

The three different load profiles all indicate a large potential for combined active and passive cooling. The different optima are all located in (or very close to) to the smallest interesting borefield size L1.

Although all three load profiles result in an optimum for maximal combined cooling, the results still indicate the influence of the shape of the load profile on the results. The TC curve for load profile A is relatively flat which indicates that the cost reductions achieved by using active cooling are rather limited. Load profile B2 on the contrary has a much steeper TC curve which clearly shows the benefit of stepping away from using passive cooling. Load profiles with a more varying cooling demand (like B2) indicate therefore again a large potential for combined active and passive cooling.

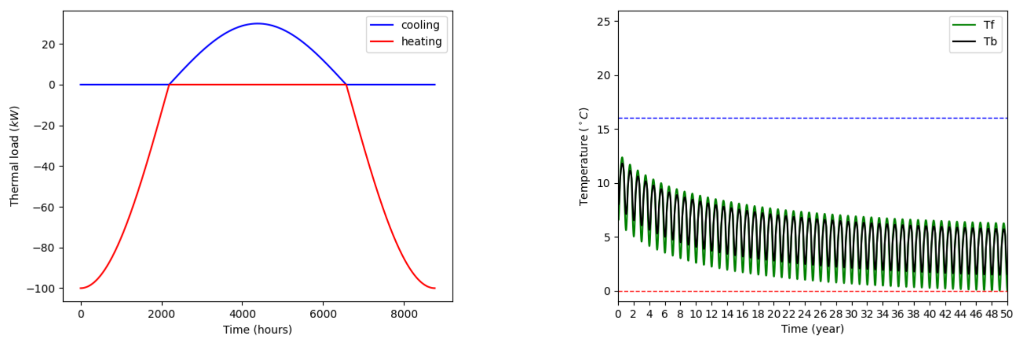
In this cooling dominated case, the share of active cooling is in all three cases in the order of 95 %, which clearly differs from the results in Q1. This is due to the increasing temperature profile of the cooling dominating load. Therefore, the average borefield fluid temperatures are higher, especially near the end of the lifetime of the borefield, and increase the need for active cooling. This results in large operating costs for cooling with respect to the total costs of the borefield.

The high share of active cooling also has consequences regarding the implementation. Although the technical implementation and control techniques of combined active and passive cooling are not a central topic in this work, it is possible to cool 100 % of the cooling load in an active way to avoid eventual implementation difficulties. This is possible without a large operating cost increase, as only the remaining passively cooled load (∼ 5%) would be cooled in an active way. The fluid temperatures are relatively low at these instances which results in cooling with a high EER and thus a limited cost increase.

The abatement costs for the different load profiles are all in the range of 100-1200 EUR/ton CO_2, which is still higher compared to the benchmark price of 80 EUR/ton CO_2 of the EU ETS allowances. Important here is that these prices are closer to the benchmark price compared to the cases in Q1. This is due to the large shares of active cooling for the load profiles in Q3, resulting in higher electricity use. The abatement cost is especially low for load profile A, which questions the potential for combined active and passive cooling in ecological terms for this specific load profile.

At the end of the lifetime of the borefield, the average fluid temperature in the borefield coincides with the maximum temperature limit. This implies the borefield cannot further be used for cooling purposes without exceeding this temperature limit. A cool-down period or heating period must be accounted for before cooling is possible again.

7.2.4 Quadrant 4: Heating Dominated and Last Year Limited



(A) Load profile used in case A in quadrant 4.

(B) Resulting temperature profile over the lifetime of the borefield.

Figure 7.10: Results for case A in borefield quadrant 4: heating dominated and last year limited profile with seasonal load variations.

Quadrant four represents a heating dominated load profile characterized by high heating peaks which causes a final year limitation. The preliminary study indicated already that there is no potential for combined active and passive cooling in this borefield quadrant as the minimum temperature limit is binding.

Profile A

These findings are compared with the results of the new approach for the following load profile:

$$Q_{heat}[t] = 100kW \cdot sin\left(\frac{2\pi}{8760}[t + 8760/4]\right) \quad \forall t \in [0, 2190] \cup [6570, 8760] \quad (7.25)$$

$$Q_{cool}[t] = 30kW \cdot sin\left(\frac{2\pi}{8760}[t - 8760/4]\right) \quad \forall t \in [2190, 6570] \quad (7.26)$$

The heating load clearly dominates in Figure 7.10a. Therefore, the temperature profile is declining in nature and is limited in the final year by the lower temperature limit of 0°C.

The sizing for passive and combined active and passive cooling yields the same results: a borefield depth of 133.29m with a total cost of 883 kEUR.

Conclusions on Q4

The conclusion of the preliminary study states that the use of active cooling had no potential for this quadrant, which is again confirmed. Combined active and passive cooling would only cause increasing operation costs without cost savings related to the investment because size reductions of the borefield are not allowed due to the binding lower temperature limit.

7.3 Discussion and generalized insights

The previous section performed different case studies in each borefield quadrant by examining synthetic load profiles. These conclusion were case- and quadrant-specific and are now generalized.

The first conclusion of these case studies indicates the potential of the different borefield quadrants. Using combined active and passive cooling has the potential to be economically favorable for load profiles with a maximum temperature limitation[6]. This can be explained as follows: the maximum temperature limit for passive cooling must no longer be respected if active cooling is possible because the strict minimal temperature difference between the borefield fluid and the indoor building circuit is no longer important. Therefore, a smaller borefield size is sufficient for the specific load profile which results in lower investment costs. The operation costs for active cooling counteract this but often do not fully outweigh the saved investment costs.

An important reflection on this conclusion regards the input parameters. The potential for combined active and passive cooling is not only determined by the load profile, also the economic and technical parameters influence the optimal cooling strategy. A further reflection on this is provided in Chapter 8.

[6] When sized for passive cooling only.

The second conclusion is the complement of the first conclusion regarding the quadrants where combined active and passive cooling has no potential. Cases with a binding minimum temperature limit do not reap the economic benefits of using active cooling as no borefield size reductions are possible. There might be potential if regenerative heating and cooling is considered at instances with near zero energy prices, for example in case a PV installation is used in combination with the borefield. This is an interesting research topic for eventual future work and touched upon again in Chapter 10.

The third conclusion regards the shape of the load profile. For the quadrants with potential for using combined active and passive cooling it became clear that load profiles with clear peaks and periods with zero load have a higher potential for combining active and passive cooling. This can be explained as the borefield fluid has the opportunity to cool down in between those peak which is beneficial in terms of passive cooling opportunities and EER for active cooling.

The fourth conclusion compares the share of active cooling to the total cooling load for the different quadrants. It is clear that this share is in general lower for Q1 compared to Q3. The reasoning behind this is already explained in the previous section. An important consequence of this lower share the limited operation costs for cooling in Q1 and additionally lower CO_2 emissions related to electricity use.

The fifth conclusion describes the general increase of heating costs with decreasing borefield size. As an increasing borefield size leads to lower fluid temperatures in the heating periods, the COP of the heat pump reduces. This reduction in COP leads to an increased electrical energy consumption and thus a higher operating cost due to heating.

The sixth and final conclusion links the economic potential of combined active and passive cooling to its ecological impact. The abatement costs for the different load profiles in Q1 and Q3 are varying which again confirms the load dependency of the results. All abatement costs are clearly above the benchmark of the EU allowances prices, but this price is expected to drastically increase in the coming years. Therefore, not all cases which are economically interesting are also justified in ecological terms. Although, 5 out of 6 cases have an abatement cost almost a full order of magnitude above the EU ETS price and therefore are justified in both economic and ecological terms.

Key Takeaways

The key insights of this chapter are listed below.

- The size of the borefield for which the TCO reaches its minimum is considered to be the economic optimal borefield size. This depth can vary between L1 (minimum possible borefield depth) and L2 (maximum relevant borefield size).
- Load profiles situated in Q1 and Q3 have a large potential to reduce the TCO by using combined active and passive cooling.
- The preliminary study concluded that there is no potential for combined active and passive cooling for load profiles in Q2 and Q4. These preliminary conclusions are confirmed.
- The potential of combined active and passive cooling strongly depends on the shape of the load profile. Frequently varying load profiles (B1) and load profiles with periods of zero load (B2) seem to profit from combining active and passive cooling more compared to relatively constant load profiles (A).
- Cooling dominated load profiles with a final year limitation (Q3) lead to rising average fluid temperature over the lifetime of the borefield, resulting generally in a higher share of active cooling compared to heating dominated load profiles with a final year limitation (Q1).

Chapter 8

Sensitivity Analysis

Chapter 7 discusses the results that are obtained by performing the described optimization on various load profiles. It also discusses interesting insights that arise when studying the results. An interesting question one might ask is: "Which parameters have the greatest impact on the TCO and to what extent can they be influenced during the design phase of the borefield?". The attentive reader might notice that this is one of the engineering research questions that were posed at the start of Chapter 1. This question is exactly what is addressed in this section.

The goal of a sensitivity analysis is to determine the effect of various parameters (or independent variables) of a mathematical model on the output (or dependent variables) of that model. In the case of this work the output of the model is the TCO for minimized borefield size, which can be divided into the investment cost and the operating cost. The operating cost is further divided into the heating related costs and the cooling related costs. Often the effect of a parameter on the TCO is not a direct effect but a combination of multiple reinforcing or counteracting effects. This section aims to highlight the various effects at play.

To structure the sensitivity analysis in a comprehensible manner, the analysis is divided in four parts. The first, Section 8.1, studies the sensitivity of the output of the model to various technical parameters: the borehole spacing, the conductivity of the soil, the equivalent borehole resistance and the lifetime of the borefield. The second, Section 8.2, studies the sensitivity of the output of the model to various temperature limits that are used in the model: the maximum average fluid temperature, the minimum average fluid temperature, the undisturbed ground temperature and the temperature limit at which passive cooling is considered possible. The third, Section 8.3, studies the sensitivity of the output of the model to various economic parameters: the electricity price, the borefield price per meter and the real discount rate used in the model. The fourth and last, Section 8.4, studies the sensitivity of the output of the model to the COP and the EER of the heat pump.

These four parts together make up a detailed answer to the first part of the question mentioned at the start of this section. The second part of the engineering research question is studied in Section 8.5. Here, the most relevant parameters are revisited and the extent to which they can be influenced during the design phase of the borefield is analyzed.

Note that this sensitivity analysis is carried out for a cooling dominated and final year limited load profile, corresponding to Q3. This results, with all parameters at their initial value, in a temperature profile as shown in Figure 8.1. This figure is a good point to return to frequently when studying the effects on the parameters in this sensitivity analysis as it helps the reader to follow the conceptual and intuitive reasoning laid out in this chapter. The sensitivities to a certain parameter are depicted as the change of the TCO relative to the initial situation. The initial values of all the parameters considered are described in the corresponding section.

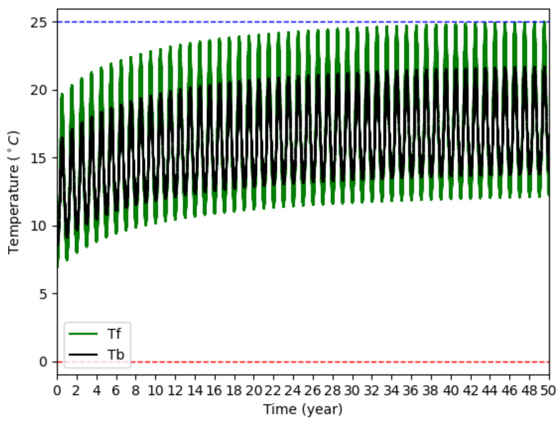


Figure 8.1: Temperature profile resulting from minimizing borefield size using all parameters at their initial value. The load profile used is cooling dominated and final year limited.

8.1 Technical sensitivity analysis

As mentioned previously, the borehole spacing (B), the conductivity of the soil (k_s), the equivalent borehole resistance (R_b^*) and the lifetime of the borefield (LT) are the independent variables whose effect on the TCO of a borefield is studied in this section. The initial values of these independent variables are $6m$, $2.1\frac{W}{mK}$, $0.12\frac{mK}{W}$ and 50 years respectively. All four of these are varied from 60% to 140% of their initial value in steps of 5% one by one. The complete technical sensitivity analysis is graphically depicted in Figure 8.2. This section discusses the cost components for each parameter starting with the borehole spacing.

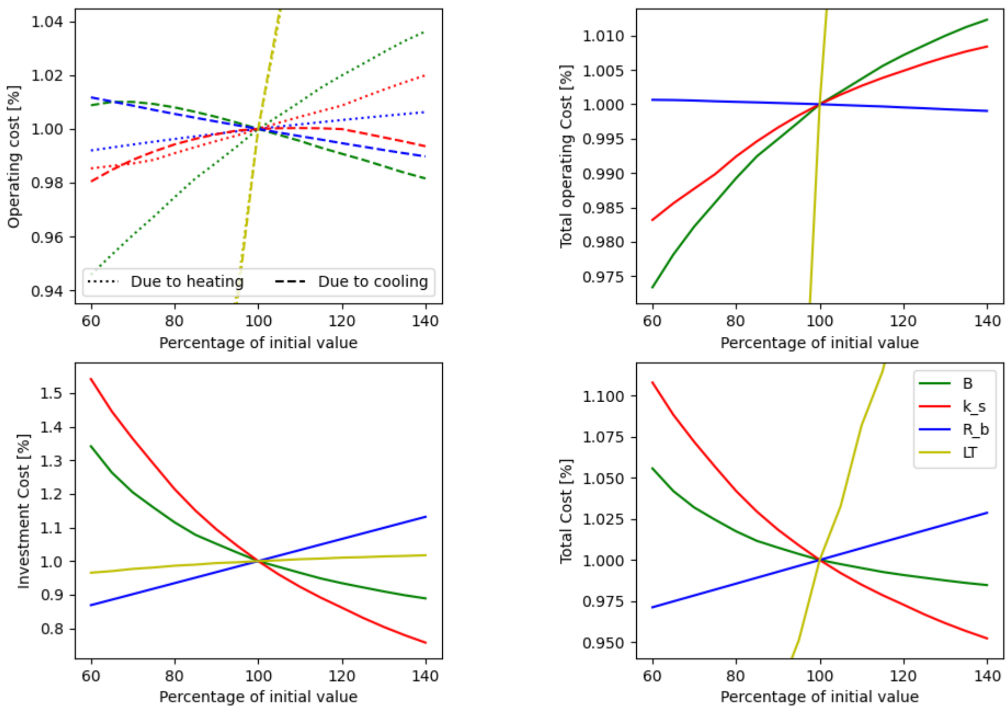


FIGURE 8.2: Results of the technical sensitivity analysis. Initial parameters: borehole spacing (B) $= 6m$, thermal conductivity of the soil $(k_s) = 2.1\frac{W}{mK}$, equivalent borehole resistance $(R_b) = 0.12\frac{mK}{W}$ and lifetime (L)T $= 50$ years.

Borehole spacing B

The effect of the borehole spacing on the investment cost is quite clear and can be explained relatively easily by intuitive reasoning. By increasing the borehole spacing, more heat can be dissipated in between boreholes for an equal rise in ground temperature. This means a smaller borefield size can be used, reducing the investment cost. Notice the non-linear relationship between the investment costs and B.

The total effect of varying B on the operating cost is a combination of two counteracting effects at play simultaneously. The first of which is the direct effect of varying B on the fluid temperature. The second of which is the indirect effect of B on the fluid temperature through the borefield size. To further clarify, the two effects are discussed for decreasing B. By decreasing B, the first effect results in a direct increase of the average fluid temperature. To respect the maximum fluid temperature limit, the borefield size must increase. The second effect thus results in an indirect reduction of average fluid temperature due to the increase in borefield size.

The first effect leads to a decreasing heating related cost (due to higher COP) and an increasing cooling related cost (due to lower EER and increased share of active cooling). The second (indirect) effect leads to a reduction in share of active cooling, a higher EER and lower COP. Both the lower share of active cooling and the higher EER lead to lower cooling related costs whilst the lower COP results in higher heating related costs. From the curve representing cooling related costs it is clear that for a small reduction in B, the direct effect is dominant whilst for a large reduction in B, the indirect effect is dominant due to the superlinear increase in borefield size. For increasing B the first effect is dominant leading decreasing cooling related costs and and increasing heating related costs.

The effect on the investment cost is more significant than the effect on the operating cost which is reflected in Figure 8.2.

Soil conductivity $\mathbf{k_s}$

The effect of the ground conductivity on the investment cost can also be explained by intuitive reasoning. Increasing k_s leads to a larger amount of heat that can be dissipated in the ground for an equal rise in temperature, allowing the size of the borefield to be reduced while still respecting the maximum average fluid temperature limit.

As with varying B, the effect of varying k_s on the operating cost is a combination of two simultaneous effects. The first being the direct effect of k_s on the temperature profile and the second being the indirect effect of k_s on the temperature profile through the borefield size. As an example, the effects are described for increasing k_s. By increasing k_s, the first effect leads to a decrease in average fluid temperature. As the average fluid temperature has decreased, the borefield size decreases also. The second effect thus leads to an increased average fluid temperature.

For increasing k_s, the first effect leads to a increasing heating related cost (due to lower COP) and a decreasing cooling related cost (due to higher EER and reduced share of active cooling). The second (indirect) effect leads to an increase in share of active cooling, lower EER and higher COP. Both the higher share of active cooling and the lower EER lead to a higher cooling related costs whilst the higher COP leads to lower heating related costs. From the curve representing cooling related costs it is clear that the first effect dominates for large increases in k_s. For decreasing k_s, the second effect is dominant.

Again, the effect on the investment cost is more significant than the effect on the operating cost which is reflected in Figure 8.2.

Equivalent borehole resistance $\mathbf{R_b^*}$

Opposite to the behavior of B and k_s, an increase in R_b^* results in a higher investment cost. This can also be easily explained as with higher R_b^*, the average fluid temperature will increase for an equal heat transfer to the borefield. To respect the maximum average fluid temperature limit, an increase in R_b^* makes a larger borefield necessary, which in turn leads to a higher investment cost.

A similar reasoning for the two effects influencing the operating costs can be done for varying R_b^*. For increasing R_b^*, the first effect results in increasing cooling related costs (lower EER and increased share of active cooling) and decreasing heating related costs (higher COP). The second effect leads to decreasing cooling related costs (higher EER and lower share of active cooling) and increasing heating related costs (lower COP). From Figure 8.2 it is clear that the second effect is dominant for both increasing and decreasing R_b^*.

Borefield lifetime LT

The lifetime of the borefield has a very strong influence on the operating cost. Increasing *LT* obviously increases the operating cost and vice versa. Due to this particular case (Figure 8.1) being cooling dominated, the average fluid temperature will continue to increase when the lifetime is extended. This results in an increase of borefield size. Vice versa, a decrease in lifetime of the borefield reduces the investment cost.

As a result of the negative real discount rate used in the model, the operating cost per year[1] increases with increasing lifetime of the borefield.

Conclusions on the technical sensitivity analysis

The effects of the technical parameters on the heating operating cost are generally larger than the effects on the cooling operating cost and the influence of the technical parameters on the total operating cost is limited compared with the effects on investment cost. The lifetime of the borefield has, comparatively, a very strong influence on the total operating cost as is expected. The operating cost per year, however, increases also with increasing lifetime.

From this technical sensitivity analysis it is clear that the variation of technical parameters have a strong direct effect on the investment cost of the borefield. More specifically, the borehole spacing and the conductivity of the soil have the strongest effect. By increasing these parameters by 40%, the investment cost can be reduced by over 20%. Section 8.5 goes into more detail on the practicalities of varying these parameters.

8.2 Temperature sensitivity analysis

In addition to purely technical parameters, there are four different temperature limits that are considered as independent variables in the sensitivity analysis carried

[1] The operating cost divided by the lifetime of the borefield gives the operating cost per year.

out in this section. These four temperature limits are: the maximum average fluid temperature (T_{maxA}), the minimum average fluid temperature (T_{min}), the undisturbed ground temperature (T_g) and the maximum temperature at which passive cooling is considered possible (T_{maxP}). The initial values of these parameters are $25°C$, $0°C$, $11°C$ and $16°C$ respectively. All these parameters are varied between their initial value minus $4°C$ and their initial value plus $4°C$. This section describes the effect of these parameters on the output of the studied model in a similar manner as Section 8.1 discussed the technical parameters. The temperature sensitivity analysis is depicted graphically in Figure 8.3. This section discusses both cost components together for each parameter starting with the maximum average fluid temperature.

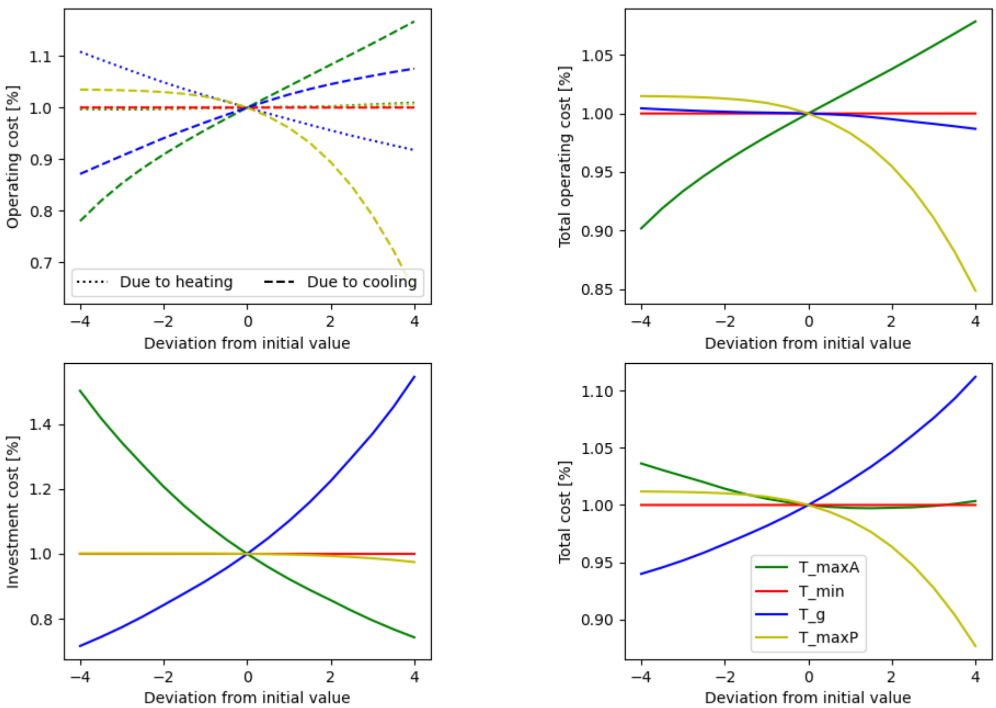


Figure 8.3: Results of the temperature sensitivity analysis. Initial parameters: maximum average fluid temperature (T_{maxA}) = $25°C$, minimum average fluid temperature (T_{min}) = $0°C$, undisturbed ground temperature (T_g) = $11°C$) and maximum temperature at which passive cooling is possible (T_{maxP}) = $16°C$.

Maximum average fluid temperature for active cooling $\mathbf{T_{maxA}}$

As can be seen in Figure 8.3, varying T_{maxA} has a strong influence on the operating cost and the investment cost. Increasing this maximum average fluid temperature limit makes it possible to reduce the size of the borefield[2] which in turn reduces the investment cost. Due to this increased temperature limit, the share of active cooling throughout the lifetime of the borefield increases as a result of the higher average temperature in the borefield. This higher average temperature in the borefield results in the increase in operating cost that can be seen in Figure 8.3. Vice versa, decreasing this temperature limit increases the investment cost as a larger borefield is needed and reduces the operating costs as the share of active cooling reduces also.

The operation cost for heating seems to increase slightly with increasing T_{maxA}. This can be explained as follows. The periods of heating generally occur when the average fluid temperature in the borefield is relatively low, rendering the COP of the heat pump in heating operation low also. When reducing the borefield size, due to the increased T_{maxA}, the temperature profile comes closer to the temperature limits reducing the fluid temperature in periods of heating. As the COP is lower at lower fluid temperatures, the operating cost slightly increases.

Minimum average fluid temperature $\mathbf{T_{min}}$

The effect of T_{min} on the TCO of the borefield is non existent in the graphs shown in Figure 8.3 as with this particular load profile the borefield size is not limited by the minimum average fluid temperature limit. However some effects can be determined by reasoning beyond the $-4°C$ - $+4°C$ deviation. If T_{min} were to increase up until the point that the borefield size would be limited by this temperature limit, the investment cost would rise with rising T_{min} due to increasing necessary borefield size. Also, at this point the temperature profile would not reach the maximum average fluid temperature limit anymore and with increasing T_{min} the maximum temperature over the lifetime of the borefield would drop due to increasing borefield size. This results in a decrease of the operating cost with increasing T_{min} as the share of active cooling decreases.

Undisturbed ground temperature $\mathbf{T_g}$

The most influential temperature parameter on the investment cost is the undisturbed ground temperature (the ground temperature at infinity in this model). Due to the temperature profile being limited by the maximum average fluid temperature limit (as can be seen in Figure 8.1), an increase in T_g requires an increase in borefield size to respect this temperature limit. This increase in borefield size brings an increase in investment cost with it as can be seen in Figure 8.3. On the contrary, decreasing T_g requires a smaller minimal borefield size which results in the decreasing investment cost that can be seen in the same figure.

An interesting thought experiment is decreasing T_g by more than 4°C. The investment cost will suddenly increase. This can be explained as the point where due to decreasing

[2] Recall this analysis is performed for a cooling dominated and cooling limited case. This implies the temperature profile increases over the years resulting in a limitation at the maximum average fluid temperature limit.

T_g, the limitation changes from the maximum average fluid temperature to the minimum average fluid temperature[3]. From here further decreasing the undisturbed ground temperature results in increasing borefield size (as now the lower temperature limit is binding) and thus increasing investment cost.

With increasing T_g, Figure 8.3 shows a slight decrease in operating costs which can be split up into a decrease in operating cost due to heating and an increase in operating cost due to cooling where the latter is slightly smaller than the former. The increase in cooling related operating costs is due to the increased share of active cooling resulting from an increase in T_g. The decrease of heating related operating costs is due to the higher average temperature which implies a higher COP for the heat pump. Again an interesting thought experiment is to decrease T_g further than 4 °C. Here the operating cost will decrease strongly at the point where the limitation changes from maximum temperature to minimum temperature. This is due to the sudden drop in share of active cooling due to the increase of borefield size as a result of the decrease of T_g.

Maximum average fluid temperature for passive cooling $\mathbf{T_{maxP}}$

The most influential parameter on the operating cost is the temperature limit at which passive cooling is considered possible. It is clear from Figure 8.3 increasing this parameter drastically decreases operating costs. After breaking this operating cost up into heating and cooling related costs it is clear this strong decline is due to the cooling related costs[4]. Obviously increasing the temperature limit up until which passive cooling is possible will reduce the share of active cooling drastically and therefore also the cooling related costs. It is noteworthy that cooling related costs here do not increase significantly with decreasing T_{maxP}. This is due to the fact that in the situation with all parameters at their initial value (which produces the temperature profile depicted in Figure 8.1) the share of active cooling is already close to the maximum, namely 94%. Further reducing T_{maxP} thus does not increase the share of active cooling significantly.

As this parameter directly influences the share of active cooling, the effects on the borefield size and thus investment cost are limited. However, it is interesting to see that with decreasing share of active cooling (due to increasing T_{maxP}) the investment cost decreases slightly. This can be intuitively explained by reasoning about the switch from active to passive cooling. In active cooling operation the heat pump extracts a certain amount of heat from the to-be-cooled building. This heat is then injected in the borefield together with the heat produced by the heat pump (due to the compression step in the heat pump). In contrast, in the passive cooling scenario there is no extra heat injected in the borefield (as any circulation pump inefficiencies

[3]Figure 8.1 supports this reasoning.

[4]Note that as the cooling related costs reduce by nearly 40% after an increase of T_{maxP} of 40% and the total operating cost decreases by only 15% for the same increase of T_{maxP}, the share of heating related costs must be larger than the share of cooling related costs.

are neglected). Increasing the share of passive cooling (i.e. decreasing the share of active cooling) thus results in less heat being injected in the borefield and so, as the borefield size is limited by the injection of heat (limited at the maximum average fluid temperature limit due to cooling operation), a smaller borefield.

Conclusions on the temperature sensitivity analysis

In conclusion of this temperature related sensitivity analysis it is clear that reducing the share of active cooling by increasing the temperature limit up until which passive cooling is possible has the largest potential to reduce the operating cost. Increasing T_{maxA} or decreasing T_g prove to be the strongest actions towards reducing the investment cost of the borefield. Section 8.5 discusses the practical side of influencing these parameters in the design phase of the borefield.

8.3 Economic sensitivity analysis

The two previous sections discussed, respectively, the sensitivity of the TCO to various technical and temperature related parameters. This section dives deeper into the sensitivity of the TCO to three different economical parameters: the electricity price (C_{elec}), the borefield price per meter (C_{inv}) and the real discount rate used to account for future expenses during the lifespan of the borefield. This real discount rate is split into the nominal discount rate (DR_{nom}) and the inflation rate of electricity use (R_i) as explained in Section 6.2. The initial values of these parameters are $0.2159\frac{€}{kWh}$, $35\frac{€}{m}$, 5% and 5.11% respectively. Identical to the technical sensitivity analysis, these parameters are varied between 60% and 140% of their initial value. The full result of this analysis is presented in Figure 8.4. At first glance, Figure 8.4 is more straightforward than Figure 8.2 or Figure 8.3. Again all four parameters are discussed one by one.

Electricity price $\mathbf{C_{elec}}$

The electricity price has a strong and straightforward effect on the operating costs with an equal effect on heating or cooling related costs. Not surprisingly, the electricity price does not influence the investment cost[5].

Borefield cost $\mathbf{C_{inv}}$

Increasing borefield cost per meter increases the investment cost of the borefield. As expected this is a linear effect. This parameter has no influence on the operating cost.

[5]In reality an increase in electricity cost would have an effect on investment cost as electrical equipment would be used during the construction of the borefield but this is neglected in this analysis.

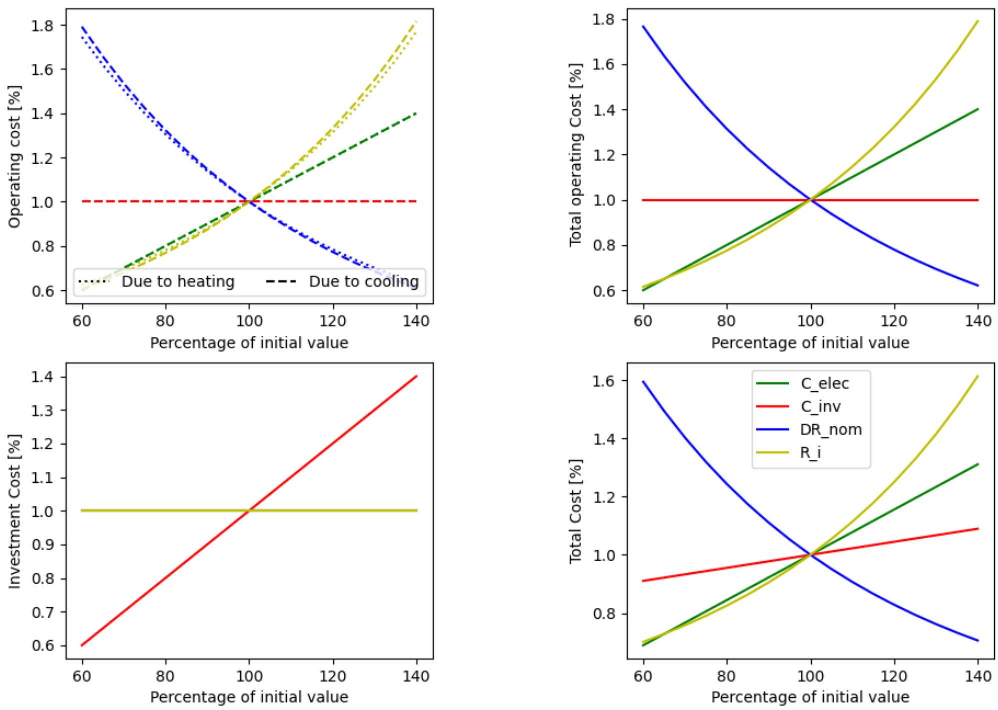


Figure 8.4: Results of the economical sensitivity analysis. Initial parameters: electricity price (C_{elec}) = $0.25\frac{€}{kWh}$, borefield price per meter (C_{inv}) = $35\frac{€}{m}$, nominal discount rate (DR_{nom}) = 5% and the electricity inflation rate (R_i) = 5.11%.

Nominal discount rate $\mathbf{DR_{nom}}$ and electricity inflation rate $\mathbf{R_i}$

Note that due to the way the real discount rate is defined (see Section 6.2), a decrease in R_i and an increase in DR_{nom} both result in an increase in the real discount rate. This can also be clearly seen in Figure 8.4 as the effect of varying R_i and DR_{nom} are opposite.

As the investment cost is a one-time cost before operating the borefield, the real discount rate has no effect on the investment cost. The discount rate, however, does influence the total operating cost in the expected way: a higher discount rate leads to a lower total operating cost and a lower dicount rate leads to a higher total operating cost.

A possibly surprising element in Figure 8.4 is the difference in the effect of the discount rate on the operating cost due to heating and cooling. It seems like the cooling related costs decrease faster than the heating related costs with an increasing real discount rate. Again, this can be explained by intuitively reasoning with Figure 8.1

about the effect of the discount rate on the total operating cost as follows.

As the used load profile is cooling dominated, the average fluid temperature in the borefield rises every year. This results in a higher yearly share of active cooling at the end of the borefield lifetime. The cooling related costs are thus more concentrated at the end of lifetime as can be seen in Figure 8.1. In contrast, the heating related costs are more uniformly spread across the lifetime of the borefield. It is for this reason that a higher real discount rate has a stronger discounting effect on the cooling related costs than on the heating related costs. This explains the difference in slope of the heating and cooling related costs in Figure 8.4.

Conclusions on the technical sensitivity analysis

As a result of this short analysis on the sensitivity of the TCO of a borefield to various economic parameters, one can say the most influential parameters are the nominal discount rate and the inflation rate for electricity. Also the electricity price has a strong influence on the TCO. Note that the choice of lifetime of the borefield has a very strong influence on the ratio of the investment cost to the operating cost. An other assumption on lifetime might result in different conclusions.

8.4 Efficiency sensitivity analysis

Previous sections studied the effects of the technical borefield and ground parameters, the borefield temperature parameters and the market economic parameters on the TCO. Aside from these, there are two more parameters that have a large influence on the TCO being the COP and the EER of the heat pump. The COP and the EER do not fall into one of the three categories. As also the temperature-dependent efficiency of the heat pump has a more central role in this work, the effect hereof on the TCO are discussed separately.

As mentioned in Section 5.1.2, the temperature-dependent COP and EER are taken from measurements done on a heat pump of Galletti for a specified regime. The initial temperature-dependent efficiencies are $COP(T_f) = 0.1220T_f + 4.365$ and $EER(T_f) = -0.3116 + 17.901$. Both the COP and the EER function are shifted vertically by adding a constant factor between -2 and +2 in steps of 0.5. This section describes the effect of varying these temperature dependencies on the output of the model in a similar manner as Sections 8.1 to 8.3. The results of this analysis are depicted in Figure 8.5.

COP

The effect of varying COP on the investment cost is limited but straightforward. By decreasing the COP, less heat is extracted from the borefield leading to higher average fluid temperatures. As the temperature profile is limited by cooling operation, this leads to the need of a larger borefield and thus a higher investment costs. These

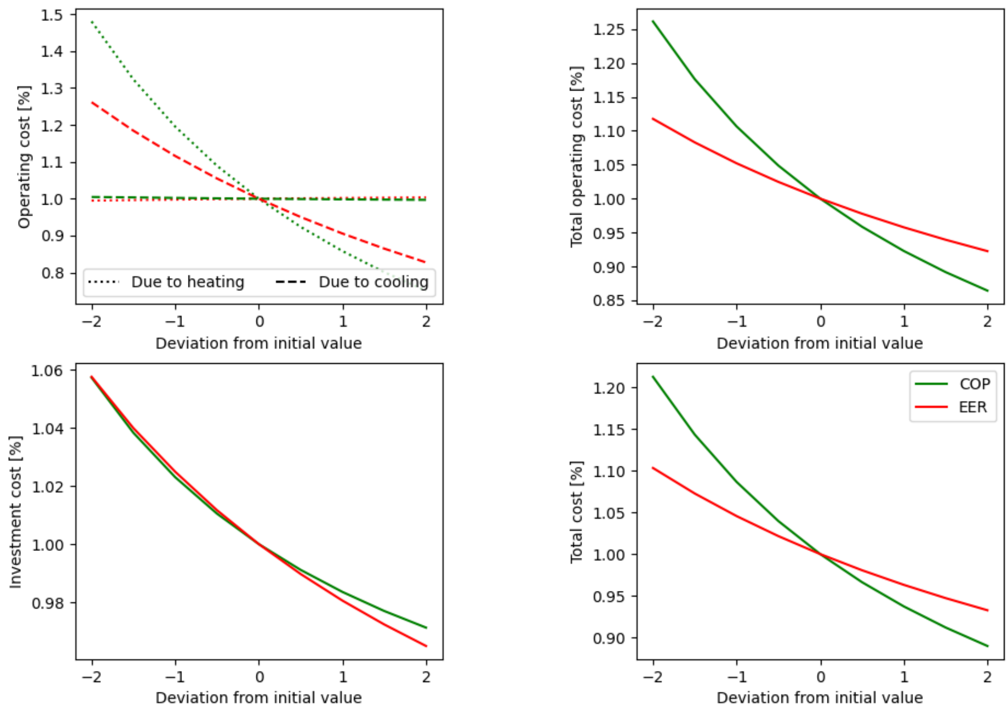


Figure 8.5: Results of the efficiency sensitivity analysis. Initial parameters: $\text{COP}(T_f) = 0.122T_f + 4.365$ and $\text{EER}(T_f) = -0.3916T_f + 17.901$.

higher average fluid temperatures also lead to a lower EER which in turn ever so slightly increase the cooling related costs. Vice versa, increasing the COP leads to a lower investment cost and a very slight decrease in cooling related costs. Varying the COP has the straightforward effect on the heating related costs.

EER

The effect of varying EER on the investment cost is very similar to the effect of varying COP on the investment cost. An increase of the EER decreases the amount of heat being dissipated into the borefield due to the compression step of the heat pump resulting in lower average fluid temperatures. As the temperature profile is limited by the maximum temperature, this allows a smaller borefield and thus a lower investment cost. These lower average fluid temperatures also lead to a lower COP which in turn ever so slightly increases the heating related costs. Vice versa, decreasing the EER leads to a higher investment cost and a very slight decrease in heating related costs.

The effects on the cooling related costs of varying the EER are similar to the effects on the heating related costs of varying the COP although less pronounced. This can be explained as the value for the EER is generally higher than the value for the EER (as can be seen in Figure 5.2). As the sensitivity analysis adds a constant to the value of the COP and EER, the relative variation will be larger for the COP.

Conclusions on the COP and EER sensitivity analysis

The TCO strongly depends on both the COP and the EER and driven mainly by the operating cost. By shifting the temperature-dependent COP downward 2 units, the TCO increases by 20%. The effect on the investment cost is limited.

8.5 Parameters in the practical design of a borefield

So far Chapter 8 discussed the general aim of the sensitivity analysis after which the technical, temperature and economical sensitivity analysis are discussed. Each of these analyses describe the main effects of the studied parameters on the TCO and its components. At the end of each section the most relevant parameters are summarized. This section aims to revisit the most influential parameters of the three analyses and discuss to what extent the value of these parameters can be influenced in the practical design phase of a borefield.

Technical parameters

The most influential parameter resulting from the technical sensitivity analysis is the ground conductivity. By increasing k_s, the expected TCO decreases strongly. As expected, the soil conductivity cannot easily be changed in the design phase of a borefield once a geographical location is chosen. Ground conductivity may vary across regions and countries depending on soil composition and moisture content. The second most influential parameter is the borehole spacing. By increasing B, the expected TCO also decreases strongly. This parameter can to some extent be influenced in the design phase but is generally limited by available space[6]. Lastly, the equivalent borehole wall resistance has a modest influence on the TCO of the borefield. Of the three technical parameters, this is by far the easiest to influence in the design phase of the borefield by altering the grout composition and U-pipe properties [43] as mentioned also in Section 2.1.1. The grout material is the material placed in between the borehole U-pipe and the circumference of the borehole to enhance thermal conductivity and so reduce the borehole resistance. By varying the pipe inner diameter, thickness and material together with exploring multi-pipe options the equivalent borehole resistance can be reduced [43].

[6]Increasing the borehole spacing significantly leads to the borefield system taking up a larger physical space. This in turn can lead to increased costs due to the price of land. This effect is not taken into account in the sensitivity analysis.

Temperature parameters

Revisiting Section 8.2 reminds the reader that the maximum temperature up until which passive cooling is possible had the strongest influence on the operating cost of the borefield and a strong influence on the TCO. T_{maxP} is determined by the average temperature in the cooling system inside of the building. By increasing the temperature at which the heat is exchanged from the to-be-cooled space to the cooling circuit inside the building, T_{maxP} could be increased in the design phase of the borefield which results in a strongly reduced operating cost. This can be achieved by increasing the surface through which this heat exchange takes place[7].

The undisturbed ground temperature has also a very strong influence on the TCO of the borefield. This parameter, similar to the ground conductivity, is geographically determined and not easily changed in the design phase of a borefield when the geographical locating is already determined.

Economical parameters

The discount rate, borefield price per meter and electricity price all have a very strong influence on the TCO of the borefield. The borefield price per meter is something that can be changed in the design phase of the borefield by substituting more expensive materials for cheaper materials. For example, a cheaper grout material can be used or a simpler single U-tube configuration can be used (see Section 2.1.1).

Doing this will, however, increase the borehole resistance which in turn increases the operation cost. The electricity price can to some extent also be influenced in the design phase of the borefield if a renewable energy source would be installed alongside the borefield. This could be a PV installation for example. Note that an installation of the sorts will by itself have a significant investment cost.

The real discount rate consists of the nominal discount rate and the electricity inflation rate. The nominal discount rate has been chosen arbitrarily at 5% and can thus differ strongly in the design phase. 5% is a value that is often used in literature. As described in Section 6.2, the electricity inflation rate is based on the HICP for electricity over a period of 10 years (2012-2021)[8]. This cannot be influenced in the design phase of the borefield.

Efficiency

From Figure 8.5 it is clear that the efficiency of a heat pump has a strong effect on the TCO of a borefield. As mentioned in Section 2.1.2, a strong driver for the efficiency

[7] An other way to increase T_{maxP} is by using high temperature cooling systems such as CCA floor/ceiling cooling. However, the temperature regime used in this model (Section 5.1.2) already assumes the use of high temperature cooling system such as CCA and ceiling cooling.

[8] Note that the previous decade has shown high values for electricity inflation rate so 5.11% might not be representative for the next 50 years. Also, the inflation rate is calculated including taxes which might also not be representative for the future.

of a heat pump is the difference between the source and sink temperature. Increasing this difference, decreases the efficiency. It is therefore that low temperature heating and high temperature cooling systems are developed and used.

Furthermore the efficiency of the compressor in the heat pump is a strong driver towards high efficiency. More expensive higher-end heat pumps have a higher efficiency due to higher quality materials and components.

Key Takeaways

The key insights of this chapter are listed below and summarized in Table 8.1.

- The maximum temperature for active cooling, the maximum temperature for passive cooling, the discount rate and the efficiency of the heat pump have the strongest influence on the operating cost over the lifetime of the borefield.
- The soil conductivity, the undisturbed ground temperature and the borefield investment cost per meter have the strongest influence on the investment cost of the borefield.
- The ground conductivity, undisturbed ground temperature, maximum passive cooling temperature limit, discount rate and efficiency of the heat pump have the strongest influence on the TCO of the borefield.
- The maximum passive cooling temperature limit, electricity price and efficiency of the heat pump are parameters with a strong influence on the TCO that can be varied in the design phase of the borefield.

Parameter	B	k_s	R_b	T_{maxA}	T_{min}	T_g	T_{maxP}	C_{elec}	C_{inv}	DR	COP	EER
OC	o	o	o	+	o	o	+	++	o	++	++	+
IC	++	++	+	++	o	++	o	o	++	o	+	+
TC	+	+	o	o	o	+	+	++	+	++	++	+
Design phase	+	o	++	o	++	o	+	+	++	o	+	+

Table 8.1: Summary of the influence of the various parameters on the operating cost (OC), investment cost (IC) and total cost (TC) together with the extent to which these parameters can be influenced during the design phase of the borefield as a result of the sensitivity analyses. Legend for OC, IC and TC: '++', '+' or 'o' represents a parameter with a strong, modest or limited influence on the cost components respectively. Legend for Design phase: '++', '+' or 'o' represents a parameter that can strongly, slightly or not be influenced in the design phase respectively.

Chapter 9

Real-life case study

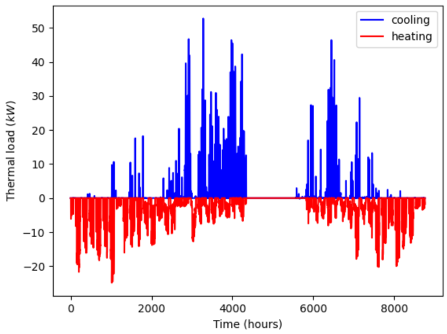
The second engineering research question posed in Section 1.2 links the insights of this research and the use of the developed tool to reality. The use of combined active and passive cooling might change investment decisions during the design phase of the borefield. This can be assessed by conducting a case study using real load profiles from industry. The synthetic load profiles in these chapters are well suited to link results to the underlying principles of borefield sizing but do not entirely correspond to real situations. This study therefore revisits the conclusions of Chapters 7 and 8 with an emphasis on the shape of the load profile.

9.1 Case study with real-life load profiles

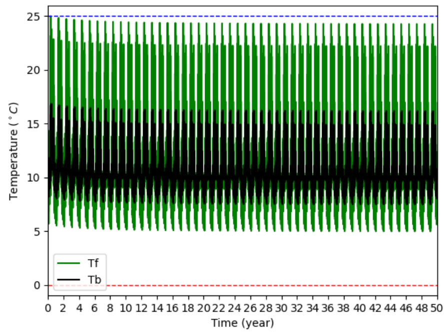
The case study looks at two different cases and identifies the cost savings possible when moving from passive cooling only to combined active and passive cooling. Subject of the first case is the load profile of the gymnasium from a Belgian high school. Subject of the second case is the load profile of the building complex 'The Loop' situated in Gent, Belgium. Both load profiles are obtained via dynamic simulations performed by Boydens Engineering [29]. The assumptions used for the sizing process of the borefield are the same as the ones listed in Section 7.1.4. The only difference is the borefield configuration, which is chosen based on the total load in the cases. The gymnasium uses a 4x4 borefield configuration, the Loop uses a 20x20 borefield configuration.

9.1.1 Gymnasium

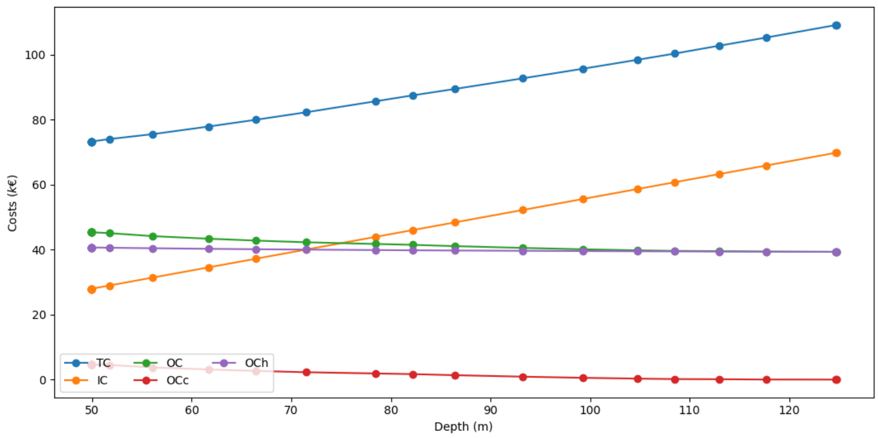
The load profile of the gymnasium is shown in Figure 9.1a. This profile is located in the first borefield quadrant which can be seen by the high cooling peaks. The imbalance of the load profile is negative because of the heating dominated load. This results in the declining temperature profile of Figure 9.1b. The relatively small imbalance of the load is also clearly visible in this figure as the temperature variation over the years is rather small.



(A) Load profile used in the gymnasium case study.



(B) Resulting temperature profile over the lifetime of the borefield.



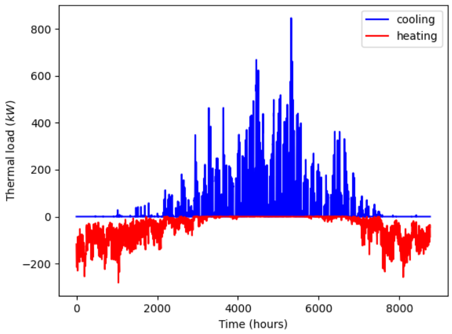
(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 49.93m.

Figure 9.1: Results for the gymnasium case study.

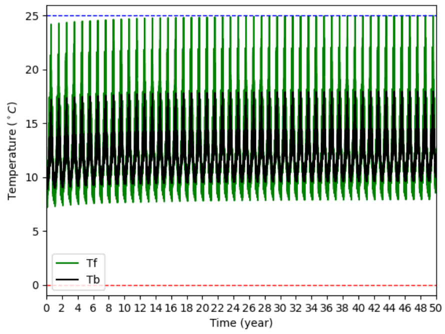
The different cost functions for this case are shown in Figure 9.1c. The TC curve strongly increases for larger borefield depths. The TCO can in other words be minimized by maximally using combined active and passive cooling. This corresponds to a borefield depth of 49.93m with total costs over the lifetime of the borefield of 73.3 kEUR. The operating cost for cooling only represents a small share of total costs due to the higher cooling EER and a limited share of active cooling of 40.88 %. The cost saving by using active and passive cooling instead of passive cooling only is significant: the TCO can be reduced by 35.9 kEUR or 33% compared to passive cooling only, driven by the smaller investment cost.

The additional CO_2 emissions in the cost-optimal solution compared to passive cooling only are 2.67 tons of CO_2 but result in a cost saving of 35.9 kEUR. The abatement cost to use passive cooling instead of the cost-optimal solution is therefore 13.4 kEUR/ton, which is very high. Therefore, the carbon savings by using passive cooling only do not outweigh the benefits of combined active and passive cooling.

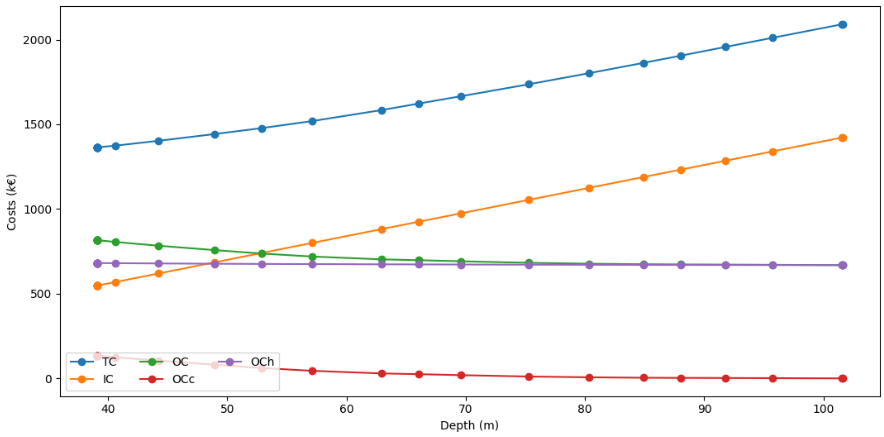
9.1.2 The Loop



(A) Load profile used in the 'The Loop' buildings case study.



(B) Resulting load profile over the lifetime of the borefield.



(C) Costs curves for increasing borefield size: total Cost (TC), investment cost (IC), total operation cost (OC), consisting of operation cost for cooling (OCc) and for heating (OCh). The optimal borefield depth is 39.10m.

FIGURE 9.2: Results for the 'The Loop' case.

The second case describes the load of a group of buildings, called 'The Loop'. The load itself is shown in Figure 9.2a and has clearly high cooling peaks. This is a cooling dominated case with a small imbalance, as can be seen by the limited temperature variations over the lifetime of the borefield. This case is therefore situated in quadrant 3 with the temperature profile of the optimal borefield depth shown in Figure 9.2b.

The cost components are depicted in Figure 9.2c. These cost curves look similar to the ones in Figure 9.1c, with again the optimal borefield size for maximal combined active and passive cooling. The TC curve is again characterized by a strong increase for larger borefield sizes underlining the potential of reducing costs by partly using active cooling. The optimal borefield size is 39.10m with a total cost of 1.36M. This is a cost saving of 730 k EUR or 34.9 % compared to the passive cooling case. A remarkable result in this case study is the relatively small share of active cooling equal to 41.5 %, which is exceptional in Q3.

The cost optimal solution with combined active and passive cooling emits an additional 77.3 tons of CO_2. The cost saving compared to passive cooling only is 727 kEUR, resulting in an abatement cost of 9.40 kEUR/ton. Similarly as in the previous case, the carbon savings by using passive cooling only do not outweigh the benefits of combined active and passive cooling.

9.2 Conclusions and discussion

This real life case study confirms the potential of using active cooling next to passive cooling to reduce total costs over the lifetime of the borefield. Although this case study may not be generalized, the potential benefits are clear. This thesis therefore confirms the need to at least consider the use of active cooling in the design phase of projects with borefields and use the newly developed tool to optimize the borefield size by combining active and passive cooling.

One key conclusion of Chapter 7 is the larger potential for combined active and passive cooling for varying load profiles as the borefield has the opportunity to cool down in between the peaks of the load profile. Therefore, the operation costs related to cooling decrease. This conclusion is confirmed in both cases, as the loads show larger variations compared to the synthetic load profiles studied in Chapter 7. The large potential in these cases is clear by the steep TC curve.

An additional insight gained from this case study is related to the share of active cooling. The load profiles in this case study are more balanced compared to the profiles used in Chapter 7. The limited share of active cooling in Q1 corresponds to these previously found results, but the share of active cooling is significantly lower in Q3. This is due to the more variable and irregular shape of the load profile, which allows the borefield to cool down in between the cooling peaks.

Both case studies indicate relatively limited carbon emissions for the large cost savings associated with the use of active cooling. Although the abatement cost only gives an initial indication on the efficiency of financial resources, it is more than a factor 100 larger than the current carbon prices in the EU in both cases. The use of combined active and passive cooling is therefore justified in terms of CO_2 emissions.

Key Takeaways

The key insights of this chapter are listed below.

- The use of combined active and passive cooling indicates a large potential for reducing the TCO compared to the use of passive cooling only in the studied cases. Introducing active cooling results in a 33% and 35% cost reduction for the gymnasium and the 'The Loop' case respectively.
- Conclusions on the potential for combined active and passive cooling for more varying load profiles from Chapter 7 are confirmed.
- The share of active cooling not only depends on the type of load, i.e. its borefield quadrant, but is also significantly lower for more varying load profiles.
- Considering active and passive cooling during the design phase of the building is a necessity to reach cost-effective investment decisions.
- The additional CO_2 emissions associated by the use of active cooling are justified due to the large potential cost saving.

Chapter 10

Future work

Chapters 7 to 9 have brought many valuable insights and conclusions concerning the design and operation of borefields using combined active and passive cooling. Apart from these insights and conclusions, new questions arose together with the demand for more research. This chapter discusses the main questions that remain at the end of this research and can serve as starting points for future work. The main topics handled here are: the sustainability of a borefield which goes into the CO_2 emissions and the impact on the soil of the borefield operation (Section 10.1), the potential of regenerative heating and cooling to reduce the TCO (Section 10.2) and finally the development of mathematical indicators to quantify the active cooling potential.

10.1 Sustainability of a borefield

The use of borefields generally is praised as a sustainable investment decision. However, there are some potentially adverse effects that have not been widely considered in the literature. Two of these effects are discussed in this section.

10.1.1 CO_2 emissions

This work has touched briefly on the CO_2 emissions related to the use of borefields. On the one hand the indirect operational CO_2 emissions due to the electricity use by the heat pump are relevant. These increase with increasing share of active cooling. On the other hand the embodied CO_2 emissions in the borefield installation and borefield materials are relevant. The bulk of the CO_2 emissions over the lifetime of the borefield result from the operational emissions [44]. This section covers ideas for future work on both sources of emissions.

Operational CO_2 emissions

As mentioned, the bulk of the CO_2 emissions over the lifetime of a borefield are due to the electricity use by actively cooling. Especially for longer lifetimes, the share of these emission increases. This work considered an constant average of 127 grams of CO_2 emitted per kWh of electricity produced in Belgium. In reality this value fluctuates over time, specially looking at the time scale for borefields, and differs based on the electricity generation mix. This section proposes a detailed analysis of the possible origins of the electrical energy used to power the heat pump now and in the foreseeable future. Potentially, by investing in renewable energy sources (RES), the operational CO_2 emissions can be reduced.

Embodied CO_2 emissions

Chapter 1 claimed ground source heat pumps to be the cornerstone of sustainable and efficient heating and cooling due to the low CO_2 emissions during operation. This indeed is a strong driver for borefield research but one must not forget embodied CO_2 that become clear when performing an extensive life cycle analysis. The production and processing of the raw materials for borefield construction, distribution and transportation of equipment and borefield components, installation and the end of life of the borefield are all processes that have CO_2 linked to them.

This section proposes an in-depth LCA approach to accurately determine the resulting CO_2 emission savings due to a smaller borefield size when including active cooling compared to passive cooling only. A good starting point for this research could be the LCA for various ground source heat exchanger configurations performed by L. Arest, P. Christodoulides and G. Florides [44].

10.1.2 Impact on ground ecosystems

Due to the close coupling of borefields with the surrounding ground, the borefield operation affects the ground in multiple ways. First and most obvious, the ground temperature changes due to heat transfers. This temperature change might have additional effects on the underground ecosystems in the proximity of the borefield. Secondly, the risks involved with leakage due to borehole degradation leading to groundwater contamination must be taken into account when discussing sustainability. These two topics (and other potential environmental risks) have not extensively been considered in the literature so far which calls for additional research. This section shortly elaborates on the two mentioned topics.

As must be clear by now, the operation of a borefield reduces or increases the ground temperature over its lifetime due to a yearly imbalance between the heating load and the cooling load. This thermal pollution could, as proposed by Ke Zhu in [45], lead to a change in microbial ecosystems which may alter soil fertility and structure. In more extreme cases, higher ground temperatures lead to a reduction in dissolved oxygen in the ground water which reduces vitality of surface flora [46].

As discussed in Chapter 8, in some cases it might be interesting to reduce the minimum average fluid temperature limit below 0 °C. In case water is used as heat carrier fluid, an antifreeze agent must be added to avoid freezing. Often also these heat carrier fluids contain additives to inhibit corrosion. The environmental risks associated with using these chemicals in the ground have not been widely concerned [45].

This section proposes an extensive analysis of the potential ecological and environmental consequences of rising ground temperatures, using antifreeze and using other performance enhancing additives.

10.2 Regenerative heating and cooling

The minimal borefield size is determined by the maximum or minimum average fluid temperature limit. The yearly imbalance[1] strongly determines how quickly the average ground temperature rises or falls over the lifetime of the borefield. This imbalance thus has a very strong influence on the necessary borefield size. Regenerative heating or cooling attempts to influence this imbalance to reduce the minimal necessary borefield size and the TCO. As Chapter 6 mentioned, regenerative heating or cooling could be an option to reduce the investment cost further. If low-cost electricity is available, regenerative heating and cooling becomes more interesting due to the low operating cost.

As an example Figure 7.10b is studied. It is very clear that the average temperature in Figure 7.10b varies strongly. This indicates that by reducing the imbalance, the investment cost can be reduced. Reducing the imbalance in this case could be done, for example, by installing solar heat collectors that inject the collected heat into the borefield with a limited operation cost. Here the economic trade-off must be considered between the savings in investment cost due to regenerative heating and the purchase- and operation cost of the heating system. Regenerative cooling would not be useful in this particular case, but might be in others.

This section proposes to consider regenerative cooling as an additional way to reduce the TCO of the borefield. Herefore external heating and cooling systems for regenerative heating and cooling must be added to the optimization algorithm. A good starting point would be the work of Peere on regenerative heating and cooling in [3].

10.3 Active cooling potential indicators

Chapter 7 shows the potential for combined active and passive cooling for various load profiles using the developed optimization algorithm. Equation (5.1) already touched upon the link between the shape of the load profile and the potential for combined active and passive cooling in a conceptual manner. Also Chapter 6 mentioned that the potential for combined active and passive cooling could be determined by using a few rules of thumb that follow from the insights of this master thesis.

[1]The imbalance is computed as the difference between the total cooling load and the total heating load. This imbalance can be computed yearly or over the full lifetime of the borefield.

This section suggest additional research that aims to mathematically describe the initial load profile using various statistical parameters. This mathematical characterization of the shape of the load profile can then be linked to the potential for combined active and passive cooling. From here some simple rules of thumb can be defined that determine the potential of combined active and passive cooling based the initial load profile.

Key Takeaways

- Embodied CO_2 emissions and the impact on the ground ecosystems related to borefields are not widely considered and call for additional research.
- Regenerative heating or cooling may, in some situations, lead to further reduction of the TCO.
- The potential for combined active and passive cooling could be described using a few rules of thumb that result from a mathematical or statistical description of the shape of the load profile.

Chapter 11

Conclusion

This work identifies a large potential for including active cooling in the design phase of the borefield. Depending on the type of load profile applied to the borefield, combined active cooling has a significant potential to reduce the total cost of ownership (TCO) by reducing the borefield size, economically justifying the use of active cooling. Furthermore, the abatement cost for CO_2 emissions in these cases is generally at least an order of magnitude larger than the current EU ETS carbon price, which also ecologically justifies the use of active cooling. The developed tool can be used to determine this potential and so contribute to the current trend toward efficient use of resources and a more sustainable world.

Methodology To compute the TCO using combined active and passive cooling, the borefield size is computed through a doubly iterative approach, taking into account an hourly time resolution. The most economical borefield size coincides with or exists between two extreme values: the minimal possible borefield depth and the maximal relevant borefield size. Bayesian optimization locates the borefield size for which the TCO is minimal. The sensitivity of the output of the developed sizing algorithm to various parameters is analyzed in an extensive sensitivity analysis. This methodology answers the second part of the first scientific research question. The others are answered below.

Can the use of combined active and passive cooling lead to a lower Total Cost of Ownership (TCO) compared to the use of passive cooling only?
The use of combined active and passive cooling can lead to a lower TCO compared to the use of passive cooling only. If the temperature profile resulting from applying a certain load profile to a borefield is limited by the maximum temperature limit for passive cooling only, a significant economical potential for combined active and passive cooling exists for that particular load profile.

An increase in time resolution of the optimization leads to an increase in accuracy of the results and an increased computational time and complexity. To what extent are the advantages of the increased time resolution worth the disadvantages when

considering active cooling?
Increasing the time resolution results in a more detailed temperature profile which is necessary to estimate the operating cost accurately. By taking advantage of the Fast Fourier Transform and the convolution operator, the increased computational intensity is mitigated. The advantages thus outweigh the disadvantages.

Which parameters have the greatest impact on the TCO and to what extent can they be influenced during the design phase of the borefield?
Of the most influential parameters, the maximum temperature for passive cooling, electricity price and efficiency of the heat pump are the ones that can be influenced most during the design phase of the borefield. Furthermore the lifetime of the borefield strongly effects the TCO.

To what extent can the use of the developed tool provide new insights in the design phase of geothermal borefields, potentially changing investment decisions?
Two case studies show the developed tool has the potential to provide new insights in the design phase of the borefield. In these cases in particular the TCO could be reduced by roughly 33% by including active cooling compared to passive cooling only.

Limitations The assumptions made within the framework of this thesis lead to several limitations. First, this work assumes an identical operating regime for active and combined cooling. In practice, careful heat pump design is necessary for this is difficult to achieve and results in technical difficulties. Second, this work does not consider actual heat emission systems (HES) and assumes the full thermal load can be extracted/injected from/into the building at all times. In practice, HES must be closely coordinated with the thermal load and operating regime. Third, the results are extremely dependent on the load profiles used and some key parameters. Varying any of these can lead to significantly different conclusions on the potential of combined active and passive cooling.

Future work A few key topics have been identified as a starting point for future research related to this work. First, the CO_2 emissions due to electricity use and the embodied CO_2 emissions vary strongly depending on the assumptions related to the electricity generation mix and the materials used in the borefield. An in-depth Life Cycle Assessment is an interesting extension of the current economic optimization tool. Second, including active cooling might have adverse environmental effects on ground eco- and watersystems. Through extensive analysis on the severity of these effects, an extra environmental cost component could be added to the TCO optimizations which might lead to new optima. Third, the use of regenerative heating and cooling technologies could reduce the TCO of the borefield regardless of the potential of combined active and passive cooling. Fourth, by analyzing the shape of the load profiles using statistical and algebraic indicators, some rules of thumb can be identified that link the shape to the potential of combined cooling. This would allow quick estimation of opportunities to reduce the TCO.

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