Improving identification of HT-ATES performance drivers and -barriers

by Wouter Rocchi

TU Delft

pwc

Improving identification of HT-ATES performance drivers and -barriers

by

W. P. Rocchi

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday January 24, 2020 at 13:00 AM.

Student number:	4275012	
Project duration:	March 18, 2019 – January 24, 2020	
Thesis committee:	Associate professor. dr. ir. P. J. Vardon,	TU Delft, supervisor
	Professor dr. ir. F. Mulder,	TU Delft
	Dr. ir. J. M. Bloemendal,	TU Delft, daily supervisor
	Ir. F. Wolters,	PwC, company supervisor
	Assistant professor. dr. ir. M. Brehme,	TU Delft

This thesis is confidential and cannot be made public until January 24, 2020.

TU Delft

Abstract

High temperature aquifer thermal energy storage (HT-ATES) can potentially solve the mismatch between heat supply and -demand. It can provide a large scale seasonal heat storage solution. Thereby it enables an increase in full load hours of the base heat source, which can benefit project performance on both costs and emissions. However, the limited number of successful pilot projects indicates the technology has not escaped its state of infancy. There is a gap from concept to implementation, which is signified by the disagreement of experts on performance drivers and -barriers of HT-ATES. This research aims to narrow the described knowledge gap, by improving identification of HT-ATES performance drivers and -barriers. Thereby it strives to improve decision making of HT-ATES implementation, and further enhance future HT-ATES application in heating projects.

The broad scope of research demands both a diagnostic and design-orientated approach, and fits seamlessly with a multi-criteria decision analysis. The analysis entails the stages of creating, evaluating, comparing and ranking of case-specific scenario's. Parametric variation changes the conditions for HT-ATES implementation across the scenario's. A simulation model is developed and connected to a groundwater model to apply the parametric variation, to create the different scenario's, and consequently to produce the quantitative information for further evaluation. During the stages of creating, evaluating, comparing and ranking, the methodology systematically produces new results on the opportunities and risks introduced by HT-ATES, and additionally on the HT-ATES performance drivers and -barriers.

The results show that HT-ATES enables the opportunity of improving project performance with respect to the internal rate of return and emissions. Groundwater impact remains the greatest risk, but it can be minimised with smart decision making. To support the decision maker and to overcome the risk of groundwater impact, the research proposes several performance-enhancing, non-explicit guidelines. The guidelines focus on realising an HT-ATES implementation, where project performance with respect to internal rate of return, emissions and groundwater impact are balanced. Thereby they explain the major HT-ATES performance drivers and -barriers. The guidelines are summarised below. The decision maker is recommended to ..

1. .. minimise the uncertainty, through thorough subsurface characterization before implementation. Secondly, to focus on aquifers with a minimum depth of *200* [m] and a minimum hydraulic conductivity of *5* [m d^{-1}]
2. .. assure network return temperatures during peak demand are below expected storage temperatures
3. .. not consider project life-times exceeding *20* years
4. .. assure yearly maximum base source heat production is always lower than yearly consumer heat demand
5. .. to strive for a flat demand curve and apply peak-shaving, by means of, for example, variable heat prices

Currently, the guidelines have the purpose of giving direction to the decision maker, but they will become more explicit once the methodology is improved, and the uncertainty and number of assumptions in the model is decreased.

Acknowledgements

Firstly, I am grateful to the Delft University of Technology for giving me the opportunity to conduct research on this topic.

I would also like to express my sincere gratitude to PwC, and in particular to Duco Brouwers and Stephane Jager for accepting me as a graduate intern, and providing me with the freedom to explore and experiment throughout the entire duration of the project. My introduction at PwC felt like a warm bath, and I experienced the company and office culture as pleasant and refreshing.

The efforts of dr. ir. Martin Bloemendal and associate prof. Phil Vardon, respectively my weekly supervisor and thesis supervisor, deserve explicit recognition. Their availability, humour, and appropriate criticism fueled my pursuits. To no lesser extend I want to express my gratitude to my company supervisor ir. Frits Wolters, who served as a mentor within PwC, and whose down-to-earth view and critical questions greatly improved this project. Frits taught me that listening is an invaluable and undervalued skill. Furthermore, I would like to thank assistant prof. Maren Brehme and prof. Fokko Mulder, for functioning as additional committee members.

In addition to my committee, there is a group of experts and organisations, that provided me with critical input for the project, who deserve a brief mention and to all of whom I am grateful. I would like to thank Stefan Aarts of Techniplan Adviseurs BV, who served as an inspiration to the simulation model. I would like to thank Joris Koorneef of TNO and Guido Bakema of IF Technology for providing me with key financial figures. I would like to thank the *3* organisations, which prefer to remain anonymous, for trusting me and sharing confidential information regarding their heating supply and -demand.

Finally, I am grateful for my dear family and friends, who supported me both during and outside office hours, and without whom I could not have accomplished the same.

W. P. Rocchi
Delft, January 2020

List of Figures

List of Tables

List of Abbreviations

ATES Aquifer Thermal Energy Storage

CAPEX Capital Expenditures

CHP Combined Heat Power

DH District Heating

DM Decision Maker

GD Geothermal Doublet

HP Heat Pump

HT-ATES High Temperature Aquifer Thermal Energy Storage

IRR Internal Rate of Return

MCDA Multi Criteria Decision Analysis

MCDM Multi Criteria Decision Method

NPV Net Present Value

OPEX Operational Expenditures

SA Sensitivity Analysis

TRE Thermal Recovery Efficiency

Contents

1 Introduction

In light of the energy transition, geothermal energy can be seen as the sustainable alternative for the currently widely adopted natural gas boiler. A geothermal doublet (GD) produces thermal energy, which can be distributed to the end-consumer by means of a district heating (DH) network. The GD output is constant, whereas the heat demand in the Netherlands is variable, with a large peak during the winter months and a low demand in summer (figure 1.1). Large scale seasonal heat storage applications, such as high temperature aquifer thermal energy storage (HT-ATES), can solve the mismatch between supply and demand. It could prove to be critical in making geothermal energy more efficient and competitive, enabling the GD to produce throughout the summer. The summer surplus heat production of the GD can be used to compensate the deficit in winter. The result would be a larger share of geothermal energy in the final energy consumption, and thereby a direct saving on fuel costs and emissions [40]. To add to this, the subsurface has proven the be an ideal medium to store large quantities of water for longer periods of time [13]. Despite the obvious potential opportunities, the number of realised HT-ATES projects is limited. This signifies the gap from concept to implementation, which is the central problem that this research project will target.

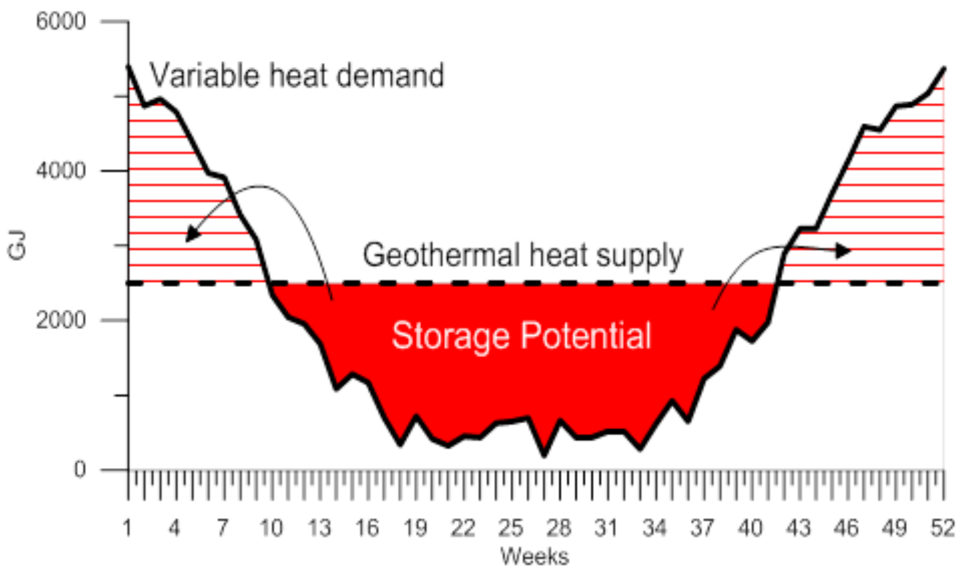

Figure 1.1: Mismatch supply and demand [63].

1.1. Preliminary literature study

This section is a continuation on the introduction and entails the foundation for further research.

1.1.1. Pilot projects ended prematurely

The concept of HT-ATES has been researched extensively since the *80's*, but a limited number of projects have been realised so far [55], of which the majority has been proven to be unsuccessful: *2* out of *3* known projects in the Netherlands have been ended prematurely, for different reasons.

1. In Utrecht the project ended because there was an unbridgeable gap between the storage temperature and the supply- and return temperatures required by the buildings [55].
2. The Zwammerdam HT-ATES project was no longer cost-effective, because the actual (connected) heat demand was smaller than the projected heat demand [55].

In both examples, conditions outside the reservoir (network temperature and heat demand) determined the performance of the HT-ATES system, and eventually resulted in closing the system. Therefore, it is remarkable to discover that most research to improve HT-ATES performance, is devoted to in-reservoir characteristics, with the common goal to improve the thermal recovery efficiency (TRE) [34]. This definition will be explained in appendix B. The appendix can be adopted by the reader to read into concepts of HT-ATES and DH.

1.1.2. Literature disagrees on performance drivers and -barriers

A recent study by Utrecht University and TNO investigates the performance of HT-ATES by evaluating the market potential. The research does so by comparing HT-ATES to natural gas boilers as the reference technology [65]. It seems somewhat redundant while conducting research within the era of the sustainable energy transition: natural gas boilers is not a technique you could consider for future heating purposes, when the world is desperate to cut emissions more than ever.

Furthermore, comparing HT-ATES to boilers is like comparing apples to pears. It will be hard to prove cost-effectiveness of an immature technology to a widely-adopted, reliable, and cheap technology as natural gas boilers. Despite all, Wesselink et al. finds opportunities for cost-effectiveness of HT-ATES, and states that lifetime of the system and heat demand are crucial pillars for a successful business case [65]. Thereby, the findings of Wesselink et al. are in line with the challenges in the aforementioned pilot projects. Conditions outside the reservoir dictate the system performance.

Plueymakers et al. believes that a mix of surface- and subsurface factors determine the overall system performance: formation layer conductivity, storage temperature and HT-ATES full-load hours are the crucial performance drivers [38]. It can be concluded that scientists are unable to agree on the critical performance factors, which serves as fuel to this research project.

1.1.3. The urge for a broader perspective

The concept of HT-ATES has to be approached with an open mind, unbiased, and with an eagle-eye perspective, since the key performance drivers are not be agreed upon. Besides economical-, environmental- and technical factors, also legal- and social factors must be taken into consideration. This broad perspective fits seamlessly with a multi-criteria decision analysis (MCDA).

The MCDA is a tool for decision makers (DM) and is considered as the the foundation of the rational decision making process [26]. MCDA for a more successful energy transition, is not revolutionary and has been done before. [...] *'Sustainability merely is a balance of social and economic activities, and the environment'* [62]. The importance of balancing criteria is acknowledged in the following citation of Georgopoulou et al., who was ahead of his time in *1997*. [...] *'In the past, the choice among alternative energy policies at regional level was based only on cost minimization. Lately, it is widely recognised that regional energy planning forms a multi-actor and multi-criteria problem'* [16]. The complexity regarding balanced decision making on energy systems is visualised in figure 1.2. It shows that the path towards the optimal solution/result is not always evident. The MCDA can support in navigating in correct direction. Other than the MCDA in the general energy transition [16, 62], a MCDA specifically focused on HT-ATES implementation, has never been performed before. Chapter 3 and appendix D entail a more detailed explanation of the MCDA.

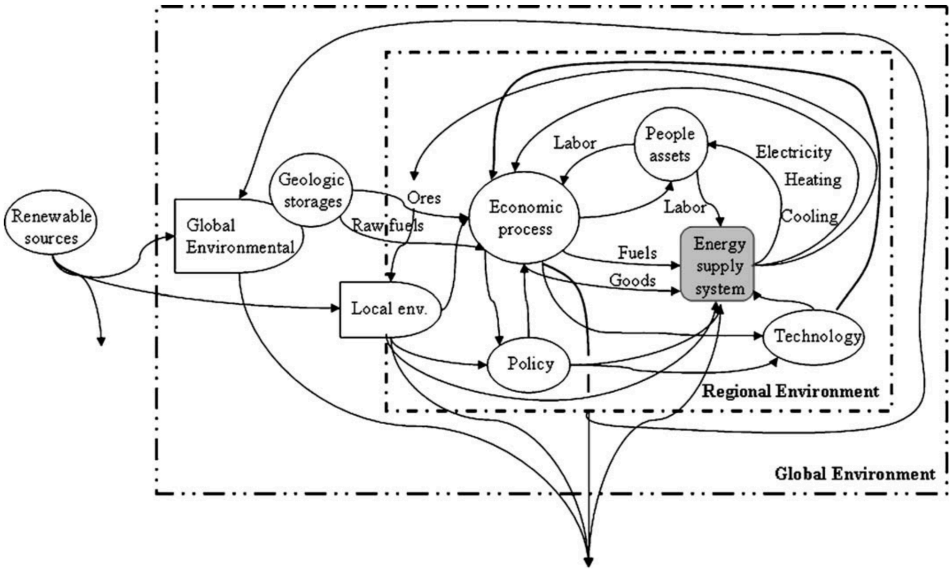

Figure 1.2: Complexity of an energy system [62]

1.1.4. Quantitative foundation for the multi-criteria decision analysis

Figure 1.2 entails several subjects that are based on quantitative information. For this reason, a simulation model is deemed necessary to support the MCDA, and to provide quantitative input to the further analysis. Chapter 2 and appendix C entail a more detailed explanation of the simulation model.

1.2. Context, objective and outline

1.2.1. Research project context

Having identified the problem and the need of a broader perspective, the step towards project contextualisation is not a difficult one. To recapitulate the previous sections: although the potential synergies of HT-ATES, DH and a GD are obvious, only a limited number of projects have been successful so far. This research aims at narrowing the existing knowledge gap from concept to implementation, by improving identification of performance drivers and -barriers. Thereby the research contributes to better decisions on HT-ATES, and eventually a more optimal use of HT-ATES in future heating projects, balancing the interests of all stakeholders. The research methodology is more thoroughly explained in chapter A. The project context is visualised in figure 1.3.

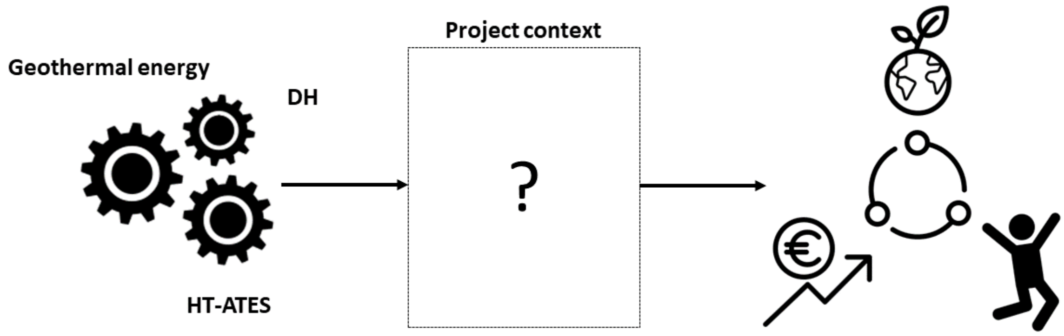

Figure 1.3: Project context

1.2.2. Research project objective

An effective research objective is useful and feasible [60]. The research objective of this project is as follows: *to improve identification of HT-ATES performance drivers and -barriers in heating projects, by delivering a simulation model and subsequent framework for decision-making.* To achieve the research objective, several steps, including intermediate objectives, are ought to be taken. Every intermediate step corresponds to a specific phase of the research. The steps towards the objective are specified below:

1. To gain understanding of the HT-ATES concept in general, by performing a literature study and by consulting experts and stakeholders
2. To develop a simulation model and a multi-criteria decision method (MCDM), by adopting the profound concept understanding
3. To create, evaluate and rank scenario's, by testing and using the simulation model and subsequent MCDM on multiple cases
4. To identify major performance drivers and -barriers, and to recognise case-wide trends, by analyzing the results

1.2.3. Research project outline

To reach the objective, the project has been structured into the following chapters:

- *Chapter 1* identifies the problem, and states the project context and research objective. Appendices A and B are a continuation of chapter 1, and provide a more detailed explanation of respectively the research methodologies and literary background.
- *Chapter 2* introduces the simulation model. It explains the purpose of the applied parametric variation, and the adopted perspective of mutation. More information regarding the simulation model is entailed in appendix C.
- *Chapter 3* entails the developed MCDM, including criteria selection, -weighting, and performance scoring. In addition, it elaborates on the method uncertainty. It is a product of an extensive literature study on decision making (appendix D).
- *Chapter 4* shows and analyses the results of the different case studies, in which the developed MCDM and simulation model are put to practice. The results have a comparative nature, due to the perspective of mutation. Additional results are included in appendix E.
- *Chapter 5* contains a step-wise discussion of the applied methodology and final results. Simultaneously, it provides recommended improvements for future application of the model and subsequent framework.
- *Chapter 6* identifies the HT-ATES performance drivers and -barriers, by formulation of *5* performance enhancing guidelines for the DM. During this process it considers the discussion in the previous chapter.

2
Simulation model

The simulation model creates different case-specific scenario's through parametric variation. The parametric variation entails the following parameters: project life-time, cut-off temperature, consumer demand, system flow capacity, thickness, depth, and hydraulic conductivity. For every scenario the model produces quantitative performance metrics on carbon emissions, groundwater temperature and financial performance. The metrics provide new insights into the function of HT-ATES within a DH network, and serve as input to the further evaluation. This specific chapter focuses on the model perspective, and the applied parametric variation within the model. The great number of assumptions forces the model to adopt the perspective of mutation. Thereby it determines the mutation of the quantitative performance metrics upon HT-ATES implementation for every scenario. Steven Aarts served as an inspiration to model set-up. Background information regarding the model logic, model assumptions, and model validation is included in the appendix C

2.1. Perspective of mutation on performance metrics

Heating projects are complex, because many factors must be taken into consideration. There are various heat sources and multiple stakeholders, with different incentives. Because time is the crucial constraint (section A.3), focus remains on HT-ATES within this research, and to lesser extent time is devoted to the (sustainable) base source and distribution network. For both several, critical assumptions are done.

To give a brief example, thermal losses in the distribution network are dependant of distance and depth of the network, of pipe diameter and - material, of type of flow (turbulent or laminar) etc. These have not been considered in the model: it assumes constant thermal losses. For this reason the model is unable to provide realistic predictions on the distribution losses. Consequently, it can not provide realistic predictions of the absolute performance on quantitative metrics.

For this reason, the model adopts the perspective of mutation, and considers the scenario without HT-ATES as a point of reference. It focuses on the relative performance. Non-implementation of HT-ATES is the base scenario, which provides the baseline of performance. The parametric variation maintains constant input and external conditions, and only adjusts and tweaks the (implementation of) HT-ATES. The consequent mutation on quantitative performance metrics (from the baseline) is the quantification of HT-ATES performance, and serves as input to the further analysis.

2.2. Parametric variation and scenario's

Parametric variation has been applied to improve understanding of the influence of parameters on the project performance with respect to the quantitative performance criteria. The parametric variation has been applied to *7* different parameters. *4* design parameters and *3* geological parameters, which have a default-, low-, and high value. They create a total of 15 scenario's, in addition to the base scenario without HT-ATES.

The control board of the HT-ATES system and the subsequent parametric variability within the model is visualised in figures 2.1 and 2.2. Both figures have the purpose of increasing understanding of the model. In figure 2.1 the HT-ATES is switched off and not contributing to satisfy consumer demand. This is the base scenario. The model produces quantitative metrics that form the baseline of performance. In figure 2.2 the HT-ATES is switched on. It contributes to satisfy consumer demand, under certain parameter conditions. This is scenario X. The model output on the quantitative performance metrics changes with respect to the performance baseline. This mutation is the quantification of the HT-ATES impact/performance, and serves as input to the further analysis.

Understanding the impact of individual parameters, and consequently the relative importance among parameters, can improve identification of HT-ATES opportunities in multiple ways. Firstly, the parametric variation directs the DM towards the optimal parameter values, and enables the DM to discard certain scenario's. For example, if a HT-ATES system with high flow capacity is more expensive, but on the contrary does not result in any additional benefits relative to the default- or low flow capacity scenario's, the DM does not have to take this scenario into further consideration. Secondly, the performance sensitivity to individual parameters learns the DM which parameters demand most focus and attention. For example, if the parametric variation shows that project performance is more sensitive to geological parameters, it learns the DM that the majority of available resources should be allocated to subsurface characterization. To minimise subsurface uncertainty and to ensure certain properties of the designated aquifer.

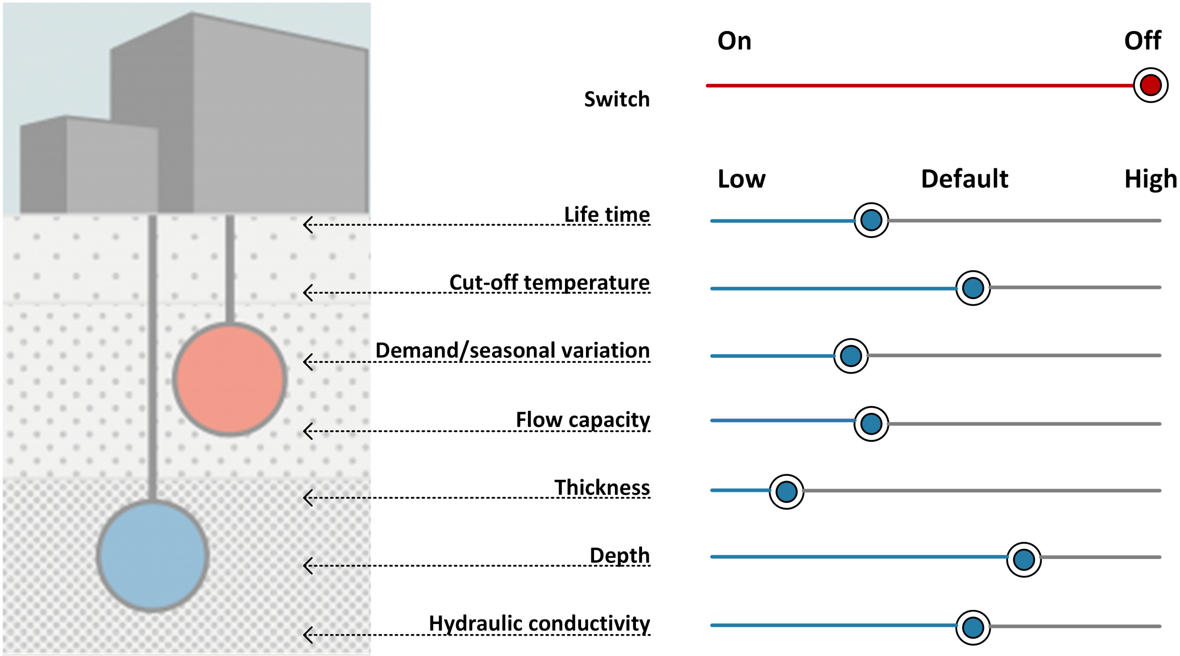

Figure 2.1: Parametric variation in the model visualised, base scenario

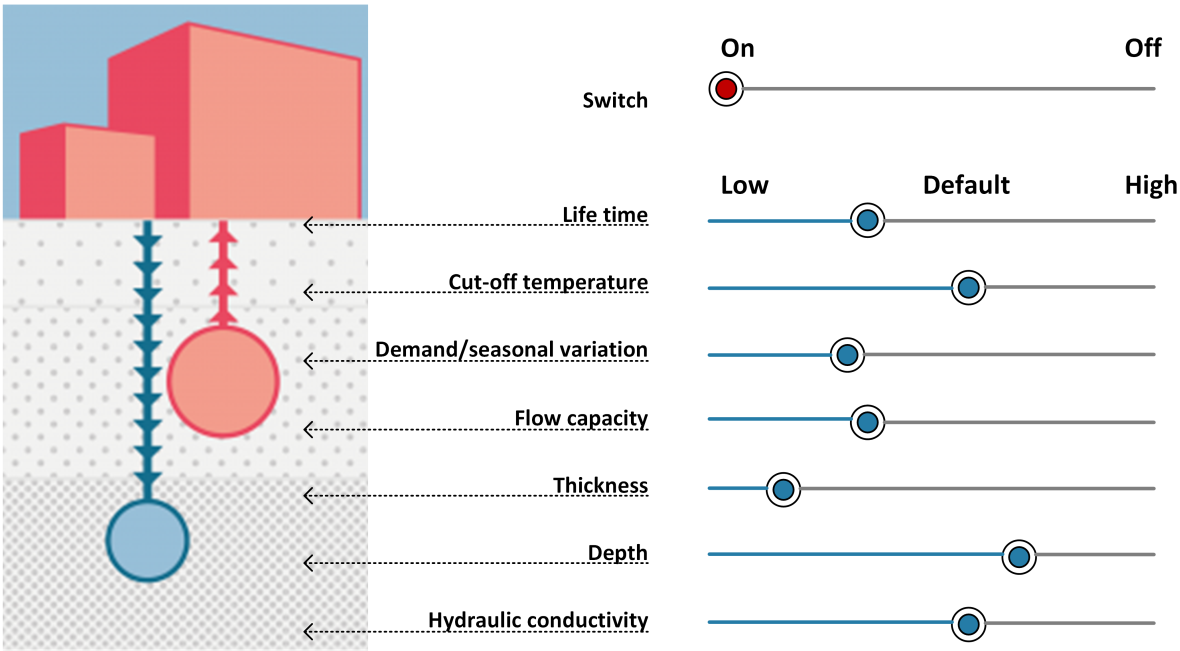

Figure 2.2: Parametric variation in the model visualised, scenario X

3

Multi-criteria decision method

This chapter entails *1* of the *2* parallel activities from the *design phase* (see appendix A). It proposes a MCDM for HT-ATES implementation. HT-ATES can be fully captured in *7* evaluation criteria. A stakeholder-specific survey determines the weighting of evaluation criteria. Quantitative criteria are scored by means of value functions. Qualitative criteria are scored by means of direct rating. Both steps of weighting and scoring entail uncertainty, which is exposed through a Monte Carlo iteration. The literature study underlying the proposed MCDM is included in appendix D.

3.1. An introduction to the multi-criteria decision analysis

3.1.1. Human decision making

The human mind is not without bias and blunder. This is illustrated by the optical illusion of Shepard's table tops in figure 3.1. What appear to be *2* distinct table tops, with unique length and width, are actually identical parallelograms. This becomes more obvious when the legs are erased and the tops are oriented into the same direction.

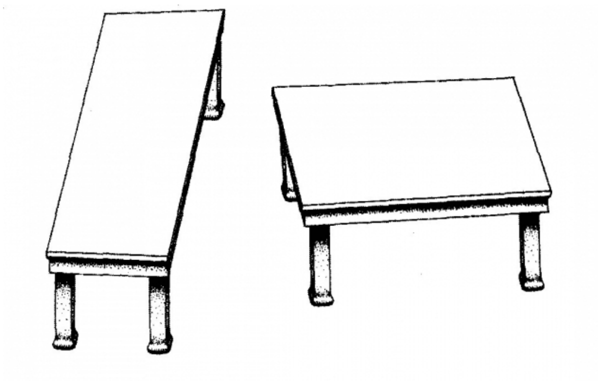

Figure 3.1: Two tables, adapted form Shepard

[...] *'Normally the human mind works remarkably well. We can recognise people we have not seen in years, understand the complexities of our native language, and run down a flight of stairs without falling. Some of us speak twelve languages, improve the fanciest computers, and/or create the theory of relativity. However, even Einstein would probably be fooled by those tables'* [51]. The example shows the human mind is vulnerable for external influential factors. In this case deceptive framing of the tables causes a misconception of the actual length and width ratio's. The same principle holds for human decision making, which can be seen for example in the supermarket. Product placement (influential factors) within a store influences the eventual purchases (decisions). If making a unbiased decision on whether to buy an apple or a pear is already difficult, how can a DM make a rational decision on implementation of HT-ATES?

3.1.2. Multi-criteria decision analysis for rational decision making

In an attempt to bypass the blunders of the human mind, and to enable more rational decision making, the MCDA has been developed. MCDA is an umbrella term for a collection of methods, which enable people to experiment with decisions, and to consider multiple criteria [52], by means of a multi-criteria evaluation. MCDA can include both quantitative and qualitative criteria [1]. Its foundation was laid by Keeney and Raiffa in an attempt to provide structure to problems with multiple (conflicting) objectives [26]. Since the publication of Keeney and Raiffa a great number of approaches have been developed. The great variety of approaches can be regarded as an advantage, because there will always exist a method that fits the purpose. However, some consider the great amount of methods as a point of weakness, because up to now there does not exist a method for deciding which MCDM is most appropriate [18].

The MCDA has demonstrated to be useful in the health care sector [52], and currently wins in popularity among DMs in the (sustainable) energy sector [16, 62], because the more traditional cost-benefit analysis does not suffice, as is explained by the following citation: [...] *'proposing a discount rate for valuing costs and benefits that will be realised or avoided only centuries in the future and under completely uncertain societal conditions is heroic, foolish, or a mixture of both'* [31].

The formulation of the multi-criteria decision problem is usually more critical than its solution, which mostly depends on mathematical skills [18]. Therefore, a concise sequence of steps has been developed for obtaining a comprehensive problem formulation. The steps are visualised in figure 3.2.

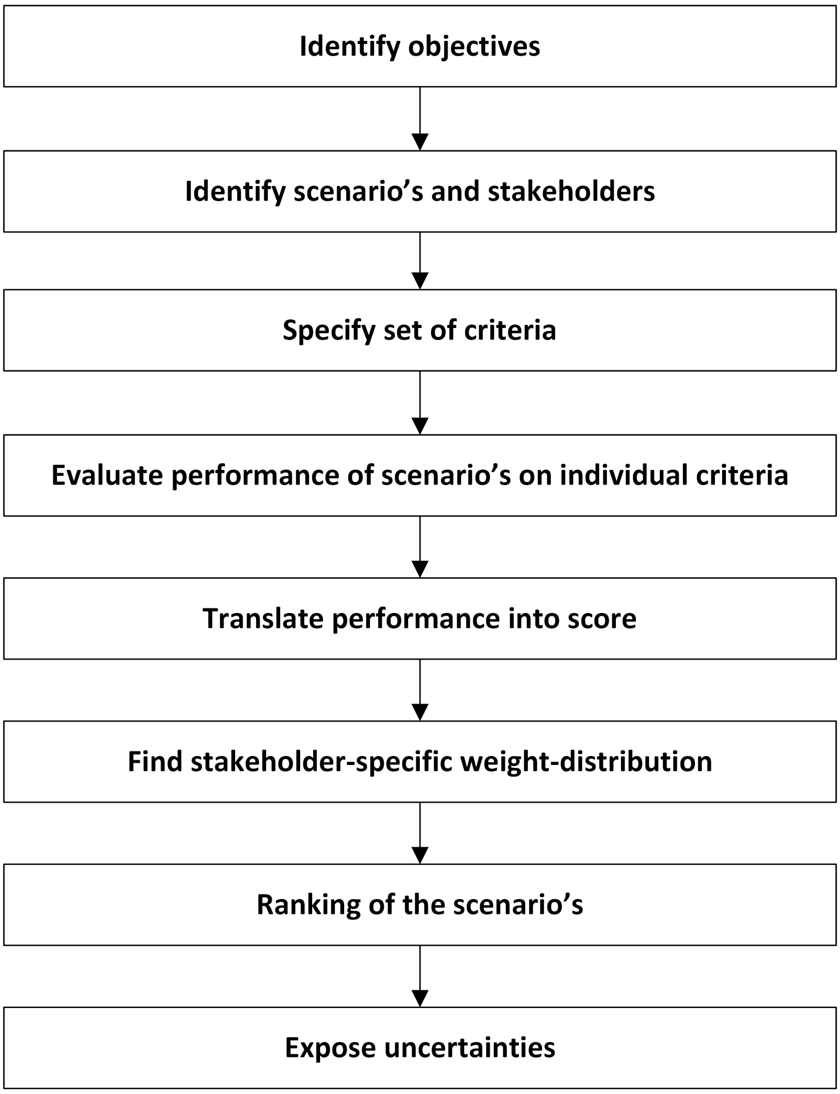

Figure 3.2: The consecutive steps of a multi-criteria decision analysis

3.2. Multi-criteria decision method for high temperature storage

The literature studies on both HT-ATES (appendix B) and decision making (appendix D) serve as input to this section. It describes a decision method for implementation of HT-ATES. The actual scoring of criteria performance, scenario ranking, and the Monte Carlo iteration, will be performed case-specifically in chapter 4.

3.2.1. Identifying objectives

Because this research is aiming to improve decisions on implementation of HT-ATES within a larger heating system, by improving identification of the opportunities, the objectives of a heating system as a whole are taken into consideration for the first step of the MCDM. It is determined that a successful heating system entails *4* main objectives (figure 3.3).

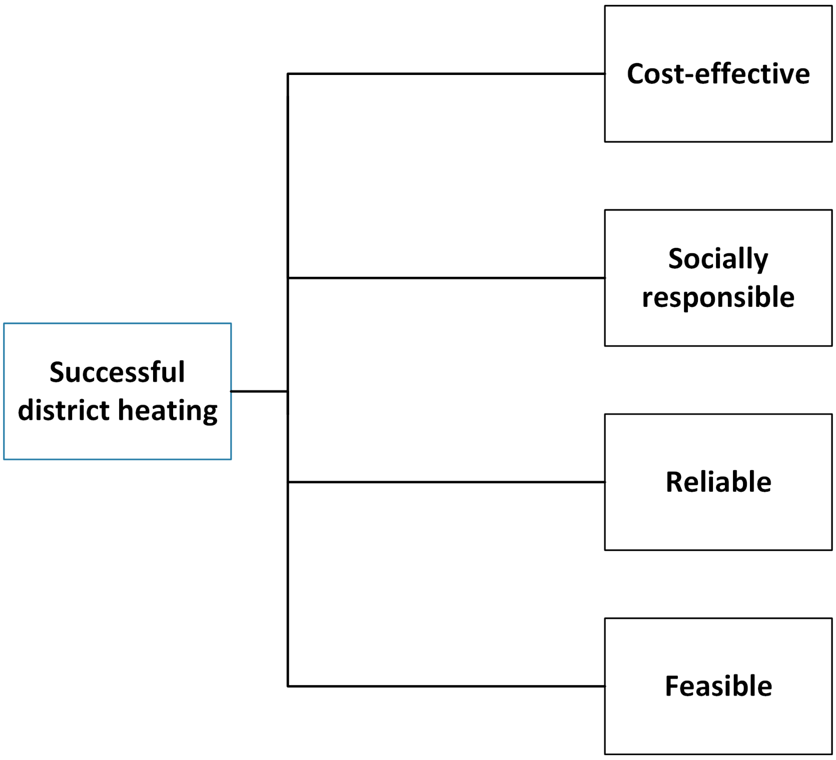

Figure 3.3: A successful heating system subdivided into main objectives

3.2.2. Identifying scenario's and stakeholders

Section 2.2 explains that the parametric variation delivers *15* scenario's, in addition to the base scenario without HT-ATES. To sum up: both design parameters, such as the cut-off temperature, or external conditions outside the scope of design, such as development of consumer heat demand, have a low-, default, and high value, and their variation creates the different scenario's. This parametric variation delivers new insights in the optimal parameter values and the sensitivity to individual parameters. The scenario's define the number of columns of the evaluation matrix (equation D.1), and demand ranking by the MCDA.

Furthermore, it is determined there are *3* major stakeholders. Those that are consuming heat from the heating system, those that are investing in the heating system, and those that are operating the heating system.

3.2.3. Specify criteria set

Wang et al. lists frequently used criteria for decision making in energy problems [62], which serve as inspiration to this criteria set. Consultation of several experts, through a process of trial and feedback, complemented the inspiration from Wang et al. and resulted in a value tree that entails *8* criteria. This can be seen in figure 3.4.

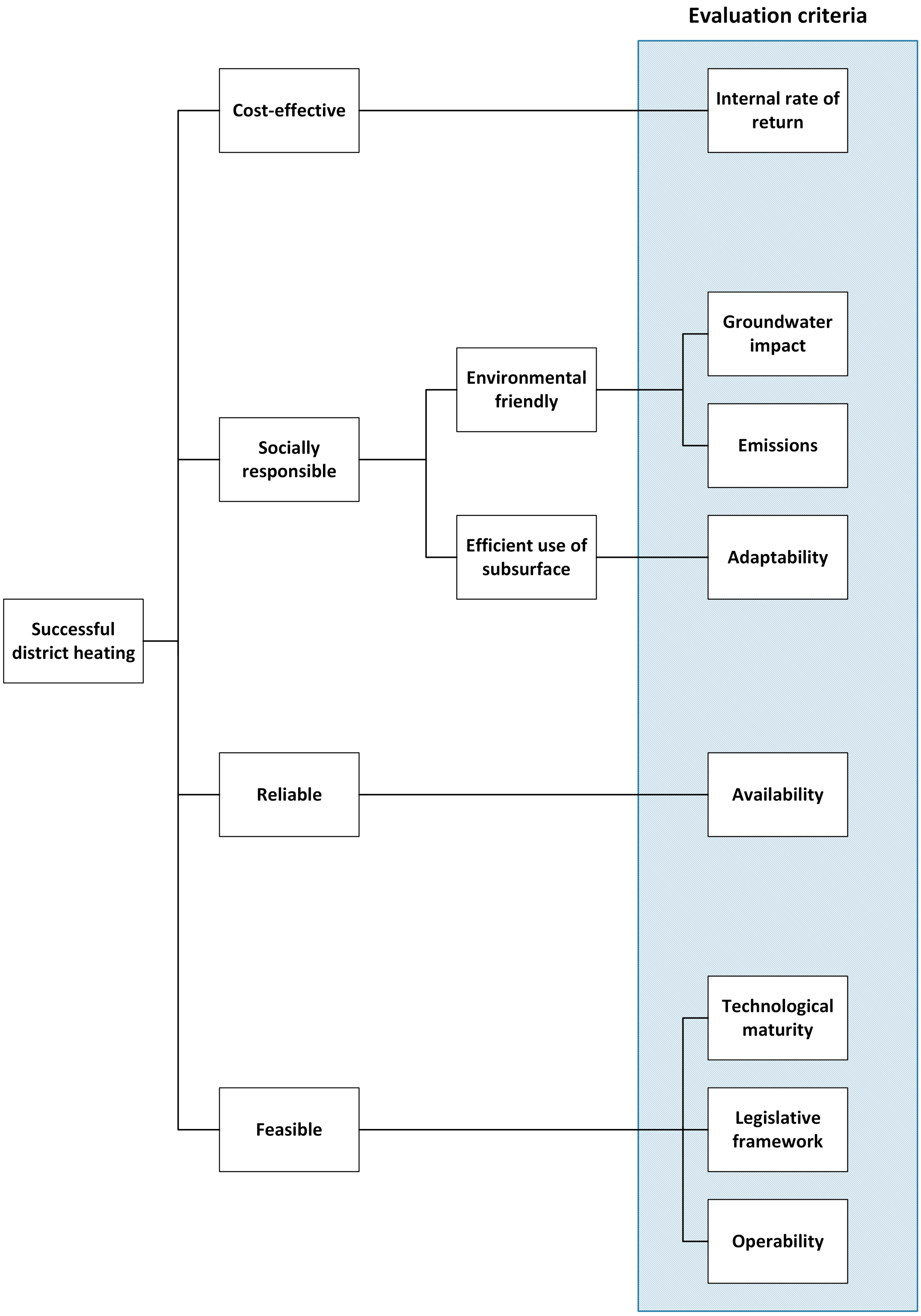

Figure 3.4: Criteria tree of objectives for a successful heating system

3.2.4. Evaluation of performance and method of scoring

The criteria in figure 3.4 are preferably evaluated in a quantitative manner, and consequently scored by means of a value function. The simulation model produces the quantitative performance metrics, that serve as input to the further analysis. However, the parametric variation in the model leads to a miscellaneous set of scenario's. The possibility exists that energy demand in *2* scenario's is significantly different, due to the parametric variation of consumer demand. Consequently, comparing their absolute emissions [kg] would be like comparing apples to pears. For this reason it is critical that quantitative criteria are evaluated in carefully selected units, that allow for good comparison. In the case of emissions resulting from distinct heat demands, a well-chosen unit for comparison is [kg MWh^{-1}]. This corrects the amount of emissions for the quantity of delivered heat.

The evaluation is performed qualitatively, by means of direct rating, in the case that quantitative data is unavailable, or if acquiring these data would be very time-consuming and therefor out of the scope of this research project. The process of direct rating is difficult because there is no foundation of quantitative metrics, which makes it susceptible to subjectivity and preferences of the DM. Additionally, the differences in scenario's are small. To refer back to an example from the criteria tree in figure 3.4: what is the change in performance on adaptability, upon alternating the cut-off temperature? It is deemed to be impossible to attach different performance scores to such minimal changes. For this reason, all scenario's that adopt HT-ATES are given equal scores on the qualitative criteria. The differences in their aggregated scores are thus determined by performance on quantitative criteria. The scenario without HT-ATES is given an individual rating on the qualitative criteria by the DM. The direct rating is binned in one of *5* categories 'very high', 'high', 'medium', 'low', or 'very low' [12]. Every bin has a range of scores, as can be seen in table 3.1.

Qualitative bin	*Score*
Very high	9-10
High	7-8
Medium	5-6
Low	3-4
Very low	1-2

Table 3.1: Scores per qualitative bin

For both quantitative and qualitative criteria, it is chosen to adopt global scaling, in which the relative change in score is more crucial than the actual score. The following subsections will elaborate on evaluation criteria and their metrics.

Internal rate of return

Net present value (NPV) and internal rate of return (IRR) are financial decision making tools. Both can be used by DM to place distinct projects in a common frame of reference [66]. Both rely on the same equation, and consider the concept of time value of money: future earnings and expenses have a different value, than present earnings and expenses of an equal amount [66]. All cash flows during the expected time of operation are discounted to present value with a certain discount rate, to obtain project NPV. NPV is the sum of these discounted cash flows, which also follows from equation 3.2.4.

$$NPV_i = \sum_{t}^{N} \frac{C_{it}}{(1+r)^t} \tag{3.1}$$

... where NPV_i is the net present value in of the i-th scenario [€], t is the time in [years], N the period of operation in [years], C_{it} the expected cash flow of the t-th year for the i-th scenario [€], and r the discount rate in [%].

The IRR is the discount rate for which a project NPV sums to *0*, thereby it is an indication of the project profitability. In this research, IRR is adopted to assess financial performance, because it is deemed to be more suitable for comparing projects of different size.

$$NPV_i = 0 = \sum_{t}^{N} \frac{C_{it}}{(1 + IRR_i)^t} \tag{3.2}$$

... where NPV_i is the net present value in of the i-th scenario [€], t is the time in [years], N the period of operation in [years], C_{it} the expected cash flow of the t-th year for the i-th scenario [€], and IRR_i the discount rate of the i-th scenario to make the project NPV *0* [%].

The IRR of HT-ATES is determined through a cost - and benefit analysis, by estimating the mutation of every cost and benefit upon implementation. The value tree in figure C.1 includes all potential costs and benefits related to HT-ATES.

The performance on IRR is translated into a score by means of a value function. The value function for IRR is linearly increasing, with *-15* and *15* as the minimum and maximum value. Figure 3.5 contains all the value functions adopted in this research. They translate the scenario performance on quantitative criteria into scores. The DM designs/chooses the value function. The process of obtaining value functions is vulnerable for subjectivity, which requires inclusion of uncertainty. It can be divided into *3* major steps:

1. Determine the extreme performance values that are likely to be encountered on a global scale
2. Determine if performance and score are positively or negatively correlated
3. Determine if the relation between score and performance is linear or different

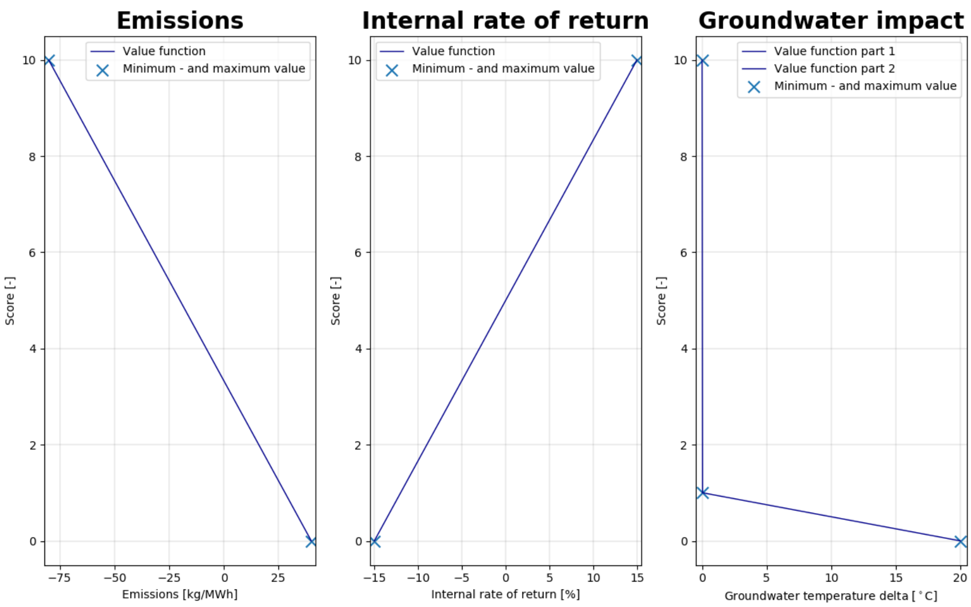

Figure 3.5: Value functions for quantitative evaluation criteria

Groundwater impact

Groundwater impact can be defined as any changes in local groundwater temperature, composition or level, due to operation of the heating system.

In some welfare states the daily consumption per person is *2000* times higher [14]. A quarter of this is provided by groundwater [14], which makes groundwater an indispensable resource that should not be taken for granted. HT-ATES can induce an increase in subsurface ambient temperature, thereby changing a variety of chemical-, microbial- and physical processes, and potentially decreasing the groundwater quality [43]. Saito et al. found a positive linear correlation between groundwater temperature and several naturally present components (B, Si, Li, dissolved organic carbon (DOC), $NH4^+$, Na^+, and K^+) [43]. For this reason, minimizing the increase in subsurface temperature is desirable.

The temperature at a location of *50* [m] below the surface is monitored, to quantitatively evaluate groundwater impact performance, in line with the method of Saito et al [43]. The resulting value function (figure 3.5) is decreasing and entails *2* parts, with a score of *10* assigned to subsurface temperature increase of *0* [°C].

Emissions

Carbon emissions are the result of electricity and heat production from fossil fuels. The world has reached consensus on the existence of a positive linear correlation between cumulative carbon emissions and the projected global mean temperature [15], and has agreed to limit the increase of global mean temperature to *1.5* [°C] via the Paris agreement [37].

Estimation of the carbon emissions factors for both gas- and electricity consumption, as is explained in subsection C.2.2, enables the DM to determine the projected carbon emissions in [kg/MWh] of delivered heat. The consequent quantitative performance is translated into a score by means of a linearly decreasing value function, in which the base scenario without HT-ATES is taken as a point of reference.

Adaptability

Adaptability is defined as the ability to respond to changing conditions. It is evaluated based on the following thought-experiments:

1. If the required heat demand is significantly higher or lower than expected, for a period of time, which scenario would better cope with the changed conditions?
2. If a neighbouring DH network is expanding and it would be logical and more efficient to connect the different networks, which scenario would better cope with the changed situation?
3. In the situation where there exists an abundance of both solar- and wind energy, which scenario would function better as a temporary 'heatsink' for a renewable electricity surplus?

The increasing penetration of renewable, intermittent electricity sources within the electricity network, increases the mismatch between supply and demand, and thereby the urge for large scale, long-term electricity storage methods rises [20]. The mismatch in a heating network is solely caused by variation in consumer heat demand. As DH networks grow larger and possibly connect, the mismatch between supply and demand will increase, and thereby the urge for, or at least the potential of, large scale seasonal storage solutions increases. HT-ATES will enable DH networks to better cope with and adopt to future changes in demand, and makes heating networks more adaptable.

Evaluation of the criteria performance is done qualitatively. On a global scale of heating systems, adaptability of a system with HT-ATES is marked as 'medium'. Adaptability of the base scenario without HT-ATES is marked as 'very low'.

Availability

Availability is defined as the relative time share, the system is in a operable state. In the specific case of heating, availability means availability of heat to consumer, either from the HT-ATES or other sources. Non-availability occurs when the available sources are unable to satisfy demand.

The following situation provides additional clarification on evaluation of performance on availability. Suppose there are *5* children, that all depend on a bicycle to commute to school. Unfortunately, the bicycles are low quality and have an availability of *80*%: every day *1* out of *5* bikes is unavailable. Their parents decide to together purchase an spare bicycle, of equal quality, to significantly decrease the unavailability to *1* bike in *5* days. This leads to an increase in the number of attended lectures. The example signifies that the availability increases when the number of components that contribute to the availability increases. The same principle holds for heating systems.

From this perspective, a scenario including HT-ATES, which has *1* additional heat source, will outperform the scenario without HT-ATES on the criteria of availability. On a global scale of heating systems both are however estimated to be more vulnerable for non-availability, than for example individual gas boilers, which is a proven and reliable technology. The availability of a system with HT-ATES is marked as 'medium, whereas the availability of the base scenario without HT-ATES is marked as 'low'.

Technological maturity

For a mature technology most initial difficulties have been solved or at least reduced, by means of further research and development. Whereas the first geothermal power plant was realised in *1904* [36], and the first reviews of DH networks have been available since *1930*, the first HT-ATES pilot plants appeared in the *80*'s, accompanied with several technical challenges [44]. Although most 'child deceases' caused by the higher temperatures have now been resolved, the technology of HT-ATES is in a less mature state, than that of geothermal energy and DH networks in general.

Evaluation of performance on technological maturity is done qualitatively. On a global scale of heating systems, both scenario's are considered to be less mature. The maturity of systems with HT-ATES is evaluated as 'very low'. Maturity of the base scenario without HT-ATES is evaluated as 'low'.

Legislative framework

A legislative framework states the rules and regulations to which all operations need to comply. The Dutch law makes a distinction between above and below *500* [meter] depth, named respectively the Waterwet and the Mijnbouwwet [38, 55]. The aquifers with high estimated potential in the Netherlands are described in appendix B. They are all located at depths within the jurisdiction of the Waterwet. The Waterwet has *2* requirements, that conflict with HT-ATES implementation [13, 38, 55], and thus pose a barrier for implementation:

1. A maximum infiltration temperature of *25* [°C] is allowed. This is not within the range of regular HT-ATES injection temperatures, which start around *50-60* [°C].
2. The quantity of injected- and produced heat have to be in balance. This poses another legislative hurdle for HT-ATES, since both the temperature of the cold- and warm reservoir of a HT-ATES system are above the ambient subsurface temperature, and are thus subject to efficiency losses to the surrounding environment.

It is evident that the Waterwet may jeopardise further development of HT-ATES. However, there is a possibility to deviate from the Waterwet, by means of pilot projects [38, 55]. Pilot projects are allowed to inject at higher temperature, and leave a responsible heat surplus in the subsurface, in exchange for additional monitoring. The learnings from these pilots can be adopted to change the Waterwet, and to improve the future legal position of HT-ATES.

Evaluation of performance on legislative framework is done qualitatively. On a global scale of heating systems, DH systems are performing worse than established heating systems, such as natural gas boilers. The legislative framework of systems with HT-ATES is evaluated as 'very low'. The legislative framework of the base scenario without HT-ATES is evaluated as 'low'.

Operability

Operability describes the ability (or relative ease) of maintaining a system in functioning condition. It is expected that the difficulty of operation of the system does not change upon implementation of HT-ATES, since most of the operation will be automated. Other than some additional operational expenditures (OPEX), which will be incorporated in the criteria of IRR, it is estimated there exist no further differences in operability of scenario's including HT-ATES and the base scenario without HT-ATES.

The result is an equal performance and consequently an equal score. This eliminates operability as a criteria that can be used for performance evaluation, which leaves *7* criteria for the further analysis.

3.2.5. Criteria weighting

A pair-wise comparison survey among stakeholders determines the criteria weight distribution. The survey-participants were asked to what extent they agreed to a certain theorem: *'I would rather save on my yearly energy bill, than limit the impact of my consumption on local groundwater'*. The weights are distributed amongst *7* criteria, due to discarding the criteria of operability from performance evaluation (subsection 3.2.4). Additionally, a reduced number of criteria is considered for the consumer weight distribution, since a consumer is assumed to not be qualified of making a substantiated assessment on the relative importance between criteria such as legislation and technological maturity. The resulting stakeholder-specific weight distributions are shown in figures 3.2 and 3.3.

Unfortunately, the number of respondents is limited, with a total of *20* respondents. This is due to the limited time and resources of the research project. It is opted to evaluate investors and operators as *1* larger stakeholder group. The limited number of respondents makes the weight distribution biased and uncertain. The weight distributions serve as an example, and can be alternated to better fit the case or the preferences of the DM. The standard deviations have been scaled to adequate values, to enable direct use in the subsequent Monte Carlo iteration (subsection D.1.6).

Criteria	*Weight*	*Standard deviation*	*Scaled standard deviation*
Availability	0.33	0.14	0.05
Emissions	0.25	0.14	0.05
Groundwater impact	0.19	0.12	0.04
IRR	0.23	0.16	0.05

Table 3.2: Consumer weight distribution, alphabetically

Criteria	*Weight*	*Standard deviation*	*Scaled standard deviation*
Adaptability	0.15	0.08	0.03
Availability	0.15	0.06	0.02
Emissions	0.19	0.07	0.02
Groundwater impact	0.18	0.08	0.03
IRR	0.09	0.07	0.02
Legislation	0.15	0.08	0.03
Technological maturity	0.11	0.07	0.02

Table 3.3: Investor/operator weight distribution, alphabetically

The survey results show that:

1. Both stakeholder groups evaluate emissions as the critical quantitative criteria. HT-ATES provides the opportunity of reducing emissions.
2. In the investor/operator stakeholder group, IRR is valued as the least important. This is surprising. Consumers put more emphasis on financial performance.
3. Consumers value availability as critical: reliability of heat is more important than its related costs or environmental impact.
4. The standard deviation of the consumer criteria weights in table 3.2 is significantly larger compared to the standard deviation of investor/operator criteria weights in table 3.3, indicating that consumers agree to a lesser extent than operators/investors.

3.2.6. Uncertainty in multi-criteria decision method

The steps in chapters 2 and 3 have been summarised in chronological order in the overview in figure 3.6. The circled steps entail uncertainty that must be included. The methods for scoring are subjective and uncertainty must be included. Secondly, the limited number of survey respondents leads to uncertainty in the relative weights, which must also be included. The performed Monte Carlo iteration adopts distributions instead of deterministic values, for both scores and weights, and thereby serves as the sensitivity analysis (SA), which exposes the method uncertainty.

1. The survey produces a mean and scaled standard deviation for every weight (subsection 3.2.5). The mean and scaled standard deviation create a normal distribution. Monte Carlo picks a weight from this distribution during every iteration, which leads to weight variation within the boundaries of the weight distribution.
2. The uncertainty in scoring is exposed through adopting uniform score distributions, following Hyde et al. [23]. The deterministic score presents the mean value of the uniform distribution. The minimum- and maximum scores of the distribution deviate *1* from the mean. Monte Carlo picks a score from this distribution during every iteration, which leads to score variation within the boundaries of the score distribution.

The variation in scores and weights influences the scenario aggregated scores, and thus influences the scenario rank. The end-deliverable is the probability a certain scenario occupies a certain rank. This is captured in a probability-of-rank matrix, which are case-specific and also differ per stakeholder group. The probability of rank matrices entail information on the sensitivity to individual parameters, and give direction towards the optimal parameter values. Moreover, they reveal the robustness and uncertainty of the MCDM. The matrices are included in the subsequent chapter, containing case-specific results.

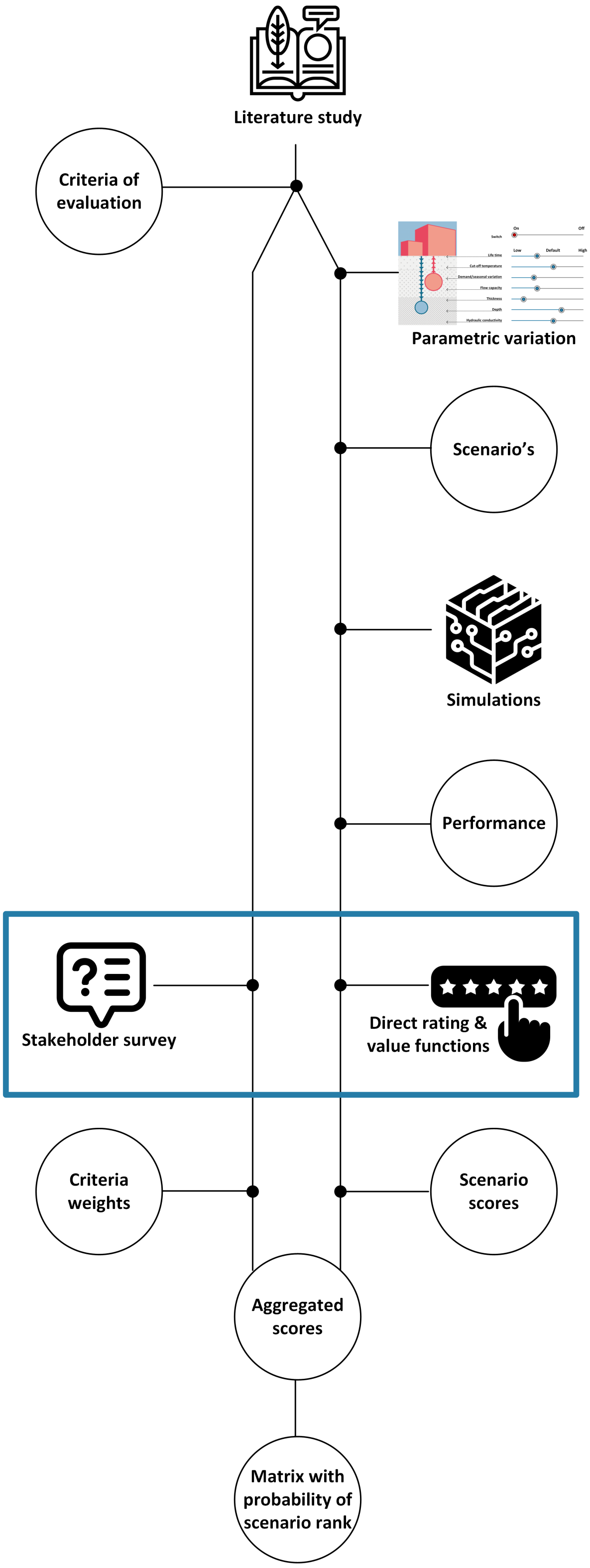

Figure 3.6: Timeline of methodology: parallel paths toward probability of scen. rank

4

Case-specific results

This chapter entails the case-specific results with a comparative nature. It is the product of the *deliver phase* (see appendix A), in which the simulation model (chapter 2) and MCDM (chapter 3) have been applied to *3* cases. Every case, starts with a general description of the situation and objective. Subsequently, the applied parametric is explained and summarised. Finally, the results are shown and analysed by means of spider plots and probability-of-rank matrices. The chapter only shows results that are relevant for the discussion and conclusion. More results are entailed in appendix E.

4.1. Case A: geothermal heat for educational institute

4.1.1. Case situation and objective

This case involves around an educational institute that strives to make its heat supply more sustainable. The institute has performed multiple feasibility studies on a geothermal energy source, combined with a DH network, to which both the campus and neighbouring residential area's are connected. A schematic drawing of the projected scenario, including all heat sources (with capacities and production temperatures), can be seen in figure 4.1.

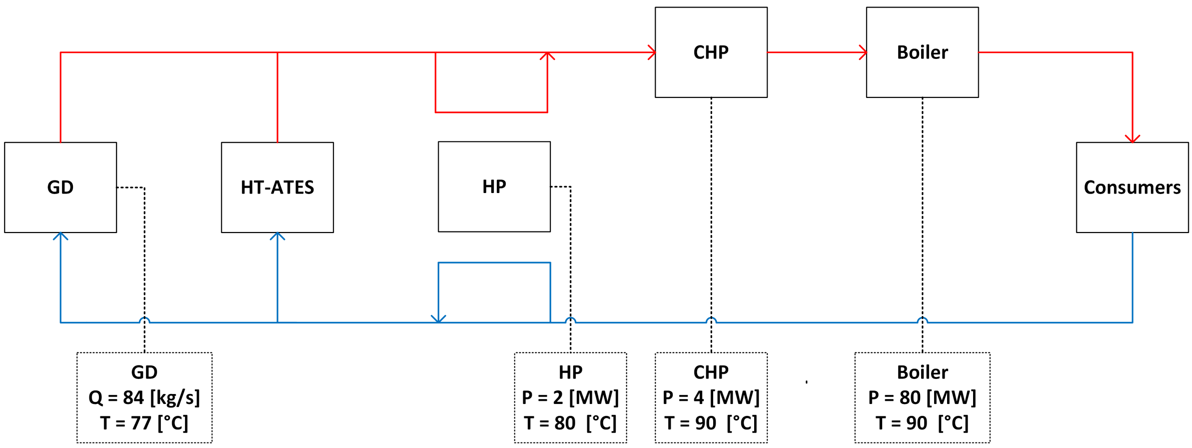

Figure 4.1: Schematic representation, case A

The board of the institute is in doubt whether they should implement HT-ATES as a secondary base source, in addition to the geothermal base source. The boundary conditions, i.e. the limits of operation, are as follows:

1. The demand is fixed and can not be changed
2. The geothermal base source is fixed an can not be changed. However, it is possible to apply a seasonal variation over the production, meaning that during low-demand peri-

ods the production flow is reduced, to better match the demand curve. It is estimated the geothermal source should operate at a minimum of 50% capacity

The scenario from the feasibility studies serves as the base scenario, because the demand for heat is well-balanced with the (sustainable) base supply. The base scenario provides a platform from which the impact of HT-ATES implementation can be investigated. Figure 4.1 and table 4.1 show the base scenario and key indicating parameters.

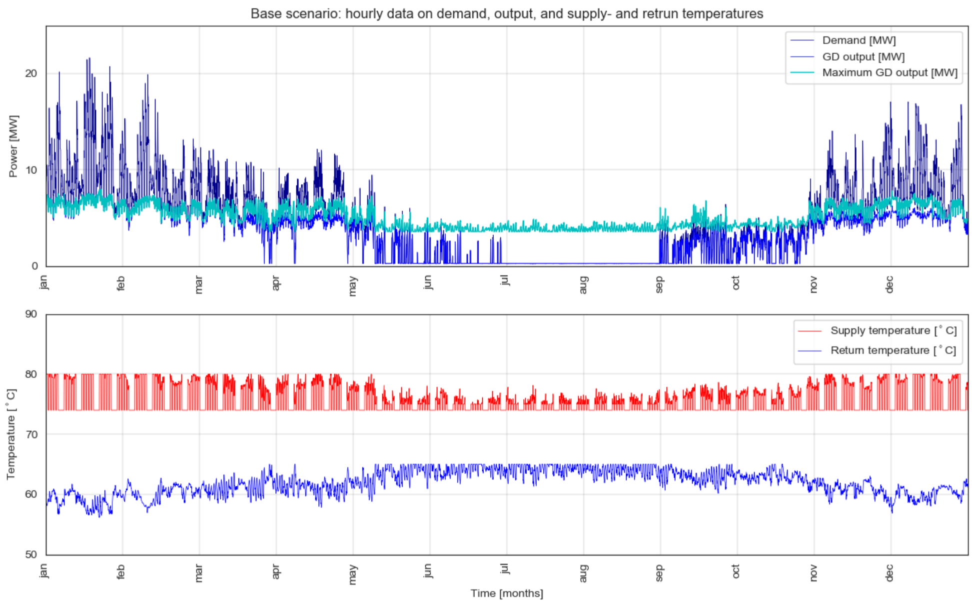

Figure 4.2: Base scenario, case A

Parameter	*Value*
Yearly demand	40 090 [MWh]
Yearly geothermal heat production	44 121 [MWh]
Used geothermal heat production	28 458 [MWh]
Peak demand/peak boiler production	21.6 [MW]/ 11.1[MW]

Table 4.1: Key figures of base scenario, case A

4.1.2. Summary of parametric variation

The parametric variation is explained in section 2.2, and further visualised in figures 2.1 and 2.2. It also is applied to case A and summarised in table 4.2. In this case, parametric variation has been applied to the seasonal variation of the geothermal energy output, due to the constraint of a fixed demand.

Parameter	*Default value*	*Low variation*	*High variation*
Life time [y]	25	20	30
Cut-off temperature [°C]	69	66	72
Seasonal variation (average) [%]	80	72.5	87.5
Flow capacity [kg/s]	85	70	100
Aquifer thickness [m]	40	20	60
Aquifer depth [m]	200	100	300
Aquifer hydraulic conductivity [m/d]	5	1	10

Table 4.2: Parametric variation, case A

4.1.3. Results and in-depth analysis

The results have been organised in spider plots and a probability-of-rank matrix, both from the investor/operator perspective. More results are included in appendix E. The spider plots enable simultaneous comparison of performance on individual evaluation criteria, and contain information on the primary value trade-offs of HT-ATES. The probability-of-rank matrix entails information on the sensitivity of the complete HT-ATES performance to individual parameters.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.29	0.43	0.23	0.05
No HT-ATES	0.33	0.29	0.23	0.15
Low aquifer hydraulic conductivity	0	0	0	1
High aquifer hydraulic conductivity	0.35	0.44	0.18	0.03
Shallow aquifer	0.02	0.12	0.32	0.54
Deep aquifer	1	0	0	0
Thin aquifer	0.01	0.07	0.23	0.69
Thick aquifer	0.33	0.44	0.21	0.02
Low seasonal variation	0.01	0.21	0.38	0.38
High seasonal variation	0.13	0.36	0.38	0.13
Short life time	1	0	0	0
Extended life time	0.04	0.2	0.42	0.34

Table 4.3: Probability of scenario rank, case A, investor/operator persp.

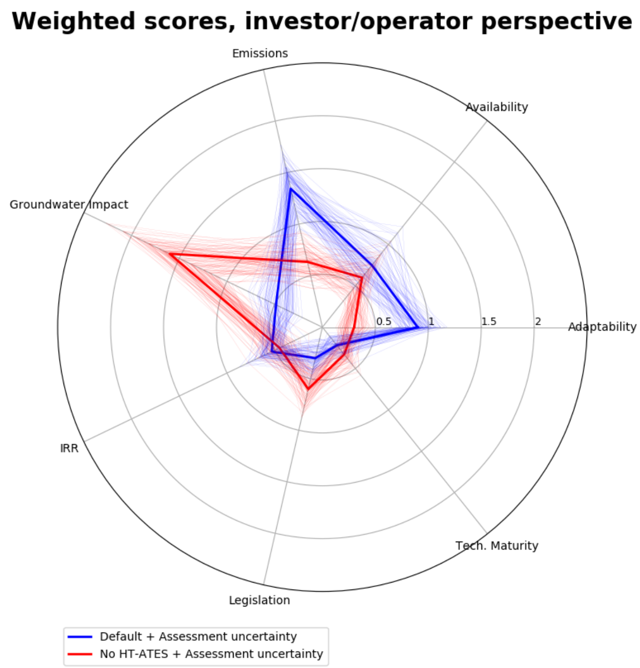

Figure 4.3: Weighted scores, case A, investor/operator persp.

The weighted scores in figure 4.3 show that the emissions, groundwater impact, and adaptability induce the largest differences in scores. These are the critical/decisive criteria in case A. HT-ATES implementation enhances performance on emissions, but on the contrary worsens the performance on groundwater impact, which is in line with expectations. The probability-of-rank matrix in table 4.3 shows that Monte Carlo distributes the probability-of-rank for both scenario's across the all quartiles. This suggests there is no clear preference for the *default scenario* over the *no HT-ATES (base) scenario*. I.e., there is no clear preference for HT-ATES implementation in case A under default parameter conditions. However, the parametric variation indicates there are opportunities for HT-ATES implementation and provides valuable insights. These are described for each parameter in the following paragraphs.

Life-time of operation

Figure 4.4 shows that groundwater impact is very *life-time* dependant. An extended life-time allows the stored heat to travel longer distances through the subsurface formations, by means of heat loss mechanisms such as conduction and convection. This enables heat losses to reach closer to the groundwater, and eventually increases the groundwater impact. On the contrary, an extended life-time of operation of the system results in an improved IRR, because the system has more years of operation to earn back the initial investment. The results imply there exists an optimal life-time, where performance on groundwater impact and IRR are balanced. In case A the model shows that the optimal life-time is 20 years or shorter, with the *short life-time scenario* sure to be ranked among the best performing scenario's, in quartile *1*.

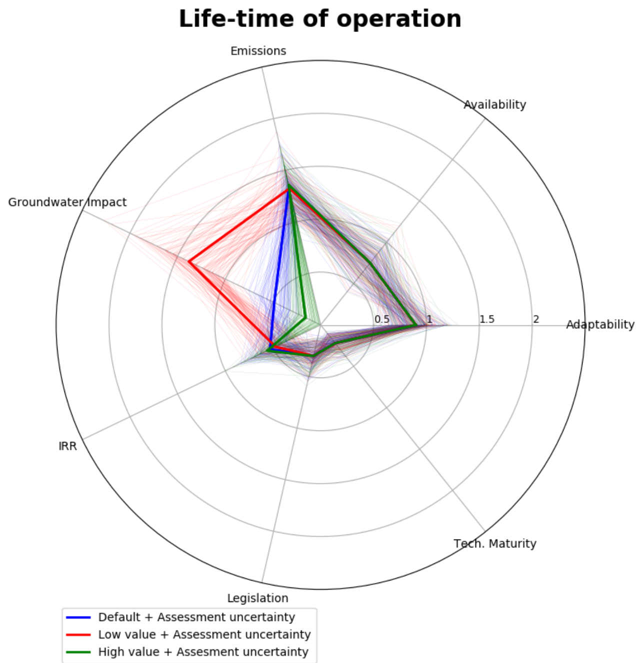

Figure 4.4: The sensitivity of performance to life-time, case A

System flow capacity

Parametric variation of system *flow capacity* within ranges that are plausible, shows that overall system performance is rather insensitive to the flow capacity. Within the model, investment costs are directly dependant on system flow capacity (table C.1). A high system flow capacity requires more CAPEX. Furthermore, it increases OPEX (OPEX are positively correlated with CAPEX). On the contrary, it also enables larger injection/production, which leads to additional subsidy income. The mutation IRR does not lead to differences in the probability-of-rank-matrix. Consequently, the scenario's can be neglected and have been excluded from table 4.3. The conclusion is that low project CAPEX is not intrinsic to successful HT-ATES implementation.

Cut-off temperature

Parametric variation of system *cut-off temperature* within ranges that are deemed to be plausible, shows that overall system performance is rather insensitive to the cut-off temperature. A high cut-off temperature results in reduced heat production from the system, which negatively affects the score on groundwater impact. The opposite is true for a lower cut-off temperature. However, within this research and within these parameter value ranges, the differences are negligible. This is also true for the other quantitative evaluation criteria. For this reason, the scenario's have been excluded from 4.3.

Geothermal seasonal variation

As explained during subsection 4.1.1, the GD and consumer demand are fixed. Alternatively, the geothermal energy production is alternated by applying a *seasonal variation*, to better fit the demand curve. High seasonal variation results in greater geothermal availability and -output, because the GD comes first in the order of dispatch. This generates additional subsidy income which benefits the project IRR, and additionally it reduces project emissions (figure 4.5). On the contrary, the increased geothermal availability results in larger temporary surpluses, and thus enhances HT-ATES heat injection. Simultaneously, the increased geothermal availability leaves a reduced window of operation for HT-ATES heat production. Increased injection and reduced production from the HT-ATES system, result in steadily heating of the subsurface, in the end negatively affecting the score on groundwater impact.

A lowered seasonal variation performs better on groundwater impact, but worse on IRR and emissions.

In this case table 4.3 shows the evaluation criteria combination of IRR and emissions is more dominant than groundwater impact alone: the *low seasonal variation scenario* mainly ranks in quartiles *3* and *4*, and the *high seasonal variation scenario* mainly ranks in quartiles *2* and *3*. The scenario ranking shows decent distribution, which indicates that seasonal variation is not a decisive parameter. Life-time is more influential and decisive for HT-ATES performance in case A.

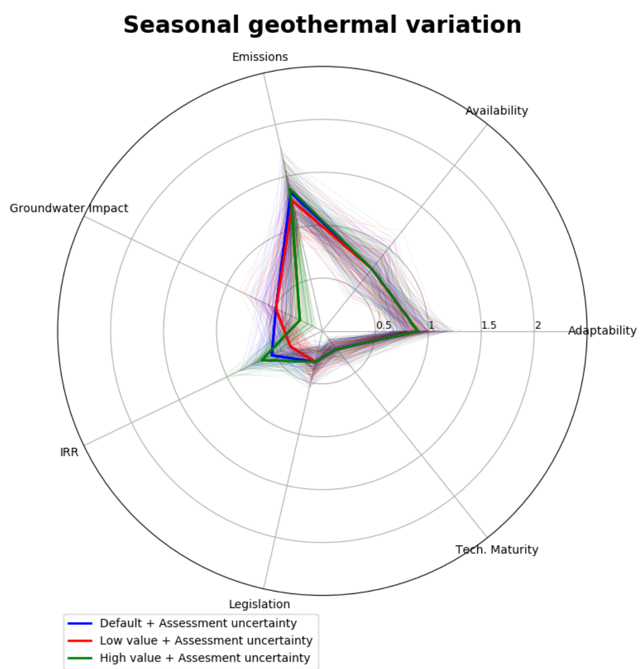

Figure 4.5: The sensitivity of performance to seasonal geothermal variation, case A

Aquifer hydraulic conductivity
Figure 4.7 shows that HT-ATES performance is extremely sensitive to parametric variation of the *aquifer hydraulic conductivity*. What is hydraulic conductivity and what are the direct consequences of a changed hydraulic conductivity? It is critical to provide the equation of Darcy to increase understanding.

$$Q = -\frac{k \cdot A \cdot \Delta p}{\mu \cdot L} \quad (4.1)$$

.. where Q is the flow in [m^3 s^{-1}], k the intrinsic permeability of the aquifer in [m^2], A the cross-sectional area of the aquifer in [m^2], p the pressure in [Pa], μ the fluid viscosity in [Pa s], L the distance within the aquifer over which the pressure difference occurs[m]. Hydraulic conductivity [m d^{-1}] is a product of the aquifer permeability and fluid viscosity.

Following the laws of Darcy (equation 4.1.3), a doubled hydraulic conductivity requires half the pumping pressure and - capacity, and therefore electricity consumption of the HT-ATES system halves. This can be regarded as the driving force behind the better scores on IRR (due to lower OPEX) and emissions in figure 4.7. Understanding the change on groundwater impact performance due to hydraulic conductivity variation requires additional explanation, which is provided by figure 4.6.

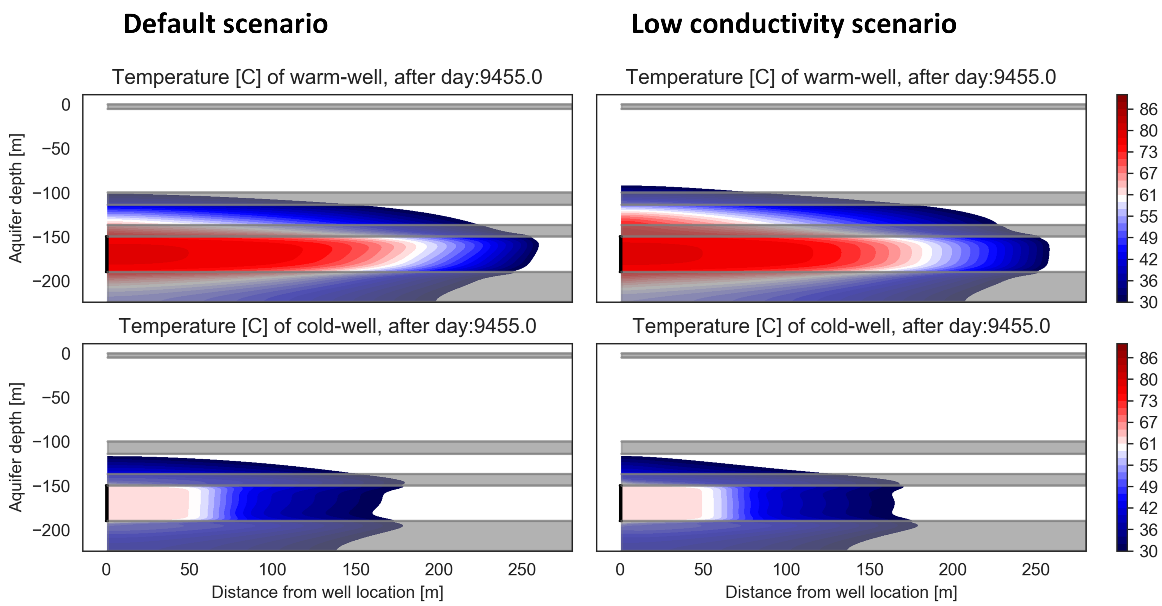

Figure 4.6: The influence of hydraulic conductivity on subsurface heat behaviour in case A

A reduced aquifer hydraulic conductivity, reduces the differences between the aquifer and aquitard. It demands higher pumping pressures to achieve equal flow rates, making it relatively more easy for heat to travel through the confining aquitard, both during injection and production. In case A, the higher pumping pressures result in relatively more heat loss during injection in the warm reservoir injection, which negatively affects the groundwater impact. This is visible in figure 4.6. The temperature isotherms of the *low hydraulic conductivity scenario* reach to more shallow depths, compared to the temperature isotherms of the *high hydraulic conductivity scenario*.

Table 4.3 confirms the relevance of aquifer hydraulic conductivity for the complete system performance: *low hydraulic conductivity scenario* is sure to be among the worst performing scenario's, in quartile *4*. The conclusion is that above all, the DM should prove and assure sufficient hydraulic conductivity in the designated aquifer.

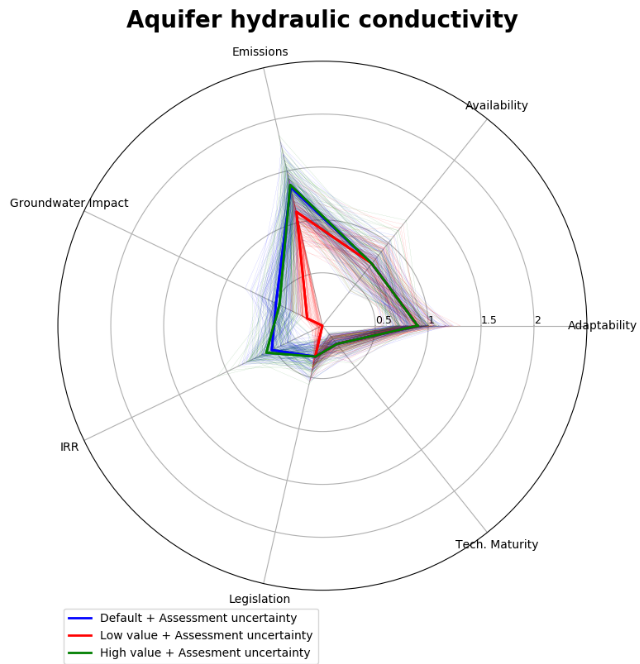

Figure 4.7: The sensitivity of performance to aquifer hydraulic conductivity, case A

Aquifer depth

Investment costs are directly dependant on *aquifer depth* within the model. A greater aquifer depth increases the upfront CAPEX. OPEX are positively correlated with project CAPEX: they will thus also increase with greater aquifer depth. Their exact relation is provided in table C.1. The greater vertical distance also requires additional electricity consumption. This further increases OPEX and furthermore increases project emissions. In summary, a greater aquifer depth negatively influences project performance on IRR and emissions. The opposing logic can be applied to a shallow aquifer, as is visible in the spider plot of figure 4.8.

Furthermore, the deep aquifer shows better performance on groundwater impact. The reservoir is at a greater distance from the groundwater, which automatically results in a reduced impact on the groundwater, compared to a default or shallow aquifer.

Tables 4.3 shows that deep aquifers perform better than shallow aquifers. This leaves the conclusion that in this case and parametric variation groundwater impact is the dominant criteria. The *deep aquifer scenario* is sure to be ranked among the best performing scenario's, in quartile *1*.

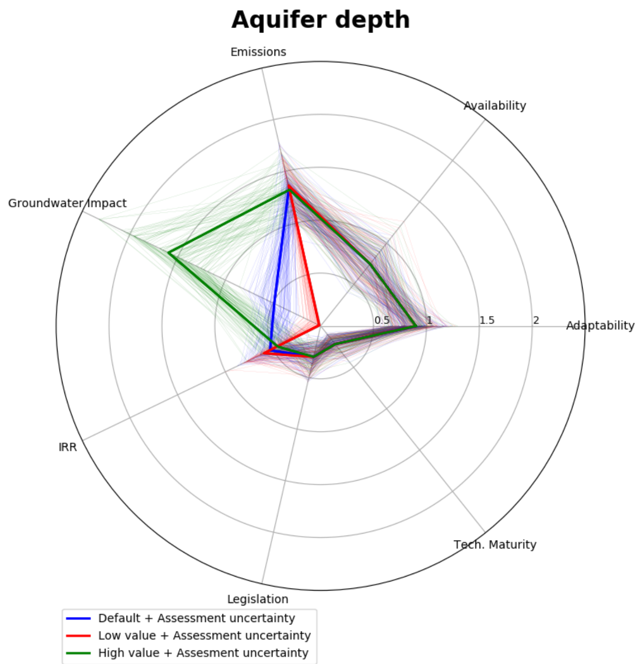

Figure 4.8: The sensitivity of performance to aquifer depth, case A

Aquifer thickness

Bloemendal et al. empirically determined that the TRE decreases linearly with an increasing ratio of surface over volume [5], because of the relatively greater surface at which conduction can take place. This finding suggests that, for the projected storage volume, the *thin aquifer scenario* has a smaller TRE. This implies that a greater amount of heat is lost, which results in an increase in groundwater impact. Simulations of the *thin aquifer scenario* and the *thick aquifer scenario* for case A confirm Bloemendal et al.: they have respectively *67* and *85* as TRE. Subsequently, the theory on resulting groundwater impact is also confirmed: the *thin aquifer scenario* has a worse score on groundwater impact.

The lower TRE of the *thin aquifer scenario* suggests that the HT-ATES sytem can produce a reduced quantity of heat. The result is that a larger portion of the demand is satisfied by the natural gas consuming boilers, which negatively influences the score on IRR and emissions. As a sidenote, the *thin aquifer scenario* requires shallower wells, which is beneficial for both the CAPEX and OPEX. However, apparently this is insignificant in comparison to the project's additional gas consumption. Figure 4.9 shows the lower score on groundwater, emissions and IRR.

The probability-of-rank matrix shows that there indeed exists a preference for thick aquifers: the *thick aquifer scenario* is most likely to ranked in quartiles *1* and *2*, among the best performing scenario's. However, the parameter is less decisive than the other geological parameters.

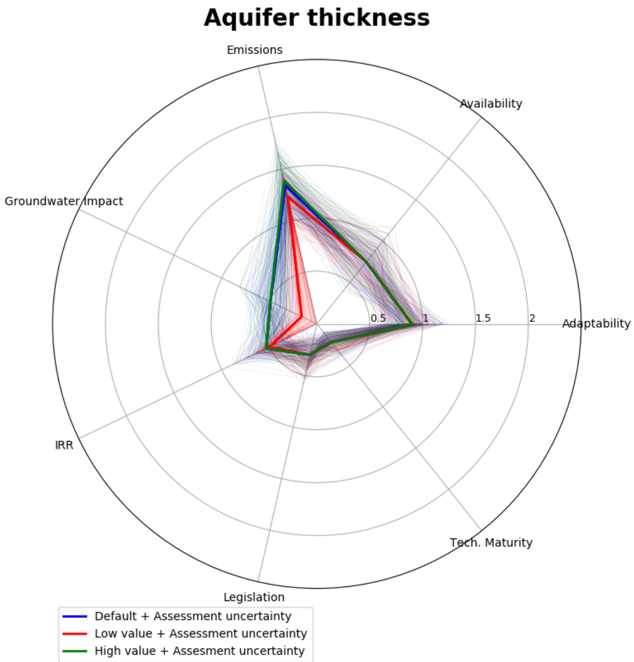

Figure 4.9: The sensitivity of performance to aquifer thickness, case A

4.2. Case B: industrial waste for residential heating network

4.2.1. Case situation and objective

Projected scenario

Case B is an existing DH network, that is projected to receive industrial waste heat as the new sustainable base source. The projected scenario, with all heat sources (including capacities and production temperatures) is visualised in figure 4.10.

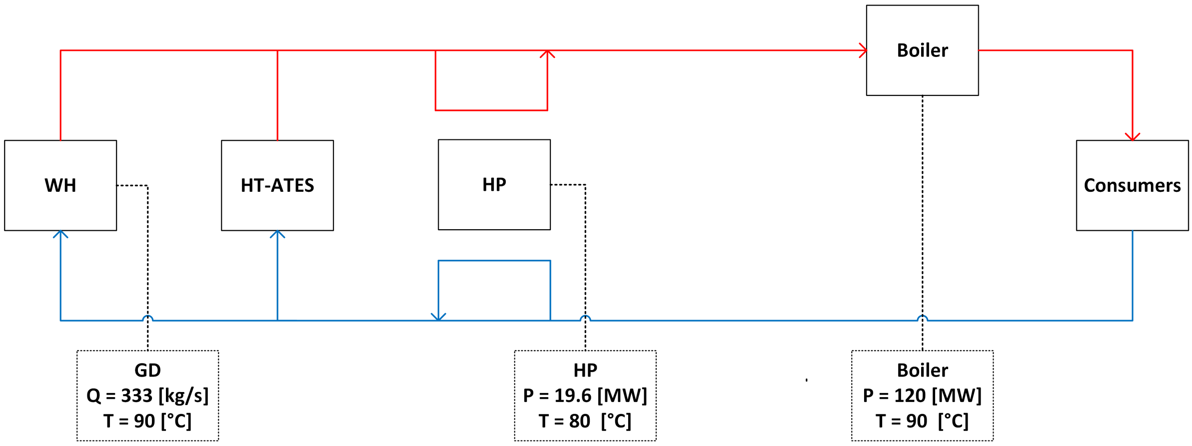

Figure 4.10: Schematic representation, case B

The municipality wants to know to what extent the demand of the DH network can be increased upon implementation of HT-ATES. This central question is accompanied by *2* limitations of operation:

1. To stay within capacities of the current sources of heat. Meaning, to not expand the boiler- or heat pump (HP) capacity, in order to satisfy the increased demand.
2. To strive for complete utilization of the available waste heat capacity.

Multiple simulations have been performed with the purpose of exploration. The simulations showed that consumer heat demand and projected waste heat supply were unbalanced: the summer surplus of heat is larger than the winter deficit.

Moreover, it showed that the outdated DH network requires very high supply- and return temperatures of up to 120 [°C] during peak demand. It is debatable if such a distribution network qualifies as being sustainable. It does not make sense to experiment with HT-ATES implementation wihtin a system that is not sustainable at heart. Consequently, the base scenario that provides the platform from which the impact of HT-ATES is investigated, is obtained by firstly lowering the required supply- and return temperatures with *25* [°C], and secondly scaling the WH supply with $\frac{1}{3}$, enabling the remaining heat to be used in other local projects. The base scenario is captured in figure 4.11 and table 4.4.

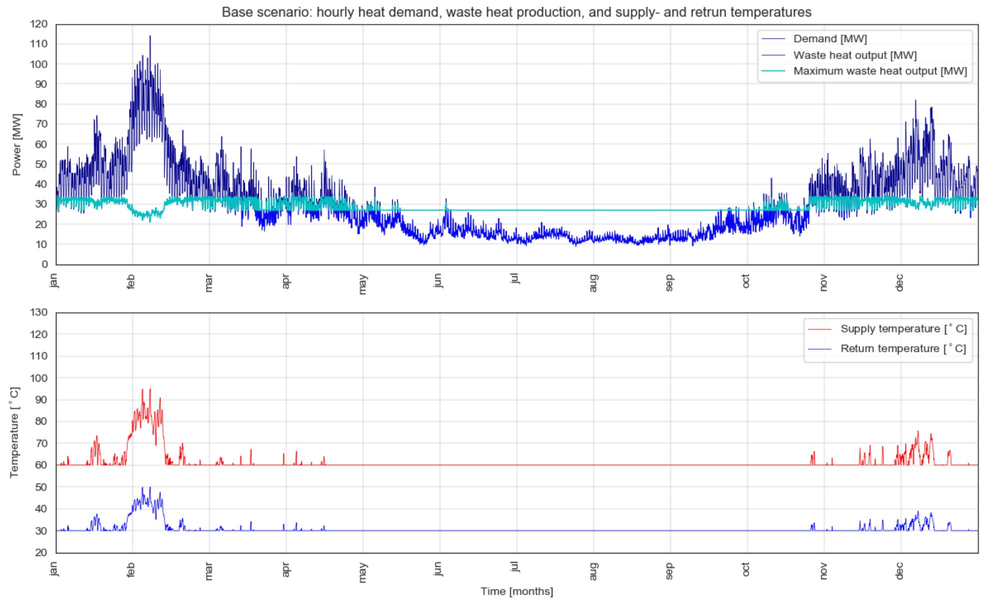

Figure 4.11: Base scenario, case B

Parameter	*Result*
Yearly demand	259 793 [MWh]
Yearly waste heat production	252 678 [MWh]
Used waste heat production	206 213 [MWh]
Peak demand/peak boiler production	114 [MW]/ 92[MW]

Table 4.4: Key figures of base scenario, case B

4.2.2. Summary of parametric variation

The parametric variation that has been applied to Case B is summarised in table 4.5. Because the initial question of the client is to what extent the demand of the network can be increased, both parametric variations on consumer demand, the low and high variation, exceed the default demand. Moreover, because the variation in supply- and return temperatures is larger throughout the period of simulation, the model is forced to adopt a dynamic cut-off temperature, opposing the constant cut-off temperature in case A. A dynamic cut-off temperature of 9 means the cut-off temperature is always 9 [°C] higher than than the simultaneous return temperature in the network.

Parameter	*Default value*	*Low variation*	*High variation*
Life time [y]	25	20	30
Cut-off temperature [°C]	9	5	13
Demand scaled [-]	1	1.15	1.25
Flow capacity [kg/s]	90	70	110
Aquifer thickness [m]	40	20	60
Aquifer depth [m]	200	100	300
Aquifer hydraulic conductivity [m/d]	5	1	10

Table 4.5: Parametric variation, case B

4.2.3. Comparison of results case B to case A

The results have been organised in the same spider plots and a probability-of-rank matrix. Both provide the perspective of operators and investors. The results from case B are mostly in line with results from the previous case study. There are some additional (sometimes contradicting) insights, which are further explained in this section. More results are included in appendix E, including the probability-of-rank matrix from a consumer perspective.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.20	0.38	0.33	0.09
No HT-ATES	0.05	0.17	0.29	0.49
Low aquifer hydraulic conductivity	0.03	0.16	0.38	0.43
High aquifer hydraulic conductivity	0.12	0.33	0.38	0.17
Shallow aquifer	0	0.01	0.06	0.93
Deep aquifer	0.99	0.01	0	0
Thin aquifer	0.17	0.38	0.35	0.10
Thick aquifer	0.21	0.39	0.29	0.11
Low scaled demand scaled	0.41	0.39	0.18	0.02
High scaled demand	0.25	0.41	0.27	0.07
Short life time	0.96	0.04	0	0
Extended life time	0	0.05	0.22	0.73
Low system flow capacity	0.02	0.17	0.43	0.38
High system flow capacity	0.21	0.40	0.29	0.10

Table 4.6: Probability of scenario rank, case B, investor/operator persp.

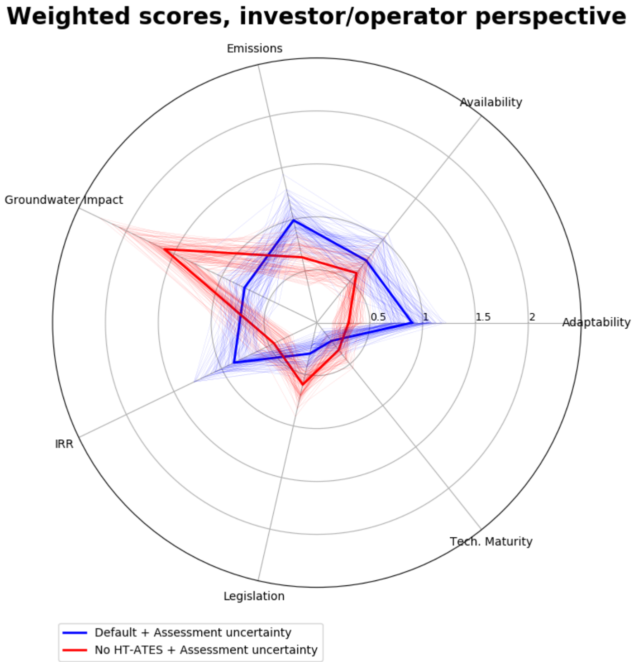

Figure 4.12: Weighted scores, case B

Implementation of HT-ATES increases the full-load hours of the base source system. It provides a second life to otherwise unused heat, and stores it for future, temporary deficits. Thereby, it can improve project performance on IRR and emissions. However, comparison of the weighted scores from case B (figure 4.12) to case A (figure 4.3), shows that these improvements are very case-specific. The data provide the insight that HT-ATES implementation under default parameter conditions in case B induces a relatively smaller reduction of emissions, whereas it enhances financial performance more severely, compared to case A. This is due to a difference in competing heat sources.

In case A implementation of HT-ATES mostly takes over production from the combined heat power (CHP) and the boilers. Thereby, it cannibalises gas-powered heat production. As a result, gas consumption decreases, and electricity consumption increases upon HT-ATES implementation. This positively affects the score on emissions, but the impact on financial performance is limited, because natural gas is relatively cheap and additionally has a higher emission factor compared to electricity (appendix C.2). In case B implementation of HT-ATES mostly cannibalises HP heat production. This results in a relatively smaller reduction in gas consumption, and an unchanged electricity consumption: the impact on emissions is limited, whereas it enhances financial performance more severely compared to case A. The cannibalization of competing heat sources is also visible in figures 4.13 and 4.14.

The probability-of-rank matrix in table 4.6 shows that there is a minimal preference for HT-ATES implementation under default parameter conditions in case B. The *default HT-ATES scenario* is most likely to be ranked in quartiles *2* and *3*, whereas the *no HT-ATES scenario* is most likely to be ranked in quartiles *3* and *4*, among the worst performing scenario's.

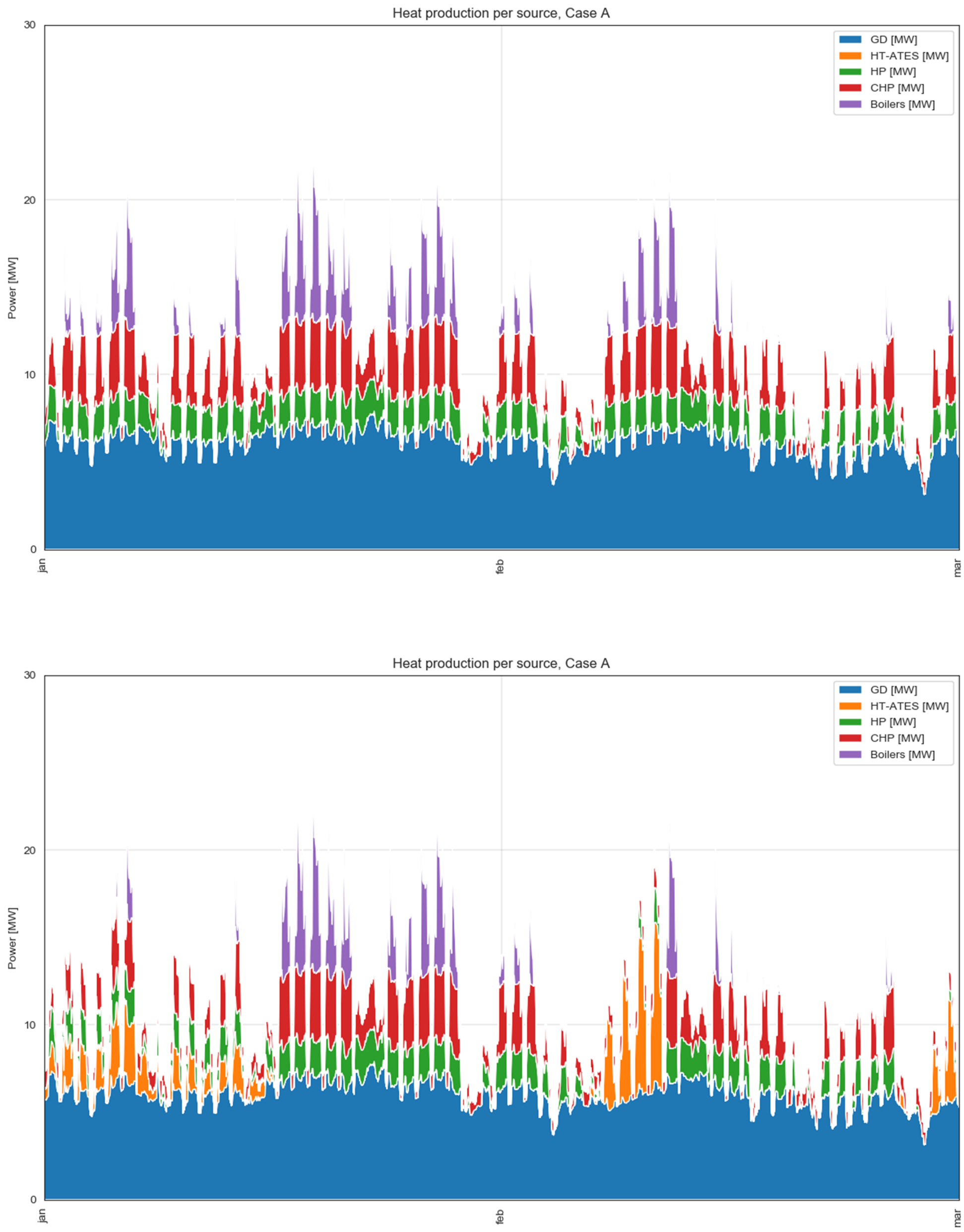

Figure 4.13: Heat production per source, before and after HT-ATES implementation, case A

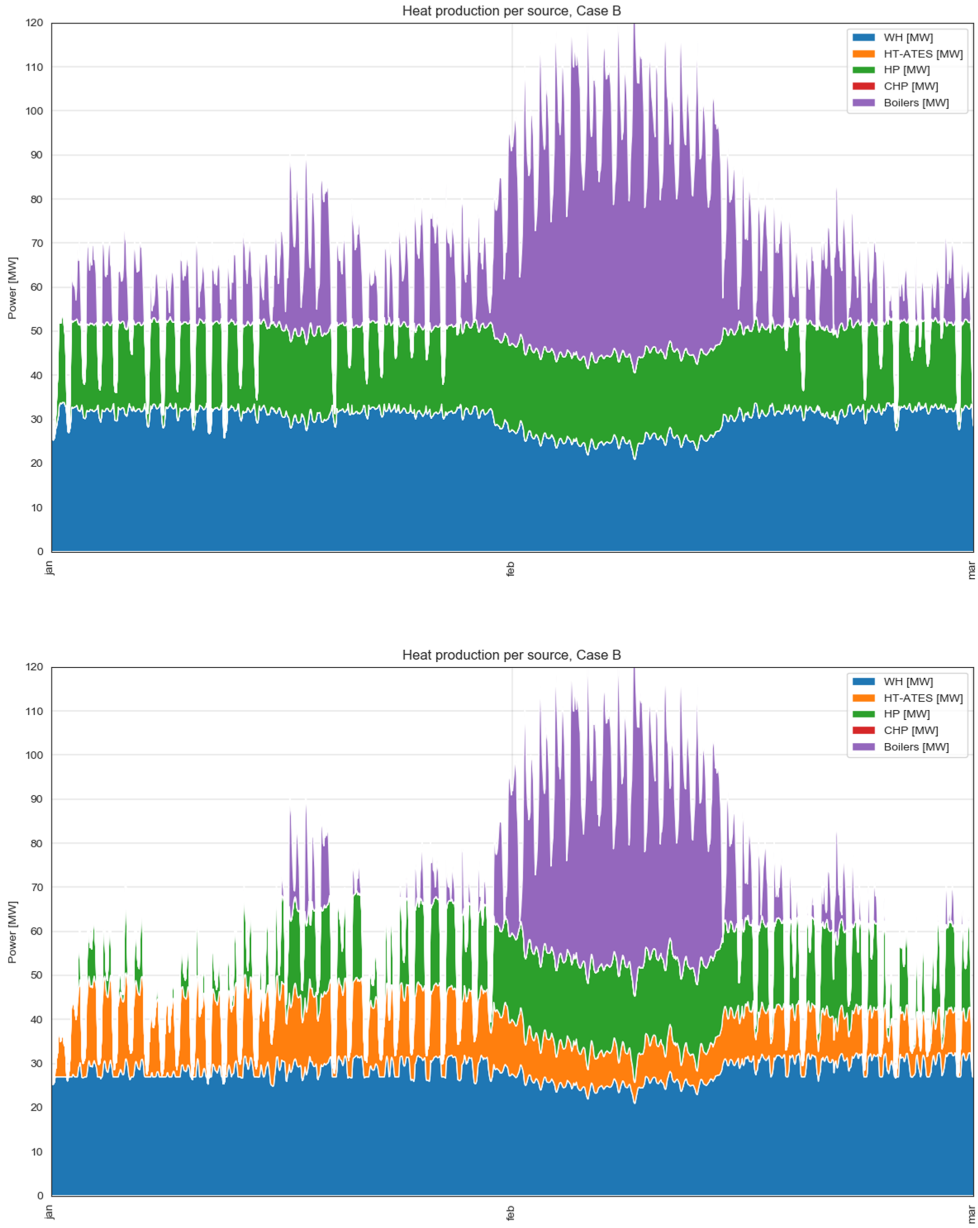

Figure 4.14: Heat production per source, before and after HT-ATES implementation, case B

System flow capacity

Parametric variation of the design parameter *system flow capacity* in case B induces more noticeable differences, compared to case A. Therefore, the parametric variation of flow capacity has been included in table 4.6. The shape of the demand curve causes the enhanced influence of system flow capacity variation. The small, steady heat surplus during summer is within the flow capacity of the *low system flow capacity scenario*, and all surplus can thus be stored. During the short peak winter demand the lowered flow capacity is limiting the contribution of HT-ATES, and not all stored heat can be reproduced. The system TRE decreases and negatively influences the score on groundwater impact. Regarding emissions and financial performance, the differences are minimal. The decreased score on groundwater impact causes the *low system flow capacity scenario* to be most likely ranked in quartiles *3* and *4*, among the worst performing scenario's. Thereby it performs significantly worse than the systems with default- or high flow capacity. However, the differences in probability of rank are not large, indicating that system flow capacity can be influential but not decisive for system performance in case B.

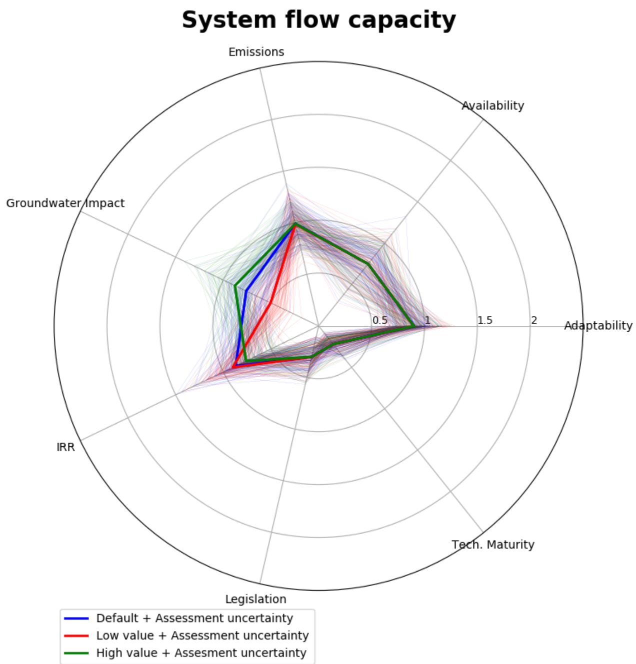

Figure 4.15: The sensitivity of performance to system flow capacity, case B

Heat demand

The parametric variation for Case B entails a variation in consumer *demand*, to explore the effects of an increased demand on the HT-ATES performance. A larger demand, which applies to both the *low scaled demand scenario* and the *high scaled demand scenario*, results in reduced surpluses of heat, and thus causes reduced heat injection. Simultaneously, the reduced amount of injected heat has to compensate for increased deficits during peak demand. The result is an enhanced draining of the reservoir, which positively influences the score on groundwater impact. However, the reduced amount of injected heat means the HT-ATES can only deliver a reduced amount of heat to the end-consumer, which reduces the financial impact of HT-ATES in both scenario's. It also reduces HT-ATES impact on project emissions: relatively more heat demand is satisfied by natural gas boilers. Figure 4.16 shows all of the aforementioned.

The probability-of-rank matrix in table 4.6 shows that groundwater impact is dominant over the other quantitative criteria: the *low scaled demand scenario* slightly outperforms HT-ATES under default parameter conditions, while being ranked most likely in quartiles *1* and *2*. Although the differences are not large. This finding implies that it is valuable to explore increasing the number of network consumers. The results show there exists an optimal demand, because the *high scaled demand scenario* is performing worse, being ranked most likely in quartiles *3* and *4*.

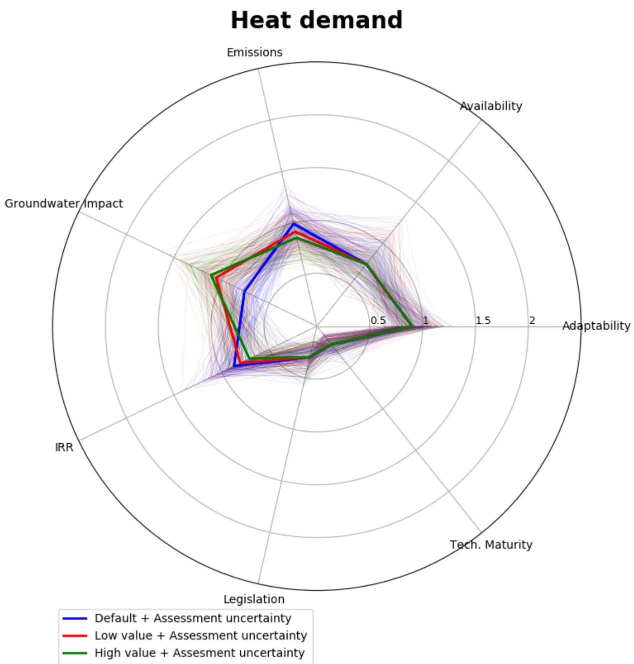

Figure 4.16: The sensitivity of performance to heat demand, case B

Changed impact of aquifer hydraulic conductivity and aquifer thickness

Subsection 4.1.3 explains that changing the *aquifer hydraulic conductivity* affects the required pumping pressure to achieve equal flow rate, following the law of Darcy (equation 2). The same theory can be applied to case B. Case B be has a very different consumer heat demand, with an astonishing peak demand during February, and a fairly constant and low heat demand for the remaining period of time. The winter peak demand results in high HT-ATES heat production, which requires large flow rates through the aquifer. The required flow rates for HT-ATES heat injection during summer are relatively small. Therefore, changing the hydraulic conductivity mostly affects HT-ATES heat production during the winter.

The *low aquifer hydraulic conductivity scenario* requires extreme pumping pressures during water production from the warm HT-ATES reservoir and subsequent injection in the cold HT-ATES reservoir. As a result, the additional heat is captured from the aquitard and confining formations of the warm reservoir, whereas additional heat loss occurs at the cold reservoir. This is confirmed by the temperature isotherms in figure 4.17.

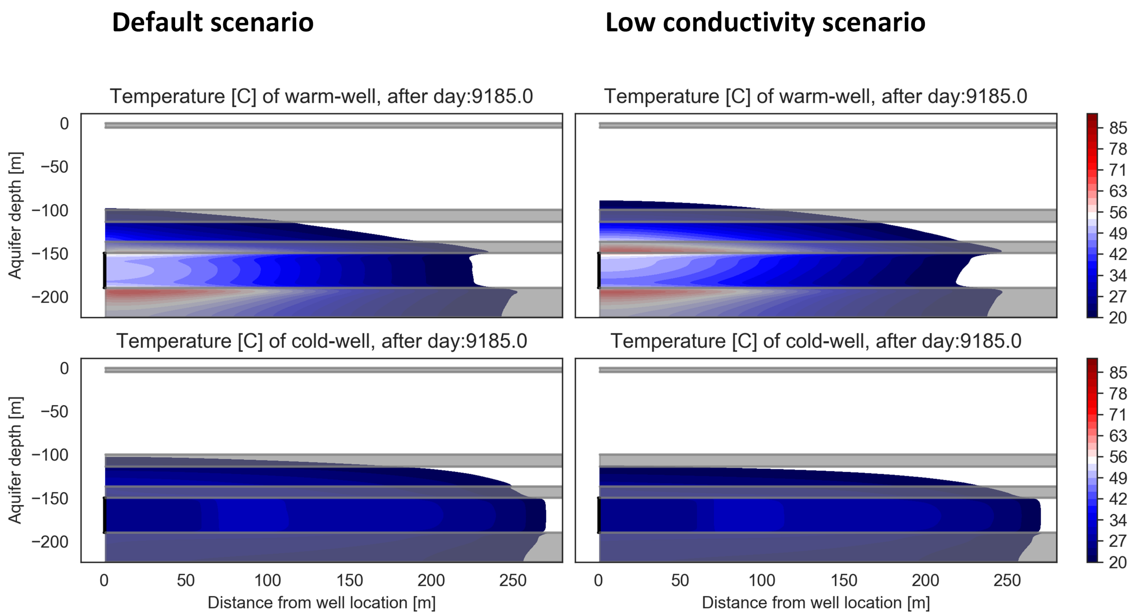

Figure 4.17: Influence of hydraulic conductivity on subsurface heat behaviour, case B

Furthermore, *aquifer thickness* determines the aquifer cross-sectional area, which also influences flow (equation 2). The *thin aquifer scenario* also requires extreme pumping pressures during HT-ATES heat production for the peak winter demand. It shows subsurface heat behaviour that is similar to the *low aquifer hydraulic conductivity scenario*.

Groundwater impact is assessed through measurement of the temperature 50 [m] below the surface above warm reservoir. In case B, the *low aquifer hydraulic conductivity scenario* and the *thin aquifer scenario* have an improved performance on groundwater impact compared to HT-ATES implementation under default parameter conditions. This is conflicting with the TRE, which is worse in both scenario's compared to HT-ATES implementation under default parameter conditions. Summarizing: in both the *low aquifer hydraulic conductivity scenario* and the *thin aquifer scenario* a reduced amount of heat is recovered/produced, whereas both scenario's show an improved performance on groundwater impact. This raises the question if such assessment of groundwater performance is a shortcoming of the simulation model and subsequent framework. It is fuel for the discussion in chapter 5. Should performance on groundwater impact be dependant on TRE, and not on a temperature at a specific location in the subsurface? Anyhow, this result provides the insight that the demand curve is capable of strongly influencing the subsurface heat behaviour and the heat loss mechanisms.

The scenario performance regarding emissions and IRR is in line with case A. The probability-of-rank matrix in table 4.6 shows that the differences in ranking between the *low aquifer hydraulic conductivity scenario* and *high aquifer hydraulic conductivity scenario*, and between the *thick aquifer scenario* and *thin aquifer scenario* have decreased, due to a changed performance on groundwater impact. Whereas in case A *low aquifer hydraulic conductivity scenario* is sure to be among the worst performing scenario's, the probability of the same scenario is distributed across all quartiles in case B. Additionally, there is no noticeable difference/preference for a thin- or thick aquifer in case B.

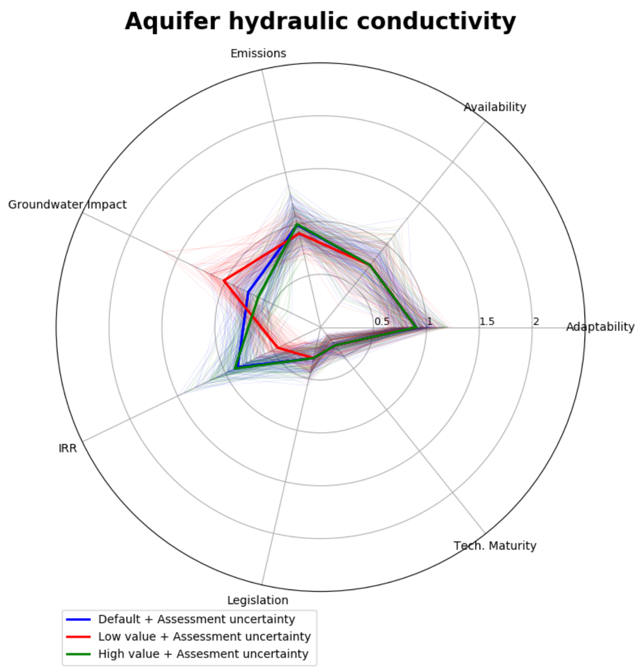

Figure 4.18: The sensitivity of performance to aquifer hydraulic conductivity, case B

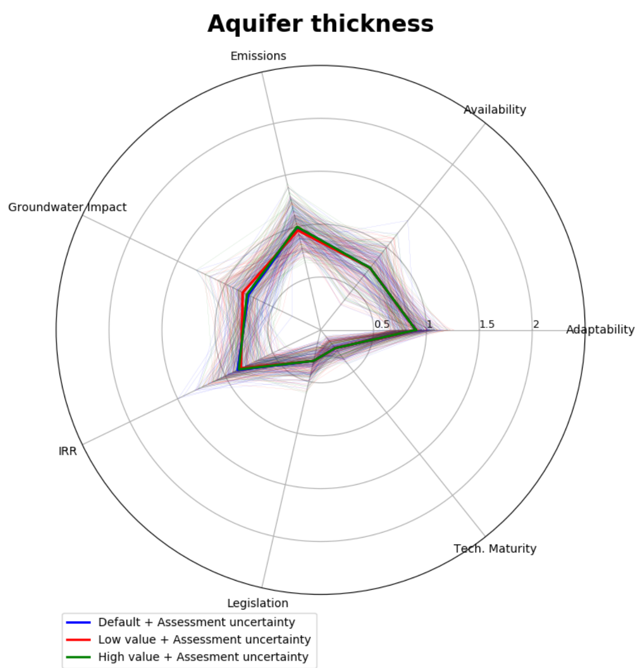

Figure 4.19: The sensitivity of performance to aquifer thickness, case B

4.3. Case C: shallow geothermal heat for expanding greenhouse

4.3.1. Case situation and objective

Case C is a very different heating project. The projected scenario, with all heat sources (including capacities and production temperatures) is visualised in figure 4.20.

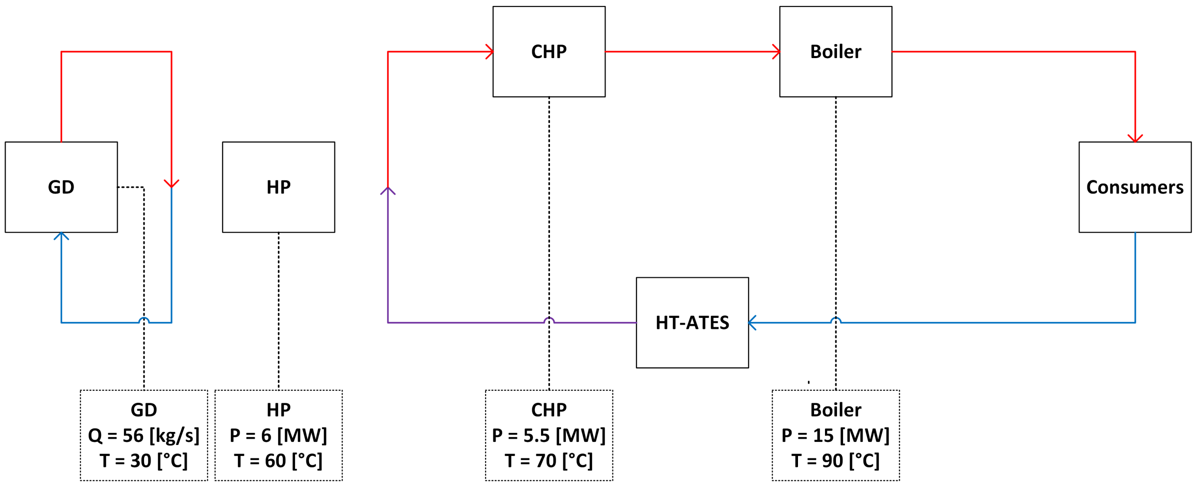

Figure 4.20: Schematic representation, case C

The other cases involve DH networks, with peak demands during winter and low demands during summer. Case C concerns a greenhouse in the Netherlands, with a very constant demand throughout the year, except for the month November, which is the period of yearly harvest. However, the constant demand has large daily perturbations. The owner of the greenhouse has invested in a shallow geothermal heat source. Additionally he is planning to expand the size of the greenhouse. A permit to increase from the current area of 12 [acres] to 18 [acres] has already been acquired. This case-study aids the owner in exploring the role HT-ATES can play in the future of his greenhouse heat supply.

Figure 4.20 shows that the set-up of the system is different from the previous cases. The production temperature of the shallow geothermal energy is constantly lower than the return temperature of the greenhouse. For this reason the GD is separated from the network, by an alternative connection of the HP: the GD is connected to the condenser of the HP, whereas the remaining network is connected to evaporator of the HP, making the HP intrinsic for geothermal energy production and contribution. Similarly, temporary heat surpluses are also channeled through the HP before subsequent injection in the HT-ATES. The capacity of the HP exceeds the capacity of the GD, which enables this alternative connection/solution.

The first simulations showed that implementation of HT-ATES in the projected greenhouse of 18 [acres] did not provide a balanced situation. The yearly base source heat production of the GD-HP-combination was larger than the yearly heat demand. It is chosen to double the size of the current greenhouse to 23 [acres] to obtain a balanced base scenario, that serves as a foundation from which implementation of HT-ATES can be investigated. The base scenario is captured in figure 4.21 and table 4.7. Figure 4.21 shows that, in addition to the constant demand throughout the year, and the dip during November harvest, the demand is more volatile than in the previous cases. Heat surpluses and deficits alternate on a hourly basis. It is uncertain if the HT-ATES' ability to react is sufficiently instantaneous, to cope with the hourly perturbations in demand. This is solved with a surface heat storage tank, that is able to absorb the hourly perturbations, and which is in connection with the subsurface HT-ATES system.

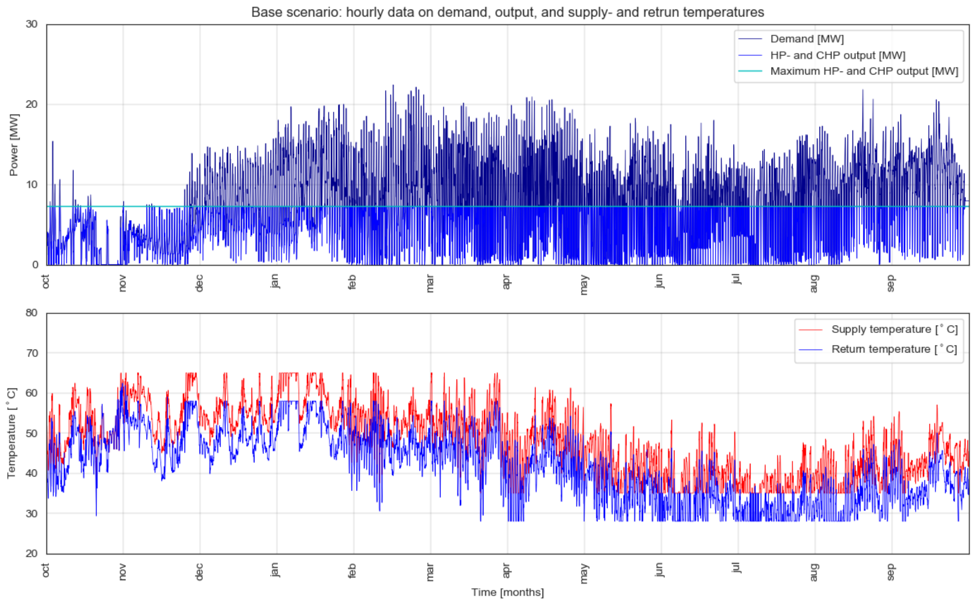

Figure 4.21: Base scenario, case C

Parameter	*Value*
Yearly demand	64 742 [MWh]
Yearly waste heat production	63 518 [MWh]
Used waste heat production	43 834 [MWh]
Peak demand/peak boiler production	22.4 [MW]/10.9[MW]

Table 4.7: Key figures of base scenario, case C

4.3.2. Summary of parametric variation

The applied parametric variation of case C is summarised in table 4.8. A parametric variation of greenhouse size has been implemented, because the planned expansion has yet to be realised. All the variations are larger than the planned *18* acres, to obtain a balanced situation and to unveil the full potential of HT-ATES within this case. The parametric variation indicates, among other things, the ideal size of the future greenhouse and consequent future greenhouse demand. Furthermore, it is chosen to again adopt a dynamic cut-off temperature, opposing the static cut-off temperature in case A.

Parameter	*Default value*	*Low variation*	*High variation*
Life time [y]	25	20	30
Cut-off temperature [°C]	9	5	13
Greenhouse area [acres]	23	21	25
Flow capacity [kg/s]	90	70	110
Aquifer thickness [m]	40	20	60
Aquifer depth [m]	200	100	300
Aquifer hydraulic conductivity [m/d]	5	1	10

Table 4.8: Parametric variation, case C

4.3.3. Results and in-depth analysis

The results are very similar to case A. Case C does not provide any new of conflicting insights, in addition to the other cases. For this reason, all case-specific figures and tables are entailed in appendix E.3.

5
Discussion and recommendations

On hindsight, HT-ATES as a concept is in a state of infancy. Literature is limited and the realised pilot projects have been unsuccessful so far. The purpose of this research is to improve identification of HT-ATES performance drivers and -barriers, and thereby to enhance decision making on future HT-ATES implementation. As a first step, this discussion aims to objectively analyse the adopted methodology. Subsequently, the methodology-analysis is projected on the results. Thereby the discussion reveals the real significance of the results (chapter 4) and directs towards the conclusions (chapter 6), which entail the key performance drivers and -barriers.

5.1. Discussing the methodology

The methodology, consisting of a simulation model and a multi-criteria decision method, is considered to be effective, because of *2* core abilities. Firstly, it is capable of creating, evaluating, comparing and ranking HT-ATES scenario's under variable conditions for implementation. Secondly, it produces new results and insights on HT-ATES performance drivers and -barriers during every stage, and thereby contributes to the larger research objective.

This section discusses the steps of the methodology in chronological order. The steps are summarised and enumerated. Corresponding comments and topics of discussion have been alphabetically enumerated. Lastly, suggested recommendations for future improvement of the methodology are indicated with a roman numeral.

1. The foundation of the multi-criteria decision method entails a set of evaluation criteria, in which the relative importance is expressed by a stakeholder-specific weight distribution. The weight distribution is obtained through a stakeholder survey.

   (a) Requirements for an adequate set of evaluation criteria are to be non-redundant, and to be comprehensive in capturing the utility of a scenario. The criteria set is one of the corner stones of the analysis. In this research project it is determined from expert advice and literature. The subjectivity in this process introduces uncertainty on whether the initial requirements are met. For example, there exists the possibility a criteria is missing, or another is redundant.

   (b) The stakeholder survey is a refreshing method to exclude the subjectivity of the decision maker from allocation of the criteria weights. A critical note on the current stakeholder survey is the number of survey respondents. A larger number of respondents will increase the validity of the weights distribution. It will produce more reliable and representative criteria weights.

i. A recommended improvement is to allocate additional time and resources to the survey, thereby assuring a minimum number of respondents.

(c) The importance of for example groundwater impact is very location dependant. This implies there exist a great variation in groundwater impact weights

i. It is recommended to determine the weights, in particular the groundwater impact weights, for every new location/case. This will improve the validity of the results. It suggests that for every new case, a new stakeholder survey has to be performed.

2. The methodology continues with creating scenario's through parametric variation in a simulation model. This step produces the quantitative information on multiple evaluation criteria, that serve as input to the further analysis.

(a) The simulation model encompasses the complete supply chain of heat, from production to consumption. It delivers quantitative information regarding groundwater impact, emissions, and financial performance. Because the system is large, and time is limited, a great amount of assumptions is incorporated in the model. This can be regarded as a model limitation. The degree of assumptions forces to approach performance from a perspective of mutation (2.1). This signifies that the relative performance of scenario's is more important than the absolute performance. All under the guise of: if a scenario outperforms the others under assumed conditions, it will most likely do so under real conditions. Decreasing the number of assumptions is strongly recommended as future improvement, as it will make the model more realistic, and the results and conclusions more explicit. Recommended improvements are for example:

i. Addition of a realistic distribution network. A network that has geo-coordinates, and in which pressure and flow properties are included. It will enable to improve prediction of network losses, and consequently will lead to more accurate quantification of HT-ATES performance.

ii. Replacement of the standardised homogeneous subsurface by a case-specific heterogeneous case-specific subsurface. Again, this will lead to more accurate performance quantification.

iii. Furthermore, thermal interference between the warm- and cold reservoir, or the possibility of using multiple wells have not been investigated in the current simulation model. Both will give results with greater validity.

iv. Addition of the possibility of failure or planned maintenance of individual heat sources. Something that is not unlikely in such innovative and complex heating systems, and something that will increase model validity.

(b) The parametric variation has limitations. The model calculation intensity in combination with the constraint of time, allows for only *3* data points per parametric variation. This seems sufficient for indicating the sensitivity to individual parameters. It allows the decision maker to recognise trends, and directs the decision maker towards the optimal parameter values. On the contrary, the limited number of data points (*3*) make the parametric variation insufficient for delivering the actual, optimal parameter values. Moreover, the adopted parametric variation is not exhaustive: the possibility exists that the performance is insensitive to individual parameter variation, but extremely sensitive to their simultaneous variation.

i. Improvement on the simulation model efficiency enables a more extensive and exhaustive parametric variation, with more data points and thus more information for the decision maker. However, it is debatable if this leads to better results. The great amount of assumptions make the absolute performance of scenario's highly uncertain, and less relevant than their relative performance. In this light, having *3* data points to recognise trends seems plenty. After decreasing the amount of assumptions, a subsequent logical improvement would be to increase model efficiency.

(c) In subsection 3.2.4 it is stated that groundwater impact can be defined as any changes in groundwater temperature, -composition, or - level. In the model, the groundwater impact is assessed by measuring the subsurface temperature directly above the warm reservoir, 50 [m] beneath the surface. The method of assessment seems inadequate, because during a few scenario's the measured temperature is conflicting with the calculated thermal recovery efficiency of the HT-ATES under consideration.

i. For this reason, it is debatable if groundwater impact can be expressed through a single temperature. A suggestion for future application would be to measure temperature at multiple locations in the subsurface, to exclude the possibility of local temperature perturbations, and to make the method more robust. This improvement would still not result in a comprehensive method of assessment, since it does not address groundwater composition or -level.

3. The multi-criteria decision method foundation and the quantitative information from the simulation model are combined during the stage of comparison and ranking. The performance of scenario's on the evaluation criteria is translated into scores, by means of either direct rating or value functions. This puts the performance on criteria of different nature onto a common scale of reference and enables comparison. Scores and weights multiply to aggregated scores, which determine the scenario ranking. Both entail uncertainty that is exposed through a Monte Carlo iteration. The final product is the probability a scenario occupies a certain rank. This is captured in a probability-of-rank matrix.

(a) There are no additional points of discussion to this stage, other than the great subjectivity that is entailed in the methods of scoring. This is exposed and corrected by the Monte Carlo iteration.

5.2. Significance of results

5.2.1. Validity of results on groundwater impact

The results of chapter 4 show that groundwater impact remains the greatest risk in all cases. In some scenario's a low performance on groundwater impact dominates and deteriorates the scenario score. However, the severe location dependency of groundwater impact importance, in combination with (the assumptions of) the simplified homogeneous subsurface in the model, and the addressed limitations regarding groundwater performance assessment, challenge the validity of the results on groundwater impact. *4* brief examples are included for additional clarification, and as food for thought:

1. Groundwater impact is allocated relatively high weights through the stakeholder survey. However, it has not been checked case-specifically if the local groundwater serves additional purposes. If groundwater is unused and consequently irrelevant to all stakeholders, it can be allocated a lower weight. This would significantly affect the results: an extended project life-time and a shallow aquifer could become preferable, since both perform better on emissions and internal rate of return.

2. The results in chapter 4 indicate that a short project life-time is preferable, because groundwater impact is very time dependant in the model. However, if the HT-ATES location is changed every *15* years, after some time the decision maker ends up with many sites that have minimal groundwater impact. Whether it is preferable to have many sites with minimal groundwater impact, or to have *1* location with great groundwater impact is again debatable. This signifies the limitations of the methods of scoring.

3. In the current model natural groundwater flow is not included. Natural groundwater causes heat loss to spread out over a larger volume, which limits the increase in groundwater temperature. The result would be a reduction in measured groundwater impact.

4. Similarly, in the current model groundwater salinity is not included. However, natural salinity would decrease the impact of HT-ATES on the groundwater composition, and would thus increase project performance with respect to groundwater impact.

The examples signify that the validity of results on groundwater impact performance is under pressure. All examples are capable of affecting groundwater impact results, and of subsequently shifting scenario preference and ranking. This enables the possibility to apply some nuance to the results, which is critical to take into account during the generic conclusions.

5.2.2. Ability to compare

The questionable validity of the groundwater performance does not lead to significant changes in the conclusions. The performance on the other quantitative criteria is also uncertain, due to a great number of assumptions. For this reason, the methodology adopts the perspective of mutation (subsection 2.1), in which the relative scenario performance is more important than their absolute performance. And despite the significant uncertainty regarding groundwater impact, the methodology maintains this ability to compare. Through parametric variation, the methodology is capable of indicating sensitivity of criteria- and scenario performance to individual parameters. Thereby, it aids in recognising trends and directs the decision maker towards the optimal parameter values. However, it does not deliver the solution. The methodology improves identification of HT-ATES performance drivers and -barriers, but does not (yet) provide the optimal HT-ATES design.

The results in chapter 4 are in line with this ability to compare. All supporting graphs, tables and additional information from chapter 4 serve the purpose of performance comparison and do not include explicit quantitative information. Consequently, the guidelines in section 6.3, explaining HT-ATES performance drivers and -barriers, have an ambiguous and general nature: they give direction, but do not provide the answer. They merely strive to create a balanced system, in which uncertainty and risk are minimised.

The methodology serves as an exemplary platform, which can be alternated to better fit the case or the preferences of the decision maker. It can be improved and extended according to the aforementioned recommendations (section 5.1), with the objective to eventually replace the general guidelines (section 6.3) with explicit rules for successful HT-ATES implementation. Until this (non-infancy) state has been reached, the methodology can aid the decision maker and give direction. It can certainly not decide.

6 Generic conclusions

All previous work serves as building blocks to this chapter, which entails the generic conclusions based on the results. It strives to recapitalise the insights and trends that have been recognised throughout the research and across the different cases. The main opportunity provided by HT-ATES implementation is the increase in full-load hours of the base source, which positively affects project performance on internal rate of return. Groundwater impact remains the greatest risk. HT-ATES performance drivers and -barriers are explained through *5* guidelines and entail aquifer hydraulic conductivity, aquifer depth, network supply- and return temperatures, project life-time, production-demand-ratio, and the demand curve shape. The guidelines enable the decision maker to maximise HT-ATES project performance, and will eventually contribute to more successful HT-ATES implementation.

6.1. HT-ATES opportunities

The case results confirm the hypothesis in chapter 1 on the potential benefits of HT-ATES. HT-ATES can improve project performance by increasing the number of full-load hours of base source production. It enables temporary heat surpluses to be stored for future demand, thereby giving otherwise unused base source heat production a second chance. Under default parameter conditions the increase in full-load hours varies from *20* to *60*%. The discussion (chapter 5) puts this result in perspective, by addressing the great number of assumptions. The additional full-load hours most likely benefit project performance on both internal rate of return and emissions. The exact performance improvement is uncertain, case-specific and largely depends on what heat sources are cannibalised upon HT-ATES introduction. In case A and case C, HT-ATES implementation cannibalises gas-powered heat sources and mostly improves performance on emissions. In case B, HT-ATES implementation cannibalises the heat pump and mostly improves internal rate of return of the project.

6.2. HT-ATES risks

The results show that groundwater impact remains the greatest risk of HT-ATES, opposing the improvement on project internal rate of return and emissions. However, the results also show that groundwater impact can be minimised to amounts that will not nullify the improvement on internal rate of return and emissions, through smart decisions on the designated aquifer and system design. The discussion (chapter 5) challenges the results on groundwater impact. Among other things, it addresses the severe location dependency on groundwater impact relevance. This enables to apply some nuance to the results, which also is entailed in the guidelines.

Furthermore, the uncertainty regarding future legislation on HT-ATES remains a great risk. If it remains equal, and heat injection above *25* [°C] remains problematic, large-scale adoption of HT-ATES in future heating projects is unlikely.

6.3. Drivers and barriers: guidelines for the decision maker

Optimal HT-ATES performance derives from balance. The decision maker is recommended to follow multiple, parallel guidelines. The guidelines aid in balancing performance on groundwater impact, emissions, and internal rate of return, which is the key to successful HT-ATES. The guidelines are enumerated below:

1. Parametric variation shows that HT-ATES performance is more sensitive to geological parameters than to design parameters. In particular aquifer hydraulic conductivity and aquifer depth are decisive parameters. For every combination of case and stakeholder group, the *low aquifer hydraulic conductivity scenario* and *shallow aquifer scenario* are most likely (and sometimes sure) to be ranked among the worst performing scenario's. This indicates that sufficient aquifer hydraulic conductivity and sufficient aquifer dept are intrinsic to successful HT-ATES implementation. The decision maker is recommended to focus on aquifers deeper than *200* [m], with hydraulic conductivity's exceeding *5* [m d^{-1}]. The discussion (chapter 5) provides the sidenote that the preference regarding aquifer geological properties can change. In particular a shallow aquifer can become preferable if for example groundwater impact becomes less relevant, and is assigned a lower weight. Aquifer thickness is not decisive, and thus of lesser importance. The decision maker is strongly encouraged to allocate appropriate resources to thorough subsurface characterisation before HT-ATES implementation, due to dominance of geological parameters. Thereby the decision maker can minimise the uncertainty regarding subsurface geological characteristics, and consequently minimise risk of unsuccessful HT-ATES implementation.

2. Case B demonstrates that HT-ATES can not be implemented in all heating projects. Case B contains an existing district heating network. Both the network and the residential area being served are outdated, badly insulated, and consequently suffer significant heat losses. The combination of high losses and limited flow capacity of the network result in high demanded supply- and return temperatures. The consumer return temperatures are greater than the HT-ATES storage temperatures, which paralyses the HT-ATES in the period where it is most needed. The return temperatures deprive the HT-ATES from functioning as secondary base source. The critical insight is that HT-ATES only thrives in relatively modern heating networks, in which heat losses and subsequent supply- and return temperatures are kept to a minimum. This enables the HT-ATES system to release its stored heat during peak winter demand. As part of the primary feasibility study, the decision maker is recommended to carefully analyse the network return temperatures during peak demand. If those exceed the expected storage temperatures, the project is unsuitable for HT-ATES implementation.

3. The consensus exists that an extended project life time is preferable, because it enables extended returns on the initial investment. This trend is recognised across all cases, with the *extended life-time scenario* having an improved score on project internal rate of return. However, the extended life-time deteriorates the performance on groundwater impact, because inevitable heat loss has more time to reach the groundwater, and consequently impact the groundwater. This implies there is an optimum in project life-time, where internal rate of return, emissions and groundwater impact are balanced. It is the task of the decision maker to find this optimum. Across all cases the *short life-time scenario*, which amounts to a life-time of *20* years, is most likely to be ranked among the best performing scenario's. For this reason, the decision maker is recommended to not consider project life-times longer than *20* years. The discussion (chapter 5) provides nuance to this guideline. For example, an improved model subsurface, which includes groundwater salinity and -flow, could cause a shift in the optimal project life-time.

4. The ratio of maximal base source heat production and consumer demand is important. Throughout the cases either geothermal energy or industrial waste heat is adopted as the base source. The results show that a larger production-demand-ratio, due to either an increased base source production or a decreased consumer demand, leads to more HT-ATES heat injection, and simultaneously leaves a reduced window for HT-ATES heat production. This causes overall warming-up of the subsurface and worsens the performance on the groundwater impact. On the contrary, a larger ratio benefits performance on emissions, because it decreases the contribution of peak boilers. Similar to an optimal life-time, there exists an optimal production-demand-ratio, where internal rate of return, emissions and groundwater impact are balanced. It is the task of the decision maker to find this optimum.

   Across all cases, the optimal production-demand-ratio is smaller than *1*. This indicates that the sum of yearly heat demand must always exceed the sum of yearly maximum base source heat production. The decision maker is recommended to assure this. The optimal ratio of a geothermal base source more closely approximates *1* than a waste heat base source in the exact same case, due to the fact that geothermal heat production is subsidised. The discussion (chapter 5) addresses the ratio can change upon for example decreasing number of assumptions in the simulation model.

5. In addition to the quantity of demand, also the shape of the demand curve is crucial. A difference in demand curve shape causes case B to show conflicting results on groundwater impact performance. In an ideal situation the demand curve would be as flat as possible, and the consequent standard deviation of base source production and demand would be small. A small standard deviation reduces the required flow rates of the HT-ATES and thus reduces required pumping pressures. This is beneficial for both HT-ATES investment costs and electricity consumption. Additionally, the reduced pumping pressures increase the barrier formed by the aquitard. The reduced pumping pressures make it relatively more difficult for heat to travel through the confining aquitard.

   The decision maker has limited ability to rigorously change the demand curve. However, the decision maker is recommended to strive for a minimum standard deviation of base source production and demand, by decreasing peak demands and increasing bottom demands. The decision maker is encouraged to shift demand with for example variable heat prices, following the example of the electricity market. From a groundwater impact perspective it is critical to always assure a minimum demand. Large heat surpluses in the network require large flow rates and pumping pressures, that cause additional heat loss during injection in the warm reservoir. This worsens the performance on groundwater impact. From a perspective of emissions and costs it is critical to limit peak demand. High demand requires a larger peak production capacity. This brings additional costs and worsens the performance on internal rate of return. The consequent increased natural gas consumption by the boilers worsens the performance on emissions.

A decision maker, who recognises the opportunities, who is aware of the HT-ATES performance drivers and -barriers, and who is committed to follow the proposed guidelines, will have a higher chance at achieving a successful HT-ATES implementation.

6.4. For the future: the possibilities of a greenfield case

Despite the general nature of the concluding guidelines, the results reveal the serious potential of HT-ATES. The increased performance on emissions and internal rate of return are achieved by merely addition of HT-ATES in an existing heating system. There have not been made any changes to the existing heating system to improve the position of HT-ATES, except for the change of network temperatures in case B. Imagine the possibilities when HT-ATES is applied in a greenfield case. A case where there exist favorable subsurface geological conditions for application. Where base- and peak heat sources and the HT-ATES are perfectly in proportion. A case where the consumer demand is peak-shaved with variable heat prices, and that has a state-of-the-art distribution network, in which losses and the consequent variation in supply- and return temperatures is limited. In such cases HT-ATES implementation would offer major advantages.

Bibliography

[1] F. Abastante, I. Lami, and P. Lombardi. An integrated participative spatial decision support system for smart energy urban scenarios: a financial and economic approach. *Buildings*, 7(4):103, 2017.

[2] M. Afman, S. Hers, and T. Scholten. Energy and electricity price scenarios 2020-2030. 2017.

[3] G. Bakema. Investerings- en onderhoudskosten ondergrondse hoge temperatuur opslag. 2018.

[4] H. Barron and C. P. Schmidt. Sensitivity analysis of dditive multiattribute value models. 1988.

[5] M. Bloemendal and N. Hartog. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. *Geothermics*, 71(November 2017):306–319, 2018.

[6] R. Büchele, A. Müller, M. Hummel, L. Kranzl, M. Hartner, Y. Deng, and M. Bons. Comprehensive assessment of the potential for efficient district heating and cooling and for high-efficient cogeneration in Austria. *International Journal of Sustainable Energy Planning and Management*, 10:3–20, 2016.

[7] J. Butler, J. Jia, and J. Dyer. Theory and methodology simulation techniques for the sensitivity analysis of multi-criteria decision models. *European Journal of Operational Research*, 7:531–546, 1997.

[8] H. Chen, M. D. Wood, C. Linstead, and E. Maltby. Uncertainty analysis in a GIS-based multi-criteria analysis tool for river catchment management. *Environmental Modelling and Software*, 26(4):395–405, 2011.

[9] R. M. Dawes and B. Corrigan. Linear models in decision making. *Psychological Bulletin*, 81(2):95–106, 1974.

[10] B. de Meulenmeester. End-consumers beware of capacity payments. 2014.

[11] J. S. Dickinson, N. Buik, M. C. Matthews, and A. Snijders. Aquifer thermal energy storage: theoretical and operational analysis. *Géotechnique*, 59(3):249–260, 2009.

[12] J. Dodgson, M. Spackman, A. Pearman, and L. Phillips. *Multicriteria Analysis: A Manual.* 2009.

[13] B. Drijver, M. van Aarssen, and B. de Zwart. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable, 2012.

[14] C. R. Fitts. *Groundwater science.* Elsevier Science Ltd., 2002.

[15] T. L. Frölicher and D. J. Paynter. Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales. *Environmental Research Letters*, 10(7), 2015.

[16] E. Georgopoulou, D. Lalas, and L. Papagiannakis. A multicriteria decision aid approach for energy planning problems: The case of renewable energy option. *European Journal of Operational Research*, 103(9):38–54, 1997.

[17] A. Ghanmi. Sensitivity analysis of bid evaluation plans for defence acquisition problems. 2015.

[18] A. Guitouni and J. M. Martel. Tentative guidelines to help choosing an appropriate multi-criteria decision analysis method. *European Journal of Operational Research*, 109 (2):501–521, 1998.

[19] X. Guo and M. Hendel. Urban water networks as an alternative source for district heating and emergency heat-wave cooling. *Energy*, 145:79–87, 2018.

[20] R. Haas and A. Ajanovic. Economic and energetic aspects of long term storages for electricity. *Elektrotechnik und Informationstechnik*, 130(6):169–176, 2013.

[21] T. Hacking. The suitability of a high temperature aquifer thermal energy storage on the TU-Delft campus. *Bachelor Thesis, Delft University of Technology*, 2017.

[22] G. Hieminga, R. Luman, and J. Witteveen. Focus on the Dutch climate challenge insight into targets, certainties and uncertainties. 2018.

[23] K. M. Hyde and H. R. Maier. Distance-based and stochastic uncertainty analysis for multi-criteria decision analysis in excel using visual basic for applications. *Environmental Modelling and Software*, 21:1695–1710, 2006.

[24] K. M. Hyde, H. R. Maier, and C. B. Colby. Reliability-based approach to multicriteria decision analysis for water resources. *Journal of Water Resources Planning and Management*, 130(December):429–438, 2004.

[25] D. R. Insua and S. French. A framework for sensitivity analysis in discrete multi-objective decision-making. *European Journal of Operational Research*, 54(2):176–190, 1991.

[26] R. L. Keeney and H. Raiffa. *Decisions with multiple objectives*. John Wiley and Sons Inc., 1976.

[27] M. V. Kljajić, A. S. Anđelković, V. Hasik, V. M. Munćan, and M. Bilec. Shallow geothermal energy integration in district heating system: An example from Serbia. 2018.

[28] F. H. Knight. *Risk, Uncertainty and Profit*. Houghton Mifflin Harcourt, 1921.

[29] S. Kranz, G. Bloecher, and A. Saadat. Improving aquifer thermal energy storage efficiency. *World Geothermal Congress*, 2015.

[30] A. Lake, B. Rezaie, and S. Beyerlein. Review of district heating and cooling systems for a sustainable future. *Renewable and Sustainable Energy Reviews*, 67:417–425, 2017.

[31] R. J. Lazarus. Super wicked problems and climate change: Liberate the future. *Cornell Law Review*, 94(July):1153–1234, 2009.

[32] A. Linhoss and J. D. Ballweber. Incorporating uncertainty and decision analysis into a water-sustainability index. *Journal of Water Resources Planning and Management*, 141 (12), 2015.

[33] Y. Liu, L. Wang, and B. Yu. Sharp front capturing method for carbon dioxide plume propagation during injection into a deep confined aquifer. *Energy and Fuels*, 24(2): 1431–1440, 2010.

[34] G. Liuhua, Z. Jun, A. Qingsong, W. Junyao, and L. Xueling. A review on system performance studies of aquifer thermal energy storage, 2017.

[35] S. Forsaeus Nilsson, C. Reidhav, K. Lygnerud, and S. Werner. Sparse district-heating in Sweden. *Applied Energy*, 85(7):555–564, 2008.

[36] U.S. Department of Energy (USDOE). A history of geothermal energy in america.

[37] Global Forum on Sustainable Energy (GFSE). Implications of the paris agreement. 2016.

[38] M. Pluymaekers, J. D. van Wees, M. van der Kuip, and V. van de Weijer. Hoge temperatuur opslag in de ondiepe ondergrond. 2013.

[39] S. Pusat and H. H. Erdem. Techno-economic model for district heating systems. *Energy and Buildings*, 72:177–185, 2014.

[40] A. Réveillère, V. Hamm, H. Lesueur, E. Cordier, and P. Goblet. Geothermal contribution to the energy mix of a heating network when using aquifer thermal energy storage: Modeling and application to the Paris basin. *Geothermics*, 47:69–79, 2013.

[41] O. Rix. Pricing the purchase of gas losses on regional gas transport networks. 2013.

[42] T. L Saaty. Relative measurement and its generalization in decision making. why pairwise comparisons are central in mathematics for the measurement of intangible factors. the analytic hierarchy/network process. 2008.

[43] T. Saito, T. Ueki, S. Ohkubo, K. Kawamoto, T. Komatsu, S. Hamamoto, and P. Moldrup. Temperature change affected groundwater quality in a confined marine aquifer during long-term heating and cooling. *Water Research*, 94(2016):120–127, 2016.

[44] B. Sanner and K. Knoblich. Advantages and problems of high temperature underground thermal energy storage. *Bulletin d'Hydrogéologie*, 17:341–348, 1999.

[45] B. Sanner, F. Kabus, P. Seibt, and J. Bartels. Underground thermal energy storage for the german parliament in Berlin. *World Geothermal Congress*, 2005.

[46] G. Schout, B. Drijver, and R. Schotting. The influence of the injection temperature on the recovery efficiency of high temperature aquifer thermal energy storage: Comment on Jeon et al., 2015. 2016.

[47] A.L. Snijders. Lessons from 100 ATES projects - the developments of aquifer storage in the Netherlands. 2000.

[48] V. M. Soltero, R. Chacartegui, C. Ortiz, and G. Quirosa. Techno-economic analysis of rural 4^{th} generation biomass district heating. *Energies*, 11, 2018.

[49] W. Sommer, J. Valstar, I. Leusbrock, T. Grotenhuis, and H. Rijnaarts. Optimization and spatial pattern of large-scale aquifer thermal energy storage, 2014.

[50] T. Tereshchenko and N. Nord. Future trends in district heating development. *Norwegian University of Science and Technology*, 2018.

[51] R. H. Thaler and C. R. Sunstein. *Nudge: improving decisions about health, wealth and happiness*. Penquin Group, 2008.

[52] P. Thokala, N. Devlin, K. Marsh, R. Baltussen, M. Boysen, Z. Kalo, T. Longrenn, F. Mussen, S. Peacock, J. Watkins, and M. Ijzerman. Multiple criteria decision analysis for health care decision making - an introduction: Report 1 of the ISPOR MCDA emerging good practices task force. *Value in Health*, 19(1):1–13, 2016.

[53] J. Tholen, J. D. van Wees, and F. Beekman. Potential for high temperature-aquifer thermal energy storage (HT-ATES) in the Dutch subsurface. *Master Thesis, Utrecht University*, 2017.

[54] E. Triantaphyllou and A. Sánchez. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decision Sciences*, 28(1):151–194, 1997.

[55] D. van Beek, S. de Boer, M. Braakhekke, and N. Buik. Kansen voor hogetemperatuuropslag en geothermie. 2014.

[56] A. van Diepen. The potential of high temperature aquifer thermal energy storage (HT-ATES) to enhance the techno-economic performance of dutch district heating systems. *Master Thesis, Utrecht University*, 2019.

[57] Ministerie van Economische Zaken en Klimaat. SDE+ najaar 2019 - zo vraagt u subsidie aan voor de productie van duurzame energie. 2019.

[58] J. H. van Lopik, N. Hartog, and W. J. Zaadnoordijk. Het gebruik van saliniteitscontrast voor dichtheidsverschil-compensatie voor het verbeteren van het terugwinrendement van warmte tijdens ondergrondse hoge temperatuur opslag. *Hydrogeology Journal*, 24 (5):1255–1271, 2016.

[59] J. W. Verbeek, E. J. T. Duin, R. H. B. Rijkers, Th. E. Wong, and J. C. Doornenbal. Subsurface structure of the Netherlands - results of recent onshore and offshore mapping. *Netherlands Journal of Geosciences*, 85(4):245–276, 2016.

[60] P. Verschueren and H. Doorewaard. *Designing a research project*. Eleven International Publishing, 2010.

[61] H. H. J. Vreuls. The Netherlands: list of fuels and standard CO_2 emission factors. 2005.

[62] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, 13(9):2263–2278, 2009.

[63] Tess Wegman. HT-ATES system case study on TU Delft campus. *Bachelor Thesis, Delft University of Technology*, 2017.

[64] S. Werner. International review of district heating and cooling. *Energy*, 137:617–631, 2017.

[65] M. Wesselink, W. Liu, J. Koornneef, and M. van den Broek. Conceptual market potential framework of high temperature aquifer thermal energy storage - a case study in the Netherlands. *Energy*, 147:477–489, 2018.

[66] W. Wetekamp. Net Present Value (NPV) as a tool supporting effective project management. 2:898–900, 2011.

[67] K. Wojdyga and M. Chorzelski. Chances for Polish district heating systems. *Energy Procedia*, 116:106–118, 2017.

A
Research methodologies

The research objective is to improve identification of both HT-ATES performance drivers and -barriers, thereby improving decision making regarding HT-ATES implementation in future heating projects. The methodology towards reaching the objective is described in more detail throughout this chapter. To summarise: this research project has both a diagnostic and a design-oriented nature, and can be structured in the phases of *discover*, *design* and *deliver*. The book *'Designing a Research Project'* [60] served as inspirational framework. It entails general guidelines and methods for designing a research project.

A.1. Research typification

This research project can be classified as a practice-oriented research, specifically a combination of a diagnostic research and a design-oriented research [60]. [...] *A practice-oriented research is meant to provide knowledge and information that can contribute to a successful intervention in order to change an existing situation* [60]. Contribution can be to one or multiple steps of the intervention cycle (figure A.1). This is the predefined sequence of steps to reach a solution to existing operational challenges, towards a successful intervention [60].

1. This research is a diagnostic research because it contributes to a better identification of favorable HT-ATES conditions.
2. This research is a design-oriented research because it proposes possible HT-ATES designs for specific cases.

Both steps contribute towards the larger objective, outside the scope of this research, of changing the existing situation: a more widely adoption of HT-ATES within heating projects. This is visualised in figure A.1.

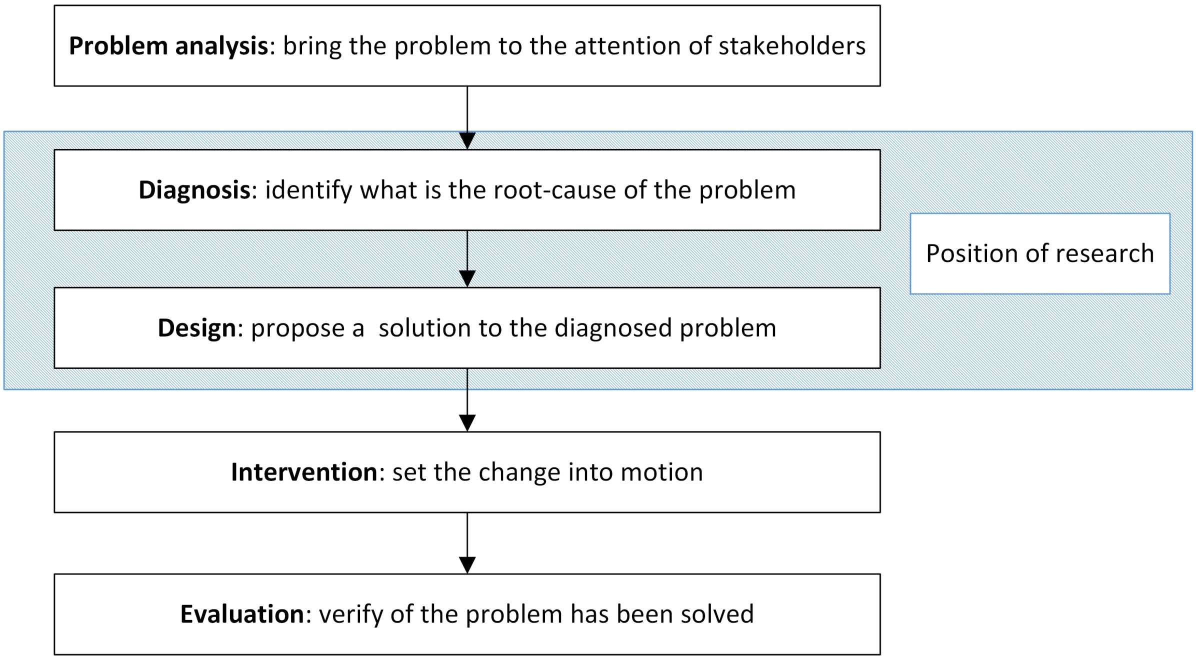

Figure A.1: The intervention cycle [60]

A.2. Research structure

A.2.1. General research framework

The research framework includes the appropriate steps that need to be taken in order to achieve the research objective, and it represents the internal logic of the project [60]. Furthermore, it is a useful step after formulation of the objective [60]. Figure A.2 is a visualisation of the research framework. It shows the research is divided into *3* consecutive phases, consisting of *discover design* and *deliver*. During this section each of the phases is explained by stating it's general objective, guiding research questions, critical inputs and projected outputs, in line with figure A.2.

A.2.2. Preliminary study

Before commencing the first phase, the *discover phase*, a preliminary study has to be done to provide a foundation for further research. The actual research can only begin if the problem has been clearly identified and a research objective has been determined. The results of the preliminary study have already been discussed in chapter 1.

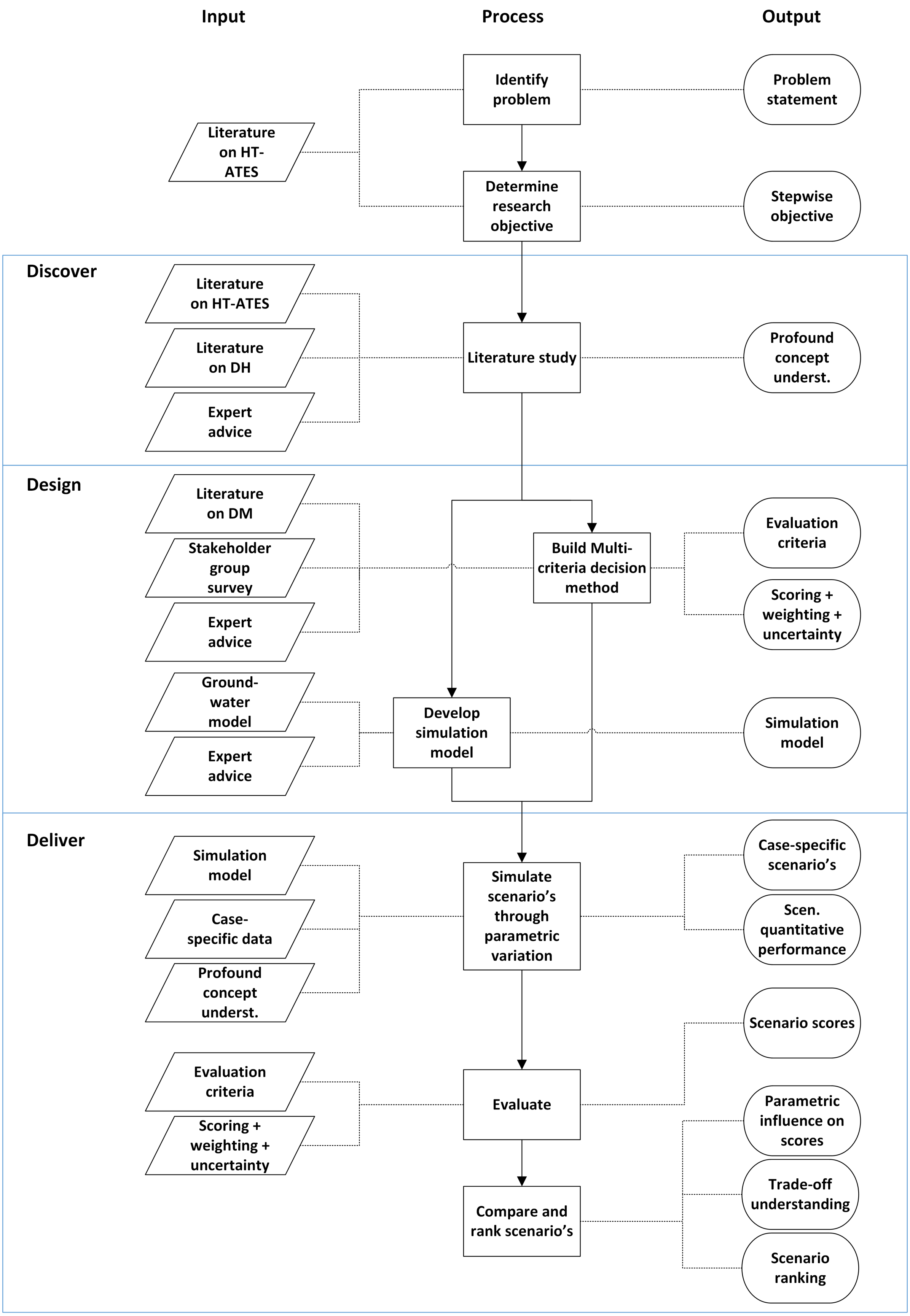

Figure A.2: Framework: discover, design and deliver

A.2.3. Discover

The objective of the *discover phase* is to increase understanding of the concepts of HT-ATES and DH. The following research questions will give more direction to the phase and its objective.

1. What factors serve as input to successful HT-ATES and DH?
   (a) What is HT-ATES, and how does it compare to regular ATES?
   (b) What are the individual performance drivers of both HT-ATES and DH?
   (c) What are the individual (technical) barriers of both HT-ATES and DH?
   (d) What are the basic subsurface heat behaviour principles?
   (e) Which formations are suitable for HT-ATES implementation in the Netherlands?
   (f) What are their synergies?

The *discover phase* consists of *1* large process: the literature study. It merely is a continuation on the preliminary study, with a more profound understanding of the concepts of HT-ATES and DH as the objective. The product of the literature study can be found in appendix B. Literature will serve as the main input to map out individual performance drivers and -barriers of both HT-ATES and DH, and to find possible synergies, In addition to the literature experts are consulted, to provide another perspective to the problem, and because both concepts are developing quickly and literature can thus be outdated.

A.2.4. Design

The *design phase* is the most comprehensive stage of the research. It entails *2* major processes with common objective to build the necessary tools for improved decision-making on implementation. The tools are not meant to make actual decisions, but merely to improve identification of the performance drivers and -barriers, in line with the project objective. The following research questions will give more direction to the phase and it's objective.

2. What is a suitable MCDM?
   (a) What are the core evaluation criteria?
   (b) How to score performance on evaluation criteria?
   (c) How to obtain relative importance between criteria?
   (d) What is the weight of individual criteria, and is the weight distribution stakeholder dependant?
3. How can an accurate simulation model be build?
   (a) What are the critical assumptions to be made?
   (b) What are the consecutive steps towards a reliable model?
   (c) How can the model be validated/tested?
   (d) How can the model results be interpreted?

The *design phase* is structured into *2* parallel processes that have individual inputs and outputs (see figure A.2). Process *1* is building a suitable MCDM. This is achieved by an additional literature review focused on decision making, by a stakeholder group survey, and by consultation of experts. The output consists of adequate evaluation criteria and methods for scoring and weighting the evaluation criteria. The other process entails the development of a simulation model. Expert advice serves as the main input. After integration with a groundwater model, the model can produce quantitative information which can aid in decision-making.

A.2.5. Deliver

Having acquired the decision-making tools in the previous phase, the objective of the *deliver phase* is to obtain, evaluate and consequently rank the scenario's. The following research questions give more direction and guidance to the phase and it's objective.

4. Taking into account the findings from the *discover phase*, what would be an appropriate parametric variation to create different case-specific scenario's?
   (a) What are the critical design choices made (by the DM), and what would be plausible value ranges?
   (b) What are the critical geological parameters, and what would be plausible value ranges?
5. How do the case-specific scenario's perform?
   (a) What is the score of scenario's on evaluation criteria?
   (b) What is the trend in primary value trade-offs?
6. How do the case-specific scenario's compare?
   (a) How does parametric variation influence the scenario score?
   (b) What is the scenario ranking, and in addition the uncertainty/probability of the ranking?
   (c) Can trends be recognised across multiple cases?

The *deliver phase* entails *3* consecutive processes. After creating and simulating the scenario's through application of parametric variation, the MCDM will take care of their evaluation, comparison and ranking. This is the logical sequence of rational decision making, as described by Keeney et al. [26] and in chapter 3. The output from both the *discover phase* and *design phase* will serve as main input, together with case-specific information. The *deliver phase* output consists of scenario performance and - scores on all evaluation criteria, which will enable the DM to obtain an insight in the primary value trade-offs and the degree of influence of different parameters. The final deliverable is a scenario ranking, in which probability and uncertainty is included. It is captured in a matrix.

A.3. Contemplating on research strategy

One of the advantages of a case study is that it is suitable for a qualitative analysis across various disciplines, and can thus provide a general picture of the research object. Hereby the emphasis is on comparing and interpreting (qualitative) data, rather than counting and calculating (quantitative) data [60]. Furthermore, a case study is more flexible during the research process. It does not require significant structuring before starting: during the process the DM can easily adjust cases or add cases to research. A third and final advantage of a case study is that the results will find higher acceptance with people in the field, because the results are of more everyday nature [60], which makes them in the end more accessible. On the downside, [...] *the external validity of results of a case study is often under pressure* [60], since only few cases are studied to achieve in-depth knowledge. To minimise the disadvantage of 'bad sampling', without giving in on the evident advantages of the case-study, the phases of *design, decide, and deliver* should be repeated for multiple cases. This will produce results with a greater external validity, that can be applied to a broader population of interest or to similar cases. From this perspective, time is the crucial constraint.

B

Technical background

This appendix is based on the performed literature study and can be adopted by the reader as an effective tool to read into the concepts of HT-ATES and DH. It is the result of the *discover phase*, as described in subsection A.2.3. It provides insights on their individual performance drivers and -barriers and potential synergies. Among other (uncertain) performance drivers and -barriers, HT-ATES subsurface heat loss remains problematic. It can be limited through favorable geology and actions by the DM. DH enables integration of clean energy in the build environment, but cost is the major barrier for implementation.

B.1. (High temperature) aquifer thermal energy storage

B.1.1. Aquifer thermal energy storage for heating and cooling

When storing thermal energy in the subsurface there are many options one can choose. Aquifer thermal energy storage (ATES) is the process of seasonal storage of thermal energy in a subsurface confined aquifer, using an open-loop bidirectional system [11]. ATES systems actively store cooled and heated groundwater, making use of a hot- and cold plume (or multiple plumes), with sufficient intermediate spacing [11]. In summertime, when there exists a local surplus of heat, water from the cold reservoir is pumped to the surface, where it absorbs the surplus of heat, before re-injection into the hot reservoir. During the winter months, the same energy is retrieved applying the reversed process.

B.1.2. Higher temperature brings both opportunities and risks

Now that the reader has obtained some affinity with the topic, it is time to introduce the concept of HT-ATES. The difference between regular ATES and HT-ATES is the storage temperatures: [...] *High temperature underground thermal energy storage refers to a minimum storage loading temperatures in the order of 50* [°C] [44]. Therefore, opposing the double function of heating and cooling of regular ATES, HT-ATES solely stores heat. HT-ATES provides the opportunity of seasonal storage of heat, and thereby increases the geothermal share in a heating network [40]. This potentially leads to a reduction in emissions and costs.

The main advantage of HT-ATES over regular ATES systems, is that the higher temperature allows that its retrieved heat can be directly used for heating purposes, without intervention of a HP. In addition, the required flow rate (and the required volume in the subsurface) to supply a specific heat demand is lower than for regular ATES [13]. Increasing the temperature of increases technical challenges, and brings additional risks compared to ATES [47]. Examples of technical challenges are clogging of the wells due to precipitation of minerals [47], corrosion of system components [45], and the control system in general [47]. To date, most technical challenges related to corrosion, precipitation and control can be solved [58].

Solving the technical challenges has not led to successful HT-ATES implementation, and most exact performance drivers and -barriers remain uncertain. However, scientists do agree that subsurface heat loss, and the consequent system TRE, is among the major performance drivers and -barriers [34]. As a result, it is the centre of most research on HT-ATES. The following sections elaborate more extensively on the TRE and the underlying subsurface heat behaviour.

B.2. Understanding subsurface heat behaviour: hydrology and losses

B.2.1. Basic aquifer geology

Requirements regarding the geological characteristics of a suitable aquifer and surrounding formations can be summarised as follows:

1. Porosity is defined as the ratio of the volume of the pore space to the total volume of the sample [14]. A high reservoir porosity results in a high potential storage volume, which is desirable.
2. Hydraulic conductivity is expressed in [m s^{-1}], and represents the 'ease' with which groundwater can flow through a medium [14]. It is a crucial parameter of the aquifer, since it determines the maximum achievable flow-rate within the aquifer. A high horizontal hydraulic conductivity is preferred. The vertical hydraulic conductivity of the aquifer is preferably small, since it will limit heat loss mechanisms such as density driven flow and vertical heat conduction. Both mechanisms will be explained more thoroughly in the following subsection.
3. Thickness of an aquifer as a requirement is very straightforward. A sufficient thick aquifer has a larger storage potential and can achieve higher flow-rates.
4. The confining layer is the formation situated directly above the aquifer. It preferably has a minimal hydraulic conductivity and a large thickness, to limit the heat loss mechanism of thermal conduction.

B.2.2. Thermal recovery efficiency

The TRE of HT-ATES, which has been mentioned several times so far, is defined as the ratio between the energy reproduced from the aquifer, and the energy stored in the aquifer, with respect to the ambient subsurface temperature, and when injection and production of water are in balance [13]. It is captured in the following formula.

$$TRE = \frac{T_{ext} - T_{amb}}{T_{inj} - T_{amb}} \tag{B.1}$$

... where TRE is the recovery efficieny in [-], T_{inj} is the injection temperature in [°C], T_{amb} is the ambient groundwater temperature in [°C], T_{ext} is the extraction temperturte in [°C].

TRE is an important performance indicator of HT-ATES, and it is largely determined by the geological characteristics in subsection B.2.1. Several are responsible for energy losses during storage, and thus control the recovery efficiency and the consequent extraction temperatures:

1. Heat conduction results in losses in the vertical domain to the confining layer. It is visible near the boundaries of the confining layers and the aquifer, in figure B.1.
2. Density driven flow (or buoyancy flow) mainly results in heat loss in the horizontal domain. It is caused by a difference in density between the 'hot' injected water and the ambient groundwater [13, 21]. The lower density, injected water flows upwards causing tilting of the thermal front (the transition zone of injected - and ambient groundwater). More density driven flow results in greater tilting of the thermal front, meaning the 'surface' between the injected and ambient groundwater increases. A greater surface enhances the the heat loss mechanisms of free thermal convection and dispersion. Dispersion are spatial and temporal variations in velocity which causes single particles of solute to deviate from the ambient flow [14, 63]. The moment within the HT-ATES

recovery cycle (either injection, stable or production) also inlfuences the thermal front tilting, as is visualised in figure B.1.

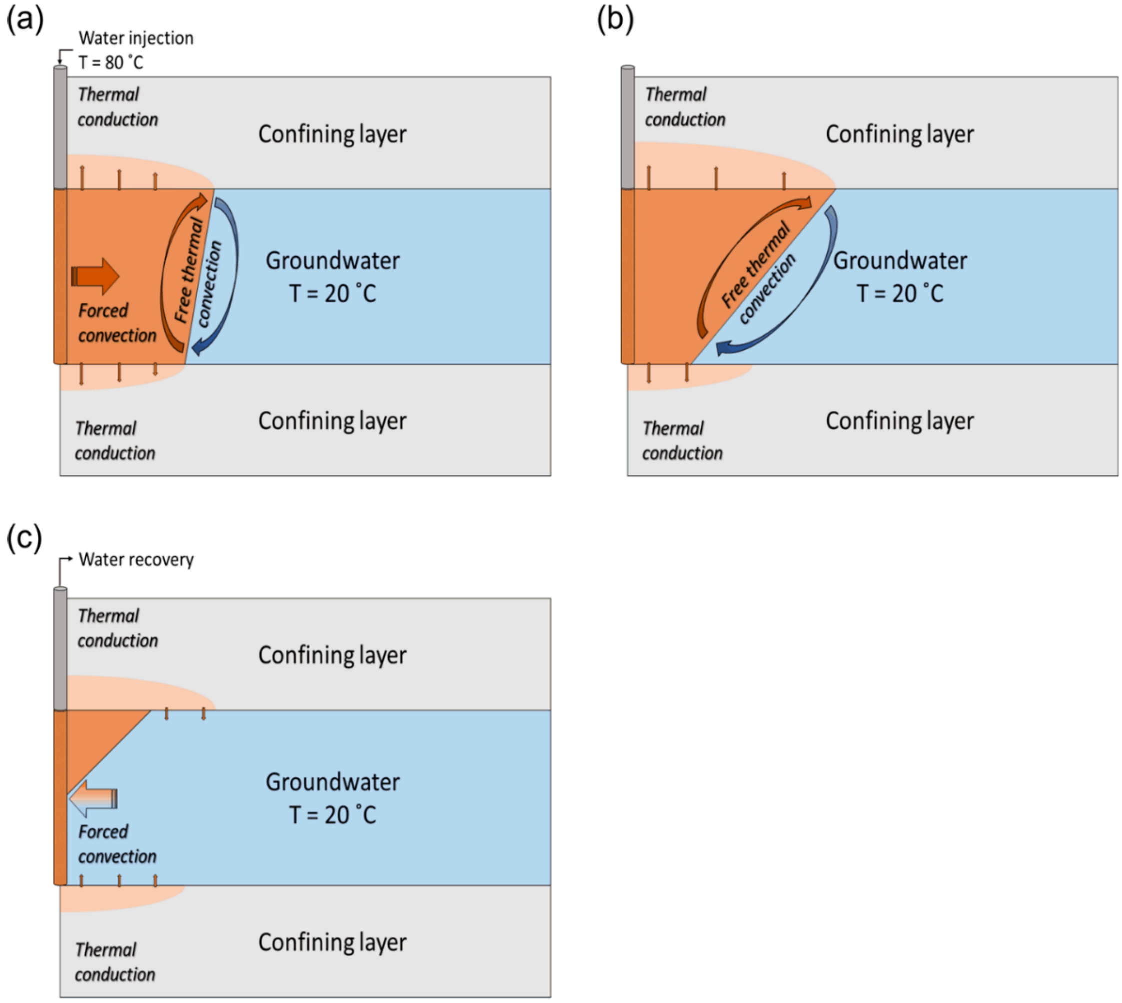

Figure B.1: Thermal front and tilting time [58]

3. Hydro-geological heterogeneity, especially in the horizontal direction, has a negative influence on the TRE of HT-ATES, yet it remains unaccounted for in design calculations on HT-ATES [49]. Examples of aquifer heterogeneity are *2* neighbouring sandstone formations with distinct porosity and conductivity, or a low permeable body partially penetrating the aquifer. Heterogeneity adds more uncertainty to the HT-ATES thermal energy output.

B.2.3. Thermal recovery efficiency optimization by decision maker

The heat loss mechanisms, and thus the efficiency of the system in general, are not solely dependant on aquifer geological characteristics, but also design choices by the DM can be of influence.

1. Although the percentage of heat lost by thermal conduction is independent on the injection temperature, it is highly unlikely [...] *'the recovery efficiency is insensitive to the injection temperature'* [46]. A higher injection temperature increases the density differences, which enhances the density driven flow.

2. Well placement plays an important role in recovery efficiency. In general, large systems will have an improved thermal efficiency, due to the more favorable surface to volume ratio [29, 49]. Not solely smart well placement, but also location of injection and production within the well influences the flow pattern, and thus affects the TRE. This phenomenon has been extensively researched for CO_2 injection (under the name plume propagation) [33]. However, no research has been found relating to HT-ATES recovery optimization.

3. Regarding the well placement, sufficient spacing should be kept between the hot - and cold wells, in order to limit thermal interference. However, there is a trade-off. The increasing demand for heat storage in densely populated area's requires efficient use of the subsurface. To maximise the total subsurface energy storage within a given space, the DM should allow for some interference. The systems lose on individual thermal efficiency [49]. This is not further considered during the research, since it focuses on individual cases.

4. Water salination is a possible solution to limit project density driven flow, and the mechanisms of dispersion and thermal convection. Through storage-water salination Van Lopik et al. is able to reduce the density difference and increase the TRE of a HT-ATES system in a high-permeability aquifer from *40*% to *69*%. HT-ATES can be applied in aquifers with higher hydraulic conductivity's, and at higher temperatures, due to the density difference compensation. This increases both the aquifer availability and storage capacity [58].

B.3. Potential formation in the Netherlands with favorable geology

Multiple aquifers in the Netherlands have characteristics that are in line with the insights from subsection B.2.1. Literature provides additional information. The Maassluis - , Breda - and Oosterhout formation host aquifers that are suitable for HT-ATES applications in the Netherlands [38]. Hacking et al. is more specific: the top part of the Maassluis formation, the formation of Oosterhout, and the Berg Sand formation (part of the Breda formation) show high potential. In addition, the Texel Greensand member must be considered as a HT-ATES reservoir [21].

Tholen et al. approaches the question of 'good' reservoir potential from a more economic perspective. Tholen et al. estimates the final levelised costs of energy, by using a Java workflow and incorporating uncertainties regarding the formation transmissivity (hydraulic conductivity) [53]. He finds that it is critical to constrain the maximum depth to 1500 meters, to allow for a chance at cost-effectiveness of your system [53]. This is due to the relatively large upfront CAPEX. The results of Tholen et al. confirm Pluymaekers et al., stating that shallow reservoirs in the Upper North Sea Group (see figure B.2) have a high potential for HT-ATES in the Netherlands. The deeper aquifers, such as the Delft Sandstone member, Rijnland group, and the Lower - and Middle North Sea Groups, show no potential [53]. In contrast to the key performance drivers and -barriers of HT-ATES (section 1.1.2), it seems that scientists are unconventionally unanimous on potential HT-ATES reservoirs in the Netherlands. Furthermore, it seems that when aquifers meet the requirements in *subsection B.2.1* to some extent, depth is decisive for suitability.

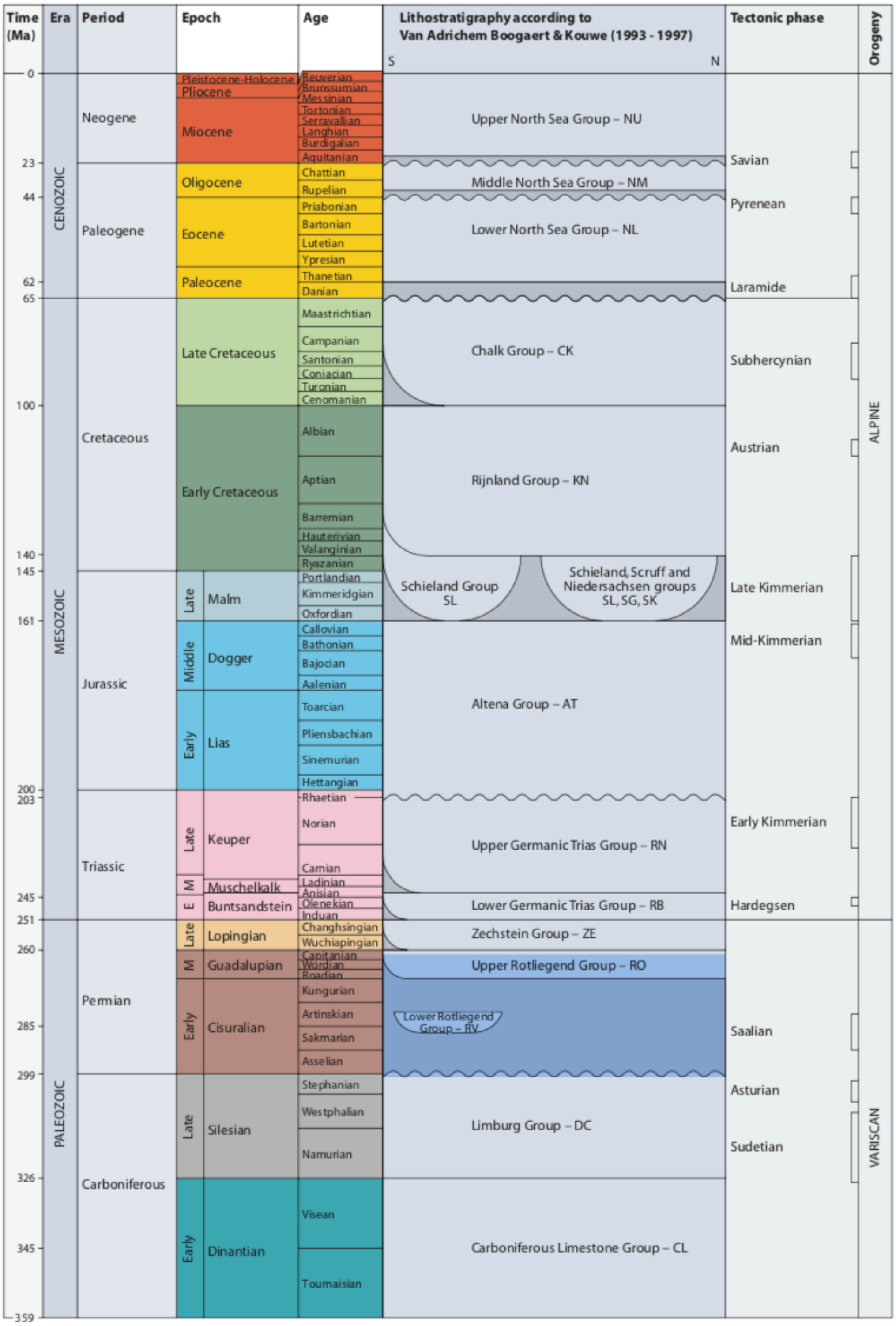

Figure B.2: The lithostratigraphy of the Netherlands [59]

B.4. District heating

B.4.1. General district heating

A heating network to connect to is one of the basal requirements for HT-ATES to succeed [40]. DH is an urban warm water network. It uses centralised generation facilities, and a network of pipelines that connect generation to consumption, by delivering warm water to the end-consumer. It is widely believed that DH has great prospects. [...] *'District heating is the most economical and rational means of heat supply for city inhabitants'* [67]. Werner et al. shares this opinion, by stating that DH has a strong potential of becoming a feasible option of heat supply in the future [64].

B.4.2. Drivers of district heating

The fundamental idea of DH has an sustainable purpose and origin: [...] *to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by adopting a heat distribution network of pipes as a local market place* [64]. However, looking at the primary energy share in currently active DH sytems, direct-use fossil fuel shares of up to *50%* can be noticed [64]. This is due to the fact the fundamental, sustainable idea of DH is not embraced in China and Russia, *2* important early-adopters of the DH technology [64].

The DH infrastructure is capable of integrating clean energy technologies into the building environment [27, 30]. A major driver therefore is the usage of renewable heat (GD) and commitment to cleaner energy technologies [27, 64]. Another driver of the DH technology is that it enables the possibility of centralised generation. Centralised generation has the scale-up advantage, an is therefor more efficient, and thus causes fewer pollution in the end [48]. The centralised generation could be provided by (more) sustainable options, such as the GD, industrial waste heat, or CHP plants. Additional (but of lesser significance) advantages of centralised generation are a reduction of poor quality fuel usage and fatal accidents, such as residential gas explosions.

B.4.3. Barriers of district heating and possible solutions

The greatest barrier of DH is the significant CAPEX and - organisation. Dense population, and thus a dense demand, can overcome the significant CAPEX [30, 39, 64]. Area's in which the demand is more sparse pose a barrier for implementation. With the increasing penetration of highly energy efficient (or even passive) buildings, creating a miscellaneous heat demand side, the negative economical effects of demand spreading are strengthened [50].

Innovation is key to adapt the current DH technologies to sparse demand and to cope with the relatively high CAPEX. Decreasing the laying depth of the pipes is a possible solution to overcome the barrier of relatively high CAPEX [35]. Moreover, enhanced costumer engagement and -interaction can provide assurance of a high connection rate (or wide utilization) in those area's where demand is sparse [35]. This connection rate is also important (but less crucial) in dense demand area's.

Significant heat losses during transport is another barrier for implementation, that is related to a sparse demand. Due to the variation in applied temperature levels, insulation standards, and heat distribution, these losses amount to anywhere between *5* and *35*% [6, 64]. Either decreasing demanded temperature, increasing insulation levels, or assurance of a higher connection rate, can decrease the heat losses.

Governmental policy is vital for improving the quality and availability of DH, by providing financial- and legislative incentive and sufficient research [30, 64]. Non-internalization of CO2-costs in fossil fuel prices currently is one of the barriers of the DH technology. It reduces DH competitiveness [6]. Carbon credits and fossil fuel taxes are examples of governmental policies that create a direct financial incentive for the end-consumer [64]. Furthermore, adequate pricing of waste-heat from industrial activities helps to stimulate DH [50, 64]

B.4.4. Future of district heating

It is expected that DH can contribute greatly to the energy transition by providing an alternative source for heating [19]. The DH networks of the future will have more functions than solely the purpose of heat transport [67]:

1. Seamless connection of additional (smaller) heat sources. This concept is known as co-generation.
2. To provide short-term storage of heat within the network.
3. To enable long-term storage solutions (such as HT-ATES).
4. To provide supervision and control, by precisely monitoring flow and temperature within the pipe. Examples are demand forecasting, and communication with producers to adjust heat production

B.5. Synergies of integration

B.5.1. Recapitulating the synergies

The advantages of integration, i.e. the synergies, of DH, GD, and HT-ATES have been elaborated on extensively. To recapitalise the findings from the literature study:

1. HT-ATES needs a heating network to connect in [40].
2. DH is driven by the usage of renewable heat (GD) and commitment to cleaner energy technologies [27, 64]
3. HT-ATES enables more efficient use of the GD, increasing the geothermal share in your DH network [40].

In retrospect, one could almost contemplate if mutual dependency is not mistaken for synergy.

B.5.2. Co-generation and the order of dispatch

Synergy or dependency is arbitrary. Either way, it is critical to elaborate on the co-generation of HT-ATES, and other optional heat suppliers within the heating network. n example of their internal connection Figure B.3 shows an example of their internal connection, which is similar case A (chapter 4). The interaction, as explained below, also serves as a foundation for the simulation model in chapter 2.

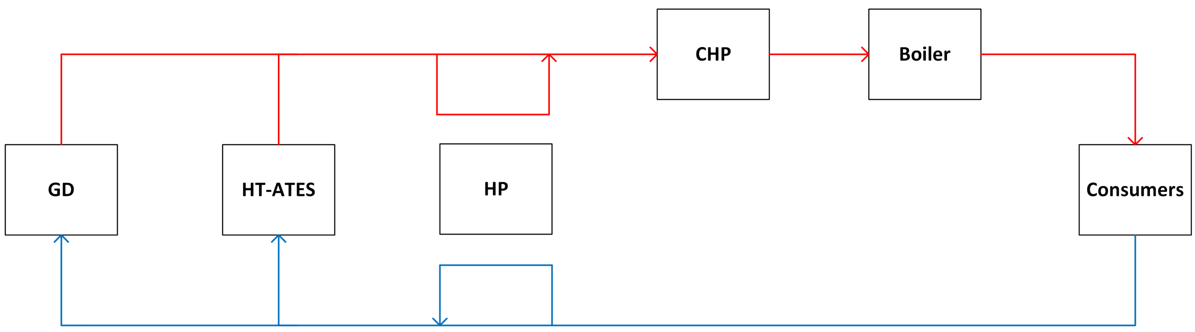

Figure B.3: Simplistic visualisation of DH network, including several energy suppliers

A DH network starts with its consumers. In this visualisation (fig B.3), and thus too in the simulation model logic, the consumers are represented by *1* large consumer. The consumer demands a variable quantity of heat, at time-specific supply - and return - temperatures, and thereby determines a time-specific required flow. The heat is provided by multiple sources, following a certain order of dispatch. The dispatch order, or order of merit, is the ranking and consequent deployment of available energy suppliers, and is visualised in figure B.4.

Energy suppliers are assigned to satisfy a part of the demand, based on ascending marginal costs of energy production. Together, the suppliers satisfy the total consumer demand, in the most efficient and economical way. In an ideal situation, the base load is provided by a sustainable source, with a large capacity and with low marginal costs. Examples are a GD or industrial waste heat. HT-ATES is second in the order of dispatch in the situation in figure B.3, behind the GD. Consequently, the remaining is satisfied by consecutively the HP, CHP, and boilers.

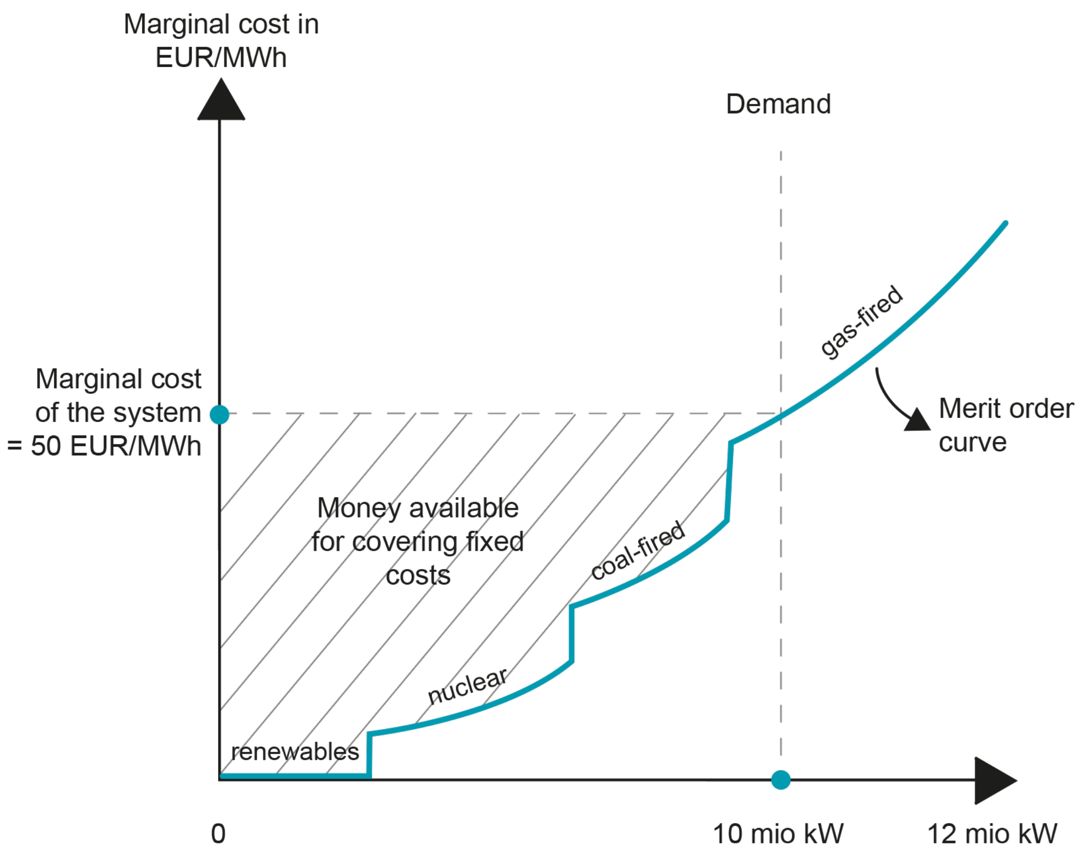

Figure B.4: Dispatch order in the electricity market [10]

C

Simulation model background

This appendix entails additional background information on the simulation model. It is a product of the *design phase*. The appendix entails the fundamental model logic, it states the critical assumptions, and explains how the model has been validated. Thereby the objective of this appendix is to increase understanding and appreciation of the simulation model.

C.1. Summary of fundamental model logic

A DH network connects consumers to producers, as is clarified in section B.4. All heat consumers and -sources, and the distribution network are included in the model. The consumers are represented by *1* large consumer, that has a time-specific heat demand [MW_{th}] at time-specific supply- and return temperatures [°C] . Thereby the consumer determines the network flow [kg s^{-1}], via equation C.1, which follows from basic thermodynamics.

$$V = \frac{Q * 1000}{(T_1 - T_2) * C} \tag{C.1}$$

... where V is the flow in [kg s^{-1}], Q the consumer heat demand in [MWh] T_1 the supply temperature in [°C], T_2 the return temperature in [°C], C the specific heat capacity of water in [J g^{-1} K^{-1}]

The heat is supplied by multiple sources, through a process of co-generation, following a certain order of dispatch. Both phenomena have been clarified in subsection B.5.2. After defining the distinct heat sources, and their connection and order of dispatch, the actual simulations can start, of which the most fundamental steps are included in the enumeration below:

1. The hourly demand data serves as input to the model, and determines the network flow via equation C.1. Following the predefined order of dispatch, the demand (flow) is satisfied, thereby determining the contribution of individual sources, including HT-ATES. Subsequently, the hourly bidirectional flows through both HT-ATES wells are determined from the HT-ATES contribution, adopting the similar equation C.2.

$$V_2 = \frac{Q_2 * 1000}{(T_R - T_L - T_2) * C} \tag{C.2}$$

... where V_2 is the flow in [kg s^{-1}] through the HT-ATES wells, Q_2 the HT-ATES heat production/contribution in [MW], T_R the (warm) reservoir temperature in [°C], T_L the temperature loss over the heat exchanger in [°C], T_2 the return temperature in [°C], C the specific heat capacity of water in [J g^{-1} K^{-1}]

2. The existing *SEAWATv4 Modflow* groundwater model is integrated with the simulation model in *python*. The groundwater model assumes axial symmetry and homogeneous horizontal aquifers and aquitards. It produces a grid with spaces to which individual properties are assigned such as, but not excluded to, temperature, density and hydraulic conductivity. The groundwater model is calculation-intensive, meaning that time is the largest constraint. Due to time limitations, the hourly well flows from the previous step are accumulated, and the model injects their sum (or produces in the case of a negative sum) every *5* days, after which the sum is reset to *0*. As a result the HT-ATES system either injects or produces every *5* days. It can not do both simultaneously. At the end of the simulation step, after injection or production, the individual grid space properties are determined, which prepares the model for the subsequent step of *5* days.

3. At some temperature, heat production from the HT-ATES is undesirable, because the electricity (costs) required for pumping exceed the thermal energy (value) of the water. This temperature is named the cut-off temperature, and it is a design parameter that is by the DM. The cut-off temperature is among the design parameters that are alternated during the parametric variation in subsection 2.2. If the cut-off temperature at some specified grid space within the reservoir is reached, the model eliminates all production and solely allows injection of heat for the subsequent simulation step (*5* days). After the new grid space temperatures are calculated, the model determines whether or not to restart heat production from the HT-ATES.

4. From heat production of the individual sources, yearly gas- and electricity consumption of the system can be determined. Both serve as a foundation for calculations on emissions and financial performance. The groundwater model registers the temperature of every grid space, after every simulation step, which are adopted to asses groundwater impact.

C.2. Critical assumptions

Several assumptions are done, to obtain an efficient and successful simulation model. This section elaborates on the critical assumptions.

C.2.1. Financial assumptions

Even though the perspective of mutation from subsection 2.1 greatly reduces the number of assumptions, some assumptions have to be done regarding the system financial performance. All financial assumptions from the enumeration below are a product of the value tree in figure C.1 and have been summarised in table C.1.

Assumption	*Value*
Electricity price	50 [€ MWh^{-1}]
Gas price	0.25 [€ MWh^{-1}]
Cost of drilling	1000 [€ $doublet^{-1}$ m^{-1}]
Investment costs	10 000 [€ h m^3]
Pump and well maintenance	[€ $doublet^{-1}$ $year^{-1}$]
Monitoring	30 000 [€ $doublet^{-1}$ $year^{-1}$]
Additional OPEX	4% of investment costs [€ $year^{-1}$]

Table C.1: Financial model assumptions

1. To estimate the costs regarding gas- and electricity consumption, firstly the DM has to estimate conversion efficiencies of the different sources, and secondly the DM has to attach a price to the consumption. Conversion efficiencies are case-specific. Gas - and electricity prices are volatile and greatly vary over a larger time span. The electricity price volatility is strengthened due to the uncertainty introduced by the impact of increasing

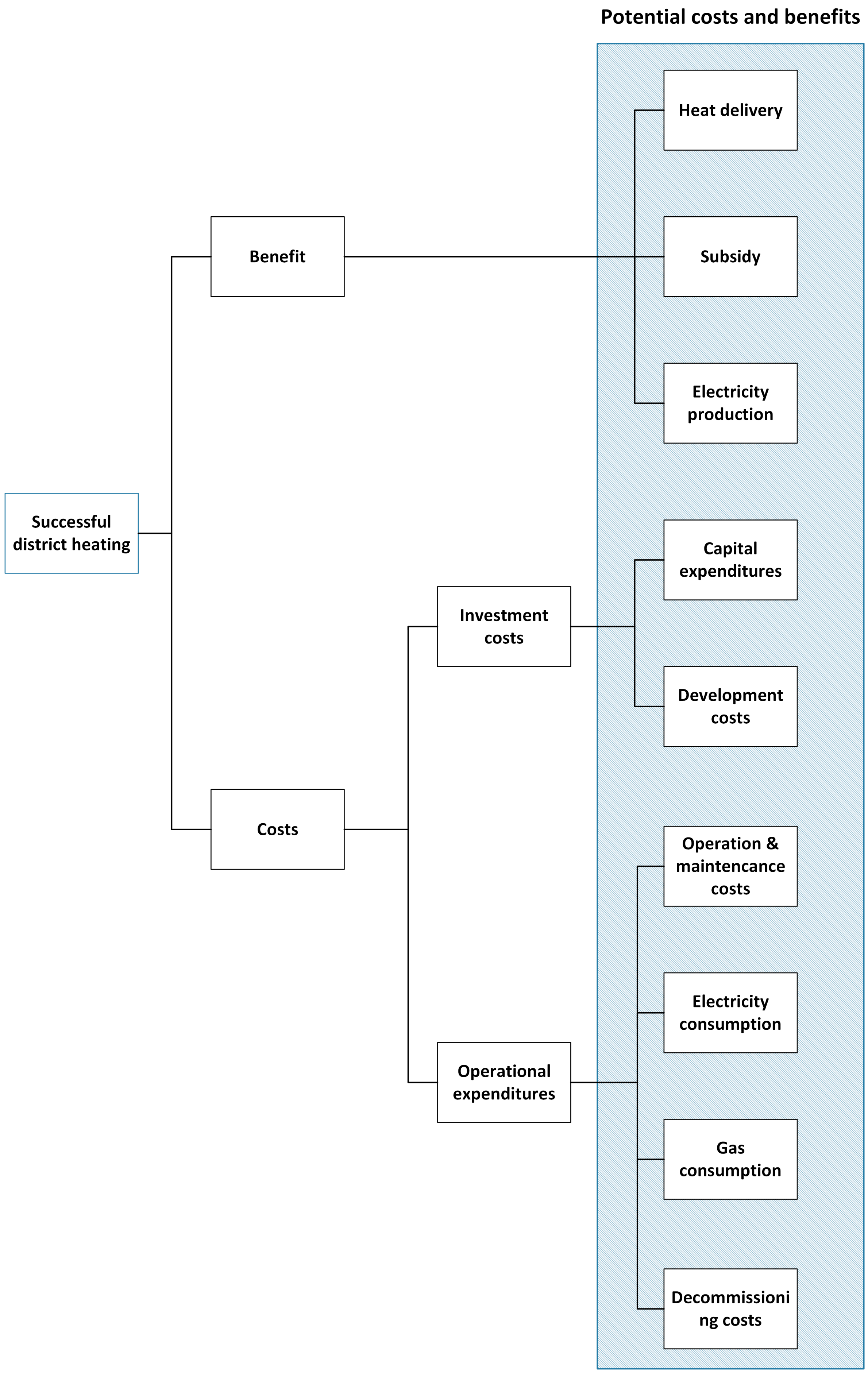

Figure C.1: Value tree of costs and benefits of a successful heating system renewable energy penetration [2]. In addition to the long-term pricing variation, there are price fluctuations during the day, because of both variable- demand and production. For the sake of simplicity it is opted to maintain constant pricing for the complete life-time, and to determine a price of 50 [€/MWh], conform indications in literature [6, 56]. The same principles hold for gas pricing. Although there will be less fluctuations on a daily or weekly basis, there exist great uncertainty of the gas price evolution in the long term. Based on literature, a constant gas price is estimated at *0,25* [€ m^{-3}] [41, 53].

2. It is obvious investment -, operation - and maintenance costs will increase upon implementation of HT-ATES. Bakema et al. [3] has empirically estimated key figures for these cost types looking at previous feasibility studies. Following the suggestion of Bakema et al., this model considers the investment costs to be a function of the HT-ATES system flow capacity, and to amount to 10 000 [€ m^{-3} h]. Additional assumptions concerning the yearly costs for operational and maintenance are mostly dependant on number of doublets. These values are also summarised in table C.1.

3. It is not necessary to estimate an average price of heat, due to the reason heat delivery does not change upon implementation of HT-ATES. However, the share of sustainable heat delivery changes upon implementation, which requires determination of the average subsidy of sustainable heat delivery.

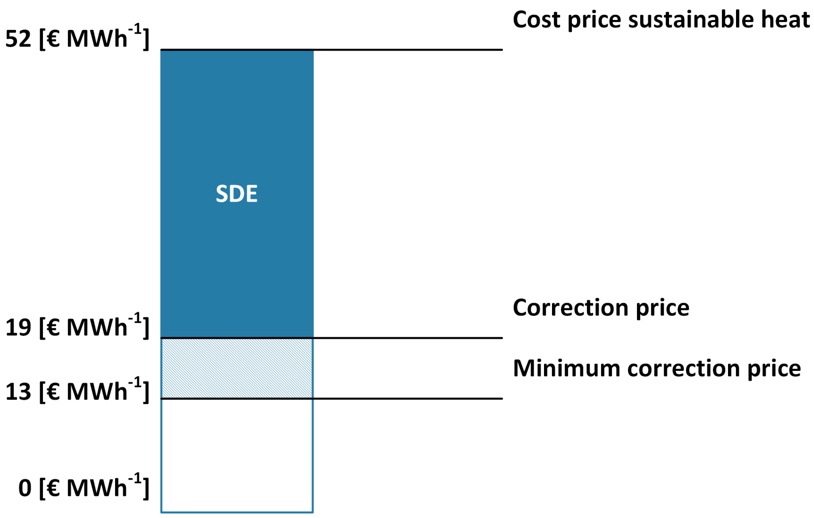

Figure C.2: Subsidy scheme in the Netherlands for shallow geothermal energy

In the Netherlands, sustainable heat subsidy is provided by the SDE+ regulation [57]. SDE+ aims to cover the difference between the cost price of sustainable heat and it's real market value. For this reason it is coupled to the gas price. The supplier of sustainable heat is guaranteed a certain heat price, indicated by the cost price of sustainable heat. The correction price presents the real market value of heat, and in the Netherlands it is coupled to the gas price. In the case of a high gas price, the market value of sustainable heat will improve, and therefor the correction price increases, decreasing the received subsidy. The SDE+ is an interaction between market and government, in the end guaranteeing the cost price of sustainable heat for the supplier. Figure C.2 shows the cost price, actual correction price, and minimum correction price for *2019* [57]. These prices are determined by the government and adopted by the model. They are maintained throughout the project life-time, and the resulting subsidy amounts to *33* [€/MWh] for shallow geothermal energy production.

C.2.2. Additional assumptions

This section model entails assumptions that are not directly related to the system financial performance. They are enumerated below:

1. Gas- and electricity consumption are translated into emissions, by estimating their carbon emission factors in [kg MWh^{-1}]. It is decided to solely consider CO_2 as carbon emission, since it takes a *85*% share of the total emissions in the Netherlands [22]. Literature states that natural gas consumption has a CO_2 emission factor of *200* [kg MWh^{-1}] [61]. It demands more thinking to find an emission factor for electricity consumption. The Dutch cabinet aims at a *61*% renewable share in the power sector by *2030* [22]. The remaining share is supplied by gas and other sources. By maintaining this ratio, and assuming that the renewable electricity is free of emissions, the CO_2 emission factor of electricity is estimated to be *80* [kg MWh^{-1}].

2. The model follows the law of Darcy to determine required pumping pressures and consequent electricity consumption.

$$Q = -\frac{k \cdot A \cdot \Delta p}{\mu \cdot L} \tag{C.3}$$

   .. where Q is the flow in [m^3 s^{-1}], k the intrinsic permeability of the aquifer in [m^2], A the cross-sectional area of the aquifer in [m^2], p the pressure in [Pa], μ the fluid viscosity in [Pa s], L the distance within the aquifer over which the pressure difference occurs[m]. Hydraulic conductivity [m d^{-1}] is a product of the aquifer permeability and fluid viscosity.

   If the hydraulic conductivity of the aquifer halves, the required pumping pressures double, to achieve the same flow rate. Consequently, the electricity costs for pumping double.

3. The adopted groundwater model divides the subsurface into grid spaces. It adopts a geological configuration that is homogeneous and has axial geometry. As a result, the reservoir is a perfect symmetrical cylinder. A section of the subsurface with a length equal to the radius of the reservoir, and a width of *1* grid space, enables to understand the entire subsurface heat behaviour. This makes the groundwater model more efficient.

4. There exists uncertainty regarding how the yearly heat demand will evolve over the system life time, in the network under consideration. It is likely that more consumers will be connected to the network. On the contrary, as buildings become more energy efficient [50], the average heat demand per consumer is expected to decrease. The model assumes these trends to cancel each other out, resulting in constant year heat demand curve throughout the project life-time

5. The model assumes constant heat losses during distribution, because model does not consider network properties such as, distance, pipe diameter, type of flow etc. This has been emphasised already in subsection 2.1.

6. The sustainable base source and the HT-ATES are connected to each other and to the network via a heat exchanger. In addition to heat losses in the grid, also heat losses at the heat exchanger have to be considered. The model assumes a constant temperature loss over the heat exchanger, as is indicated by T_L in equation C.2. Conversion efficiencies of the remaining heat sources depend on source type and -specification, and have been specified per case.

7. The simulation model does not consider risk of failure of components, or down-time related to (un)planned maintenance. As a results the availability of heat is *100*%: in every scenario all consumer heat demand is always satisfied.

C.3. Validation and testing the model

The number of steps within the simulation model suggest that it is vulnerable for faults and errors. During development several checks have been build-in to validate the model accuracy. The checks are enumerated below:

1. At the end of simulations the model checks if the sum of heat demand equals the sum of heat production from the different sources.
2. At the end of simulations the model checks for irregularities in both flow and flow temperatures: it checks if conservation of energy and conservation of mass are secured. It checks if negative flows do not occur. Regarding the bidirectional flows to/from the HT-ATES reservoir, the model assures that there is no simultaneous injection and production.
3. During several test-simulations, heat sources were changed in size or turned off, and it was checked if the model reacted appropriately.
4. Several test-simulations were performed with extraordinary demand input. Consequently, it was checked if the model crashed for logical reasons. If the model didn't crash, it was checked if the output of quantitative metrics changed correspondingly.

D

Multi-criteria decision analysis background

This appendix is based on a literature study on decision making in general, and the MCDA in specific. It also is a product of *design phase* and describes the steps ought to be taken towards a comprehensive MCDA. Thereby, it provides the foundation of chapter 3, in which a MCDM is developed. The appendix elaborates on criteria selection, - scoring, and weighting. Furthermore, it discusses methods for exposing uncertainty in all of these stages.

D.1. Stages of the multi-criteria decision method

D.1.1. Identifying objectives

According to figure 3.2, a rational decision starts with stating clear objectives. The objectives should be specific and realistic [12]. Moreover, the objectives can be conflicting and the objective hierarchy is not unique [26]. The non-uniqueness attribute means there does not exist *1* correct set of objectives for a specific problem. An illustrative example (figure D.1) of conflicting objectives in a successful surgery was adopted from Keeney and Raiffa [26]. The doctor performing surgery on any patient has the the overall objective to *'do the best for the patient'*. This objective can be subdivided into the objectives to *'avoid death'* and *'minimise treatment costs'*.

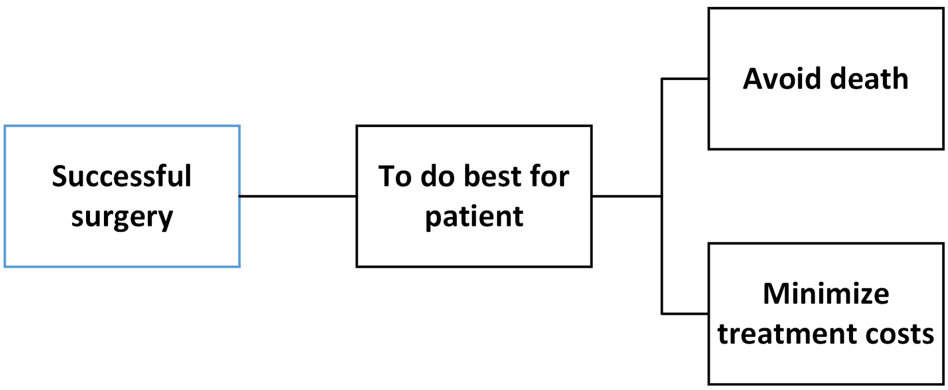

Figure D.1: Simplistic objective hierarchy of successful surgery [26]

D.1.2. Identifying scenario's and stakeholders

Subsequently, the scenario's under consideration have to be defined. It can be helpful to consider the acting stakeholders simultaneously, as it will force the DM to overthink if the set of objectives is comprehensive.

D.1.3. Specify criteria set

Criteria are attached to the objective hierarchy, to obtain a value tree. Multiple sources are unanimous on requirements regarding a set of criteria [12, 26]:

1. *Non-redundancy* in a criteria list means that double counting of any effects should be avoided.
2. *Completeness* in a criteria list refers to the ability to capture the full utility of every scenario, and thus adequacy in indicating the degree to which an scenario meets its total objective.
3. *Operability* is a requirement to ease the journey of the DM. It means that individual criteria should be meaningful and understandable to the DM. Moreover, operability refers to the criteria being measurable, and useful to the purpose of the study.
4. *Decomposability* in a criteria list refers to the organisation in a value tree. This will enable the DM to segment into mutual independent sub-lists of smaller dimensionality, which will allow for easier evaluation and comparison.
5. *Minimum size* of the criteria list refers to the fact that it is desirable to keep the number of criteria as small as possible, without giving in on *completeness* of the criteria set.

At this stage the DM has determined the limits of the evaluation space, which can be summarised with the evaluation matrix (equation D.1). In the later stages this matrix is to be filled, step by step.

$$E = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{D.1}$$

... where x_{ij} is to be produced by the i-th criteria and the j-th scenario, m is the number of criteria, and n the number of scenario's.

D.1.4. Evaluation of performance and method of scoring

Criteria performance can be evaluated both quantitatively and qualitatively. The result is a performance matrix, which can obtain different units per criteria.

$$P = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{mn} \end{bmatrix} \tag{D.2}$$

... where x_{ij} is the performance of the i-th criteria and the j-th scenario, m is the number of criteria, and n the number of scenario's.

Scoring is the translation of performance measures that have different units per criteria, onto a common scale [52], to allow for comparison. A usual scale will range from *1* to *10*. In addition, scores represent the DM appreciation of a certain change in performance on a criteria, such that an equal change on the scoring scale is equally preferred [52]. For example, a change from *2* to *3* is equally appreciated as from *4* to *5*. The first step of scoring performance on individual criteria is to set up an interval scale. There are *2* methods for establishing the interval scale: global scaling and local scaling. Global scaling exceeds the limits of the evaluation space and assigns scores of *1* and *10* to respectively the worst and the best levels of performance [...] *'that are likely to be encountered in a decision problem of the general type currently being addressed'* [12], but that are not necessarily among the scenario's. Local scaling assigns extreme scores to the worst and the best levels of performance among the scenario's under evaluation, and thus does never exceed the limits of the evaluation space. The advantage of global scaling is that it is relatively easy to add scenario's during a later phase. A disadvantage is that global scaling requires additional judgements to determine the extremes.

There exist *3* widely adopted methods of scoring criteria performance [12]:

1. *Value functions* represent the score along the range of values of a specific criteria. Value functions adopt the same principles as commodity trading. When there exist *2* commodities, X and Y, the trader has to decide on the value trade-off, i.e. what amount of X he or she is prepared to lose, to gain *1* Y [26]. Likewise the DM has to decide on the relationship between the performance and score: firstly whether score and performance are positively correlated, and secondly whether the relationship between score and performance is linear [52]. To give a brief example for additional clarification: the correlation between amount of profit and score is positively aligned. However, with the first scenario being already very profitable, and another scenario operating around the break-even mark, does an equal increase in profit result in an equal gain in score? These are questions the that demand answering from the DM.

2. *Direct rating* is the most intuitive and efficient method of scoring available. Direct rating can be applied when there exists a shortage of measurable data [12], time and/or resources. On the downside direct rating is vulnerable for inconsistency, because sometimes the direct rating judgements have to be performed by different experts, due to the distinct nature of criteria. Moreover, direct rating is susceptible for expert preference: [...] *'those with the most appropriate expertise to make the judgements may also have a stake in the outcome of the decision'* [12].

3. *Pair-wise comparison* establishes scores through comparison. There exist many variations such as Analytic Hierarchy Process (AHP) or MACBETH. These methods are regarded as effective, but on the downside they are more calculation intensive and therefor also more time-consuming [12].

The deliverable of the scoring process is an score matrix (equation D.4), which is equal in size to the evaluation matrix and the performance matrix, and in which scores are assigned for every criteria and scenario.

$$S = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{mn} \end{bmatrix} \tag{D.3}$$

... where x_{ij} is the score of the i-th criteria and the j-th scenario, m is the number of criteria, and n the number of scenarios..

D.1.5. Criteria weighting

Once all criteria have [...] *'their internal impact reclassified to a common scale'* [62], the consequent step is to determine each criteria's relative importance for the decision problem. The relative importance is indicated by assigning criteria weights [16, 62]. The criteria weight distribution can vary for different stakeholders.

There exist many accepted methods for assigning criteria weights. However, most of them rely on *1* of the following basic principles:

1. *Equal weights method* requires minimal input from the DM. Although the method appears very simplistic, the results can be nearly as good as optimal weighting methods [9].

2. In *Rank-based methods* the DM establishes an importance ranking of the criteria, which determines the weighting. Rank-based weighting has been criticised, because it does not consider relative importance among criteria [62].

3. *Rate-based methods* are similar to rank-order methods, with the only difference being that relative importance of the criteria is taken into consideration. Similar to direct-rating for scoring, as can be read in in subsection D.1.4, it is susceptible for expert preferences.

4. With *pair-wise comparison* the relative importance of criteria is established by comparison. Participants are asked to judge which of the criteria is more crucial, and to what extent [62]. Methods like the AHP also adopt pair-wise comparison for weight distribution. [...] *'It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations.'* [42].

The deliverable is an weight matrix (equation D.4), in which weights are assigned for every stakeholder and scenario.

$$W = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \tag{D.4}$$

... where x_i is the assigned weight for the i-th criteria, and m is the number of criteria. The weight matrix is different for each stakeholder group.

A relatively simple multiplication of the score- and weight matrices can provide aggregated scores and consequent ranking of scenarios. In this case the scores and weights are treated as being deterministic [24]. However, the subjective nature of the steps, working towards an scenario ranking, generates uncertainty that needs to be taken into consideration. The many assumptions demand additional evaluation.

D.1.6. Uncertainty in multi-criteria decision method

In decision-making, the decided ranking occurs with some unknown probability, and thus the DM faces uncertainty [28]. A successful SA is capable of quantifying this uncertainty. It makes the [...] *'sensitivity analysis essential and intrinsic to MCDA'* [12].

However, it appears to be that the many of the proposed methods of SA have significant limitations, because there is [...] *'absence of a procedure to conduct the sensitivity analysis'* [25]. Frequently occurring limitations of proposed methods for SA are:

1. The SA is performed upon completion of the decision process [24], whereas it should be integrated in the decision analysis process, such that [...] *'it is embedded into a continuous cycle process during which at each stage of the decision process the analysis can go back to previous stages to check, add, or modify parts of the problem'* [54].
2. Varying *1* parameter at a time, also know as the single attribute approach, as is adopted in the research of Barron and Schmidt [4], can be misleading because it ignores the possibility an scenario ranking is insensitive to variation of individual parameters, but sensitive for their simultaneous variation [7, 23, 24].
3. The focus is on uncertainty in criteria weights, whereas there also exist uncertainty in performance and consequent score [24, 54]

For these reasons, an approach is suggested, which adopts a Monte Carlo iteration. Through stochastic variation of both weights and scores the iteration indicates the sensitivity to variations in ranking, and thereby quantifies the reliability of the MCDA. The approach can be better explained by the following equation.

$$S(A_j) = \sum_{i=1}^{m} W_i V_i(x_{ij}) \tag{D.5}$$

... where $S(A_j)$ is aggregated score of the j-th scenario, W_i the weight of the i-th criteria, V_i the value function of the i-criteria for translation into score, x_{ij} the performance of the j-th scenario on the i-th criteria, and m the total number of criteria.

Equation D.5 is known as the linear additive model, which summarises all stages of the MCDA, from performance evaluation to criteria weighting, in *1* compact formula. Due to the subjective nature of every stage, the MCDA is vulnerable to the preference of a DM in every stage, and thus uncertainty should be included in every stage [8]. Hyde et al. suggests to use uniform distributions for criteria weighting and performance values instead of deterministic values, thereby obtaining the probability a certain scenario occupies a certain rank, and thus quantifying the uncertainties in the MCDM [24]. An alternative for uniformal distributions would be a stochastic SA with normal distributions for criteria scores and weights, specified by an average value and standard deviation [32]. Ghanmi suggests stochastic random sampling of the criteria weights, as an alternative for using weight distributions [17].

To summarise the subsection, there exist multiple alternatives for an SA. Regardless of chosen method, it is crucial that the method adopts simultaneous multi-attribute variation of both weights and performance values. Furthermore, it is important that the method is used before completion of the decision process. These findings were taken into consideration when choosing the SA of this research.

E

Additional case-specific results

E.1. Case A: shallow geothermal heat for educational institute

This section entails additional tables and figures of case A.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.25	0.45	0.25	0.05
No HT-ATES	0.22	0.29	0.27	0.22
Low aquifer hydraulic conductivity	0	0	0	1
High aquifer hydraulic conductivity	0.42	0.41	0.16	0.01
Shallow aquifer	0.04	0.19	0.39	0.38
Deep aquifer	0.99	0.01	0	0
Thin aquifer	0	0.06	0.25	0.69
Thick aquifer	0.29	0.45	0.24	0.02
Low seasonal variation	0	0.06	0.27	0.67
High seasonal variation	0.26	0.45	0.25	0.04
Short life time	0.97	0.03	0	0
Extended life time	0.05	0.25	0.45	0.25

Table E.1: Probability of scenario rank, case A, consumer persp.

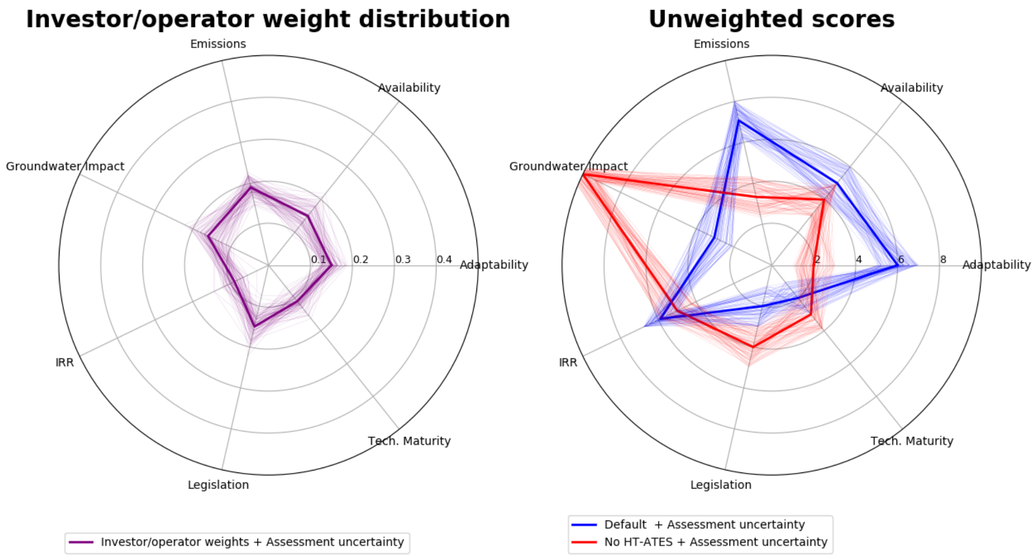

Figure E.1: Weight distribution and unweighted scores, case A, investor/operator persp.

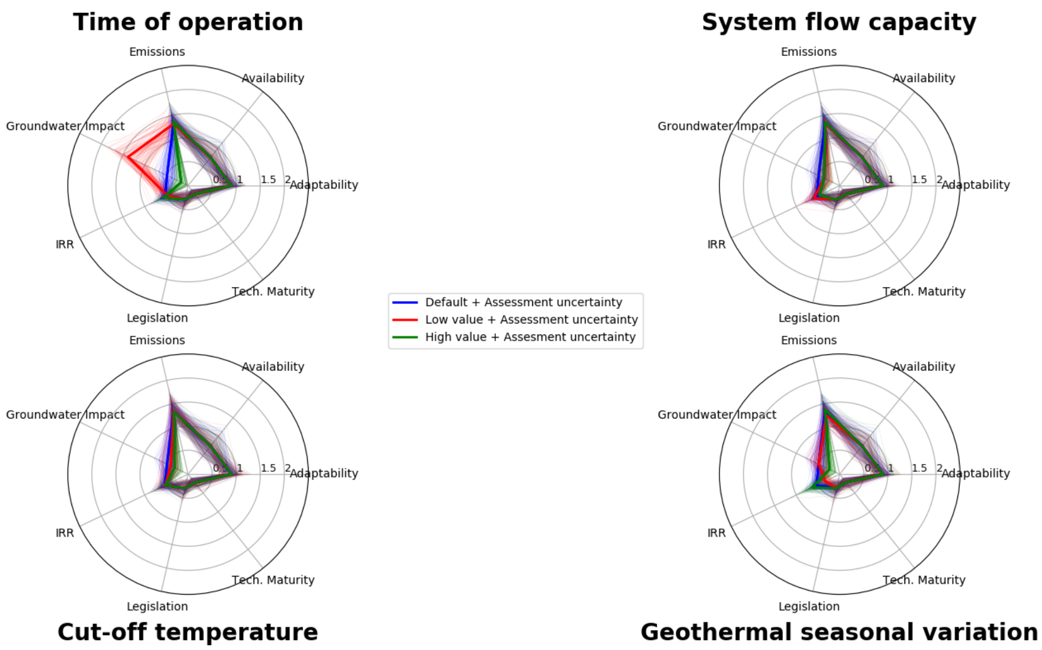

Figure E.2: Parametric variation of design, case A, investor/operator persp.

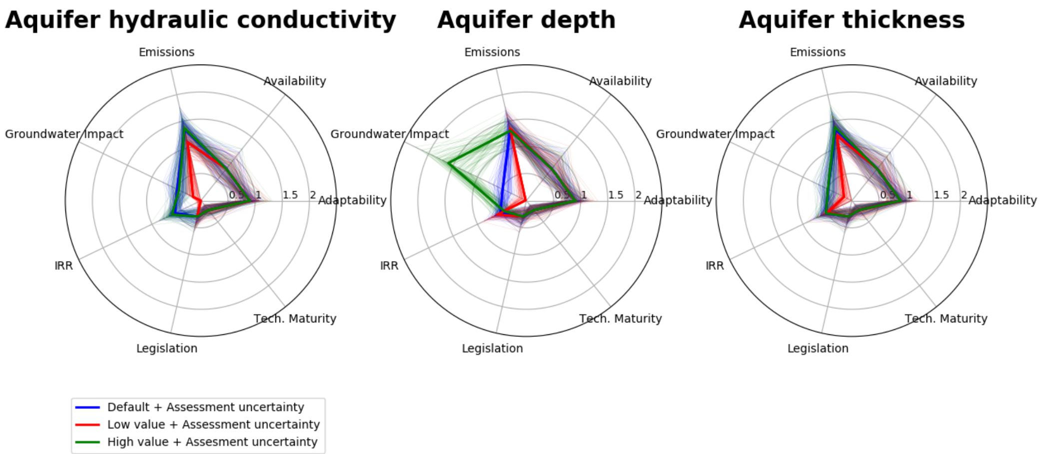

Figure E.3: Geological parametric variation, case A, investor/operator persp.

E.2. Case B: industrial waste heat for residential heating network

This section entails additional tables and figures of case B.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.26	0.38	0.31	0.05
No HT-ATES	0	0.04	0.14	0.82
Low aquifer hydraulic conductivity	0	0.02	0.12	0.86
High aquifer hydraulic conductivity	0.20	0.39	0.33	0.08
Shallow aquifer	0	0.03	0.20	0.77
Deep aquifer	0.93	0.07	0	0
Thin aquifer	0.20	0.40	0.33	0.07
Thick aquifer	0.27	0.38	0.30	0.05
Low demand scaled	0.37	0.39	0.20	0.04
High demand scaled	0.12	0.35	0.38	0.15
Short life time	0.95	0.05	0	0
Extended life time	0	0.05	0.22	0.73
Low system flow capacity	0.08	0.29	0.46	0.17
High system flow capacity	0.13	0.36	0.40	0.11

Table E.2: Probability of scenario rank, case B, consumer persp.

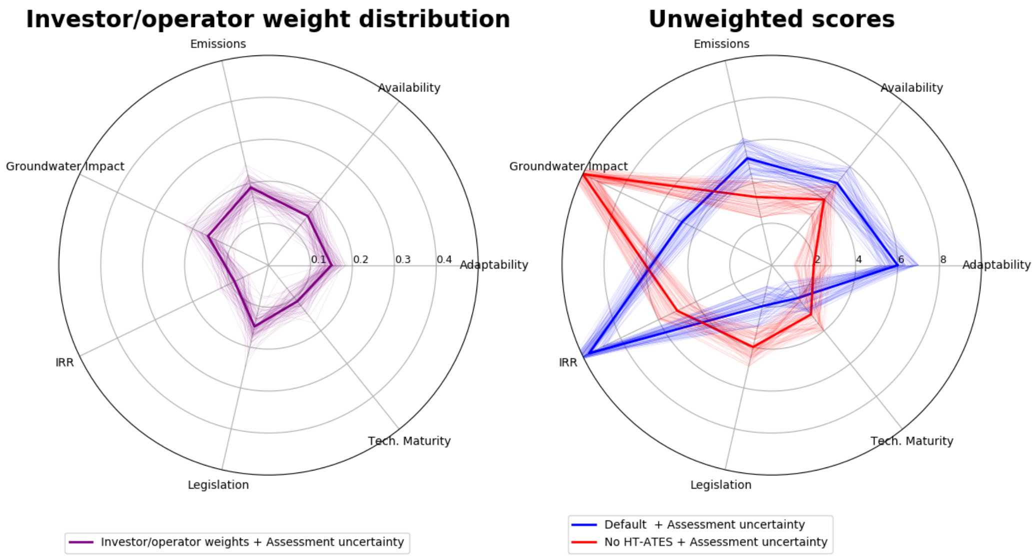

Figure E.4: Weight distribution and unweighted scores, case B, investor/operator persp.

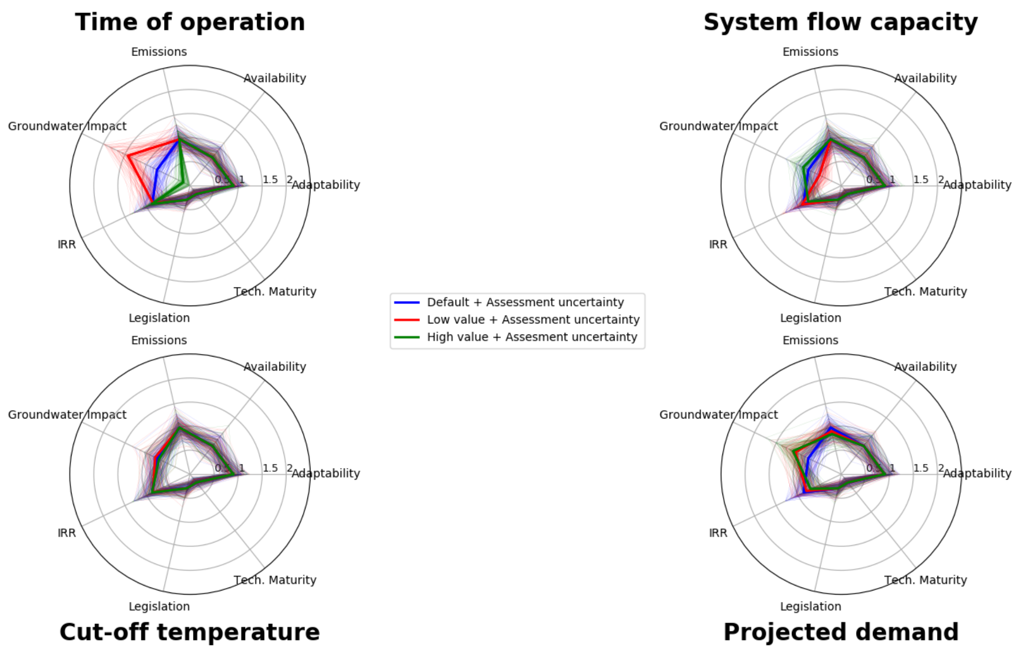

Figure E.5: Parametric variation of design, case B, investor/operator persp.

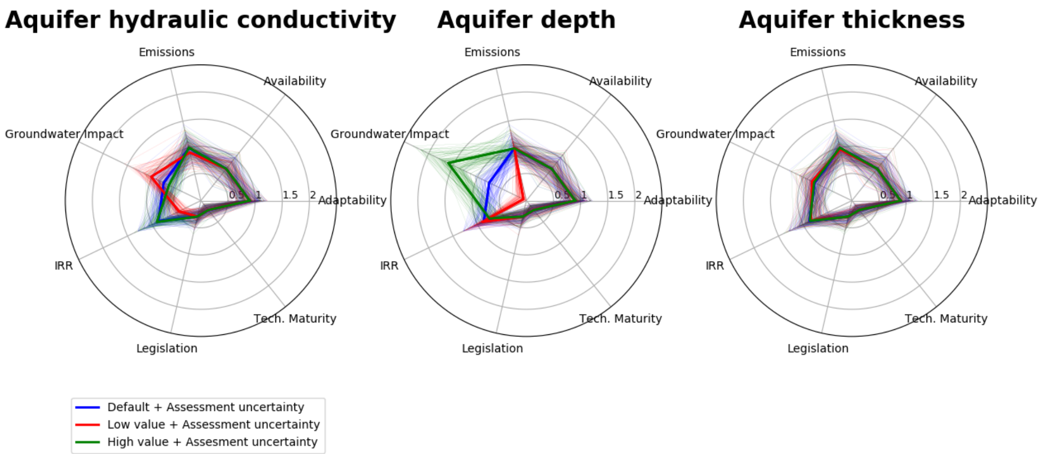

Figure E.6: Geological parametric variation, case B, investor/operator persp.

E.3. Case C: shallow geothermal for expanding greenhouse

This section entails additional tables and figures of case C.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.16	0.46	0.34	0.04
No HT-ATES	0	0.01	0.12	0.87
Low aquifer hydraulic conductivity	0	0	0	1
High aquifer hydraulic conductivity	0.55	0.35	0.10	0
Shallow aquifer	0.01	0.05	0.30	0.64
Deep aquifer	0.92	0.07	0.01	0
Thin aquifer	0.03	0.24	0.55	0.18
Thick aquifer	0.30	0.44	0.24	0.02
Small area	0.03	0.24	0.53	0.20
Large area	0.36	0.46	0.17	0.01
Short life time	0.94	0.06	0	0
Extended life time	0	0.02	0.19	0.79
Low cut-off temperature	0.29	0.47	0.23	0.01
High cut-off temperature	0.05	0.28	0.52	0.15

Table E.3: Probability of scenario rank, case C, investor/operator persp.

Performance	*Best*	*Good*	*Bad*	*Worst*
Scenario	*Quartile 1*	*Quartile 2*	*Quartile 3*	*Quartile 4*
Default	0.21	0.43	0.31	0.05
No HT-ATES	0	0.01	0.08	0.91
Low aquifer hydraulic conductivity	0	0	0	1
High aquifer hydraulic conductivity	0.76	0.21	0.03	0
Shallow aquifer	0.05	0.16	0.45	0.34
Deep aquifer	0.62	0.26	0.11	0.01
Thin aquifer	0.07	0.29	0.46	0.18
Thick aquifer	0.23	0.42	0.31	0.04
Small area	0.02	0.17	0.44	0.37
Large area	0.45	0.41	0.13	0.01
Short life time	0.88	0.11	0.01	0
Extended life time	0.01	0.3	0.25	0.71
Low cut-off temperature	0.27	0.43	0.26	0.04
High cut-off temperature	0.06	0.27	0.47	0.20

Table E.4: Probability of scenario rank, case C, consumer persp.

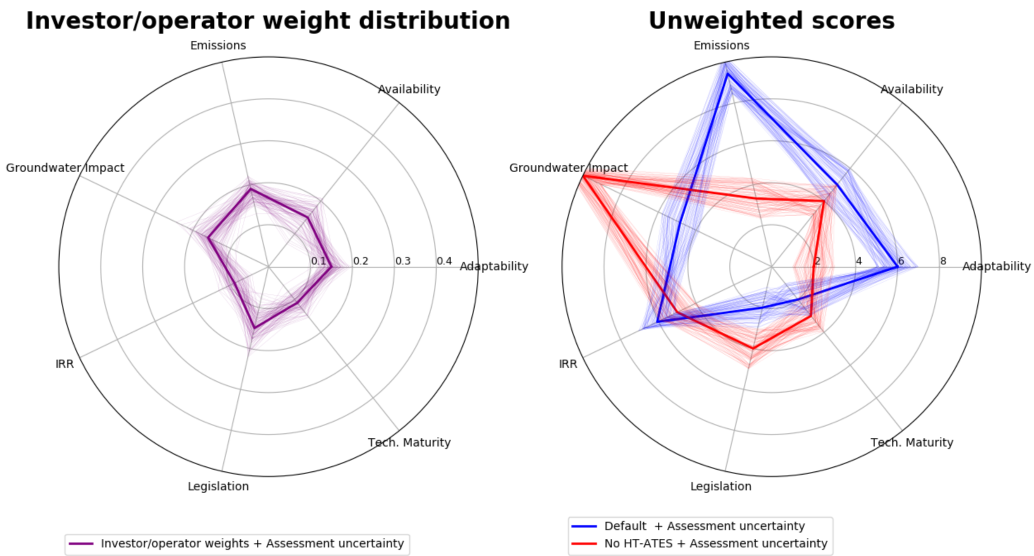

Figure E.7: Weight distribution and unweighted scores, case C, investor/operator persp.

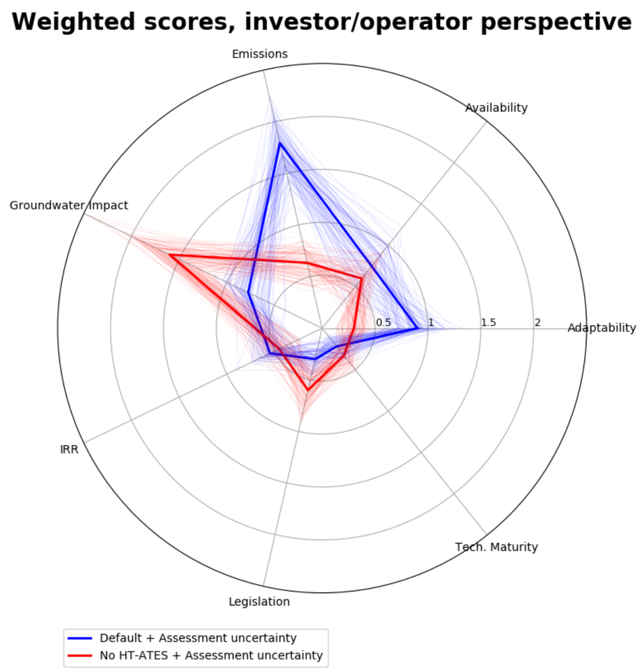

Figure E.8: Weighted scores, case C, investor/operator persp.

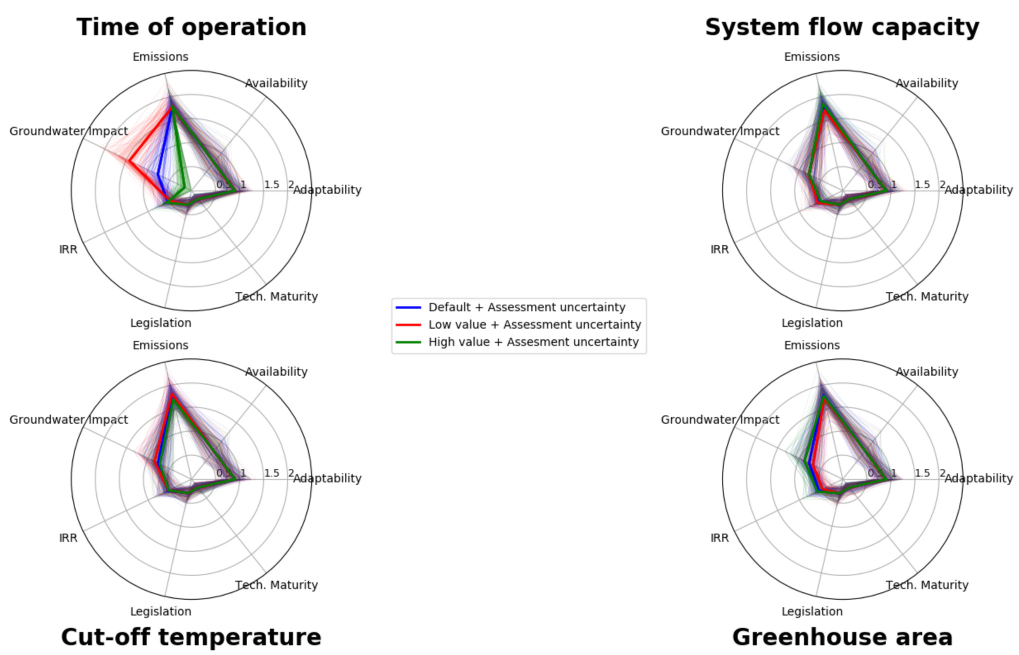

Figure E.9: Parametric variation of design, case C, investor/operator persp.

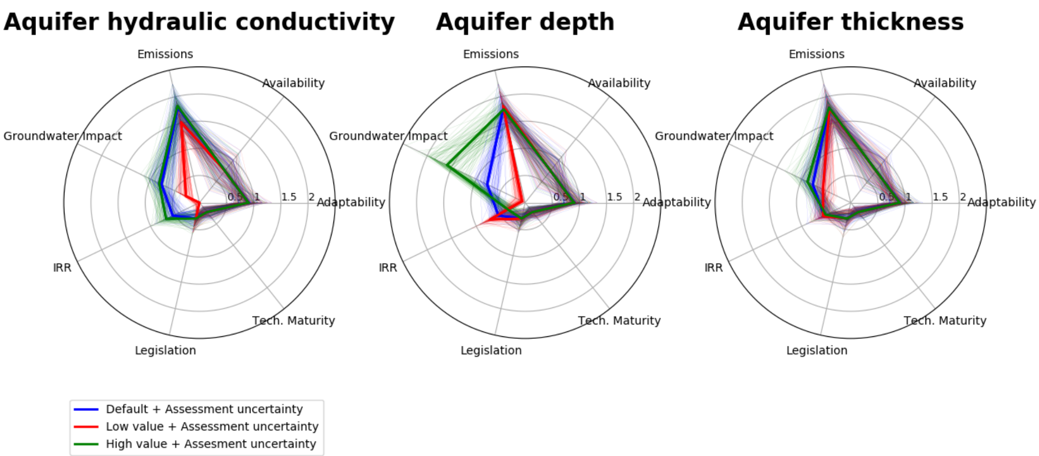

Figure E.10: Geological parametric variation, case C, investor/operator persp.