MSc Sustainable Development

Thesis

Costs of Deep Geothermal Energy in the Netherlands

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Abstract

The costs of deep geothermal energy in the Netherlands are analysed. A database is constructed using data from the existing projects in the Netherlands and nearby countries, producing an equation for costs of drilling. A model is developed in Java, building on prior models developed by TNO, using the methodology for calculating SDE+ subsidies by ECN. This model primarily calculates the Unit Technical Costs of deep geothermal projects. This allows for rapid assessment of the economic attractiveness of locations and quick comparison to the SDE+ base rates for possible subsidy applications.

Foreword

Much of this research would not have been possible without the internships I followed at ECN and TNO. The following paragraphs give a short description of how my internships came about and are also for readers who are not acquainted with these organisations.

ECN

ECN is the Energy Research centre of the Netherlands, located in Petten, with ancillary locations in Amsterdam, Brussels, and Beijing. It was developed around the small experimental nuclear reactor at Petten to research new energy technologies. As such, it performs cutting edge research on solar, wind, biomass and energy efficiency technologies. In addition to these more laboratory-based fields of research, there is a Policy Studies unit which does primarily research from a policy/economic point of view and from the point of view of social sciences, usually through building models and scenarios and writing papers and advices. Into this unit I was invited to research geothermal energy as an intern. As geothermal energy is not at the heart of research at ECN, knowledge of this energy technology is limited and ECN does not have much on offer today for development of geothermal energy. My supervisor was Paul Lako, a senior researcher in the Policy Studies department, who had worked on advice for the SDE+ subsidy in 2011.

TNO

TNO is the Netherlands Organisation for Applied Scientific Research**.** It performs a frontline research role in many areas, primarily for the Dutch government, which provides significant funding. One of TNO’s responsibilities, through its DINO and NLOG sectors, is collating the known information of seismic and core data resulting from oil and gas research. With the expertise that came with this responsibility, it was natural for TNO to also start performing research into geothermal energy, as there are many similarities between the two. Jan-Diederik van Wees is a senior researcher in the Sustainable Geo-Energy unit, and also works at the University of Utrecht in the Geosciences department. After interviewing him in the course of my internship at ECN, it became clear that collaboration between ECN and TNO would be very useful, with my internship as its fulcrum. TNO possesses great knowledge of the subsurface, and ECN Policy Studies has important expertise from the economic and policy side. It was thus decided that I would also be a guest intern at TNO alongside my internship at ECN.

Dedication

This one is for my dad, Dirk Jan Straathof.

I wish you were here to read it.

Acknowledgements

This thesis was written during an immensely difficult time for me, and I'm incredibly grateful for all the help and support I received during this time. In particular, I want to thank the many colleagues at ECN and TNO who made working there so interesting and so much fun. Also, I strongly appreciate all the people who graciously allowed me to interview them, who answered my queries and brought me in contact with the required expertise. However, certain people deserve special recognition:

Robert, for being my supervisor and getting this project started, and helping me out in times of trouble.

Paul, also for being my supervisor, and for the many discussions, debates and of course the Lange Afstand Loop!

Jan-Diederik, who was also my supervisor, for accepting me at TNO and allowing me to build on the tremendous work they have already accomplished.

Maarten, for helping me significantly with Java, and with my badge at TNO!

Marloes, my fellow intern, with whom I learned to write in Java together.

And of course I want to thank my family and friends, for everything.

Last but not least, I can't forget Yvonne, who is simply amazing!

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1 Introduction

Geothermal energy refers to energy contained within our planet Earth. The etymology derives from ancient Greek, where “geo” refers to Earth and “therme” to heat. In general, the Earth can be regarded as a sphere, with the Earth’s interior warmer than its surface. The surface is a suitable temperature for human and all other life as we know it, but relatively speaking, it is the coldest part of the Earth. The far hotter interior has heat which originates from the residual heat of formation of the Earth, as well as the decay of radioactive isotopes. It is thus theoretically possible to utilize this temperature differential to produce useful energy.

The Earth can be considered nearly spheroid in shape, with a radius of about 6370 km. Along its radius, there are three identified zones, defining concentric spheres: the core, the mantle and the crust. The innermost is the core, with a radius of 3470 km. It is predicted to have a temperature of at least 4000°C, and a pressure of at least 360,000 MPa. However, this has not been proven empirically, as human technology is thus far incapable of reaching such depths. (Barbier, 2002)

In fact, human technology cannot even reach the second layer, the mantle, which is about 2900 km thick and consists of very hot rock. The outermost layer is the crust, on which we reside, which is also the thinnest: it varies from about 7 to 65 km in thickness. This layer is also the coldest, as the heat that conducts from the interior is passed from here to the atmosphere and then space. (Barbier, 2002) Fortunately for humans, the atmosphere’s natural greenhouse effect keeps the surface warm enough to be survivable. Only the top ten meters or so of soil are susceptible to changes in atmospheric temperatures, and are for the Netherlands characterised by an average temperature of 10°C. Below that, the Earth’s crust warms up as one gets deeper, on average by about 30°C/km, although this can vary from 10-100°C/km depending on location. (Tester et al, 2006, Rogge, 2003)

1.1 Technologies

There are several technologies, which fall under geothermal energy in common parlance. It thus becomes necessary to define the types examined in this thesis. The following technologies can all be categorized as geothermal energy, in that they extract energy from the ground:

1. geothermal heat pumps, which extract heat from the shallow underground by taking advantage of a heat pump
2. heat and cold storage, which stores heat during the summer and cold during the winter in shallow underground reservoirs
3. volcanic geothermal, which extracts heat from natural shallow hotspots and is only feasible near volcanoes and the edges of tectonic plates
4. deep aquifer, which involves a borehole drilling deep into the earth to extract warm water from an aquifer (also known as a hydrothermal system)
5. enhanced geothermal systems (EGS), the successor of hot dry rock, which usually drills even deeper but also has to fracture rock to allow water flow.

These technologies fall roughly into two families: the former two are shallow, relatively small scale, and very low temperature technologies, and the latter three are deeper, larger scale higher temperature systems. Heat pumps and heat and cold storage are relatively mature technologies in the Netherlands, and implemented under many homes and buildings. These two, and volcanic systems which are not applicable for the Netherlands due to its lack of tectonic activity, will not be addressed in this report. Instead, the focus will be on the deep technologies: aquifer (hydrothermal system) and EGS.

1.2 Deep geothermal

The primary system under investigation is deep aquifer geothermal (hydrothermal system). An aquifer is an underground layer of porous rock, such as sandstone, which bears water in the pores. With the temperature rising by around 31°C /km depth, an aquifer at two kilometres deep will typically have a temperature of around 70°C. This water is at a useful temperature for many residential and horticultural applications. Should such an aquifer be available beneath the customer of interest, it can be interesting to drill for geothermal energy. Apart from a sufficiently high temperature, the aquifer will also need to have a suitable transmissivity, which is defined as

$$Transmissivity = thickness\ x\ permeability$$

The thickness of the aquifer is the height of the aquifer, as long as this is contiguous, not broken by sealing faults or other layers of less porous rock. The permeability is a measure of how easily water flows through the pores of the rock structure, and is roughly related to porosity. If the transmissivity is high enough, a sufficient flow rate can be established for the topside purposes. Of the two critical characteristics required for geothermal energy, transmissivity is often harder to guarantee beforehand than temperature for a prospective exploiter.

If the aquifer is thought to be suitable, it can be accessed by a well. The well is drilled from the surface and extracts water through a pump and a pressure differential. To maintain aquifer pressure, a second well is needed to reinject water. The reinjected water is at a lower temperature for thermodynamic reasons. The temperature differential between the extracted and injected water is used to extract useful energy. A pair of wells, consisting of an injection and a production well, is known as a doublet. If the water is between 60°C and approximately 100°C, this can only be used for heating, considering the economics of geothermal power generation.[1] Thus a heat exchanger is installed and the heat of the subsurface water transferred to fresh water above ground. This fresh water is used for whatever purpose required, and the now cooler geothermal water is injected back into the aquifer completing the closed loop. At no point is the geothermal water exposed to the open atmosphere, and thus no gases escape to the atmosphere and there should be no contamination of the aquifer during operation.

1.3 Enhanced Geothermal Systems and Electricity Production

To generate electricity, temperatures of at least 130°C are preferred. Thermodynamically speaking, the temperature should be as high as possible, provided that the technology to access geothermal prospects with such high temperatures is commercially available. In other words, to reach such temperatures, one needs to drill deeper, as per the previously defined temperature gradient. However, pressures at these depths are also greater, as there is more overbearing rock. This extra pressure usually reduces the porosity of rock layers, which in turn reduces the transmissivity. Therefore, there are few aquifers with temperatures in the range usable for electricity generation. In

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[1] One small power plant in Chena, Alaska uses 73°C water to produce electricity, but this is an exceptional case. (Holdmann, 2007)

this case, a suitable reservoir situation has to be stimulated. This is what Enhanced Geothermal System (EGS) means. A process known as fracking is used to create multiple fractures in the hot dry rock. These fractures can be carefully controlled and directed, and create the necessary porosity and transmissivity for a usable geothermal source. With the rock between the injector and producer well suitably fractured, water can flow between the two. This water returns to the surface at a high temperature and can be used for the desired purpose.

Whether EGS is used or not, if the temperature of the water is high enough, it can be used to produce electricity via a turbine. Sometimes, both electricity and heat are produced in what is called a Combined Heat and Power (CHP) facility. Several types of electricity producing facilities are possible for geothermal power, but all involve a generator producing electricity being turned by a gas heated geothermally. At low temperatures (<130°C) it is best to use a binary system like either a Kalina cycle or an Organic Rankine Cycle (ORC). These cycles are called binary because the hot geothermal water transfers the heat in a heat exchanger to a secondary liquid (sometimes called the working fluid). The working fluid evaporates with this heat, and this gas goes into the turbine. The turbine drives the generator, and electricity is produced. In a Kalina Cycle, the working fluid is an ammonia and water mix, and in an ORC, the working fluid is one of many organic liquids. Both can be calibrated specifically for the particular geothermal plant so that the optimum efficiency is reached.

At higher temperatures, it is more common to use flash or dry steam cycles (sometimes in tandem with an ORC) to produce electricity, because they are more efficient. Both of these cycles do not use a secondary liquid, but the geothermal liquid itself is used. This can be more damaging to the turbine and can result in the escape of undesired gases.

After the heat is extracted from the geothermal water, it is pumped back into the aquifer through the injection well. The pumps require electricity which can either come from the geothermal plant (if it produces electricity), when it will be called parasitic demand, or it needs to come from an external source.

For further information on electricity generation for geothermal power, Rogge (2006) and Koehler (2006) are recommended.

2 Problem definition

The ever-increasing consumption of fossil fuels as an energy source is not sustainable for two main reasons. Firstly, fossil fuels are non-renewable, and while plentiful, will become increasingly more expensive to discover and produce. Secondly, there are dire environmental consequences resulting from the combustion of fossil fuels. The most fearsome is global climate change, which is the worldwide disruption of climatic patterns due to excess heat trapped in the Earth's atmosphere by the so-called greenhouse gases, chief among them carbon dioxide. However, other consequences include rising acidity of bodies of water and soils, smog, release of particulates harmful to human health and oil spills such as in the Gulf of Mexico recently. While some technological and policy solutions have been developed for some of these issues, such as catalytic converters and NO_x and SO_2 reduction (desulphurization) in coal-fired power plants, it is clear that a structural energy transition is needed to avert the most serious consequences of fossil fuel use.

This has led to the rise of renewable energy sources, primarily wind, solar and biomass. A reliable energy source which happens to be out of the spotlight is geothermal energy. This is despite some obvious advantages geothermal has over other energy sources. Compared to biomass and fossil fuels, geothermal is advantageous in that it has no fuel costs, and fuel does not need to be transported. Also, there are very few emissions of greenhouse (or other harmful) gases associated with geothermal energy. This is especially true for the closed-loop doublets used in the Netherlands. Conversely, fossil fuels and biomass both directly emit greenhouse gases such as carbon dioxide (albeit without net CO_2 emission if biomass is grown sustainably), as well as other emissions such as nitrous oxides and sulphur dioxide, which need to be sequestered with filters. Compared to solar and wind power, two high-profile renewable energy sources, geothermal is advantageous because it provides constant base-load energy, it occupies very little surface space, and it has a long lifetime. The first is a major advantage: wind and solar energy do not operate constantly, perhaps 2500 (wind) to at most 4000 (solar) hours in a year, and then not always at predictable or useful times. Geothermal can reliably produce energy for at least 7500 predictable hours if there is demand. The second is a smaller advantage, but still worth mentioning. Wind energy requires large, highly visible turbines. Solar energy requires a great deal of south-facing, shadow-free surface area. In comparison, geothermal requires a small building once it is installed, although the construction phase does require an area of about a football pitch. There are two main disadvantages keeping the widespread development of geothermal energy back from fulfilling its potential: high and uncertain investment costs, and technological and geological uncertainty regarding production levels of energy.

It is therefore the intention of this report to investigate the costs of geothermal plants, and create a flexible model that can provide an assessment of these costs at various locations and incorporate the inherent uncertainty to produce a useful financial estimate.

2.1 Research Question

With that goal in mind, this research project investigates the following research question:

What are the costs of deep geothermal heat and power in the Netherlands now and over the next 30 years?

The costs should be determined in absolute costs per project, and then evaluated for several factors, including cost/depth (in €/m) and cost of energy (in €/kWh or €/GJ). Initially, a simple empirical trend of past and current costs can be developed, but the final result is an integral analysis of all costs involved in the project, with uncertainty ranges and variations depending on relevant factors. Costs should include the initial investment costs (including cost of exploration, drilling, and production of the wells), and fixed and variable operation and maintenance costs.

2.2 Research sub-questions

What factors decide the costs of a project, and what influence do they have?

For the initial investment, in particular the costs of depth and breadth of wells are analysed, in addition to the costs of capital and insurance. Furthermore, an assessment of the operational and maintenance costs is needed. Moreover, the influence of the market should be evaluated, particularly the influence of the prices of oil and gas (which may impact on the drilling costs), and steel (which will influence material costs).

The investment costs also include the equipment needed to provide the desired product (heat, electricity or both) to the location, which could range from a simple heat exchanger for horticultural purposes, to an entire district heating network, to an Organic Rankine Cycle. Each of these scenarios should be examined.

What influence do government policies have on the costs?

Current government policies such as the MEI and UKR are incidental investment subsidies. The potential SDE+ subsidy is now for both heat and electricity, what kind of shift in investment can this cause? Can such subsidies encourage wavering project planners to make the investment jump? Or are the incidental subsidies and the (adjudged to be) expensive guarantee fund not sufficient?

How do the costs of drilling compare to the costs abroad?

Are the many realised projects in Germany, France, and the U.S.A. comparable in nature to potential Dutch projects? What differences are there (in geological, economic and policy terms) and how do these affect the costs?

How will delays affect the costs?

A common issue with projects appears to be delays before, during and after drilling. How much do these delays cost the project owners?

2.3 System Boundaries

The scope of this project is deep geothermal energy in the Netherlands over the next 30 years. “Deep” means, by law, deeper than 500 m from the surface, but to be commercially attractive it generally refers to at least 1500 m deep. Geothermal refers to the residual heat of formation and the heat from radioactive decay in the Earth’s core. Although current technologies are only capable of reaching several kilometres into the crust, it is still far warmer than the surface. The energy derived from this is extracted from the subsurface in the form of warm water (either liquid or gaseous depending on the conditions), and either heat or electricity, or both, can be derived from this carrier. Current Dutch applications are mainly heat for horticultural and residential purposes (district heating), but others are possible.

The project looks specifically at current and future geothermal heat and power in the Netherlands. However, comparisons are drawn to geothermal power in other countries, especially (nearly) neighbouring countries like France and Germany. This is because more or a similar number of projects have been realized in these countries, providing more experience and data. These can be compared and contrasted with the Dutch situation.

Of the several different types of geothermal power, this project will focus mainly on aquifer systems, as these are the ones currently in use in the Netherlands at the time and those being developed. Enhanced Geothermal Systems will also be looked at, because while these are not in use at the moment, they do appear to be the future system of choice next to more shallow geothermal energy systems used for heating.

The technical boundaries of a system include the underground source, the injection and production wells, and any surface installations for converting and transporting the energy to the existing demand. This includes heat exchangers and turbines. However, it is mainly the economic side of a project that is investigated.

2.4 Previous work

When researching the literature of geothermal energy, it quickly becomes clear that the seminal work in this section is that of Tester et al, an MIT study in 2006 performing a large-scale economic analysis of deep geothermal energy in the United States of America. The 12 co-authors are all experts in the field and have written often on the topic. Tester et al provides a strong, detailed analysis of geothermal energy, including the costs and how these have developed over time. One of the key results is that there has been a tremendous increase in costs since the early 2000’s.

The main reasons why this work is needed when Tester et al has already been published is because geothermal energy in the Netherlands is not developed in the same manner as the Unites States. The USA primarily derives geothermal energy from aquifers in volcanic conditions. These tend to be shallower and hotter than Dutch reservoirs. Additionally, they tend to be more remote and thus useful for electricity production but not heat production, whereas Dutch geothermal energy thus far is all in the form of heat. This resulted in a wholly different approach to geothermal energy in the USA compared to the Netherlands. It is not uncommon in the USA to perform “wildcat” drillings, which have only a 25% success rate. In contrast, in the Netherlands drilling will not start until all available information has been collected and the greatest possible knowledge of the situation is available.

In the Netherlands, significant research has been performed by TNO. The model ThermoGIS is a model which provides a map of subsurface water reservoirs (also known as aquifers) in the Netherlands. This information is derived from the known seismic and well data that has been provided to TNO. As such, it can make estimates of all the important data for aquifers at a given location, such as temperature, thickness, depth and permeability. This information is used to calculate a likely heat in place and potential recoverable heat for a well at a particular location. An attached economic module called DoubletCalc determines the cost and other economic aspects of such a project. For in-depth description of ThermoGIS and DoubletCalc, Kramers, et al (2012) and van Wees, et al (2012) are recommended.

ECN Policy Studies is responsible for advising the Ministry of Economic Affairs on subsidy issues (SDE+), in collaboration with KEMA (a private consultancy owned by DNV). The SDE+ scheme (a subsidy named Besluit stimulering duurzame energieproductie +) has been expanded in 2012 to include projects delivering heat as well as projects delivering electricity and green gas. As a result, significant new research was needed on the costs of renewable technologies delivering heat, in particular geothermal heat.

3 Methodology

This chapter presents the two products that will lead to answering the research questions. First, a database is compiled, and then a model is developed. The approaches to these two products are briefly described.

3.1 Database

To determine the cost of geothermal energy in the Netherlands, it was decided to first develop a database of recently completed geothermal projects. This was done for several reasons. First, it gave a good indication of the state of the technology and the economic dimension. Secondly, it provided a useful cache of case studies for both the author and ECN. Thirdly, it allowed for a test of the drilling cost results of Tester et al (2006) and van Wees et al (2009) as they apply to the current Dutch situation. Fourthly, it allows some measure of comparison between the Dutch facilities already developed, and similar facilities in nearby countries.

This database contains publically available information on these projects, with a key emphasis on the technical and economic aspects, especially depth, production capacity and cost. Microsoft Excel proved to be a useful tool for making such a database.

The database builds on data gathered in Lako et al (2011), and is supplemented by an in-depth literature and news article search. Projects are identified first through national geothermal organisations, such as Stichting Platform Geothermie for the Netherlands, and then researched using a search engine for news articles and websites which contain relevant details. Care needs to be taken to identify discrepancies between articles. Usually, in such cases, the quality of the source is assessed, and the point in time it was authored. A later report will probably have a more complete picture of the investment costs.

Selected projects are primarily recent (since 2002), and in Europe in non-volcanic conditions. The choice of timeframe is because literature (Tester et al, 2006) and discussions with experts shows that since about this time, the cost of drilling has been dramatically higher. This rise is attributed to a rise in the price of oil, a diminishment in the number of drilling rigs and the advent of shale gas drilling. Thus, comparison with older geothermal projects is not helpful in predicting costs of future and current projects. The choice of locations limits projects to primarily those in the Netherlands and Germany, with a few projects in France, Denmark and Hungary. Not included are projects in Iceland or Italy, where volcanic subsurface conditions mean wells are significantly less deep, and other equipment is needed to deal with the higher temperatures. Also not included are projects in Turkey or Eastern Europe, where costs of labour are lower and thus not representative of projects in the Netherlands. Projects in Germany and neighbouring countries are legitimately included, as many drilling companies operate in both countries. Drilling rigs can be easily transported in containers by trucks.

Data on the projects comes from publically available sources, including national geothermal databases if accessible, media reports, company websites and publications. While there may be some scepticism regarding the accuracy of such data, there is little reason for this. Many projects are by small companies that only intend to develop one source, and thus there is no reason for them to obfuscate their data. Additionally, some technical data needs to be published publically as a requirement of government subsidies and permits. Thus there is little uncertainty in technical and geological data. One area that is generally vaguer is the costs, as there are competitive reasons to keep this general, especially for drilling companies. Furthermore, the costs that are quoted tend to be rounded off to the nearest million. However, as most projects cost at least 10 million euro, this means the uncertainty for cost figures is less than ten percent. The reliability of these statements can be checked if there are multiple sources available, or perhaps if there are preliminary studies. Overall, the end results are expected to be accurate enough for this research.

Once the database has been built and filled with projects, trends and patterns can be evaluated. This includes, but is not limited to, average costs per meter, average cost per kWh, costs developing over time, and that per country and depth category. These trends and costs can be inserted into the model developed in the second stage.

3.2 Modelling

As the results of the database will show, there is not yet a significant amount of data available to empirically answer many of the sub-questions to the research question. There is a great deal of uncertainty involved and every geothermal site is different. An effective way to handle that is to develop a model. A successful model will be user-friendly, allowing the user to set variables. Such a model is flexible enough to adapt to different geotechnical and economic situations and should have the capacity to answer the various research sub-questions.

The language of the model was a difficult decision. Given the author's past experience, a model in Excel seemed the most probable way forward. However, a meeting with the Sustainable Geo-energy group at TNO, a group which had already accomplished significant model development in Java, led to the decision to write this model in Java, expanding on the expertise and knowledge at that institute. Java is a programming language, and is written and manipulated using a programme called Eclipse, which provides a sort of digital workbench. The result is a model called DoubletCalc, which performs geotechnical and economic calculations. TNO already had an early version of DoubletCalc, see van Wees et al (2010), and have also produced a new version recently (van Wees et al, 2012).

4 Results

This chapter provides an overview of the results that have been obtained in the research project. First, the results from the database are presented. Next the model is described in several stages. First, the way it was put together, by presenting the changeable variables and the calculations that operate on them. Then the user interface is shown, along with a typical, hypothetical project. Finally, the model is tested using available data for two potential projects.

4.1 Database results

The section describes the main results from the database. The database includes 62 deep geothermal installations that have recently been built in the Netherlands and other European countries which have reasonably similar subsurface conditions as the Netherlands. Of these, 34 have publically available drilling cost totals which are considered reliable. These 34 geothermal projects are thus used in the analysis to follow.

Most (27 out of 34) of the facilities are used exclusively for heating. In general, these projects are cheaper as the wells are less deep and the installations do not require a turbine. However, plants where the heat is used for district heating can carry significant network construction costs with them. Of the 27 projects only producing heat, 20 are for district heating, six for greenhouses and 1 for heating an airport. Interestingly, all the greenhouse projects are in the Netherlands.

Six of the 34 projects are for CHP, with the majority using that heat for district heating or in a cascade system for nearby buildings. Just one project only produces electricity, and that is the experimental Soultz project (France), which tested EGS.

It should be clear that the database is not exhaustive. This is indicated by the mere fact that nearly half the projects, (28 out of 62) are not used in the analysis because there is not enough publically available information on them. Furthermore, some of the data, especially costs, has a significant uncertainty margin due to the nature of the reporting. However, it does provide an interesting indication of the state-of-the-art costs, and the current trends.

4.1.1 Country divisions

The figure below shows in which European countries the 34 geothermal projects in the database have been realized:

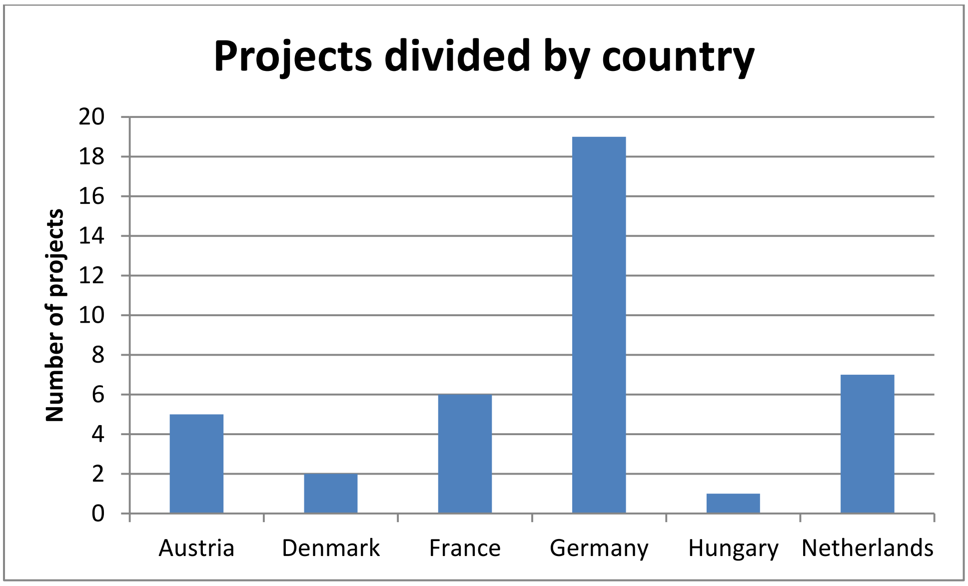
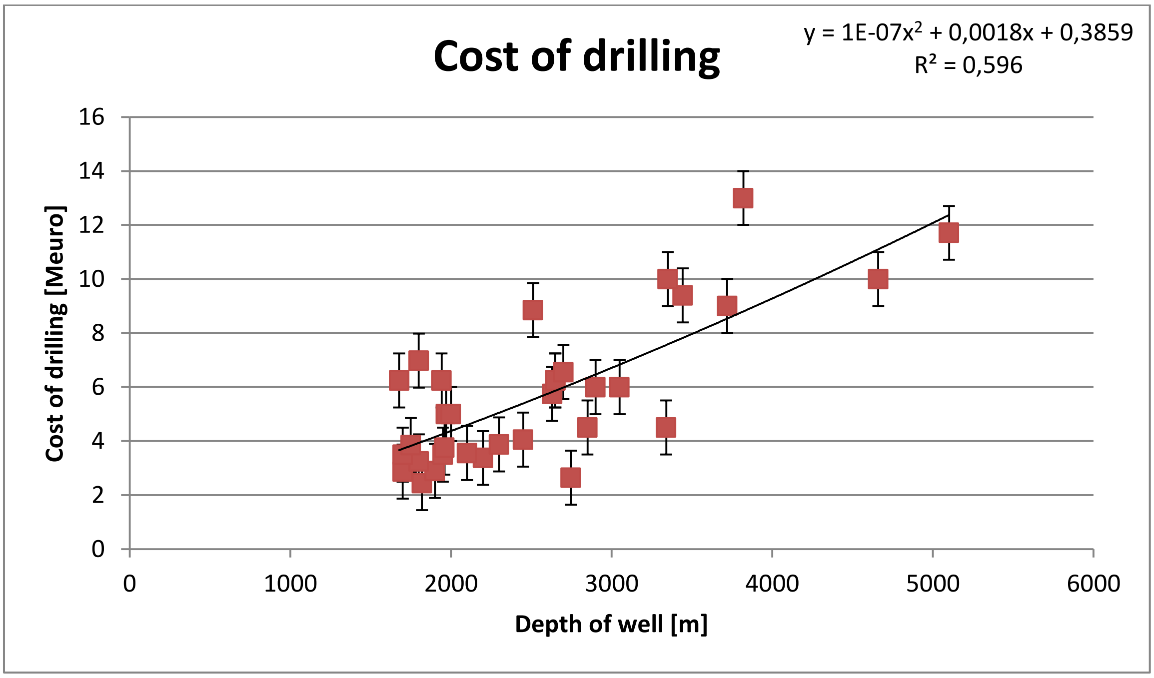


Figure 4.1 Division of projects in database by country.

The sample is thus clearly mostly based on German projects, though the Netherlands is also well represented in the database.

4.1.2 Cost per meter

One of the key results of the database is the relationship between drilling costs and depth of the well as shown in the figure below.



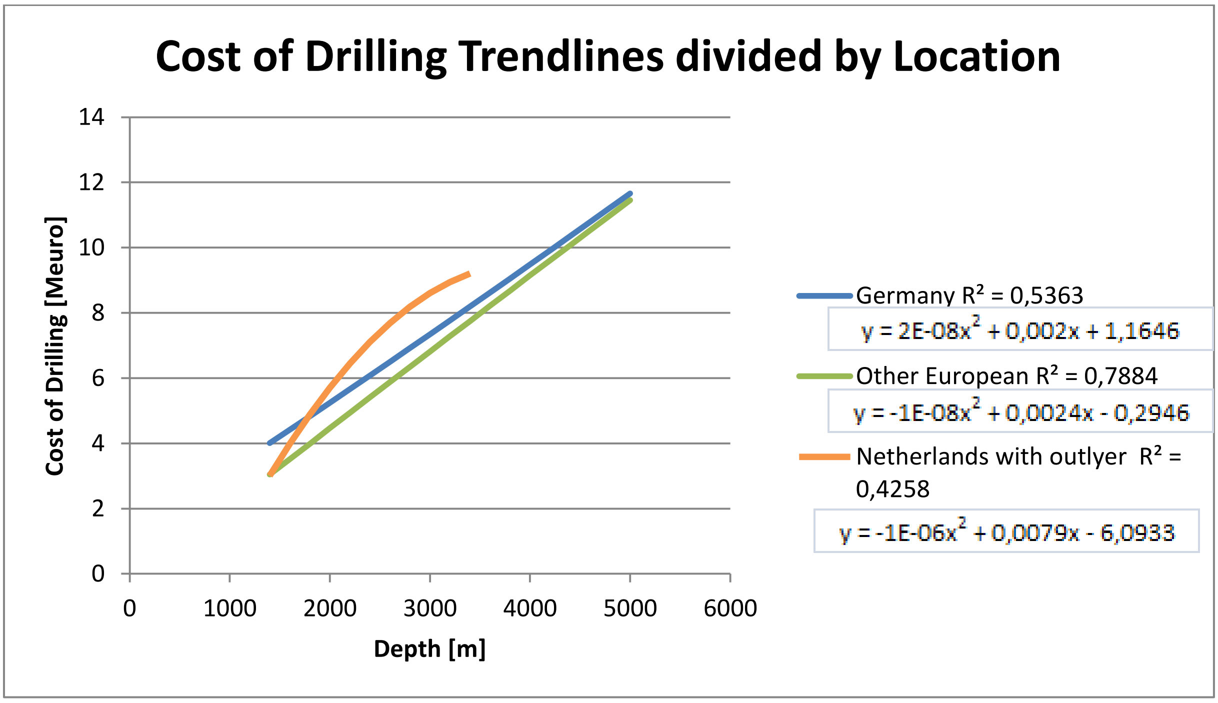


Figure 4.2a and b Cost of drilling over depth of well, and b) cost of drilling divided by country.

Figure 4.2a shows thirty-four data points. The most accurate equation for a trendline is displayed. The figure shows that there is a general relationship between cost and depth: deeper wells tend to be more expensive in terms of drilling costs. However, the R^2 value of 59% indicates that while depth is linked with costs, the relation is not strong. The smallness of the error bars indicates that the weakness of the relationship between depth and drilling costs is not due to the uncertainty of the data points.

Figure 4.2b shows that same data, divided by country. To protect possible confidentiality of projects, only the resulting trendlines are shown. Again, the R^2 values are small, indicating a poor fit between trendlines and data points. The Dutch curve is of particular interest.[2] It has been shortened because there are no data points above 3000 m depth, but it appears to shrink with depth. This can be attributed to insufficient data, as there are only 7 data points, and these are of relatively shallow depths. Given the proximity of the lines, it could be expected that with more projects, the curve will resemble those of other European projects. The German and 'other European' trendlines are surprisingly similar.

4.1.3 Cost per capacity

The figure below shows the relationship between output capacity and the cost of drilling.

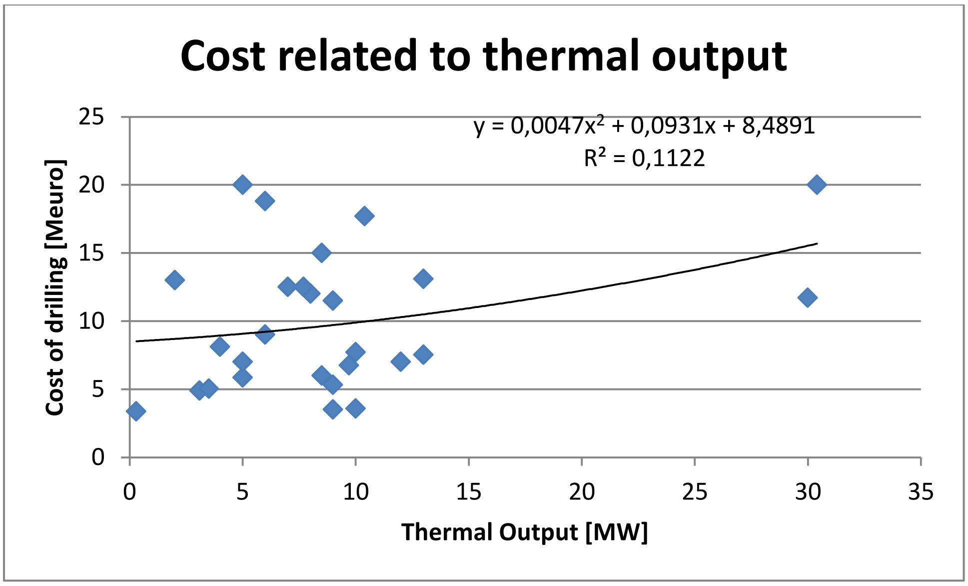


Figure 4.3 Cost of drilling over thermal output.

The data points in the figure show that the relationship between drilling costs and thermal output is not strong at all since the R^2 value is only 11%. The relationship between thermal output and drilling costs is not significant, especially compared to the relationship between depth and cost of drilling and depth. Nonetheless, this relationship is still commonly mentioned in reports. From this result, it appears clear that if a cost equation is needed to describe a geothermal facility, this is better done through a cost per depth formula than cost per output.

4.2 Model Development, Calculations and Output

The model is effectively the major result of this project. Thus the construction, testing and results from the model are all listed here, in one consecutive section.

My alternative version of DoubletCalc builds upon the model developed by TNO (Van Wees, et al, 2010, 2012) and is written entirely in the programming language Java. This alternative model comes

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[2] One curiosity is that six of the points form a line with an R^2 value of 96%. This is a surprisingly close correlation between depth and costs of drilling. However, the projects are mostly of similar depth and this is likely a coincidence.

in two versions: Heat and CHP (combined heat and power). The Heat version is more narrow and streamlined towards use by horticulturalists, and has the most recent TNO update on the geotechnical side (van Wees et al, 2012). The Heat version is also intended to be linked to the ThermoGIS model which is currently being revamped by TNO. The CHP version is designed for a more academic purpose, as it is very unlikely that the geothermal CHP market will develop strongly in the near future. However, this means the CHP model is also used to try out a few experiments such as overland pipelines and delay effects.

4.2.1 The **Heat Model**

Variables

The user interface of DoubletCalc allows the user to manipulate nearly all variables, and thus many results can be produced. The geotechnical variables were developed by TNO and are shown in Appendix B. Further information on them can be found in van Wees et al (2012). The economic variables that are changeable are shown in the tables below. Key among these are geotechnical variables such as depth, porosity and temperature, and lifetime, interest and debt-equity ratio as economic variables.

Changeable Economic variables	
Economic lifetime	the expected lifetime of the plant, mainly dependent on equipment and the aquifer
Pump replacement frequency	one major operational cost is the frequent replacement of pumps, especially the ESP in the production well. This variable caters for that need.
Heat exchanger season factor	the season factor is the fraction of the year that the plant is operational
Load Hours	derived from the season factor, represents the number of hours per year the plant is on
Electricity price to buy	the range of the expected costs of electricity, which is needed to run the pumps
CAPEX for heat exchanger	the investment cost of the heat exchanger
CAPEX pump	the investment cost of the ESP
Well cost scaling	the scaling factor in front of the TNO drilling cost equation
Fixed OPEX rate	the operational costs which are constant year to year, especially standard maintenance
Variable OPEX rate	the operational costs which vary from year to year. In the ECN methodology, this is primarily cost of electricity. Since that is covered elsewhere in this model, this is set to 0.
Pump workover costs	the cost of replacing the ESP every few years as designated by the pump replacement frequency
Tax rate	the Dutch tax rate on businesses
Inflation	the yearly percentage by which money loses value over time
Interest on the loan	the interest rate on the loan required for the initial investment
Debt percentage	the percentage of the total investment which is funded by debt. Certain guarantee schemes and loans are dependent on a certain level of equity from the exploiter.
Required return on equity	the rate at which the capital investor expects returns on investment, usually derived by comparison to other potential projects

Table 1: List of changeable economic variables in DoubletCalc.

All of these variables are alterable by the user. However, if the user does not know, then there are standard, default values available.

Outputs and Calculations

The next step is to run the long list of geothermal and economic variables through the program to produce a variety of outputs. The outputs of the model include capacity, kWh produced, and the capital investment costs and the annual expenses. This allows for a calculation of the Unit Technical Cost (UTC), which is used to determine the base rate for the SDE+ subsidy. The UTC is the key output, which in general terms is calculated as:

$$UTC = \left(\frac{total\ discounted\ expenses}{total\ discounted\ produced\ heat}\right)$$

This gives a result with units [€/GJ]. The UTC value can be compared directly with other technologies and effectively produces the breakeven price of selling heat from that technology. In the SDE+, this is used on many renewable technologies, and directly compared with a benchmark price which represents the standard price of heat from non-renewable, cheaper alternatives such as a gas-fired boiler.

In the HEAT model, the total discounted expenses are calculated as such:

$$total\ discounted\ expenses = Equity\ part\ of\ initial\ investment + \sum_{year} discounted\ annual\ expenses$$

Each of these elements consists of a large number of sub-elements, some of which are related, but as indicated above, clearly fall into two categories: Initial investment, and annual costs. The initial investment is a sum of all costs of construction of the plant, which are the dominant pre-operational costs when compared to surveying and planning costs. For a heat plant, construction is considered to be the sum of the drilling costs of the wells, the costs of all the pumps, including the electric submersible pump in the production well, the heat exchanger, and possible pipeline, hydrocarbon separator and reservoir stimulation costs.

Investment costs

Of these investment costs, the most difficult to compute and predict are the well costs. No two wells are alike, even the two wells of the same project, and the cost of each has to be calculated separately. However, as Tester et al (2006) and van Wees et al (2012) have shown, it is possible to use an equation to describe the costs of drilling. TNO have decided to use the following equation:

$$Drilling\ cost\ well\ [M€] = W * (0.2 * d^2 + 700 * d + 250{,}000)$$

Where W is a factor called Well Cost Scaling, which allows for a rapid change to the equation if market conditions were to fluctuate significantly. The variable d stands for depth. The Results chapter gives an indication of how accurate equations are for predicting drilling costs, but for this section, it is useful to continue using TNO's equation.

The sum of the initial investment costs is thus:

$$\begin{aligned}Initial\ investment\\ &= Drilling\ cost\ production\ well + \ Drilling\ cost\ injection\ well + cost\ heat\ exchanger\\ &+ cost\ pumps\ \ + cost\ pipeline\ [if\ applicable] + \ costs\ stimulation\ [if\ applicable]\end{aligned}$$

The initial investment is paid in the first year of the model, represented as Year 0. This is mostly in accordance with actual practice, as drilling of the wells takes two to four months, depending on the depth and possible trouble encountered, and construction of the facilities takes perhaps half a year for heating networks but far less for horticultural heating purposes.

This initial investment is comes from three sources. The Debt-Equity Ratio variable determines how much comes from the capital investment by the owner and other shareholders, and how much is covered by loans from a bank. The third source is the EIA subsidy, which is a relatively small amount coming from the Dutch government. The EIA subsidy stands for Energie-Investerings Aftrek, which translates as a tax deduction on investments in energy technology. The amount awarded as EIA is determined as 41.5% (as per legal mandate) of the total investment, multiplied by the corporate tax rate, divided by 1 plus the interest rate of the project. In other terms:

$$EIA\ awarded = total\ investment * 41.5\% * \frac{corporate\ tax\ rate}{(1+r)}$$

Where total investment is the previously determined sum of capital expenditures, r is the project interest rate, and the corporate tax rate is currently set at 25.5%.

In general, government subsidies and the government guarantee scheme for drilling require an equity percentage of at least 20%, not including the EIA. Thus, in general, up to 80% of the capital expenditures are covered by loans in horticultural projects. This allows the project owner to delay his capital costs at the price of annual interest. The interest (i) is a key factor in annual costs, together with the lifetime (L) of the loan. For the purposes of this analysis, repayment of the loan is assumed to be accomplished in equally sized annual instalments. Other important terminology is principal, which refers to the amount of money borrowed initially and present value and future value. The present value (pv) is the size of outstanding debt at the outset, L=0, and the future value (fv) is what the size of the outstanding debt at a given point in time, L = y. The annual loan payment (pmt) is calculated using the following equations:

$$pv_0 = \ principal\ at\ year\ 0$$

$$pmt = \frac{i}{(1+i)^L - 1} * \ -(pv_0 * (1+i)^L$$

$$fv_y = -(pv_0 * (1+i)^{y-1}) - \ (pmt * ((1+i)^{y-1} - 1))/i$$

From these equations, it can also be determined how much of each yearly payment is payment of interest (ipmt) and how much is repayment of the principal (ppmt). This is accomplished like so:

$$ipmt_y = \ fv_y * i$$

$$ppmt_y = pmt - \ ipmt_y$$

The loan payments are only some of the annual outgoing cash flows. There are also operational and maintenance costs, both fixed and variable. Fixed operational costs are seen as a function of produced heat, thus directly related to the size of the facility. This value is alterable by the user in the start-up screen of the model, set by default to 5% of the capital expenditure. Variable operational costs are the sum of the costs of electricity for the electric submersible pump (ESP) and the occasionally necessary replacement of pumps. The price of electricity can be described as a triangular function to represent uncertainty over time of how this will develop. The pump workover costs are another alterable feature, and the frequency of replacement can also be modified.

$$OPEX_{total} = \sum OPEX_{elec} + \ pump\ workover\ costs + fixed\ OPEX\ costs$$

$$OPEX_{elec} = pump\ power\ produced * Load\ Hours * price\ of\ electricity\ to\ buy$$

Here the pump power produced is determined from the Coefficient of Performance of the pump, and the load hours are the number of hours in a year that the facility is operational.

Another source of costs is taxes. Corporate taxes in the Netherlands are levied in a complicated way over the expenditures, since it is assumed that profits in one part of the company are compensated for by expenditures in another area. Thus the corporate tax rate of 25.5% is applied to the sum of the operational costs, depreciation and the interest part of the loan payment. (Taxes over the principal were already paid at the moment of investment).

$$Taxable\ Income\ [y] = \sum all\ operational\ costs\ [y] + \ depreciation\ [y] + \ ipmt[y]$$

Under this tax construction, the net income of year y is thus determined as the sum of the discounted operational costs, the loan repayment, and the taxes paid. It is described as income even though, in this case, it is a negative number consisting only of expenditures.

$$Net\ income\ [y] = \sum all\ operational\ costs\ [y] + pmt + taxes\ paid\ [y]$$

If the net income is discounted and summed up for all years in the economic lifetime, the total discounted expenses can be determined, which allows calculation of the UTC.

The discounted heat produced is determined by simply discounting the annual heat production over the same interest rate as the annual expenses are discounted over. The annual heat produced is determined as a function of temperature and flow rate, which stem from the geological properties of the doublet.

Finally, 0.25 €/GJ is added to the UTC as transmission costs. The resultant value is considered the SDE+ base rate, the price at which projects are evaluated for the SDE+ subsidy. The SDE+ base rate is the value which is compared to the SDE+ correction amount, which is the price of a competitive, non-renewable technology (probably natural gas fired boilers). The difference between the base amount and the correction amount is what will be granted to the project owners as subsidy, per approved GJ renewable heat produced.

For the geotechnical calculations, see van Wees et al 2012.

4.2.2 The CHP Model

The CHP model is similar to the HEAT model in many ways, but is less streamlined and practical and allows room for more fanciful aspects, such as the co-production of electricity. A variable called the Primary Energy Division is used to determine how much of the primary energy is devoted to the production of electricity and how much is used for heat. Electricity production requires additional investment costs and brings with it additional operational costs, as there are more parts involved such as the turbine.

Additional investment costs are mainly the installation of an electricity-generating cycle such as an Organic Rankine Cycle (ORC), or a Kalina Cycle, which use secondary working fluids such as organic compounds or ammonia to turn a turbine and generate electricity. At higher temperatures, it may also be worthwhile to use flash or steam cycles as alternatives. While ORCs and Kalina turbines can operate with sub-100°C temperatures, efficiency will be very low and the project will not be cost-effective in the Dutch climate. Thus, deeper drilling is required, which also raises investment costs. Furthermore, at these depths, stimulation of the reservoir may also be needed, which is another investment cost. All of these options can be modified in the model.

The electricity generating part of the plant has a separate load hours curve, as heat is more dependent on demand side load curves, while electricity can in theory produce continuously throughout the year under base load.

The efficiency of turbines is approximated using a temperature dependent equation which also comes from TNO (van Wees, 2012):

$$Electric\ Efficiency = (-0.00007 * T^2) + \ 0.09 * T - 1.0088$$

The investment of turbine costs are also determined using an equation dependent on the capacity of the turbine. Capacity is calculated as a function of electrical efficiency and primary energy allocated to the generation of electricity:

$$\begin{aligned} &Electrical\ Capacity \\ &\qquad = Heat\ generation\ capacity * Primary\ Energy\ Division \\ &\qquad * Electrical\ Efficiency \end{aligned}$$

Turbine and associated investment costs are then determined as

$$Investment\ Costs\ elec = Electric\ Capacity\ [kW] * 1000\ €/kW$$

This constant has been confirmed by turbine construction companies who have preferred to remain anonymous.

Capital expenditures can further be increased for electricity generating purposes through stimulation costs. At greater depths, permeability of the reservoir has a tendency to decrease, resulting in lower flow rates and thus a lesser capacity. Through a variety of means collectively labelled stimulation of the reservoir (also “fracking”), the reservoir can be broken open further to enhance flow rates and thus result in a greater productivity, a process which has been proven in the oil and gas industry but not often applied to geothermal projects. Stimulation costs can vary wildly, depending on the extent needed, and are often (see Lako et al, 2011) taken as a lump sum. Here, the stimulation costs are one more adaptable variable for the user and are considered a capital investment.

4.2.3 Effect of Government Policy

There are several government policies that can have effect. There are several lump sum subsidies, such as the MEI or provincial grants, which provide the project owner with an upfront sum of money. However, these will likely be phased out with the SDE+ subsidy, as owners will probably be prohibited from having both subsidies. For this analysis, a subsidy of 2 M€ is chosen and compared with the effect of the SDE+.

Then there is the government guarantee, which will return the owner with 85% of his investment in case his project fails up to a maximum of 7.2 M€. This is only granted with P90 predictions of success, so failure is quite unlikely. The premium is 7% of the refundable amount, paid before drilling. This results in investment costs being higher. The owner can also seek private insurance, but these premiums are not in the public domain. Large companies tend to ignore insurance for their projects, as determined by personal interviews.

Due to recent hydrocarbon finds in geothermal wells, the government is now also requiring more expensive wellheads with Blowout preventers (BOP) and hydrocarbon separators. This also drives up investment costs. While none of these have been implemented yet, for the purposes of this calculation this is chosen to be an additional investment of 1M€.

4.2.4 Effect of distance

To examine the research sub-question regarding deviated drilling versus a surface pipeline, the CHP model is modified. A small addition to the program allows the effect of distance between the source and the demand facility to be investigated, primarily as compensation for not drilling in a deviated fashion. In modelling terms, the Well Cost Scaling is reduced to account for straight drilling instead of deviated, which makes it cheaper, but additional investment costs have been added to account for the pipelines that need to be laid. The cost of the pipeline is added as capital investment and is the product of the distance between the wells, the diameter of the pipe, and a price per meter length per centimetre diameter. This last value comes from discussions with industry experts, who find 2 €/(m length * cm diameter) a reasonable estimate.

In this section there is potential for it to be expanded if desired to also add the investment costs of a district heating network. However, because a district heating network is a significantly large investment which is not involved in the actual production of heat, this is not yet included in the analysis.

4.2.5 Time delay

The last research sub-question asks about the effect of delays on projects. To examine this, another minor amendment of the CHP model is usable. One of the greatest vexations of project management is delays. The cost of delays can be demonstrated by inserting a time delay either before or after drilling. If it is after drilling, then this has the effect of delaying production but also certain expenses, like operational costs, but not costs of capital such as loan repayments. This allows for comparison between a regular project and one suffering from delays. For example, the The Hague Aardwarmte project, in the Netherlands, has lain still for two years despite the drilling having gone relatively smoothly. This was because the district heating network was lagging behind, due to the construction sector crisis. The (financial) consequences of such a delay can be investigated with this modification.

4.2.6 Cost of drilling equation

The cost of drilling is the most difficult part of the model to demonstrate, as will be shown in the Results chapter. TNO has an equation which it uses often, but how does this measure up against empirical results as shown in the database?

4.3 Model Results

The analysis of results is divided by the variants of the model. First, the Heat-only model, which is destined to be coupled to ThermoGIS, is looked at. Secondly, the CHP model, which looks at possible co-production or sole production of electricity, is examined. , Effects of delay and distance between the wells of the CHP model are also investigated.

4.3.1 Heat-Only Model Results

The Heat-Only model is designed for practical use, and thus only offers the (in the Netherlands) commonly developed option of using geothermal energy for heating. It assumes that the user wants to develop a geothermal plant for warming a greenhouse (although use for district heating is also possible with a different return temperature).

The model is called DoubletCalc, and written in programming language Java using the helpful tool Eclipse, which is a sort of workbench for writing Java. DoubletCalc is written by TNO (Van Wees et al, 2010), but with permission, a new version has been developed by this author. This new version leaves most of the geotechnical side of the DoubletCalc model intact. For example, the flow rate calculations, balancing of pressures and temperatures and the co-efficient of performance determination are all the same in the unmodified version of DoubletCalc and this version. What has been changed entirely is the economic side of the model. This has been modified to determine, primarily, the Unit Technical Cost, as is done in the ECN SDE+ calculations. The UTC divides all the expenses over all the output of energy and determines a single price for each unit of energy produced. With this result, the facility can easily be compared to other geothermal facilities, or even other technologies.

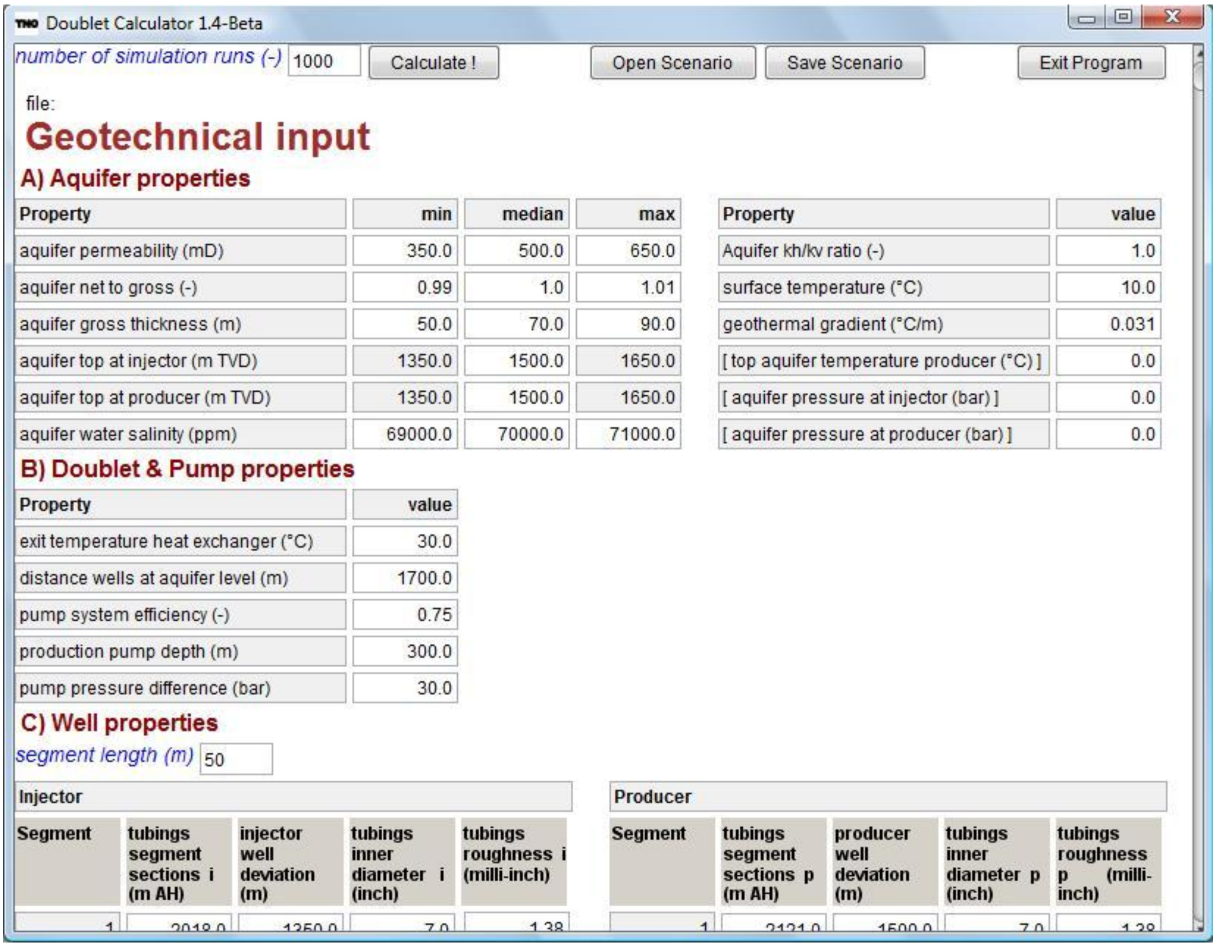
Once opened, the model presents the user with an input screen. On this screen nearly all variables are presented and can be altered if desired. Default values are present in the input screen, which correspond to certain general conditions or scenarios in the Netherlands. The units of each variable are shown in brackets next to the name. Several things will be highlighted from the input screen displayed below.

Because many variables, such as permeability and reservoir thickness, are not known to great certainty before the wells are drilled, these are represented by uncertainty curves. A minimum, median and maximum value is needed for these variables, which are then interpreted as triangular distributions.

The number of simulation runs in the top left corner refers to the number of times that the scenario is processed. For each run, a single value from each of the triangular distributions is chosen and used to calculate the UTC for that run. The results of each run are then aggregated and presented as a distribution in the output section. More runs will result in a more detailed and accurate final curve.

Fewer runs means the calculations are finished more quickly and this setting is useful if the user is on a slow computer.

In Figures 4.4 below, the input screen is shown. It is one whole screen, with the lower sections reached by scrolling down:



number of simulation runs (-) 1000

file:

Geotechnical input

A) Aquifer properties

Property	min	median	max
aquifer permeability (mD)	350.0	500.0	650.0
aquifer net to gross (-)	0.99	1.0	1.01
aquifer gross thickness (m)	50.0	70.0	90.0
aquifer top at injector (m TVD)	1350.0	1500.0	1650.0
aquifer top at producer (m TVD)	1350.0	1500.0	1650.0
aquifer water salinity (ppm)	69000.0	70000.0	71000.0

Property	value
Aquifer kh/kv ratio (-)	1.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.031
[top aquifer temperature producer (°C)]	0.0
[aquifer pressure at injector (bar)]	0.0
[aquifer pressure at producer (bar)]	0.0

B) Doublet & Pump properties

Property	value
exit temperature heat exchanger (°C)	30.0
distance wells at aquifer level (m)	1700.0
pump system efficiency (-)	0.75
production pump depth (m)	300.0
pump pressure difference (bar)	30.0

C) Well properties

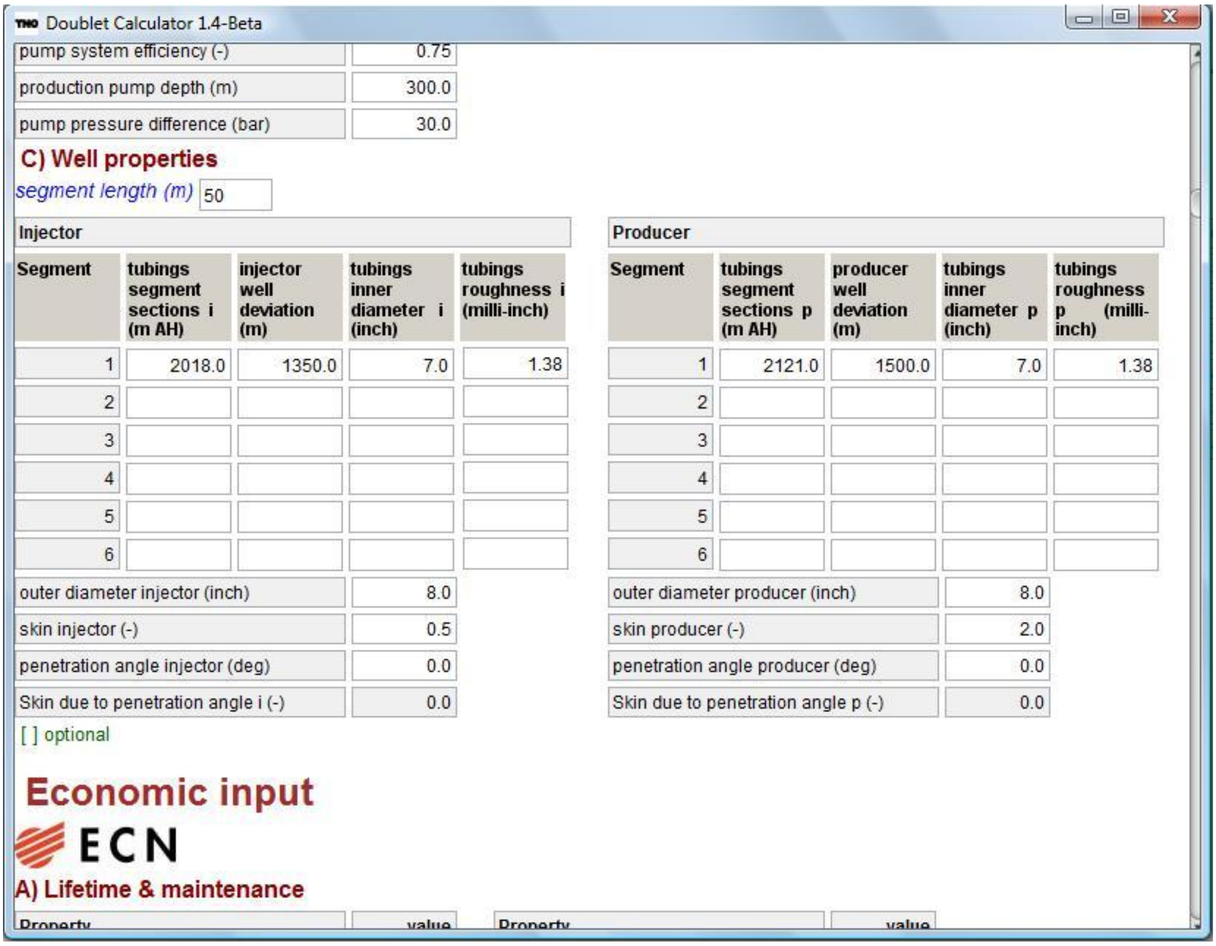
segment length (m) 50

Injector

Segment	tubings segment sections i (m AH)	injector well deviation (m)	tubings inner diameter i (inch)	tubings roughness i (milli-inch)
1	2018.0	1350.0	7.0	1.38

Producer

Segment	tubings segment sections p (m AH)	producer well deviation (m)	tubings inner diameter p (inch)	tubings roughness p (milli-inch)
1	2121.0	1500.0	7.0	1.38



pump system efficiency (-)	0.75
production pump depth (m)	300.0
pump pressure difference (bar)	30.0

C) Well properties

segment length (m) 50

Injector

Segment	tubings segment sections i (m AH)	injector well deviation (m)	tubings inner diameter i (inch)	tubings roughness i (milli-inch)
1	2018.0	1350.0	7.0	1.38
2				
3				
4				
5				
6				

outer diameter injector (inch)	8.0
skin injector (-)	0.5
penetration angle injector (deg)	0.0
Skin due to penetration angle i (-)	0.0

Producer

Segment	tubings segment sections p (m AH)	producer well deviation (m)	tubings inner diameter p (inch)	tubings roughness p (milli-inch)
1	2121.0	1500.0	7.0	1.38
2				
3				
4				
5				
6				

outer diameter producer (inch)	8.0
skin producer (-)	2.0
penetration angle producer (deg)	0.0
Skin due to penetration angle p (-)	0.0

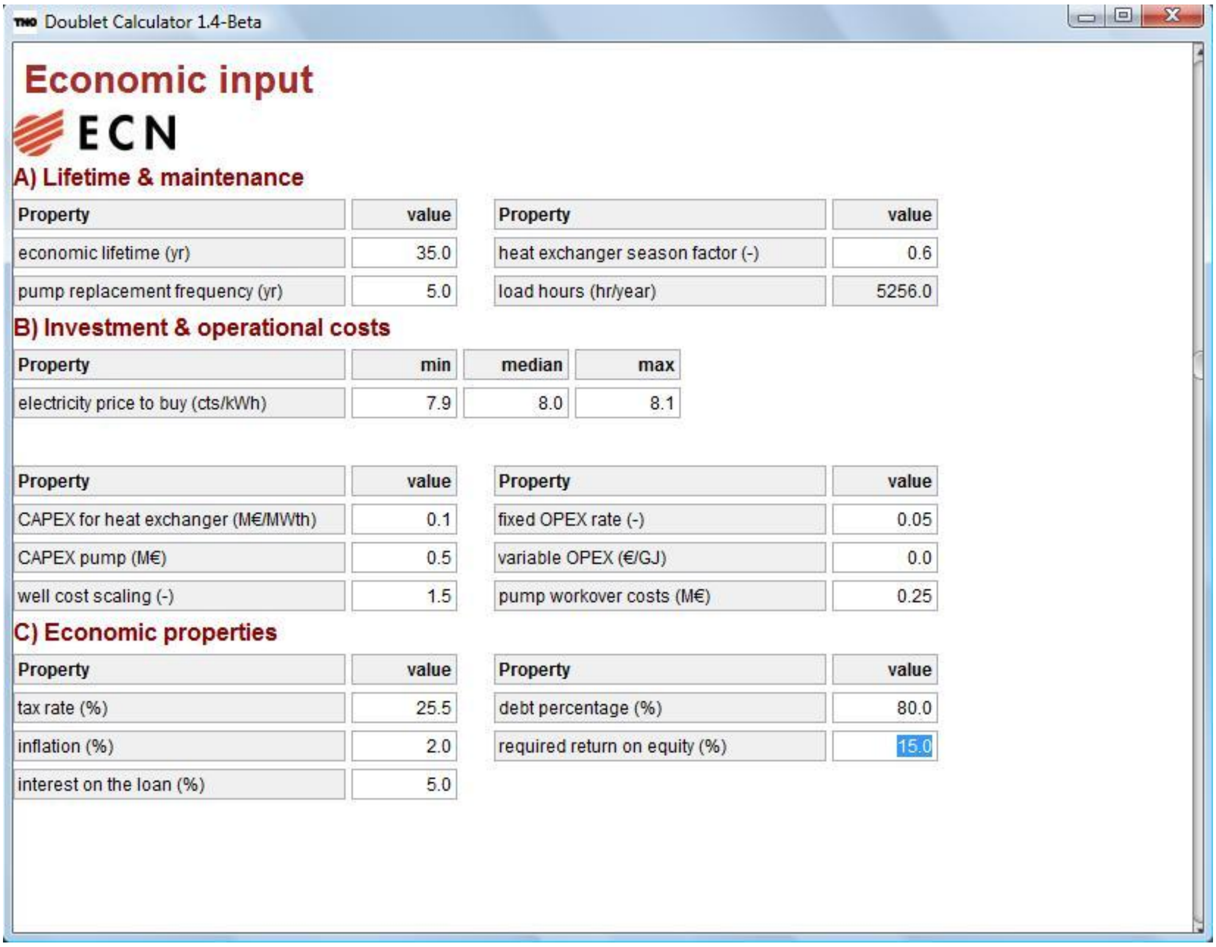
[ ] optional

Economic input

ECN

A) Lifetime & maintenance

Property	value	Property	value



Economic input

A) Lifetime & maintenance

Property	value	Property	value
economic lifetime (yr)	35.0	heat exchanger season factor (-)	0.6
pump replacement frequency (yr)	5.0	load hours (hr/year)	5256.0

B) Investment & operational costs

Property	min	median	max
electricity price to buy (cts/kWh)	7.9	8.0	8.1

Property	value	Property	value
CAPEX for heat exchanger (M€/MWth)	0.1	fixed OPEX rate (-)	0.05
CAPEX pump (M€)	0.5	variable OPEX (€/GJ)	0.0
well cost scaling (-)	1.5	pump workover costs (M€)	0.25

C) Economic properties

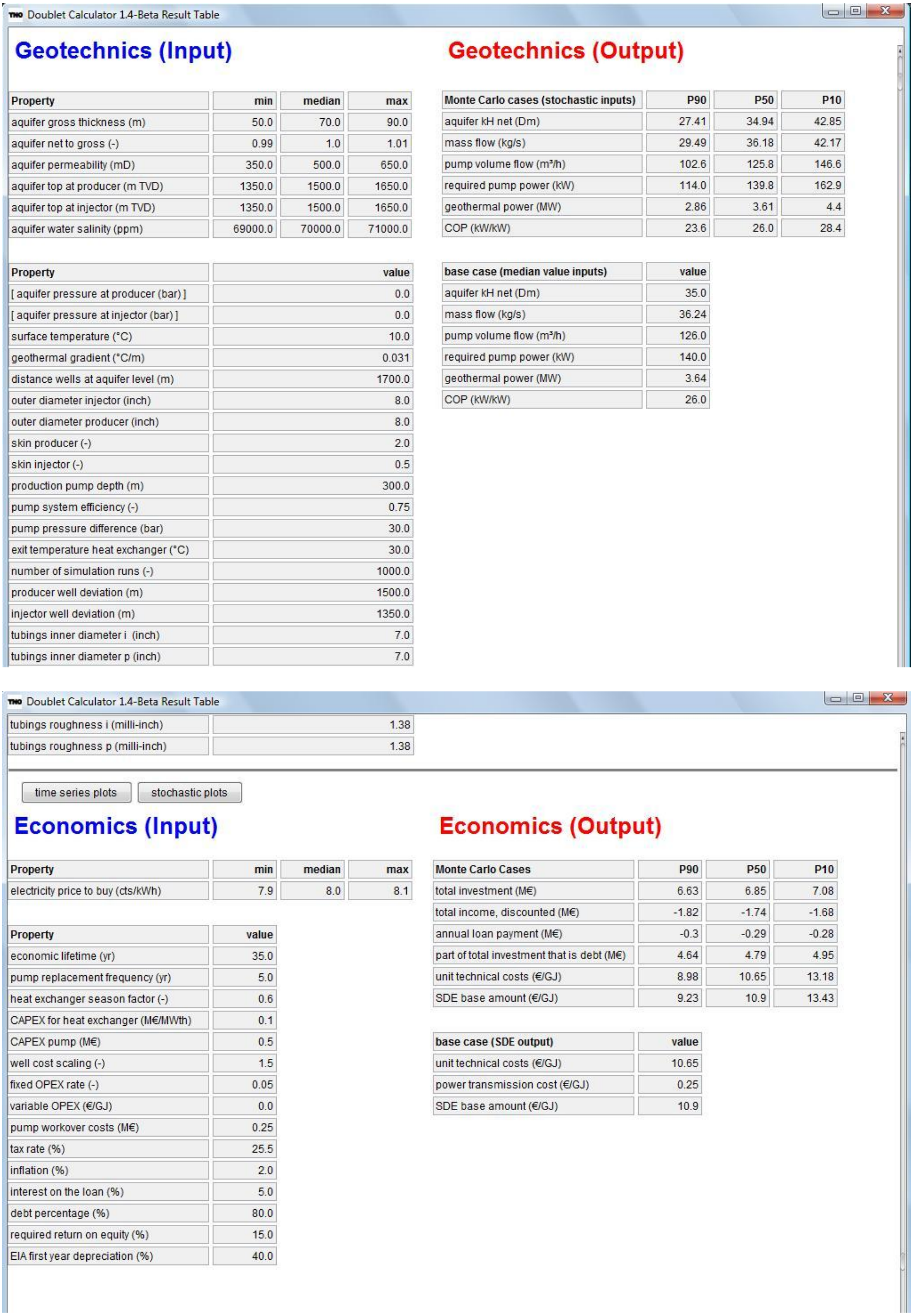
Property	value	Property	value
tax rate (%)	25.5	debt percentage (%)	80.0
inflation (%)	2.0	required return on equity (%)	15.0
interest on the loan (%)	5.0		

Figure 4.4 a, b, and c: Collectively, the input screen of DoubletCalc (Heat version).

These three figures show the input screen. The first describes the geological conditions of the targeted reservoir, the second the technical details needed to drill there, and the third the economic conditions of the project.

When all the fields have been adapted to the user's satisfaction, the user should press "Calculate!" and the system will start processing. Should any input variables have been improperly entered, such as a negative permeability or if the minimum and maximum of a distribution don't make sense, an error message will appear. If everything runs smoothly, an extra window with the output screen appears.

Using the default input values, the following Output screens come up:



Geotechnics (Input)

Property	min	median	max
aquifer gross thickness (m)	50.0	70.0	90.0
aquifer net to gross (-)	0.99	1.0	1.01
aquifer permeability (mD)	350.0	500.0	650.0
aquifer top at producer (m TVD)	1350.0	1500.0	1650.0
aquifer top at injector (m TVD)	1350.0	1500.0	1650.0
aquifer water salinity (ppm)	69000.0	70000.0	71000.0

Property	value
[aquifer pressure at producer (bar)]	0.0
[aquifer pressure at injector (bar)]	0.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.031
distance wells at aquifer level (m)	1700.0
outer diameter injector (inch)	8.0
outer diameter producer (inch)	8.0
skin producer (-)	2.0
skin injector (-)	0.5
production pump depth (m)	300.0
pump system efficiency (-)	0.75
pump pressure difference (bar)	30.0
exit temperature heat exchanger (°C)	30.0
number of simulation runs (-)	1000.0
producer well deviation (m)	1500.0
injector well deviation (m)	1350.0
tubings inner diameter i (inch)	7.0
tubings inner diameter p (inch)	7.0
tubings roughness i (milli-inch)	1.38
tubings roughness p (milli-inch)	1.38

Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	27.41	34.94	42.85
mass flow (kg/s)	29.49	36.18	42.17
pump volume flow (m³/h)	102.6	125.8	146.6
required pump power (kW)	114.0	139.8	162.9
geothermal power (MW)	2.86	3.61	4.4
COP (kW/kW)	23.6	26.0	28.4

base case (median value inputs)	value
aquifer kH net (Dm)	35.0
mass flow (kg/s)	36.24
pump volume flow (m³/h)	126.0
required pump power (kW)	140.0
geothermal power (MW)	3.64
COP (kW/kW)	26.0

Economics (Input)

Property	min	median	max
electricity price to buy (cts/kWh)	7.9	8.0	8.1

Property	value
economic lifetime (yr)	35.0
pump replacement frequency (yr)	5.0
heat exchanger season factor (-)	0.6
CAPEX for heat exchanger (M€/MWth)	0.1
CAPEX pump (M€)	0.5
well cost scaling (-)	1.5
fixed OPEX rate (-)	0.05
variable OPEX (€/GJ)	0.0
pump workover costs (M€)	0.25
tax rate (%)	25.5
inflation (%)	2.0
interest on the loan (%)	5.0
debt percentage (%)	80.0
required return on equity (%)	15.0
EIA first year depreciation (%)	40.0

Economics (Output)

Monte Carlo Cases	P90	P50	P10
total investment (M€)	6.63	6.85	7.08
total income, discounted (M€)	-1.82	-1.74	-1.68
annual loan payment (M€)	-0.3	-0.29	-0.28
part of total investment that is debt (M€)	4.64	4.79	4.95
unit technical costs (€/GJ)	8.98	10.65	13.18
SDE base amount (€/GJ)	9.23	10.9	13.43

base case (SDE output)	value
unit technical costs (€/GJ)	10.65
power transmission cost (€/GJ)	0.25
SDE base amount (€/GJ)	10.9

Figure 4.5 a and b: Collectively the Output screen of DoubletCalc (Heat version).

On the left, the input values are repeated, so that the user knows where these figures came from. On the right, the geotechnical and economic outputs are shown. The key output is the UTC, but other output values are also displayed, such as the total CAPEX, the total expenditures over time and subcomponents of those such as the annual loan payment.

Both the geotechnical and economic section have additional buttons labelled "Time Series Plots" and "Stochastic Plots". These buttons lead to graphs which display, respectively, the time dependent variables varying over time and the Monte Carlo plots for time independent variables.

Time dependent variables such as Interest part of the Loan Payment. This graph represents the annual cost of debt over all the Monte Carlo iterations. The five lines stand for the range of possibilities depending on circumstances. Minimum and maximum designate the most extreme scenarios, and P10, P50 and P90 stand for the likelihood that the interest part of the loan payment is over that value out of a hundred. The interest is less every consecutive year as more of the principal has been paid off by that time, reducing the interest. The graph is negative, representing the fact that the owner loses less money over time to interest payments.

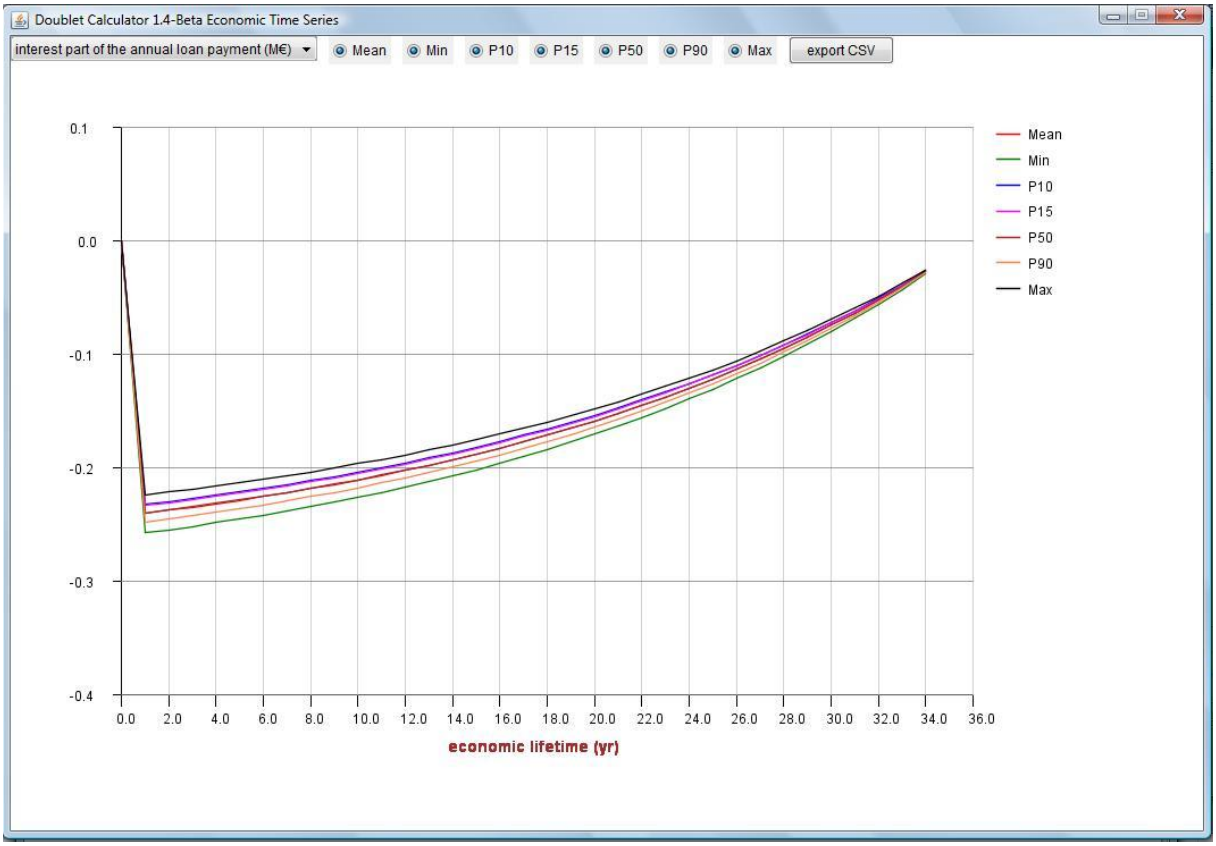


Figure 4.6 The interest payment per year, one of the output graphs of DoubletCalc.

The discounted yearly expenses, seen in the Figure below, represent the outflow of cash due to operation and maintenance costs. The sharp peaks every five years are due to the replacement of the ESP, which is a necessary but relatively expensive operation. The frequency and cost are among the adaptable input variables.

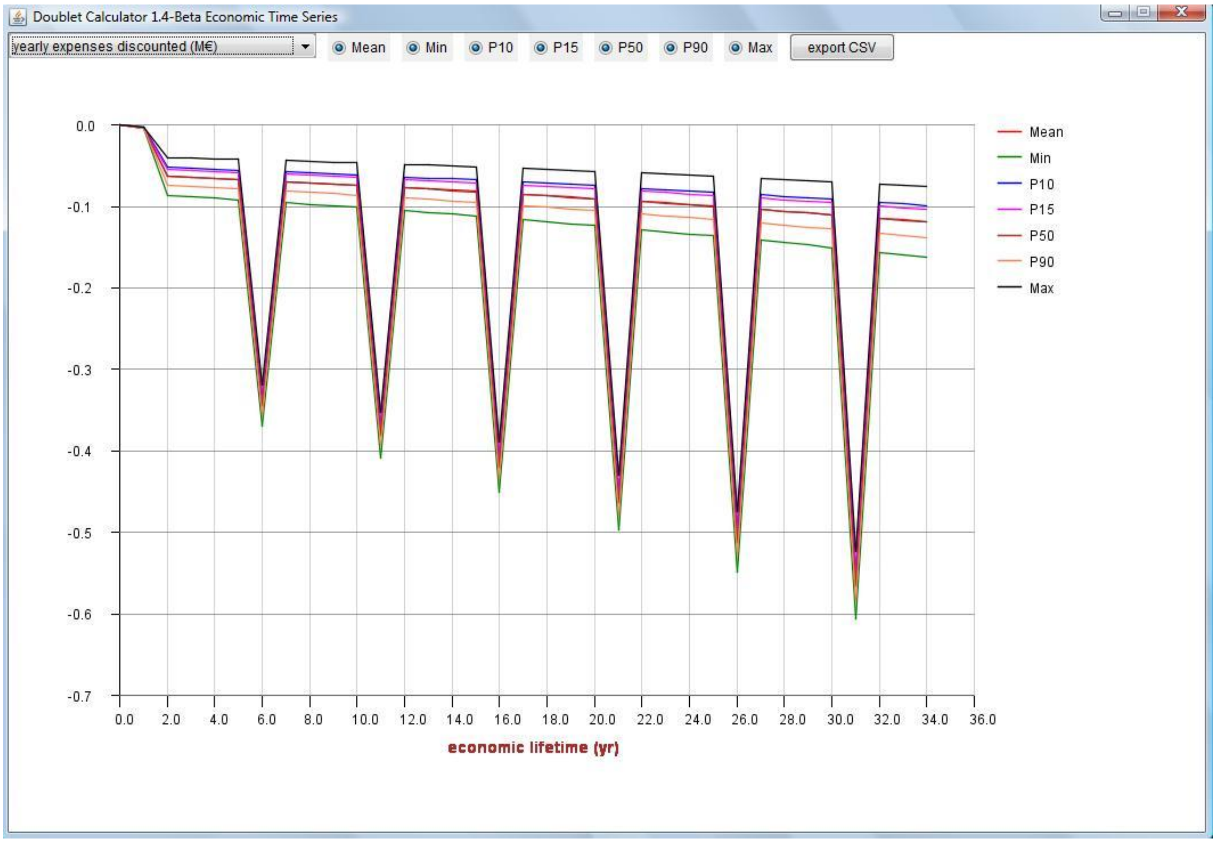


Figure 4.7 The yearly expenses payment, one of the output graphs of DoubletCalc.

The taxable income is the sum of several outgoing cash flows, including the operational costs, depreciation of the plant, and the interest part of the payment. These are considered business expenses, and thus taxed under Dutch business tax law, since it is assumed that businesses making profits in one part of their operation invest those profits in other parts of their company. Again, the sharp peaks of the pump replacement are clearly seen in this curve. Because this is looked at as income, the values are all negative since they are outgoing cash flows.

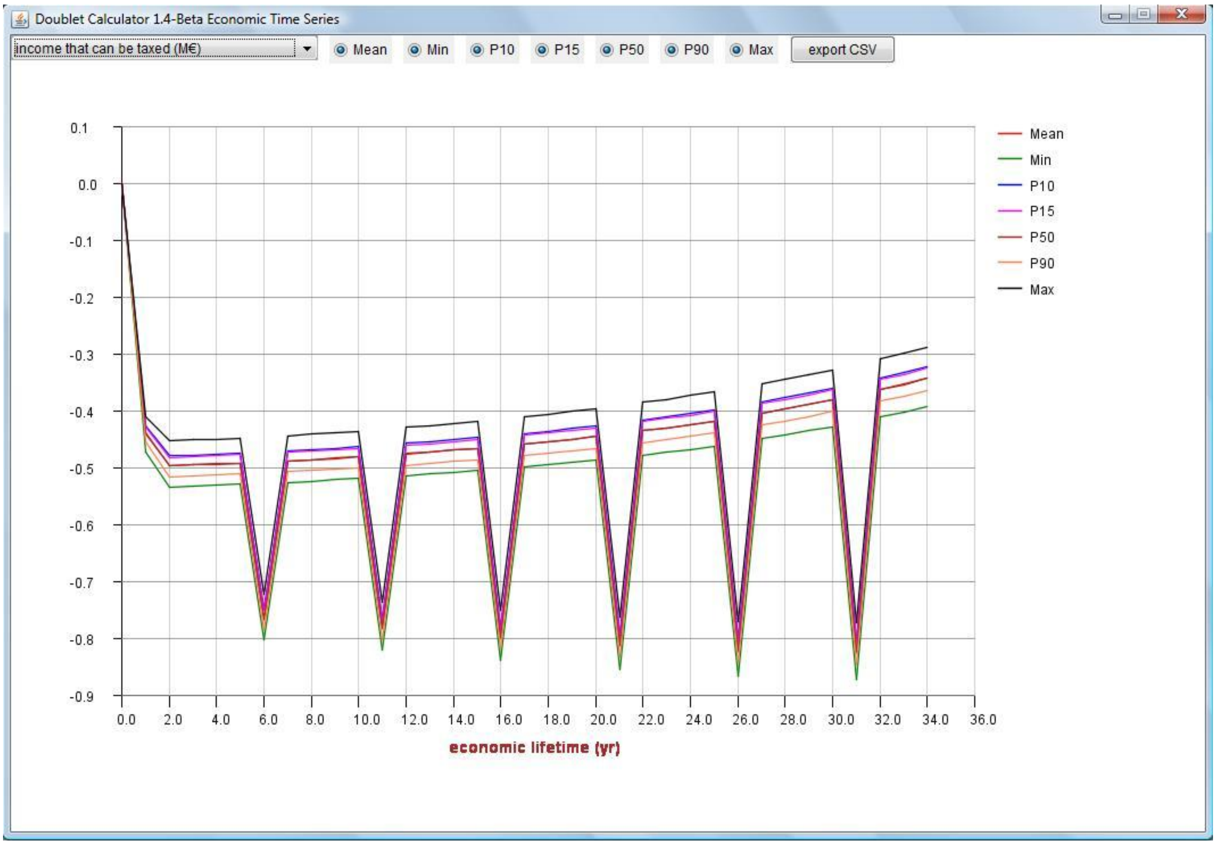


Figure 4.8 The taxable income of the project, one of the output graphs of DoubletCalc. Note that the y-axis is negative.

The taxes paid yearly are simply a function of the taxable income and the tax rate. It is a positive amount because, under Dutch tax law, it is effectively added to the yearly income (a negative amount), from a different, profitable unit of the company.

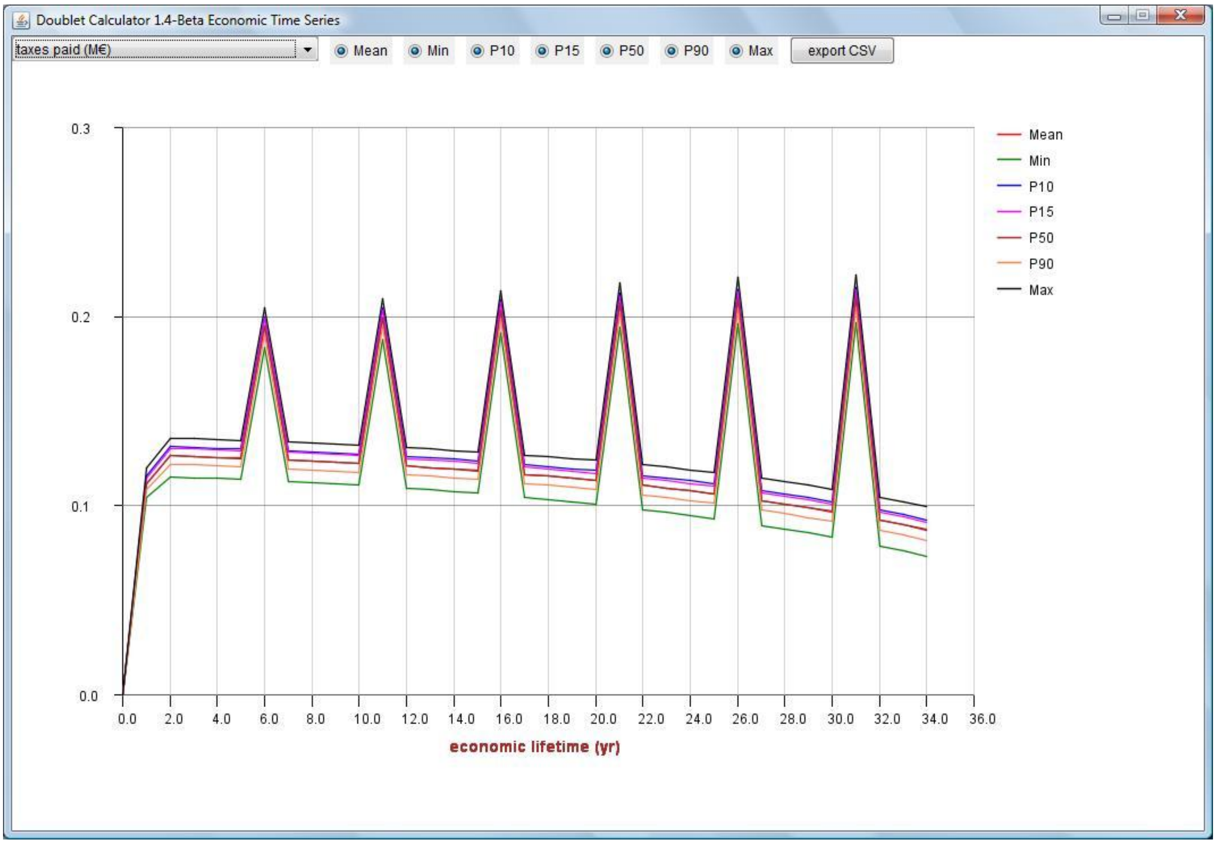


Figure 4.9: The yearly paid taxes is also an output graph of DoubletCalc.

The Net Income after taxes is also displayed.

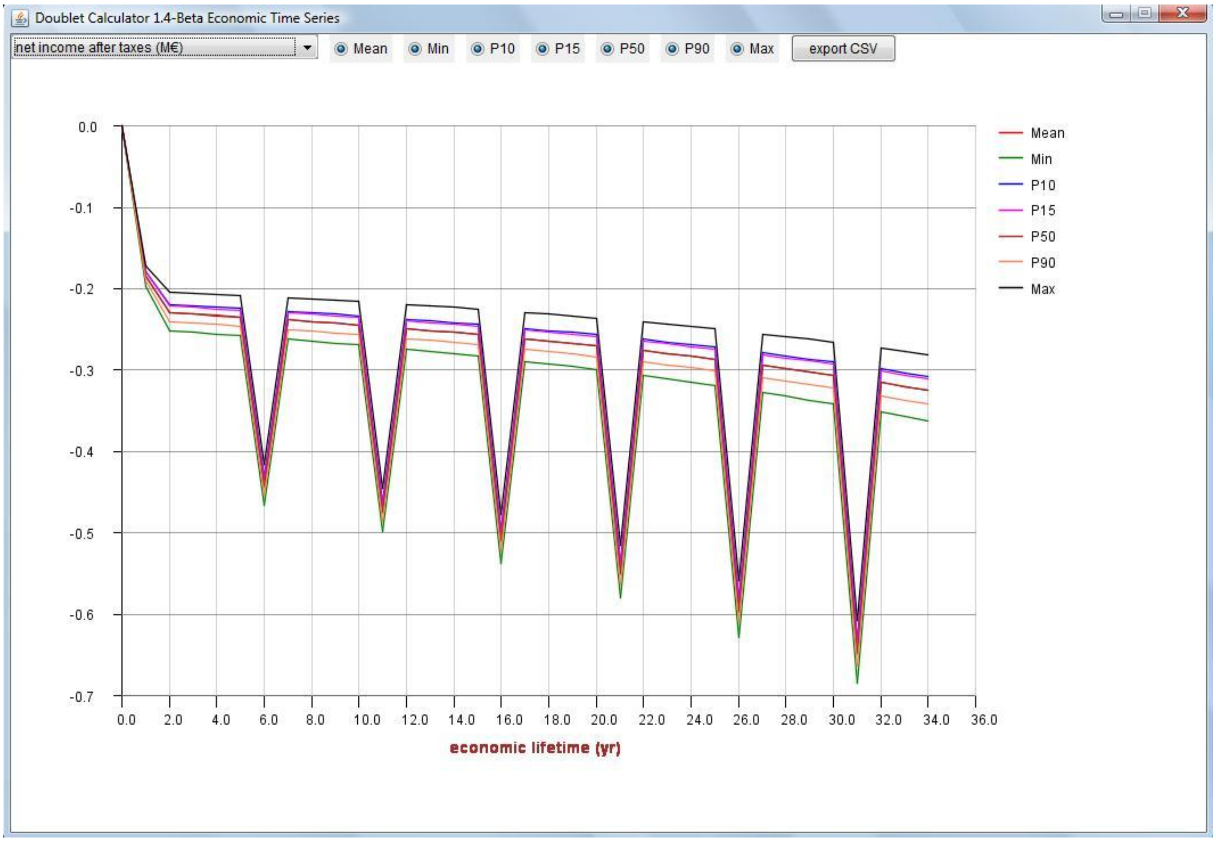


Figure 4.10: The Net Income after taxes, another output graph of DoubletCalc.

This is useful for an exploiter who needs to know what the annual cashflows will look like. A summation graph, with all of the above, is also available.

Some variables are not time dependent, or are aggregate results over the lifetime of the project. Such time independent variables are shown as a Monte Carlo (MC) curve, which displays the values resulting from each MC simulation, such as the predicted initial capital investment shown below.

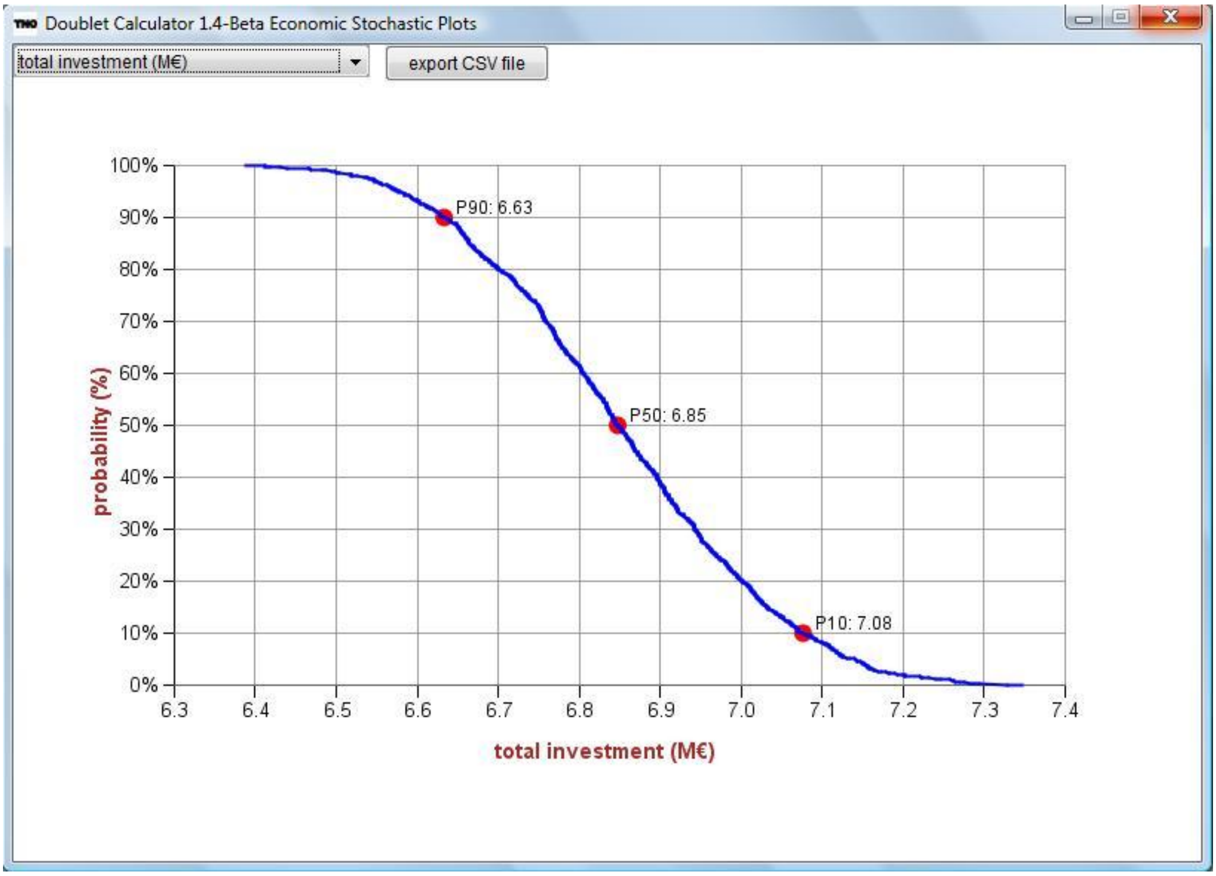


Figure 4.11: This is a probability distribution of the total investment, one of the available graphs in DoubletCalc.

P90, P50 and P10 refer to the chance that the given value is above that number. So a P90 of 6.63 M€ means that there is a 90% chance the initial capital investment is above 6.63 M€.

Also shown are the expected cumulative discounted total expenses, not including capital expenditures.

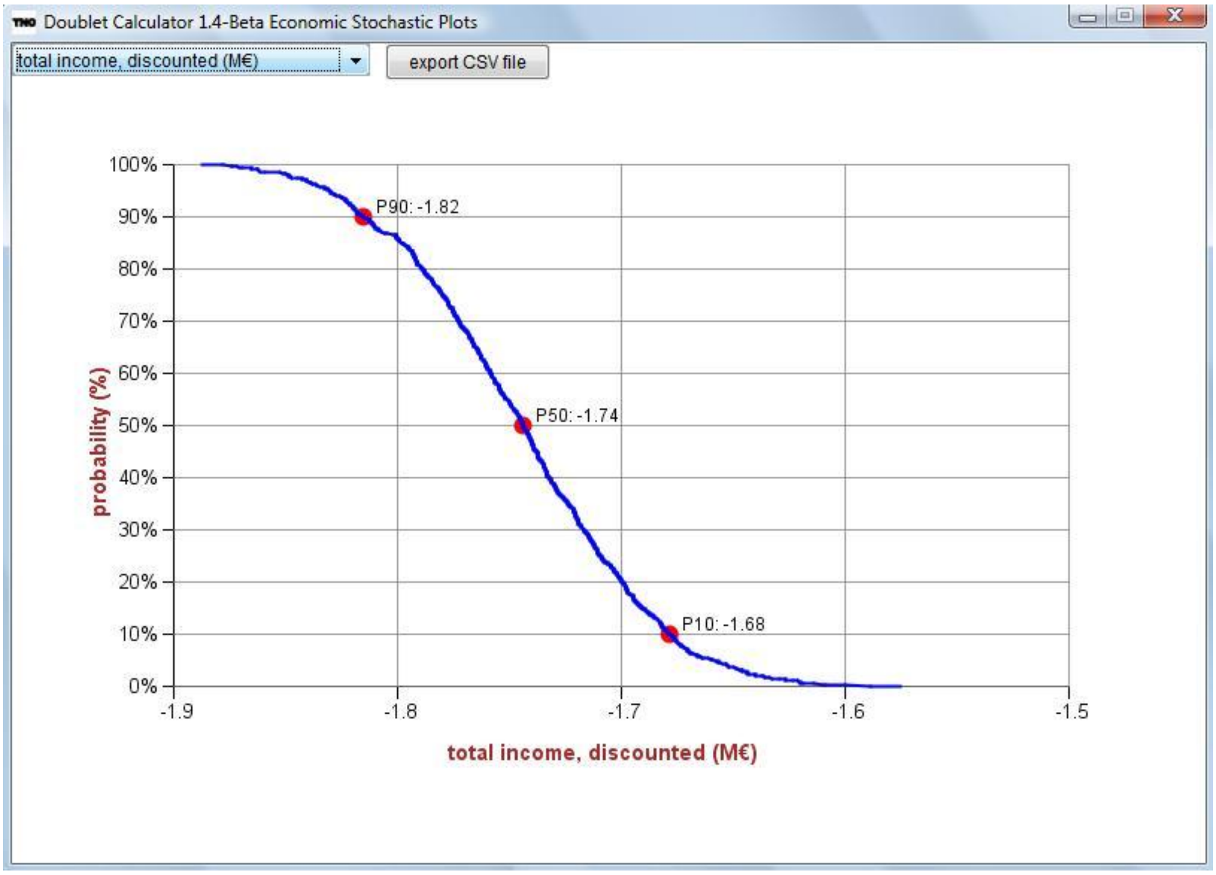


Figure 4.12: A probability distribution of the cumulative discounted total income.

And most crucially, the expected Unit Technical Cost:

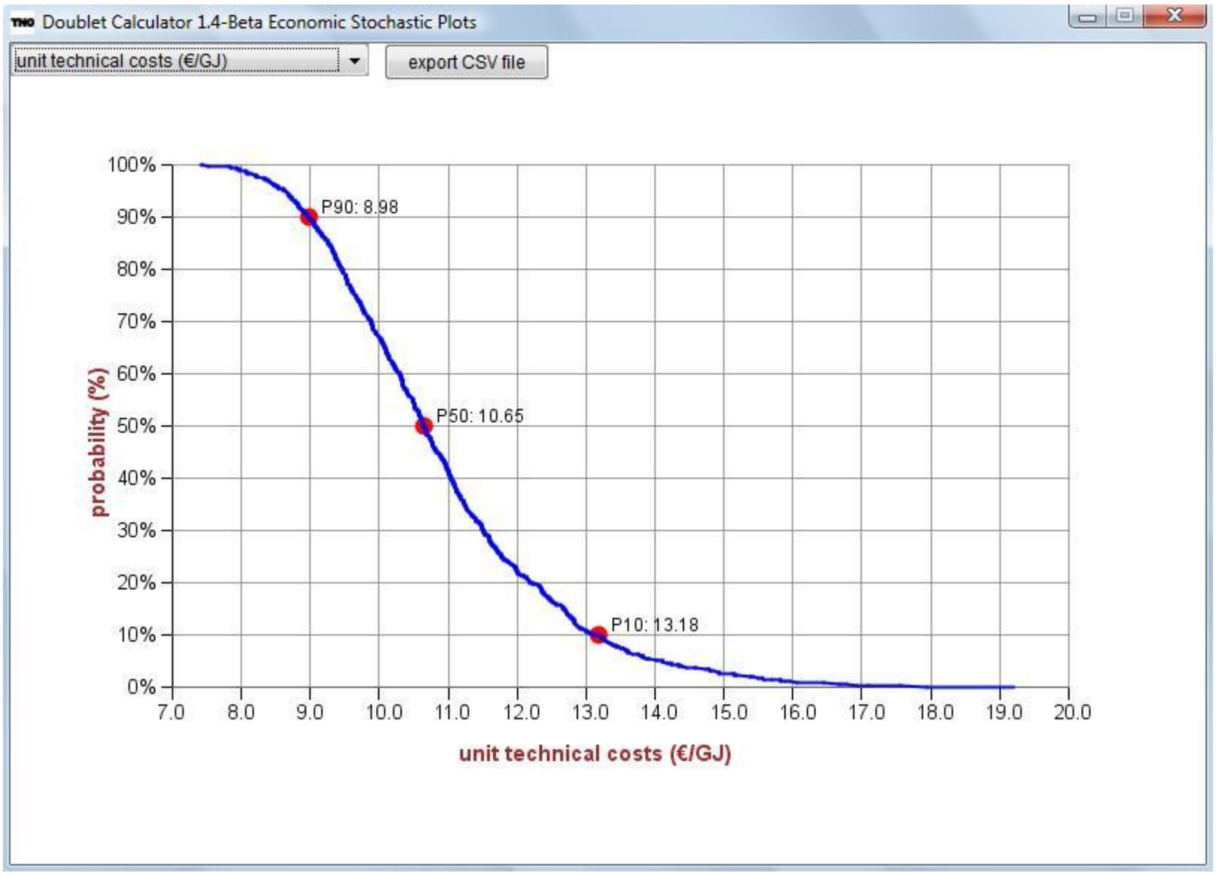
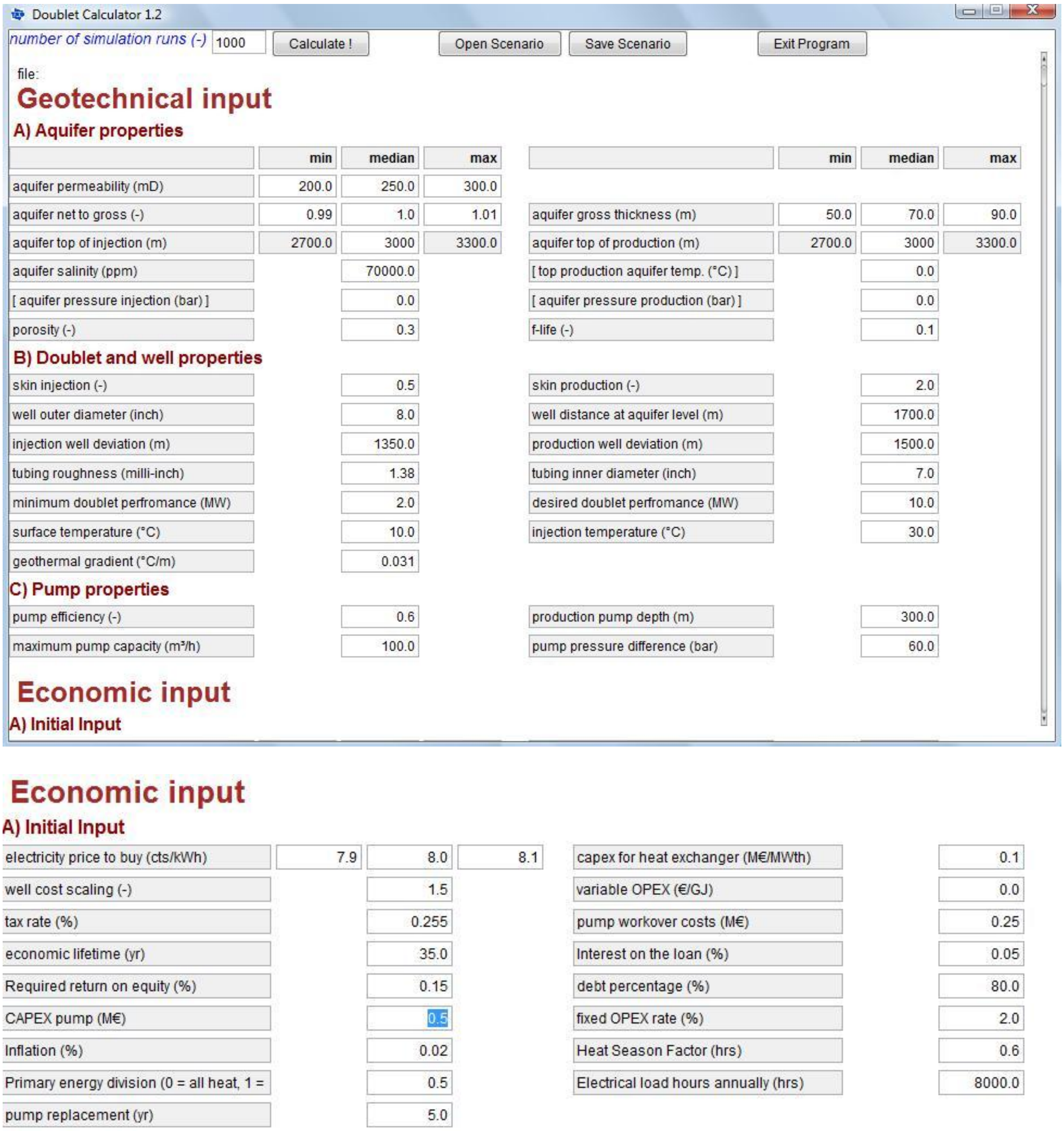


Figure 4.13: A probability distribution of the Unit Technical Cost, another output screen available on DoubletCalc.

This project is thus 50% likely to result in a UTC of at least 10.65 €/GJ. The 90% guarantee, often required by investors, for this project is a UTC of 13.18 €/GJ, which is relatively expensive. For comparison's sake, the ECN SDE+ reference scenario for heat production results in a UTC 10.65 €/GJ.

4.3.2 Heat and Electricity Model

An adaptation of the original model also allows for the (co-)production of electricity by using a factor to divide the primary energy to heat and electricity purposes. For this model, the input screens are slightly different, including the primary energy divisor, separate load hours for electricity and heat production, and additional capital investment costs.



number of simulation runs (-) 1000

file:

Geotechnical input

A) Aquifer properties

	min	median	max		min	median	max
aquifer permeability (mD)	200.0	250.0	300.0				
aquifer net to gross (-)	0.99	1.0	1.01	aquifer gross thickness (m)	50.0	70.0	90.0
aquifer top of injection (m)	2700.0	3000	3300.0	aquifer top of production (m)	2700.0	3000	3300.0
aquifer salinity (ppm)		70000.0		[top production aquifer temp. (°C)]		0.0	
[aquifer pressure injection (bar)]		0.0		[aquifer pressure production (bar)]		0.0	
porosity (-)		0.3		f-life (-)		0.1	

B) Doublet and well properties

skin injection (-)		0.5		skin production (-)		2.0	
well outer diameter (inch)		8.0		well distance at aquifer level (m)		1700.0	
injection well deviation (m)		1350.0		production well deviation (m)		1500.0	
tubing roughness (milli-inch)		1.38		tubing inner diameter (inch)		7.0	
minimum doublet perfromance (MW)		2.0		desired doublet perfromance (MW)		10.0	
surface temperature (°C)		10.0		injection temperature (°C)		30.0	
geothermal gradient (°C/m)		0.031					

C) Pump properties

pump efficiency (-)		0.6		production pump depth (m)		300.0	
maximum pump capacity (m³/h)		100.0		pump pressure difference (bar)		60.0	

Economic input

A) Initial Input

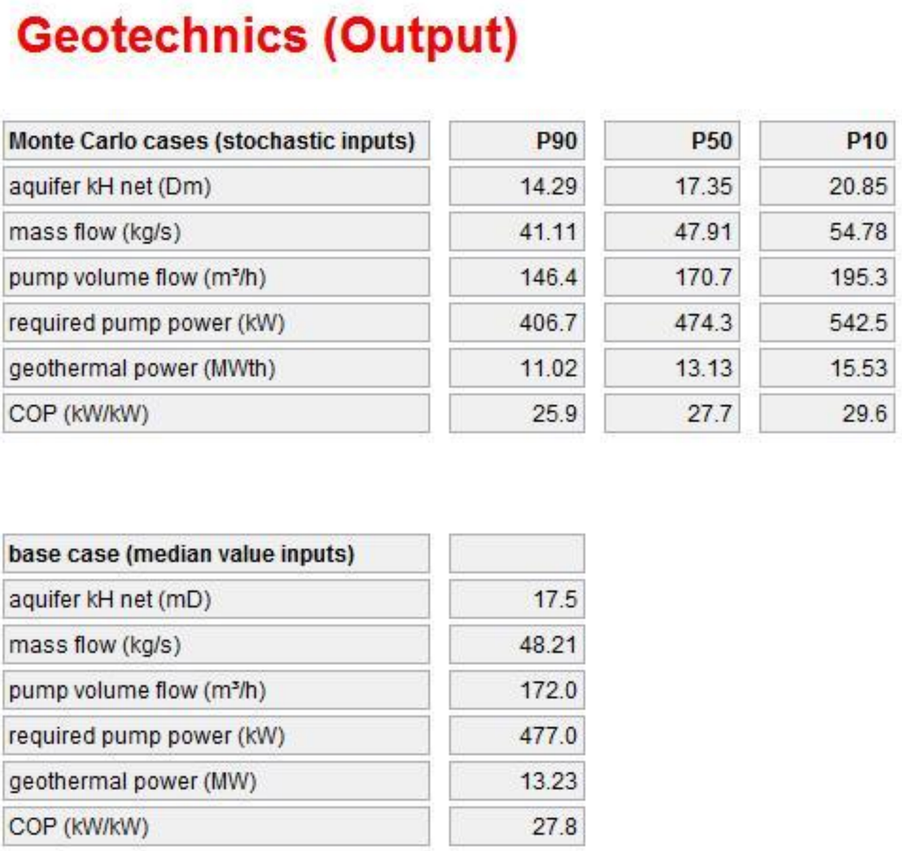
Economic input

A) Initial Input

electricity price to buy (cts/kWh)	7.9	8.0	8.1	capex for heat exchanger (M€/MWth)	0.1
well cost scaling (-)		1.5		variable OPEX (€/GJ)	0.0
tax rate (%)		0.255		pump workover costs (M€)	0.25
economic lifetime (yr)		35.0		Interest on the loan (%)	0.05
Required return on equity (%)		0.15		debt percentage (%)	80.0
CAPEX pump (M€)		0.5		fixed OPEX rate (%)	2.0
Inflation (%)		0.02		Heat Season Factor (hrs)	0.6
Primary energy division (0 = all heat, 1 =		0.5		Electrical load hours annually (hrs)	8000.0
pump replacement (yr)		5.0			

Figure 4.14a and b: Together, the input screen of the CHP version of DoubletCalc.

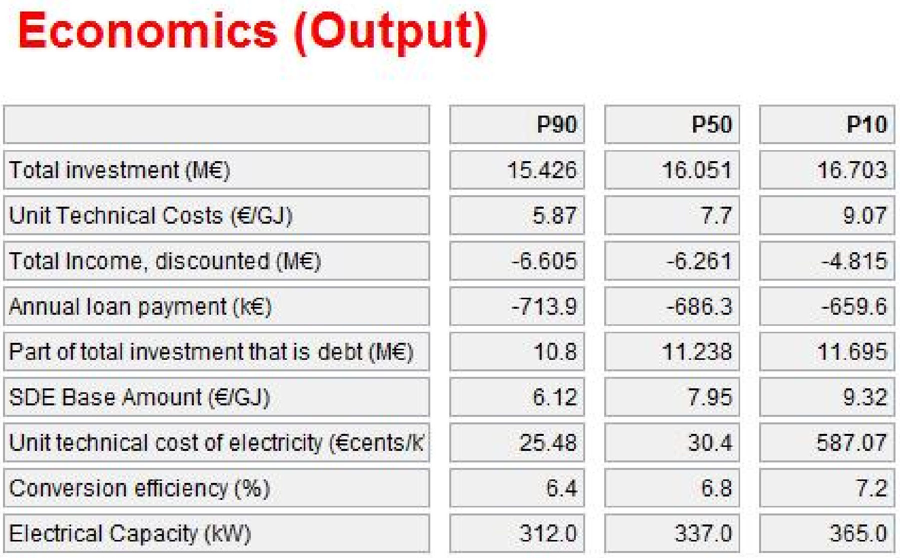
As a demonstration, the input values shown above were used for this project. Taking a generic project at 3000 m depth, a regular geothermal gradient and with a 50%/50% primary energy division, the following results are yielded:



Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	14.29	17.35	20.85
mass flow (kg/s)	41.11	47.91	54.78
pump volume flow (m³/h)	146.4	170.7	195.3
required pump power (kW)	406.7	474.3	542.5
geothermal power (MWth)	11.02	13.13	15.53
COP (kW/kW)	25.9	27.7	29.6

base case (median value inputs)	
aquifer kH net (mD)	17.5
mass flow (kg/s)	48.21
pump volume flow (m³/h)	172.0
required pump power (kW)	477.0
geothermal power (MW)	13.23
COP (kW/kW)	27.8



Economics (Output)

	P90	P50	P10
Total investment (M€)	15.426	16.051	16.703
Unit Technical Costs (€/GJ)	5.87	7.7	9.07
Total Income, discounted (M€)	-6.605	-6.261	-4.815
Annual loan payment (k€)	-713.9	-686.3	-659.6
Part of total investment that is debt (M€)	10.8	11.238	11.695
SDE Base Amount (€/GJ)	6.12	7.95	9.32
Unit technical cost of electricity (€cents/k	25.48	30.4	587.07
Conversion efficiency (%)	6.4	6.8	7.2
Electrical Capacity (kW)	312.0	337.0	365.0

Figure 4.15a and b: Together, part of the Output screen of the CHP version of DoubletCalc.

The output values above were produced. Note that the UTC for heat is quite low at a P50 of 7.70 €/GJ, while the UTC for electricity is remarkably high at a P50 of 30.4 €ct/kWh. Also curious is the very high P10 of 5.97€/kWh. This is because, at this temperature, production of electricity is not efficient at all, and parasitic demand from the pumps is relatively high. It would not be recommended to start a CHP geothermal project at such a location.

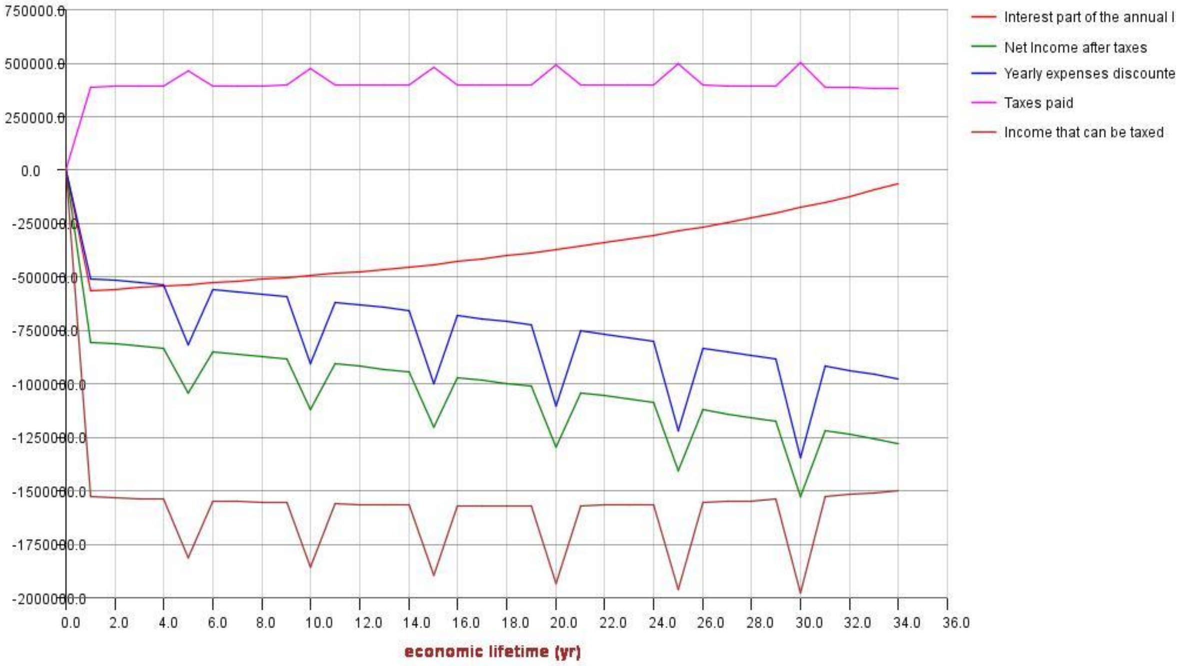


Figure 4.16: The summary screen of variables changeable over time, available in DoubletCalc.

The graph above shows the variation over time of the time-dependent variables. Yearly costs are higher than the geothermal heat project and pump replacement costs play a proportionally smaller role than in the Heat only model.

4.3.3 Factors affecting cost

One of the research sub-questions addresses which factors have the most significant influence on costs. This can be determined from the model, by creating a so-called Spider Diagram. For this diagram, a base case is chosen and the UTC calculated of that situation. Next, several main variables are each individually modified to determine the effect of that mutation on the UTC. These results are then collated in Excel and graphically represented, giving a clear visual indication of which variables have the most significant effect on the UTC.

This was done for a heat-only plant with the following base case variables:

Variable	Value
Permeability (mad)	500
Depth (m)	2000
Return T (degrees C)	30
Temperature Gradient (C/m)	0,031
Well Cost Scaling (-)	1,5
Lifetime (yr)	30
Debt Percentage (%)	80

Interest rate (%)	5
Load Hours	5256

Table 4.2: the basic settings of a hypothetical project tested in DoubletCalc.

The base case UTC was 7.23 €/GJ. The resulting Spider Diagram is the Figure below:

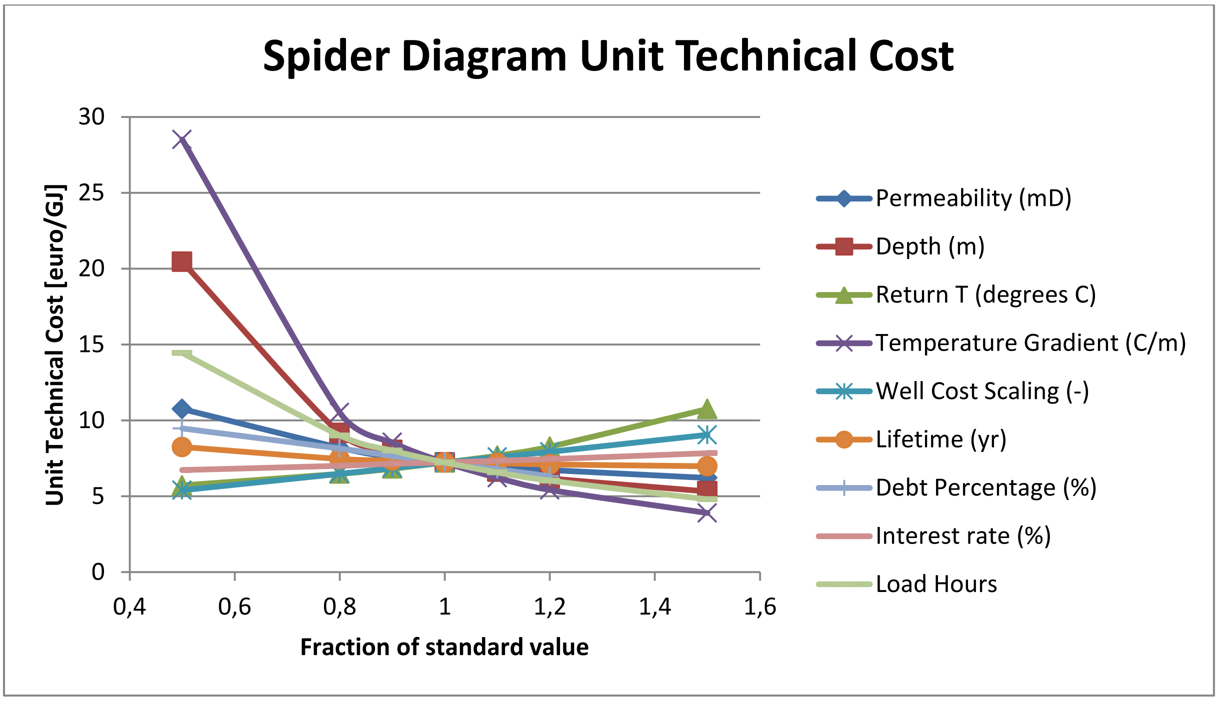


Figure 4.17: A Spider diagram showing the effect of certain variables on the UTC for a hypothetical project.

The variable with the greatest effect on UTC is the temperature gradient, followed by the depth. Intriguingly, both of these are geological variables, implying that accurate knowledge of the reservoir conditions is critical for an accurate budget proposal. The next three most influential variables are the load hours, the return temperature and the permeability. The latter of these is another geological variable, and the former two are technical. Economic variables such as interest rate and debt percentage are actually of relatively little influence on the UTC.

4.3.4 Effect of Government policy

There are three government policies examined: the effect of a lump sum subsidy such as the MEI, the effect of paying the premium for a government guarantee of the project, and the effect of the additional cost of a blowout preventer and hydrocarbon separator. Taken in isolation, the effects of these policies are roughly analysed by modification of the investment costs, as shown in the Figure below. These effects are calculated relative to a project with the default conditions of the CHP model, except that the permeability is set to 200 Dm, with only the depth changing as per the y-axis.

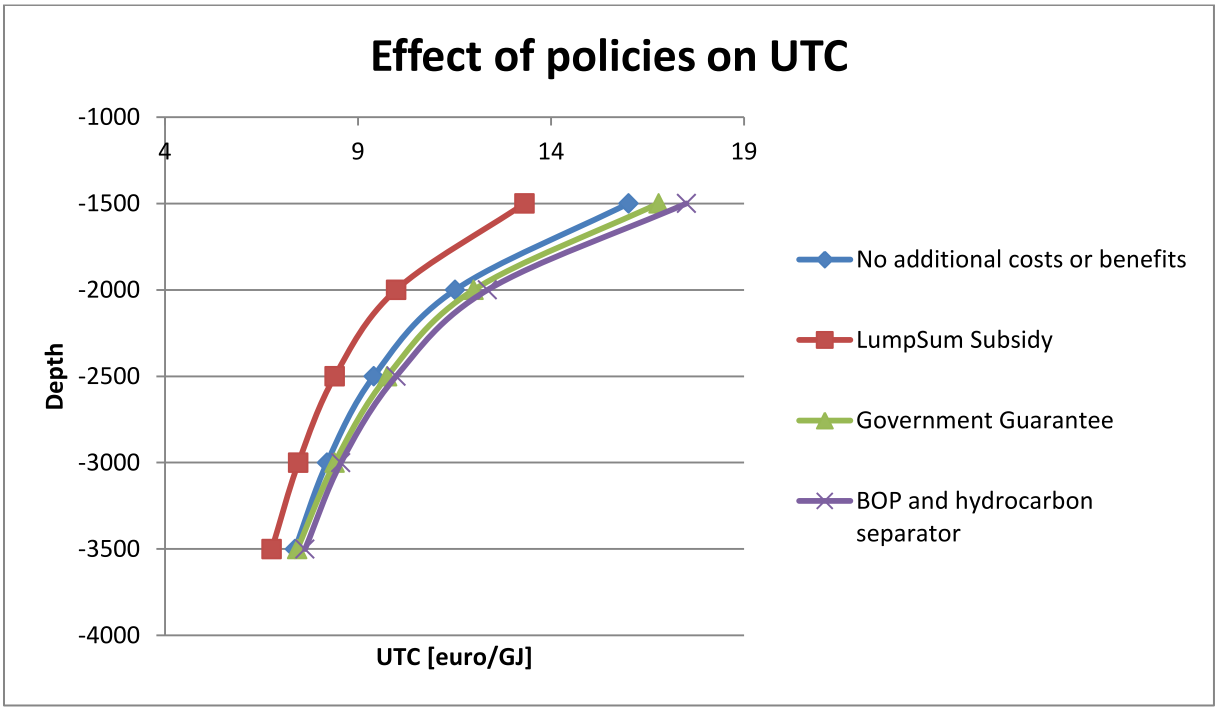


Figure 4.18 Effects on UTC of isolated policies.

These policies, in isolation have the most effect when depth is small, as investment costs are also relatively low. The effect of a lump sum subsidy is quite noticeable on the UTC, reducing it by at least 0.6€/GJ for this project. However, compared with the SDE+, which would effectively reduce the UTC to the correction rate, the lump sum cannot be seen as the preferred option.

The effect of the premium is quite small, although private insurance may be more expensive. This UTC increase ranges from 0.06€/GJ for the deepest to 0.60€/GJ for the shallowest project. This needs to be weighed against a possible payout of 85% of the investment to a maximum of only 7.2M€. It will be up to individual developers to decide. The effect of the premium is quite small, especially if the SDE+ is allowed to take effect.

The BOP and hydrocarbon separator are additional costs that are prudent regardless of government policy, given the troubles experienced at some current projects. The UTC does rise with these additional investments, but this ranges from about 0.25€/GJ to 1.50€/GJ from deepest to shallowest. Given that the deeper projects are more attractive anyway; this may not be a significant setback.

4.3.5 Results with distance effects

Drilling of the wells is generally performed in a deviated fashion, so that the two wellheads are adjacent and there is no significant need for overland pipelines. At the aquifer level, the wells are significantly further apart. In this model, that distance is kept to at least 1700m to avoid thermal breakthrough during the economic lifetime of the project. Thermal breakthrough is when the cold water front from the injection well reaches the production well. Granted, this has been warmed somewhat by the surrounding rock, but it is usually the start of a precipitous decline in well productivity.

A small modification of the CHP model allows a look at the consequence of drilling directly vertical and using a pipeline to connect the two well heads.

P50	**WCS 1.5**					
		With deviated wells		With vertical wells and pipeline		
Depth	Capacity	Investment	UTC	Investment	UTC	Difference in UTC
m	MW	Meuro	euro/GJ	Meuro	euro/GJ	euro/GJ
1500	6,62	7,351	9,86	6,695	9,38	0,48
2000	11	9,46	7,12	8,534	6,66	0,46
3000	20,67	14,556	5,21	13	4,83	0,38
4000	32,04	20,843	4,5	18.532	4,11	0,39

Table 4.3: Results of deviated drilling versus using an overland pipeline.

It is clear that the cost of deviated drilling is more than the cost of laying a pipeline between the two wellheads. Why then are most modern geothermal facilities designed with deviated drilling?

One notion is likely to be ease. With the two well heads next to each other, there is no need to relocate the entire drilling operation for the second well, which can be an expensive and time consuming operation. Secondly, the linking of two wellheads separated by at least 1500m is not always an option, as the land may not be owned by the owner and there may be obstructions such as buildings, roads and streams. Thirdly, maintenance and security of the system is easier with the two wellheads near each other, and therefore likely cheaper too.

4.3.6 Results with delay effects

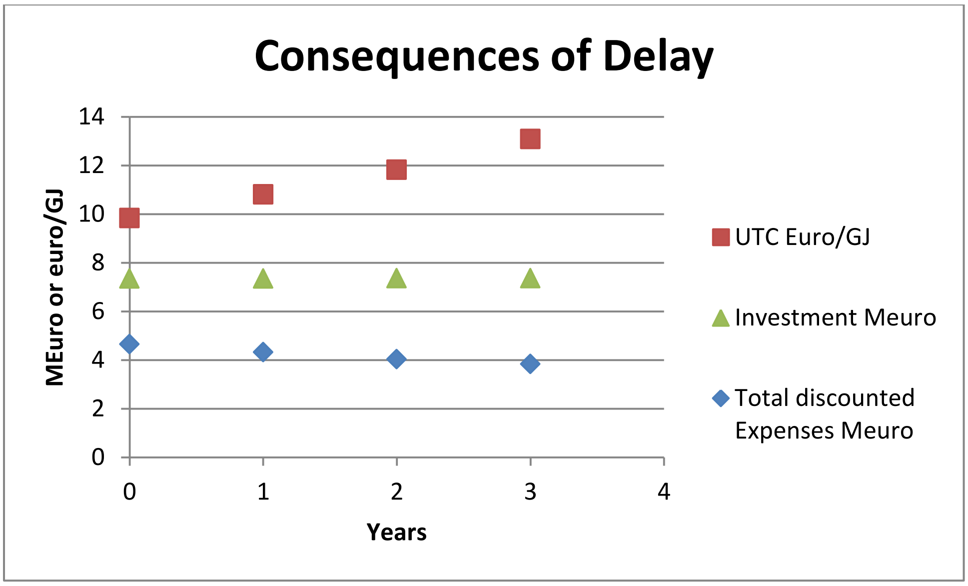


Figure 4.18: A graph showing the consequences of delay, in years, on UTC, investment and total discounted expenses.

The results of delay are increasing Unit Technical Cost: a rising trend of about an extra 1€/GJ per year. This is a significant increase, and clearly indicates that delays are unwanted. However, there are declining total discounted expenses. This is because the years of delay have sunk investment costs which need to be repaid, but no income in the form of heat produced. However, it should be noted that this analysis does not include the cost of replacing the energy that is now missing in the years of delay. If the owner has already signed Energy Purchasing Agreements, there will be significant additional costs attached to making these.

4.4 Testing of Model

This section describes the outcomes of a number of tests that have been performed to check the workings of the model. First, the model is checked against the ECN calculations for the SDE+ subsidy. Secondly, the model is compared with two potential projects in the Netherlands.

4.4.1 Checking model against ECN values

A useful check of the model is whether it agrees with the ECN calculations for the SDE+ subsidy. Since it is based on those, the two should produce similar results, despite the Monte Carlo approach. However, there are some differences in approach which need to be addressed for such a test.

In the SDE+ calculations, capital costs are calculated from a €/kW value (Lensink et al, 20XY), which in (Lako et al, 2011) is shown to be based on a €/m for drilling costs with additional investments added on. Capital costs thus need to be fixed at certain values in Eclipse.

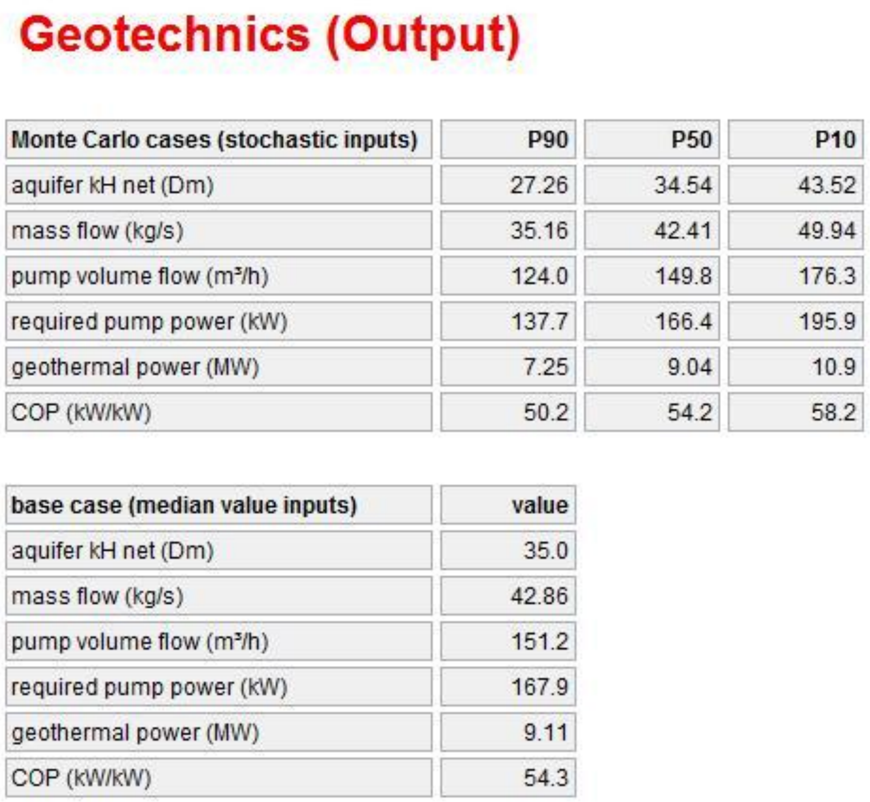
Similarly, the operational costs need to be fixed in Eclipse so that they correspond with the calculated SDE+ values. The uncertainties can be reduced by reducing the width of the variables defined by distributions. If these steps are taken, the SDE+ calculations and the output of this model will match. However, this removes some of the strengths of the model, namely the Monte Carlo analysis and the more detailed construction of investment and operational costs.

4.4.2 Check model against potential projects

A useful test of the tool is by running it against existing or planned projects to examine whether such values correspond to actual and otherwise predicted UTCs. Two projects being discussed at the Dutch level are the recently completed project of Honselaarsdijk, also known as Green Well Westland, and the planned project of Hoogeveen.

Honselaarsdijk

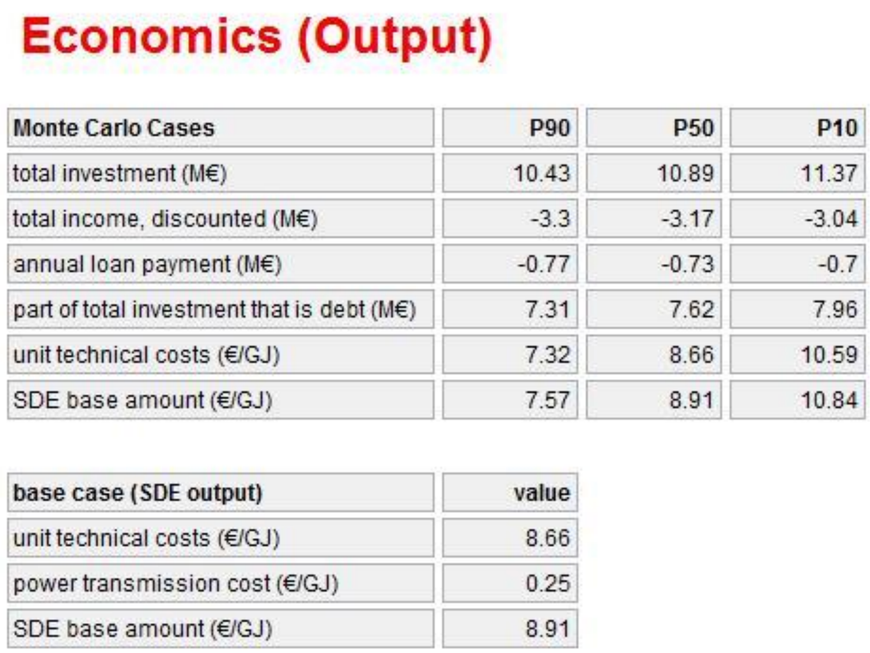
Honselaarsdijk is the Netherlands' newest geothermal project, with two wells drilled to a depth of 2850m producing water at a temperature of 85°C. This heat is used by five horticulturalists for heating their greenhouses. A small network has been laid to connect each greenhouse to the wells. The measure of collaboration and co-dependency among the horticulturalists is typical of future geothermal projects, as there are indications of cost-effectiveness of scaling effects. At the Geothermie Update in Amsterdam on the 18th of April and the PGK tour of the facility on the 9th of March, 2012, the co-exploiters of the well gave an indication of the cost of the wells and associated developments. Using the known starting values of the Honselaarsdijk project into the HEAT-only model, the following results emerge:



Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	27.26	34.54	43.52
mass flow (kg/s)	35.16	42.41	49.94
pump volume flow (m³/h)	124.0	149.8	176.3
required pump power (kW)	137.7	166.4	195.9
geothermal power (MW)	7.25	9.04	10.9
COP (kW/kW)	50.2	54.2	58.2

base case (median value inputs)	value
aquifer kH net (Dm)	35.0
mass flow (kg/s)	42.86
pump volume flow (m³/h)	151.2
required pump power (kW)	167.9
geothermal power (MW)	9.11
COP (kW/kW)	54.3



Economics (Output)

Monte Carlo Cases	P90	P50	P10
total investment (M€)	10.43	10.89	11.37
total income, discounted (M€)	-3.3	-3.17	-3.04
annual loan payment (M€)	-0.77	-0.73	-0.7
part of total investment that is debt (M€)	7.31	7.62	7.96
unit technical costs (€/GJ)	7.32	8.66	10.59
SDE base amount (€/GJ)	7.57	8.91	10.84

base case (SDE output)	value
unit technical costs (€/GJ)	8.66
power transmission cost (€/GJ)	0.25
SDE base amount (€/GJ)	8.91

Figure 4.19a and b: Together, the output screen of the test of Honselaarsdijk, having used publically available data as input or default values.

The key outputs from the screens above are the geothermal heat output, listed from 7.25 to 10.9 MWth, and the total investment, which has P90 to P10 values of 10.43 to 11.37 M€. While the

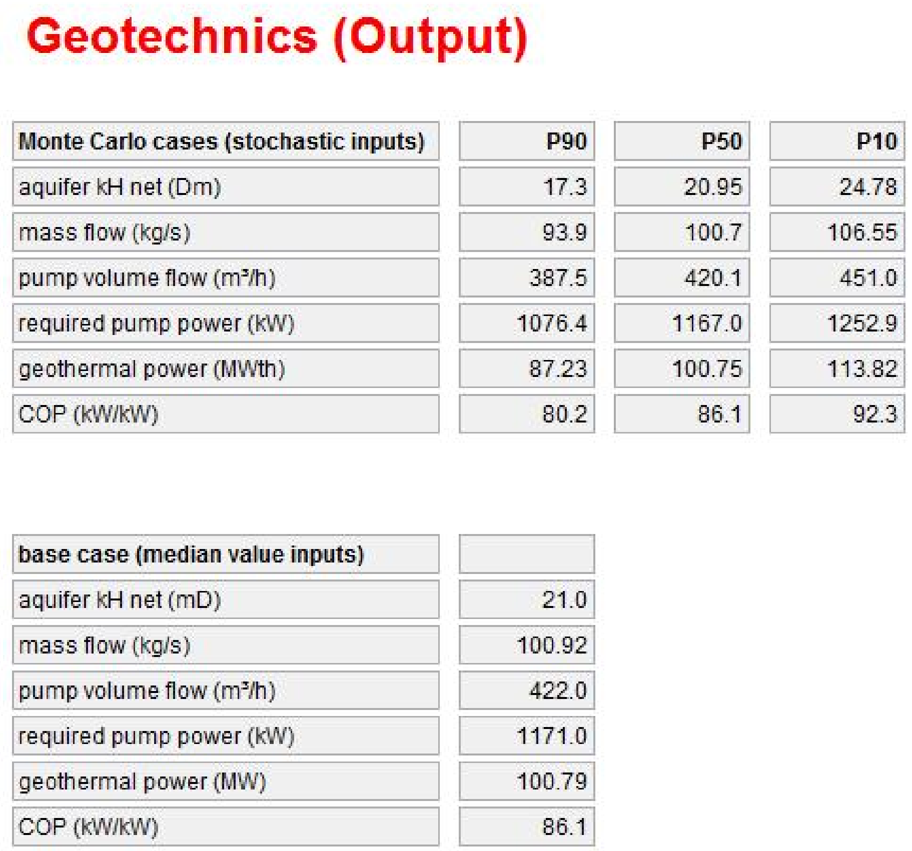
Honselaarsdijk project is still tallying up the total capacity of the plant and the cost of effectiveness, these values encompass the values predicted unofficially by those involved.

The predicted UTC is 8.66 €/GJ. This is clearly below the SDE+ base rate of 10.90 €/GJ, which further underlines the relative cost-effectiveness of this project. It is reasonable to assume that the most cost-effective projects are the ones implemented before the start of the SDE+ subsidy.

This test indicates that for standard geothermal projects in the Netherlands, the tool gives very reasonable results.

Hoogeveen

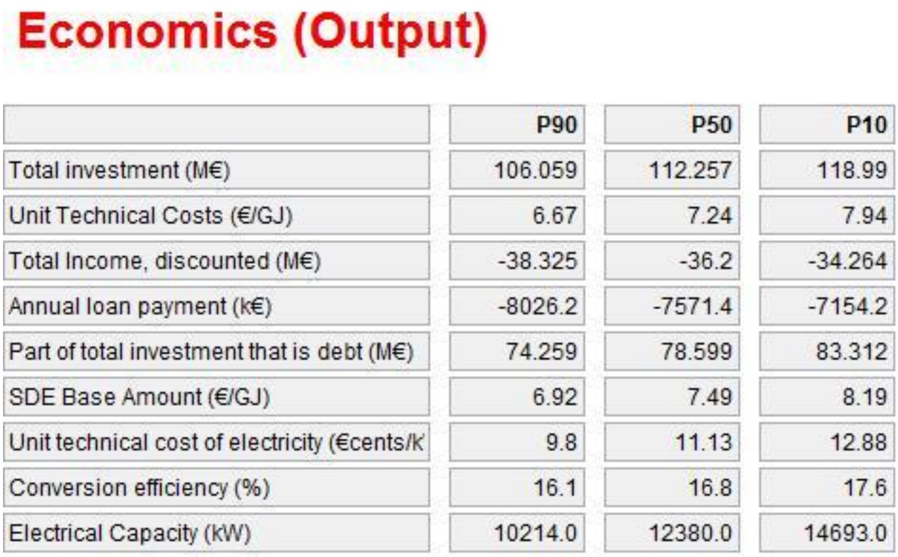
At a recent GEO-ELEC workshop in Utrecht, representatives of companies advising the Hoogeveen municipality presented their novel plan for Hoogeveen. Wells of 7 km deep are to be drilled to a likely porous layer, producing heat at a temperature of 270°C. This indicates a far higher geothermal gradient than is usual in other geothermal wells in the Netherlands. Useful permeability at such a depth is highly unlikely, so extensive fracking will be needed, costing up to 12M€ alone. The total cost of the project is estimated at over 132 M€, resulting in a facility producing around 12 MW electrical at 16% conversion efficiency and at least 40% of the primary energy will go to heat (Willemsen and Smeets, 2012). Therefore, this is a CHP project and the CHP model is tested. However, it should be mentioned that this is a highly unusual case, as no geothermal project currently exists at such a depth, neither in Europe nor elsewhere in the world.



Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	17.3	20.95	24.78
mass flow (kg/s)	93.9	100.7	106.55
pump volume flow (m³/h)	387.5	420.1	451.0
required pump power (kW)	1076.4	1167.0	1252.9
geothermal power (MWth)	87.23	100.75	113.82
COP (kW/kW)	80.2	86.1	92.3

base case (median value inputs)	
aquifer kH net (mD)	21.0
mass flow (kg/s)	100.92
pump volume flow (m³/h)	422.0
required pump power (kW)	1171.0
geothermal power (MW)	100.79
COP (kW/kW)	86.1



Economics (Output)

	P90	P50	P10
Total investment (M€)	106.059	112.257	118.99
Unit Technical Costs (€/GJ)	6.67	7.24	7.94
Total Income, discounted (M€)	-38.325	-36.2	-34.264
Annual loan payment (k€)	-8026.2	-7571.4	-7154.2
Part of total investment that is debt (M€)	74.259	78.599	83.312
SDE Base Amount (€/GJ)	6.92	7.49	8.19
Unit technical cost of electricity (€cents/k	9.8	11.13	12.88
Conversion efficiency (%)	16.1	16.8	17.6
Electrical Capacity (kW)	10214.0	12380.0	14693.0

Figure 4.20a and b: The output screen of a test using certain publically available values for the possible future project at Hoogeveen.

The key outputs are a predicted investment cost of 106 to 119 M€, with UTC for heat being around 7.2 €/GJ, and for electricity at 11.1 €ct/kWh. The predicted electrical capacity ranges from 10.2 to 14.7 MW. Compared with the predictions in Willemsen and Smeets (2012) the project cost is too low by about 15% and the output is too low, though the predicted output does fall in the P90 to P10 range. Looking at the sub-elements, it is clear that the low investment cost comes from low power plant costs in the model (around 14M€ compared to 36M€ according to Willemsen and Smeets). However, comparison of predicted UTCs of heat and electricity is impossible, as those have not been published for this particular project. It does seem, however, that UTCs are relatively low for geothermal projects, and that with the SDE+ subsidy, this project would be very interesting financially speaking.

The Hoogeveen project is exceptional in scope and planning and DoubletCalc does not predict its costs as well as its planners. This emphasises that some more work needs to be done for projects with such extreme depth. However, it is a good result that this model is still fairly close to predicting its financial parameters.

4.5 Coupling with ThermoGIS

The next step is to couple the updated version of ThermoGIS with DoubletCalc. This has not yet been accomplished, but will develop after discussions with TNO. These models complement each other very well, as ThermoGIS will call up the known geological data for any location in the Netherlands. This data is then automatically inserted into DoubletCalc. The user can then adapt the technical and economic options as desired. Then the outputs are quickly produced, allowing the user to predict the economic attractiveness of a project in the Netherlands in minutes. Of course, DoubletCalc can be attached to any similar GIS map, but the Dutch ThermoGIS is among the world’s most detailed due to all the seismic data gathered for oil and gas research.

5 Discussion

This chapter discusses the results that were described in chapter 4. First the value of the database is compared to the TNO equation for the cost of drilling wells. Secondly, there is some discussion on potential applications for the model, and lastly the sub-research questions are addressed directly.

5.1 Value of Database compared to TNO equation for costs

The database produced a trendline of costs of drilling. This needs to be compared to the equation used in DoubletCalc and that developed by Tester. This is shown in the figure below.

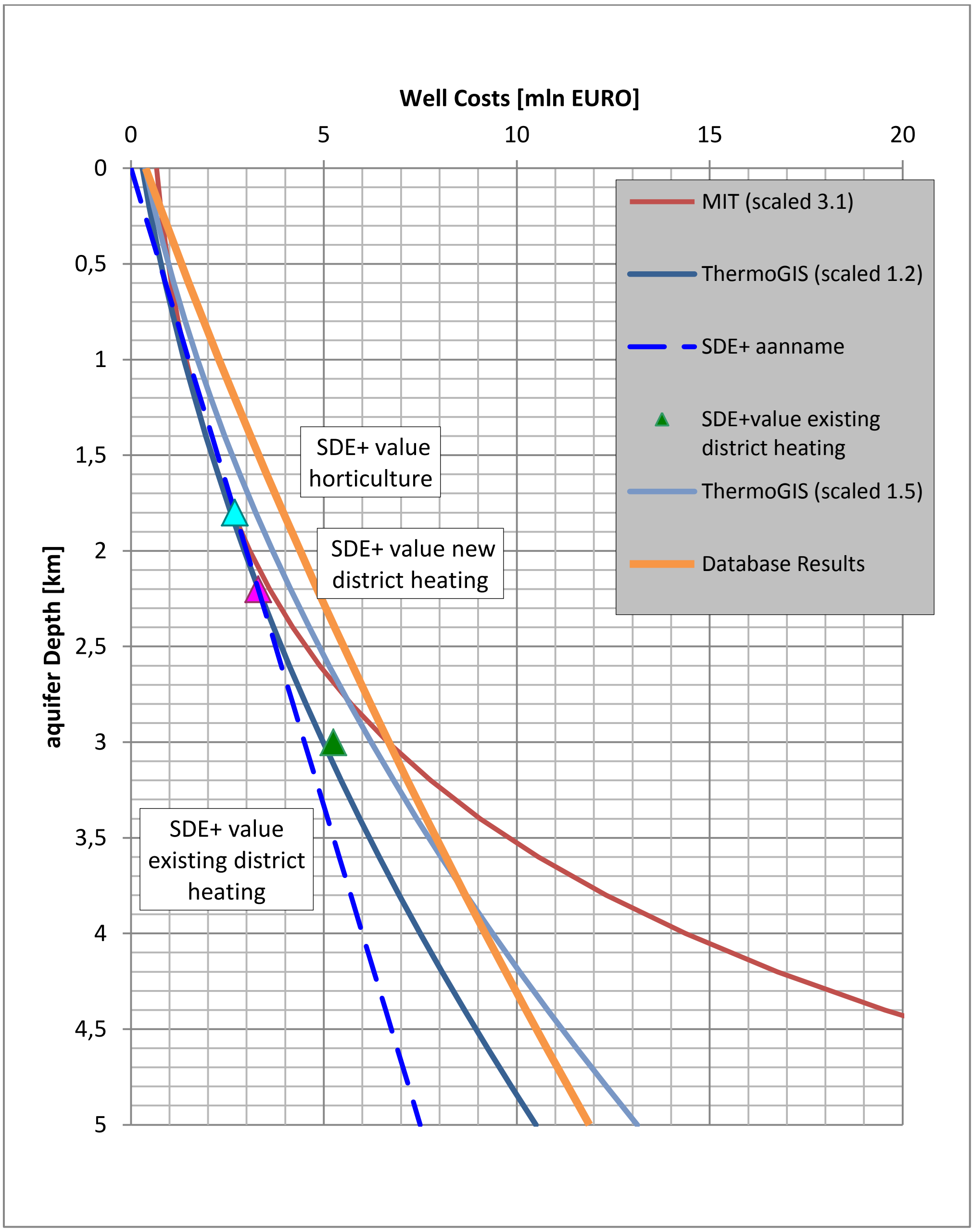


Figure 5.1: Graph of cost of drilling against depth curves from Tester et al, 2006, ThermoGIS and the database from this study. Adapted from Van Wees, private communication. Note that here ThermoGIS refers to the equation used in DoubletCalc.

The graph above displays five trendlines that have been developed by different models of the cost of drilling as a function of depth. Tester et al is based primarily on wells drilled in the USA and Central America. It is notable for starting moderately; up to about 2km depth, it presents the cheapest estimate of drilling. After this it sharply climbs. The SDE+ line comes from the three data points suggested for the SDE+ subsidy, which were determined by ECN in the very first SDE+ publication in 2011 (Lako et al, 2011). The ThermoGIS equation is displayed with two different scaling factors. A factor of 1.2 closely corresponds to the SDE+ points, and is thus most useful for analysing applications to that subsidy scheme. However, the ThermoGIS 1.5 scaling is more closely in line with the empirical European analysis. This is shown by comparing the ThermoGIS 1.5 scaling trendline to the trendline resulting from the database of this research. Perhaps surprisingly, the database trendline is the most expensive for the depths from 1km to 2.75km, in which most Dutch projects fall. Beyond 3km, the database trendline is surpassed by Tester's trendline and the ThermoGIS 1.5 line.

5.2 Uncertainty analysis of Monte Carlo

One of the strengths of Monte Carlo is that it effectively incorporates uncertainty analysis in the model. When input figures include inherent uncertainty, these can be represented by distributions instead of fixed values. The level of uncertainty is represented by the breadth of the distribution. This uncertainty then trickles through the model to produce broader output distributions of the UTC, heat output, and investment costs. Should conditions be known with greater certainty, the output distributions will be correspondingly narrow.

Thus, this model is can be separately applied at multiple stages of the planning process, because an improvement in the quality of input data results in more accurate output predictions.

5.3 Value of model

Once the model has been properly coupled to the new version of ThermoGIS, it will provide prospective geothermal project developers and owners with a useful quick analysis of the chances of a successful project at their location. Ultimately, due to the uncertainties involved of the reservoir conditions at each location, and the uniqueness of each geothermal project, more detailed (and expensive) analysis will be required. However, this tool will be particularly useful for municipalities, to decide whether to make arrangements for potential geothermal projects, for horticulturalists and building corporations, who are curious about alternative methods of heating their facilities, and for planners on a national scale who want to develop a sense of the potential available in the Netherlands.

The usefulness of this particular variation of the model, based on the SDE+ subsidy calculation method, is that it makes a direct comparison to the subsidy model scenarios. Should the P90, or at least the P50, of a project be less than the model cost as per the SDE+, then this represents a geothermal project that will likely be financially attractive.

Conversely, this tool can be used at the end of the SDE+ application process by the civil servants of AgentschapNL to perform a quick double check of the applications.

5.4 Use for scientific publication

This model is also useful for scientific publications. For example, using ThermoGIS and this version of DoubletCalc, van Putten et al (2012) analysed the relationship between porosity and permeability in aquifers. This article is shown in Appendix A.

5.5 Answering the Research Sub-questions

This section will provide the answers that have been obtained to the research sub-questions that were posed in section 2.2.

What factors decide the costs of a project, and what influence do they have?

The spider diagram, in section 4.3.2, made of the main factors of the Heat-only model show that the geophysical parameters have the greatest effect on costs, particularly the depth and the geothermal gradient. The technical parameters of the return temperature and the load hours also have significant effect on the UTC. Perhaps surprisingly, the financial aspects of the project, such as the economic lifetime and the interest rate of the loan, do not have as significant an influence on the costs.

This is probably because the geological variables affect the total investment and the heat produced more significantly, and the economic variables affect the annual expenses. Relatively speaking, the annual expenses play a smaller role than the total investment and the heat output.

What influence do government policies have?

Government policies form an integral part of business cases for geothermal projects. Nearly all current geothermal projects in the Netherlands took advantage of some sort of initial lump sum subsidy, and now the EIA subsidy. With the opening of the 2012 SDE+ subsidy, 30 applications have been submitted, laying claim to the bulk of the money available. While in personal interviews potential developers have expressed a preference for initial lump sum subsidies, the spate of SDE+ applications indicates that they are happy with this alternative. Economically speaking, they are borne out in this.

The government guarantee is of more debatable influence. If a project fails, the guarantee will refund 85% of the investment costs, to a maximum of 7.2 M€. The project manager does need to pay a premium of 7% of that amount beforehand. Furthermore, there are only several sporadic opportunities available to take advantage of this option, *inter alia* because for some projects the investment costs exceed the maximum of 7.2 M€. The premium has only a small effect on UTC, but then the reimbursement in case of failure can be small compared to the investment costs due to the imposed cap.

Recent events with hydrocarbon catchment have resulted in blowout preventers and hydrocarbon separators being installed. The additional investment costs do raise UTC.

How do the costs compare to the costs abroad?

The database results from Section 4.2 indicate that costs in the Netherlands are likely in line with European costs, but that more and deeper projects need to be realised to be certain. The comparison between European and American trendlines in section 5.1 indicates that costs in Europe for deeper projects might be cheaper than in the United States. However, this may be due to a lack of very deep projects in the Netherlands affecting the trendline, as indicated by the Hoogeveen test.

Distance effect

Economically speaking, it is advantageous to drill vertically and put a pipeline between the two wells, as shown by the test in Chapter 4. However, it is far more common for the wellheads to be adjacent and the wells drilled in a deviated manner. This is likely for practical reasons: ease of drilling and maintenance.

Cost of delay

Delays after the initial investment has been made cause the UTC of a general project to rise by about 1 €/GJ per year.

6 Conclusion

This project has analyzed the costs involved with the drilling of wells for geothermal energy, with the purpose of providing a useful tool for predicting these costs in the Netherlands and attempting to incorporate the uncertainty involved in that process. There is need for such a project, as there are indications that geothermal energy in the Netherlands is starting to grow rapidly. Therefore, the project aims to answer the following research question:

What are the costs of deep geothermal heat and power in the Netherlands now and over the next 30 years?

The answer to this question is in the model. It takes the many factors that influence the costs, ranging from the geological, to the technical and economical and processes them. This model can be applied to every unique location and situation, and is easily adaptable if necessary. The complexity and uncertainty of geothermal costs are assimilated, and the Unit Technical Costs and other economic outputs can be determined. Once coupled with the new version of ThermoGIS, it will allow anyone to determine the costs of geothermal energy for a location in the Netherlands. Their main results can be directly compared to the SDE+ base rate to determine the economic feasibility of their potential project.

As such, this model is of most use to potential project developers, especially horticulturalists. It is also of use for civil planners, environmentalists, energy companies, and industry, all of whom can determine how useful and cost-effective geothermal energy can be for them. Civil servants involved in energy policy or energy subsidies can also use it.

The model's strengths lie in its flexibility. Many input variables are considered, and more can be added if further research shows they impact the costs. This is demonstrated by the quick analyses of the consequences of deviated drilling. This small sub-module can be expanded to include the investment and operational costs of a district heating network if desired. Another strength is the ease of use. Downloading it will be straightforward once it is published, and then anyone can operate the model. Furthermore, the model responds well to the uncertainty that is inherent in geothermal energy planning. If significant preliminary research has been performed, then the quality of this data is preserved for the outputs. If the developer is still in the early stages of planning, then at least it will help them understand the likelihood of success.

However, that strength is also a weakness: it is dependent on the quality of the data put in. Accurate UTC predictions are difficult without quality information. The cost of this information is not fully included in the model.

If further time and expense were available, it would be interesting to combine this model with a sort of decision tree, based on real option theory. This would incorporate the various stages of geothermal decision making effectively, provide a better indication of the value of insurance, and also the question of sunken investment costs. However, that economic theory is significantly more complicated to implement and for users to understand.

Ultimately, the resultant model is practical and useful. It is easy to use and straightforward to adapt. It is hoped that at least the Heat-only version will be published by TNO, and thus available for use by all and sundry. It may be involved in more publications like the one in the Appendix, and may be useful to ECN Policy Studies as well.

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Appendix B: Geotechnical Variables of DoubletCalc

The changeable geotechnical variables of the Heat version of DoubletCalc are presented here since they are developed by TNO, in van Wees et al, 2012.

Changeable Geotechnical variables	**Description**
Aquifer permeability	the measure of how smoothly water moves through the aquifer
Aquifer gross thickness	the continuous vertical extent of the aquifer layer with the same properties
Aquifer top at injector	Depth of the aquifer at the point of the injection well
Aquifer top at producer	Depth of the aquifer at the point of the production well
Aquifer water salinity	level of dissolved salts in the water
Surface Temperature	average temperature of the surface (for the Netherlands, generally considered to be 10°C
Geothermal gradient	the average increase in temperature with increasing depth
Top aquifer temperature producer	Not an essential category, as it will be calculated, but can be used to set the temperature of the aquifer at the production well
Aquifer pressure at injector	also calculated, but can be used to set the pressure in the aquifer at the injection well
Aquifer pressure at producer	also calculated, but can be used to set the pressure in the aquifer at the injection well
Exit Temperature Heat Exchanger	the temperature of the geothermal liquid at the end of the heat exchange cycle which is reinjected into the aquifer
Distance Wells at Aquifer level	the distance between the two wells in the aquifer. Due to deviated drilling, this is often different from the distance between the two wellheads
Pump system efficiency	the efficiency of the pumping system
Production pump depth	the depth at which the electrical submersible pump (ESP) is placed in the production well to pump up the geothermal water
Pump pressure difference	the difference in pressures of the water on either side of the pump
Segment lengths	each well gradually narrows as it gets deeper, as each successive segment has to fit through the previous segment in a telescoping effect. Generally, depending on the depth, there are 3-5 decreasing breadths of the pipes. Here the length of each segment is requested.
Outer diameter injector	the pipe is narrower than the drilled hole, as for flow purposes during drilling, two separated streams are required. Here, the breadth of the drilled hole, which corresponds directly to the breadth of the drillbit, is requested.
Skin injector	skin is a term which refers to the roughness of the edge of the well, which results in a slowing down of the water if it cannot flow smoothly
Penetration angle injector	deviated drilling means the well will enter the aquifer at an angle
Skin due to penetration angle	because the well is not vertical due to deviated drilling, the water flow is hampered, which is represented by this variable
Outer diameter producer	same as for injector
Skin Producer	same as for injector
Penetration angle producer	same as for injector

Appendix C: Article

The author, through the Heat version of DoubletCalc model described in Chapter 4, contributed to the article “Finding a way to optimize drilling depths in clastic aquifers for geothermal energy”. This article has been submitted to the journal *Geothermics*. Reviewers requested minor revisions which are now being applied. The unrevised version of the article is shown in full below.

Finding a way to optimize drilling depths in clastic aquifers for geothermal energy

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Abstract

Clastic aquifers are marked by decreasing porosity and associated permeability with depth. As temperatures increase with depth, a trade-off in performance occurs resulting in a theoretical optimal depth in performance. This relation has been tested for one of the main geothermal aquifers in the Netherlands, underpinned by publically available oil and gas data. The results demonstrate that optimal depth can be clearly identified, corresponding to a pronounced and sharp minimum in levelized cost of energy (LCOE). Optimum depth ranges between 1.5 and 3 kilometres depending on regional porosity-permeability variations. Particularly in cases where subsurface aquifers have strong variations in depth over short distance, calculating optimal depth can assist in optimising exploration and production.

Highlights

Porosity-depth and associated porosity-permeability relationship; Trade-off in performance due to porosity-permeability and temperature distribution with depth; Strong sensitivity of optimal depth in LCOE to porosity-permeability relation.

Keywords

Geothermal energy; Clastic aquifer; Porosity-depth relationship; Porosity-Permeability relationship; Optimal drilling depth; hydraulic stimulation.

Introduction

The performance of a geothermal doublet is linear proportional to the flow rate and the temperature difference of the produced and re-injected temperature of the percolating brine. The key parameter in the calculation of flow rates is the transmissivity, which is the mathematical product of the permeability and thickness of the clastic aquifer.

Clastic aquifers are generally marked by decreasing porosity and associated permeability with depth (Ehrenberg et al., 2009). Uncertainties in porosity of a few percentages can result in an order of magnitude change in permeability. With a decrease in porosity with depth, the permeability decreases, as well as the associated flow rates. As a consequence of lower flow rates with depth, the performance of a geothermal doublet decreases with depth. Further, temperature increases with depth with a location-specific temperature gradient. Uncertainty on the temperature gradient is marked by about 10-20%. As temperature increases with depth, higher temperature differences between injection and production temperature of the brine can be obtained with increasing production depth. This results in an increase in performance of a geothermal doublet with depth.

As the temperature increases with depth while the porosity and associated permeability decrease with depth, these relationships show a trade-off in performance, such that a theoretical optimal depth can be found for a specific temperature gradient and porosity-depth curve, and associated porosity-permeability relationship. The theoretical optimal drilling depth is at the depth level where the levelized costs of energy (LCOE) are minimal. Specification of this theoretical optimal depth is interesting because highest financial risks in geothermal projects are represented by drilling costs. Optimizing subsurface reservoir location beforehand can avoid subsequently higher costs afterwards.

In mature oil and gas basin areas, such as the Netherlands, a comprehensive dataset on the subsurface exists. Therefore, it is possible to obtain relationships of the temperature gradient, porosity and underlying permeability as a function of depth. With these relationships, the applicability for establishing and using a theoretical optimum drilling depth in clastic aquifers can be tested. In the Netherlands, the national geothermal information system ThermoGIS encompasses key hydrological properties such as temperature gradient and porosity-depth trends (and underlying uncertainties) for multiple clastic aquifer which are suitable for geothermal energy (for more information see Pluymaekers et al., 2012). For the performance calculation of a geothermal doublet with depth, an in-house techno-economic performance assessment (TEPA) tool called DoubletCalc is available. With the detailed information on the subsurface and the TEPA-tool, we are able to analyse the performance of a geothermal doublet with depth and try to find the theoretical optimal drilling depth where LCOE are minimal.

To our knowledge, no performance optimization studies for a geothermal energy system on drilling depths in clastic aquifer are done, adopting variable temperature and porosity distributions, along with other natural uncertainties and engineering options for drilling. Kremnjov et al. (1970) have evaluated an optimal well depth with nomograms and a nonlinear well cost dependence with depth, based on oil and gas wells and a constant geothermal gradient of 33 °C/km. Aksoy (2007) has optimized the operational depth of downhole pumps in a geothermal field. Further, there are some studies in enhanced geothermal systems (EGS) who have modelled optimal drilling depths for varying temperature gradients between 50 °C/km and 200 °C/km with maximum capacity and minimal costs as criteria (e.g. Sanyal et al., 2007) and who have optimized subsurface reservoir settings and locations to minimize costs with the EGS model developed by the MIT Energy Laboratory, e.g. Tester et al. (1994) and Kitsou et al (2000).

To enhance knowledge and in order to try to find the theoretical optimal drilling depth where LCOE are minimal, performance of a geothermal energy system in a clastic aquifer in the Rotliegend stratigraphic group in the Netherlands will be modelled with depth by:

modelling a porosity-depth and a porosity-permeability relationship and calculate the performance over a depth range of 1000 to 4000 kilometers;

performing a sensitivity analysis on parameters within a geothermal doublet system to evaluate the uncertainty on and sensitivy of performance of a geothermal doublet in clastic aquifers and confirm porosity, associated permeability and temperature are most determinant and therefore important to alternate in depth.

This paper will continue in section 2 by providing a short discription of the TEPA-tool DoubletCalc. Section 3 builds a reference case used to find the optimal depth and shows the results on the optimal depth. Section 4 reviews the sensitivity in parameters involved in a geothermal doublet to identify which parameters performance is most sensitive to. Section 5 discusses the sensitivity of the optimal depth to different parameters. Section 6 expands the results to evalute the effects for hydraulic stimulation and Section 7 provides some concluding remarks.

DoubletCalc

DoubletCalc is developed by TNO and allows for a geotechnical and economical performance assessment (TEPA) of a geothermal doublet system (Van Wees et al., 2012). DoubletCalc is written in a Java-based source code and runs in Eclipse. Multiple interdependent geotechnical and economical input and output parameters are included (table 1). Calculations are based on Monte Carlo simulations which allow for a probabilistic output. We explain the structure of DoubletCalc by dividing the discussion into the technical and economical performance calculations.

FIGURE 1

2.1 Technical performance calculation

DoubletCalc is designed as a closed system and divided into multiple nodes (figure 1). When calculating doublet power, the following aspects are included

Pressures losses due to fluid flow in the aquifer;

Pressure losses in the vicinities of the producer and injector due to skin;

Pressure losses in the producer and injector due to friction between the brine and inner casings;

Pressure effects due to gravitational forces and caused by pumping within the producer;

Heat exchange with the surrounding geosphere.

The relevant properties of the water modelled in DoubletCalc are density, viscosity and heat capacity. Density is a function of pressure, temperature and salinity. Viscosity and heat capacity are functions of temperature and salinity.

The major three underlying boundary conditions for the geotechnical performance calculations are the mass balance, impulse balance and energy balance. The mass balance determines an equivalent mass flow from the producer to the injector. The impulse balance determines that the sum of pressure difference over all the components is zero. An energy balance is valid at every component, including heat flow between wells and the surrounding geosphere and a temperature drop in the heat exchanger. The well distance is iteratively chosen to sustain a lifetime of 75 years in order to incorporate a probable thermal shortcut due to heterogeneties in the aquifer.

Performance parameters for the geotechnical calculations are geothermal output power (MWth) and the coefficient of performance (COP). The COP is the ratio of doublet power and gross required pump power and is a measure for the efficiency of the system. A COP target can be set by the user. A COP target of 15 is assumed for renewable energy.

2.2 Economic performance calculation

A Java program called DoubletCalc is used to determine the economic performance calculation of the geothermal doublet. For this study, DoubletCalc has been modified to work based on the calculations used for determining the Dutch SDE+ subsidy (Lensink et al, 2011). These are used because they give a more accurate picture of the costs faced by a small business owner such as a horticulturalist. The primary result is the Unit Technical Cost (UTC, in €/GJ), in this case also known as the Levelised Cost of Energy (LCOE), which determines the cost per unit heat produced. It is determined by the total expenditures by the project owner, divided by the total amount of heat produced. Total expenditures is the sum of the equity part of capital investment costs (CAPEX) and the cumulative discounted annual expenditures, which consist of fixed and variable operation and maintenance costs (OPEX), pump replacement costs, the yearly loan payments (including interest), and taxes. CAPEX consists of the costs of heat exchangers and pumps, and well costs scaled with depth. CAPEX will be covered by three means: debt, equity, and EIA tax rebate, the ratio whereof can be altered by the user. Debt is represented as a loan, with a fixed interest rate. The annual loan repayments consist of interest and principal, as with a standard mortgage. Taxes are calculated according to the Dutch model, with the 25.5% tax rate levied over the sum of the interest part of the loan repayment, the depreciation and the operation and maintenance expenditures. The total heat produced is a cumulative discounted sum of the annual heat outputs. This results in the UTC, which allows for easy comparison with other renewable technologies.

For more information about DoubletCalc, see Van Wees et al (2012).

Building a reference case for the optimal depth

The existence of the theoretical optimal depth due to a trade-off in performance by decreasing porosity and associated permeability and increasing temperatures with depth, is tested with a clastic aquifer in the Rotliegend stratigraphic group in the Netherlands. A temperature gradient of 31 ºC/km is adopted, which is established from well data for the Netherlands (Bonte et al., 2012). The porosity-depth and porosity-permeability relationship are established for the Rotliegend stratigraphic group based on well data available in the national geothermal information system ThermoGIS (2012).

A clastic aquifer in the Rotliegend stratigraphic group is chosen because of its high geothermal potential (Figure 2), availability of well data and because it is subject to many exploration activities. At the moment, a geothermal doublet in the Rotliegend stratigraphic group is drilled in the Koekoekspolder at a depth of 1950 meter (Figure 2). The temperature of the water is 73 °C and the thickness of the aquifer is 90 meters. The possible flow rate within this doublet is 140-150 m^3/hour and 5 MW of thermal energy can be produced. We focus our analysis on the clastic aquifer in the region of the Koekoekspolder in the Rotliegend stratigraphic group and discuss generic implications for other regions subsequently.

FIGURE 2

3.1 Porosity-permeability relationship

The porosity-permeability relationship for the Rotliegend stratigraphic group in the area of the Koekoekspolder is established based on available well data taken from ThermoGIS (figure 3):

$$\ln(k) = 0.28\,x - 0.06 \qquad (1)$$

In which:

$k = permeability\ in\ mD$

$x = porosity\ in\ \%$

FIGURE 3

3.2 Porosity-depth relationship

For the wells in the region of the Koekoekspolder, the porosity at depth is only available in a range of 1500 to 2300 meters. This range is too small to develop a porosity-depth relationship for the modelling range of 1000 to 4000 meters. It is therefore decided to establish a porosity-depth relationship based on well data from the entire Rotliegend group. The form of the established porosity-depth relationship is in accordance with exponential porosity-depth relationships established in Hantschel and Kauerauf (2009) for multiple clastic lithologies. Burial anomalies are included by developing a porosity-depth relationship based on the maximal burial depth instead of the observed burial depth (Pluymaekers et al., 2012).

The average porosity-depth curve for the Rotliegend group is given by the following relationship (figure 4):

$$y = (43.4e^{-0.0005*x}) + b \qquad (2)$$

In which:

$y = porosity\ in\ \%$

$x = depth\ in\ meters$

$b = offset\ (default\ 2.87)$

From figure 2 it is evident that the area surrounding the Koekoekspolder has higher than average porosity and associated permeability values. This can be related to less facies mixing and presence of horizontal heterogeneities compared to other regions (Allen and Allen, 2005). It is clear from figure 3 that the range in the porosity-depth relationship is large. Therefore, the offset factor b (equation 2) in the porosity-depth relationship for the entire Rotliegend stratigraphic group is corrected to obtain a fit with the observed porosity values at depth available from the wells in the region surrounding the Koekoekspolder. An upward shift of the offset value b of 2.87 represents the wells in the area surrounding the Koekoekspolder, which corresponds to half a standard deviation in terms of the trend.

FIGURE 4

3.3 Transmissivity

As mentioned in section 3, the area surrounding the Koekoekspolder has higher porosity and permeability than average. The apparently small uncertainties in porosity result in an order of magnitude change in permeability via the units in the porosity-permeability relationship. Because the area of interest has higher than average porosity values and to evaluate the effect of relatively small uncertainties in porosity on the associated permeability, we model the upside of the porosity-depth trend in the Rotliegend stratigraphic group and evaluate the effects, via the porosity-permeability relationship, on the key performance parameter transmissivity. The upside is modelled by adding between 0.5 and 2.0 standard deviations via the offset factor b on the porosity-depth relationship established from well data for the entire Rotliegend stratigraphic group. Figure 5 visualizes the order of magnitude change in transmissivity via the porosity-permeability relationship from small uncertainties in porosity.

FIGURE 5

3.4 optimal depth

Adopting a temperature gradient specific for the Netherlands of 31 °C/km and porosity-depth and porosity-permeability relationships established for a clastic aquifer in the Rotliegend stratigraphic group in the Netherlands in the region of the Koekoekspolder, performance of a geothermal doublet is calculated with depth and plotted in Figure 6. The results show that theoretically an optimal drilling depth in a clastic aquifer exists and it corresponds to a pronounced and sharp minimum in LCOE. The optimal depth in doublet power is found at 1.79 kilometres with 4.92 MWth and the optimal depth in minimal LCOE is found at 1.61 kilometres with 9.28 EUR/GJ. In the Koekoekspolder, a doublet is drilled at a depth of 1.95 kilometres.

FIGURE 6

Sensitivity of Monte Carlo performance calculations to input parameters

To find the robustness of the established theoretical optimal depth in performance, in this section we analyse the sensitivity of the model results to variations in techno-engineering and economical parameters in perspective to natural uncertainties in porosity and temperature. To this end, a one-way sensitivity analysis of performance with Monte Carlo performance calculations in doublet power (MWth) and LCOE (EUR/GJ) is performed by adjusting relevant parameters with -/+ 10%. The resulting performance is compared with the baseline scenario of the results for the Koekoekspolder, which is the performance of the geothermal system with default parameters as listed in Table 2. Default parameters and relationships for the baseline scenario of the Koekoekspolder used in the TEPA-tool DoubletCalc.

TABLE 1

The results of the 10% increase and decrease in relevant parameters on performance in doublet power and LCOE are visualized in tornado plots in Figure 7, Figure 8 and Figure 9.

FIGURE 7

FIGURE 8

FIGURE 9

From the tornado plots with Monte Carlo performance calculations is apparent that doublet power and LCOE are most sensitive to changes in porosity (and associated permeability because a porosity-permeability relationship is established in this study), the temperature gradient and the re-injection temperature. Changes from -10% to +10% in porosity result in a change in performance between -41% and 52%. Changes from -10% to +10% in the temperature gradient result in a change in performance between -35% and 44%. Changes from -10% to +10% in the re-injection temperature result in a change in performance between -20% and 24%. Other parameters have a much smaller influence on the performance of the geothermal system.

The re-injection temperature is a user-defined parameter and does not have a relationship of performance with depth. The temperature gradient and the porosity are not user-defined and do have a relationship with depth. It is therefore interesting to optimize these parameters within subsurface exploration. The results of the sensitivity analysis reinforce the importance of subsurface optimization due to the presence of a trade-off in performance from decreases in porosity and associated permeability and increases in temperature with depth, such that a theoretical optimal depth can be found.

Sensitivity of optimal depth for the Rotliegend aquifers

Monte Carlo performance calculations, adopting variable temperature and porosity distributions, along with other natural uncertainties and engineering options for drilling, show that performance in doublet power and LCOE is most sensitive to changes in the temperature gradient and porosity. To find the sensitivity of the established optimal depth in performance for possible spatial variations in temperature gradient and porosity-depth relationships as shown in section 3 for the Rotliegend stratigraphic group, we evaluate the effects of different temperature and porosity-depth distributions on the optimal depth, as these characteristics are found to be the main parameters in the sensitivity analysis on the performance of a geothermal doublet.

5.1 Temperature-gradient distribution

A temperature distribution of temperature gradients between 29 °C/km and 35 °C/km is applied, which is a realistic range for temperature gradients in subsurface of the Netherlands (Bonte et al., 2012). Monte Carlo performances are calculated with depth using the temperature distribution and default parameters (Table 1). The results on the optimal depth can be found in Figure 10.

FIGURE 10

Remarkably, the temperature gradient only has a minor influence on the optimal depth. With variable temperature gradients, the optimal depth in LCOE differs slightly between 1.52 and 1.62 kilometres. Overall, the optimal depth shows little sensitivity to changes in the temperature gradient.

5.2 Porosity-depth distribution

The porosity-depth distribution applied includes additions of between 0.5 and 2.0 standard deviations via the offset factor to the porosity-depth relationship as established for the entire Rotliegend stratigraphic group (see section 3). As already described, porosity and permeability in the region of the Koekoekspolder are higher than average, therefore we model the upside of the porosity-depth relationship for the entire Rotliegend stratigraphic group. Monte Carlo performances are calculated with depth using the porosity-depth distribution and default parameters (Table 2. Default parameters and relationships for the baseline scenario of the Koekoekspolder used in the TEPA-tool DoubletCalc.The results on optimal depth can be found in Figure 11. Sensitivity of optimal depth in performance to changes in the porosity-depth relationships with additions of standard deviations between 0 and 2.0.

FIGURE 11

Apparent from figure 11 is the strong dependence of the optimal depth on the actual porosity-depth and associated porosity-permeability relationships. With the porosity-depth distribution applied, the optimal depth ranges between 1.5 and 3 kilometres. The doublet drilled in the Koekoekspolder fits this range.

Optimal depth with hydraulic stimulation

To enhance flow rates and increase the performance of a geothermal doublet, wells can be hydraulically stimulated. With hydraulic stimulation, permeabilities are enhanced and we therefore expect the optimal depth to be increased along with a reduction of LCOE.

Hydraulic stimulation is simulated in DoubletCalc with the skin parameter. The skin parameter reflects the pressure effect due to drilling and the drilling fluids as compared to the homogeneous situation before drilling. A negative skin factor means that wellbore flow efficiency is greater than 100% and therefore has a similar effect as hydraulic stimulation of a well.

In the performance assessment of the aquifer, the required pressure difference between the producer / injector well with the aquifer pressure to obtain a target flow rate, is defined as (Verruijt, 1970 and Dake, 1978):

$$\Delta p_{w,aq} = p_{w} - p_{aq} = Q_v \frac{\mu}{2\pi k H R_{ntg}} \left(ln \left(\frac{L}{r_{out,w}} \right) + S \right) \quad (3)$$

In which:

$p_w = well\ pressure\ [Pa]$

$p_{aq} = initial\ hydrostatic\ pressure\ at\ a\ well\ inflow\ in\ the\ aquifer\ [Pa]$

$\mu = brine\ viscosity\ [Pa\ s]$

$k = permeability\ [m^2]$

$H = aquifer\ thickness\ [m]$

$R_{ntg} = net\ to\ gross\ ratio\ [-]$

$L = lateral\ well\ distance\ [m]$

$r_{out,w} = outer\ well\ radius\ [m]$

$S = skin\ factor\ [-]$

To simulate enhancement of permeabilities by hydraulic stimulation we assume an artificial increase of the contact surface area with the reservoir formation to 200 m^2/m. This corresponds to an increase in the well radius from $r_{out,w}$=0.2032 to an artificial well radius of $r_{fraccing=}$31.85 meters, and can be used to estimate an adjusted skin factor:

$$S' = \ln\left(\frac{L}{r_{fraccing}}\right) - \ln\left(\frac{L}{r_{out,w}}\right) \tag{4}$$

For a constant lateral well distance of 1500 meter, eq. (4) results in an adjusted skin parameter (S') of -5.055, which is inserted in DoubletCalc to simulate the effect of hydraulic stimulation.

Hydraulic stimulating involves additional costs. Credible data on stimulation costs are limited due to confidentiality. Sanyal et al. (2007) and Tester et al. (2007) report stimulation costs but values described vary significantly. Based on in-house expert knowledge it is therefore decided to add 10 % of CAPEX to total CAPEX when hydraulic stimulation is applied.

The results on the optimal depth when hydraulic stimulation is applied, are shown in Figure 12. With hydraulic stimulation to enhance permeabilities, doublet power and LCOE significantly increase and decrease respectively. The optimal depth in both maximum doublet power and minimal LCOE increase to 1.82 km with 6.39 MWth and 1.64 km with 8.21 EUR/GJ respectively. The 10% addition to CAPEX as stimulation costs is based on expert knowledge and not empirically sustained, but when realistic values are approached, hydraulic stimulation is interesting because optimal LCOE are lower compared to the case without hydraulic stimulation.

FIGURE 12

Conclusion

We have shown with Monte Carlo performance calculations, along with other natural uncertainties and engineering options for drilling, that performance of a geothermal doublet is most sensitive to changes in the temperature gradient and porosity. While clastic aquifers are marked by decreasing porosity and associated permeability and increasing temperatures with depth, a trade-off occurs in performance with depth, resulting in an optimum with lowest levelized cost of energy (LCOE),

The trade-off in performance with depth is tested for a clastic aquifer in the Rotliegend stratigraphic group by establishing aquifer-specific porosity-depth and porosity-permeability relationships. With a temperature gradient of 31 °C/km and the established relationships for the Rotliegend aquifer, Monte Carlo performance calculations show that an optimal depth exists which corresponds to a pronounced and sharp minimum in LCOE. This optimal depth depends strongly on the actual porosity-depth relationship and ranges between 1.5 and 3 km. Remarkably, variations in the temperature gradient between 29 and 35 °C/km have only a minor influence on optimal depth.

We have expanded the results of the clastic aquifer to a geothermal system where permeabilities are assumed to be enhanced by hydraulic stimulation. In this situation, optimal depth in doublet power and LCOE increase. While permeabilities are increased with hydraulic stimulation and the temperature gradient is not adjusted, again, these results show the sensitivity of performance with depth to porosity-depth relationships and associated porosity-permeability relationships.

Our findings show that it is important to include porosity-depth and associated porosity-permeability characteristics in geothermal exploration for optimizing the subsurface reservoir location. Optimizing reservoir location beforehand can avoid subsequently higher costs afterwards. Particularly in cases where subsurface aquifers have strong variations in depth over short distance, defining optimal depth can assist in optimising exploration and production.

Glossary

CAPEX - Capital Expenditures, million EUR

OPEX - Operating Expenditures, million EUR

LCOE - Levelized Costs of Energy, EUR/GJ

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FIGURES

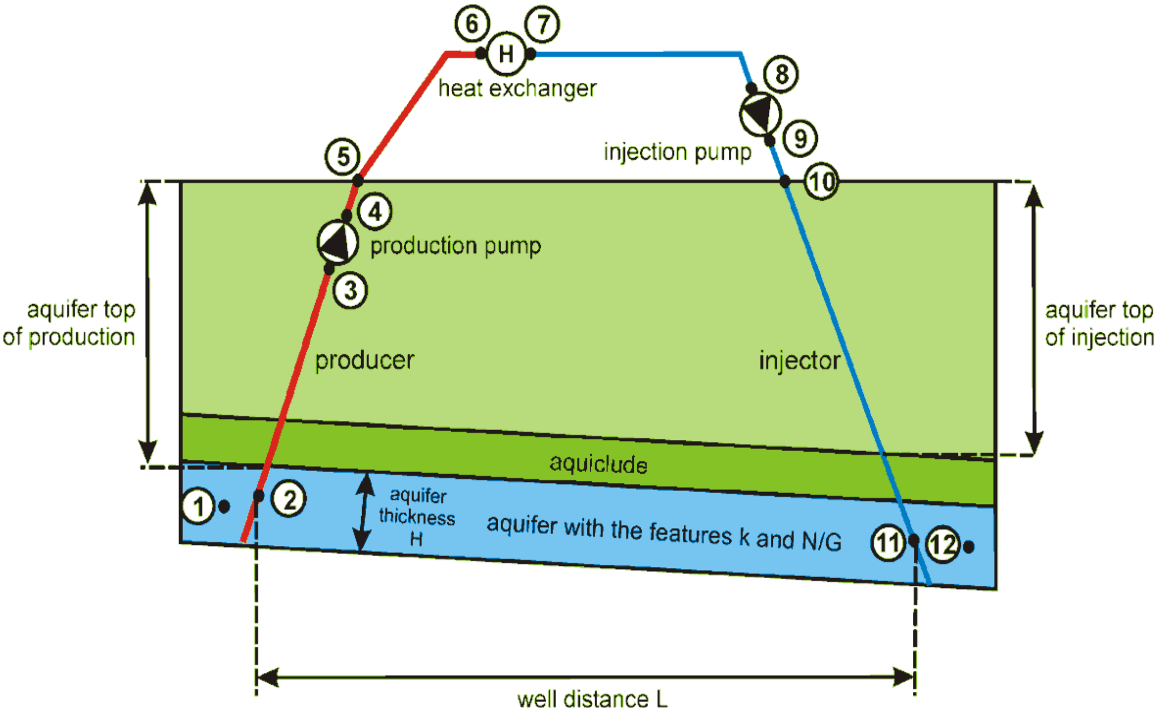
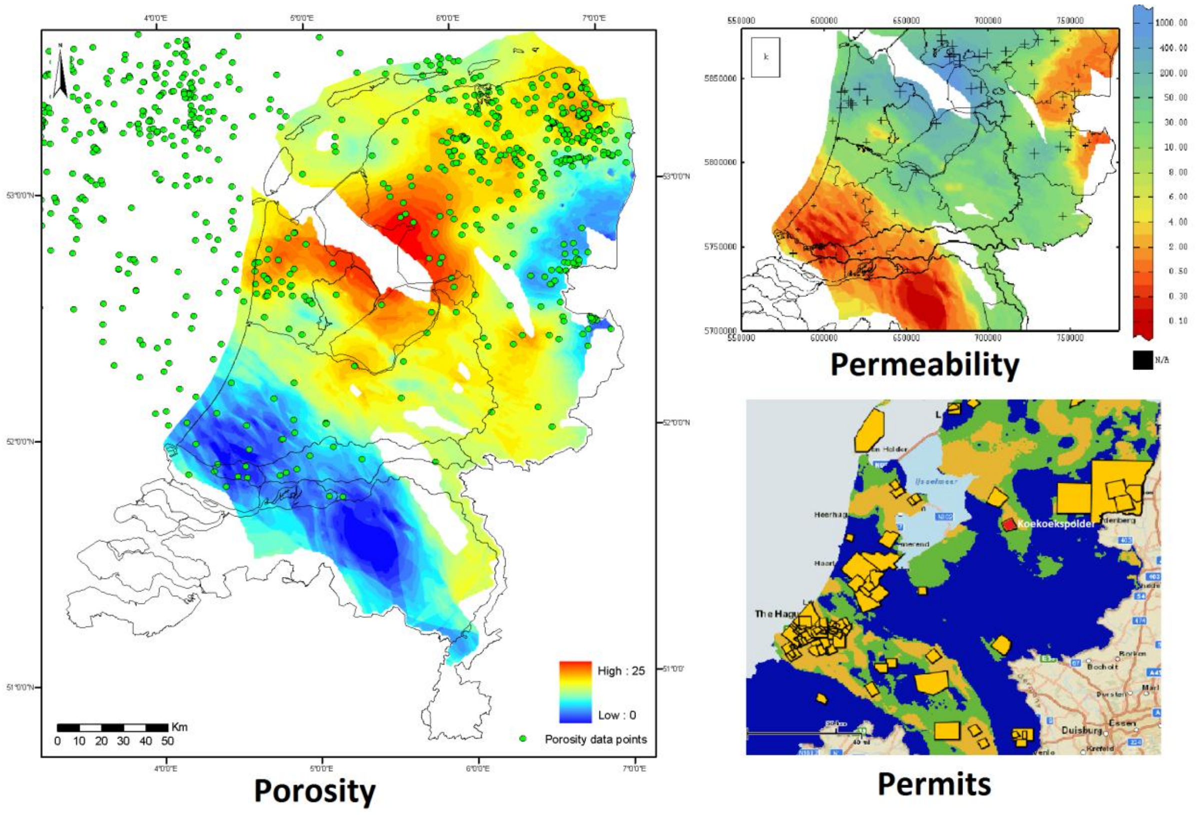


Figure 1. Internal structure of the in-house TEPA-tool DoubletCalc (van Wees et al., 2012).



Porosity

Permeability

Permits

Figure 2. Hydrological properties of the Rotliegend stratigraphic Group in the Netherlands and the permits issued for multiple stratigraphic groups in the Netherlands where the Koekoekspolder is indicated, which is used for validation purposes (based on Kramers et al., 2012 and ThermoGIS, 2012).

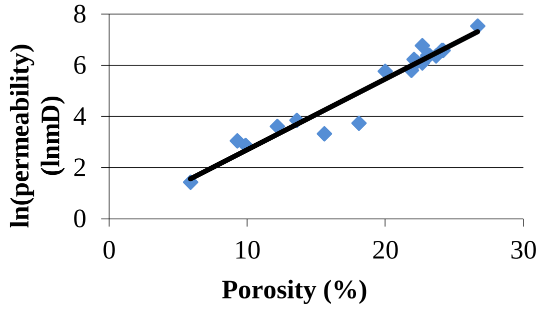


Figure 3. Porosity-permeability relationship for the Rotliegend stratigraphic group from 20 petro-physical analyses of wells in the region of the Koekoekspolder. The correlation coefficient of the established relationship is 0.94.

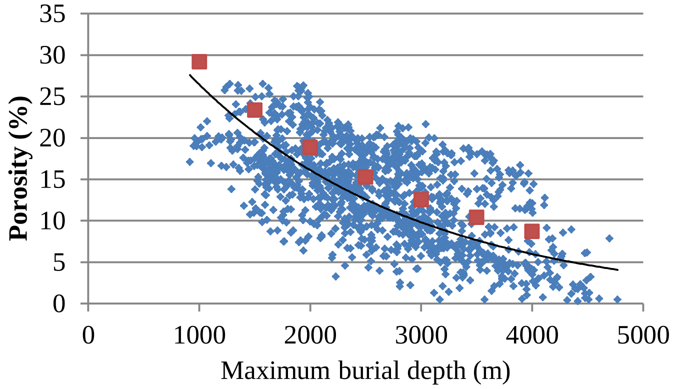


Figure 4. Porosity-depth relationship (trend line) based on well data from the entire Rotliegend stratigraphic group and the relationship added with 0.5 standard deviation (red squares) to represent the clastic aquifer in the Rotliegend stratigraphic group surrounding the Koekoekspolder (Pluymaekers, 2012).

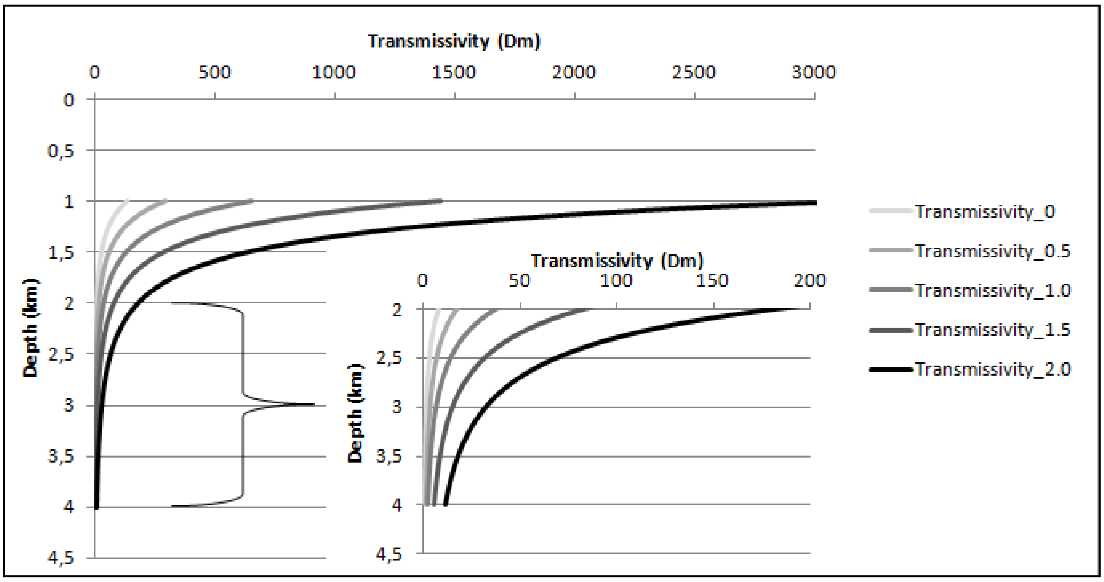


Figure 5. Transmissivity values for the upside of the Rotliegend stratigraphic porosity-depth relationship by adjusting the offset factor b with 0.5 – 2.0 standard deviations.

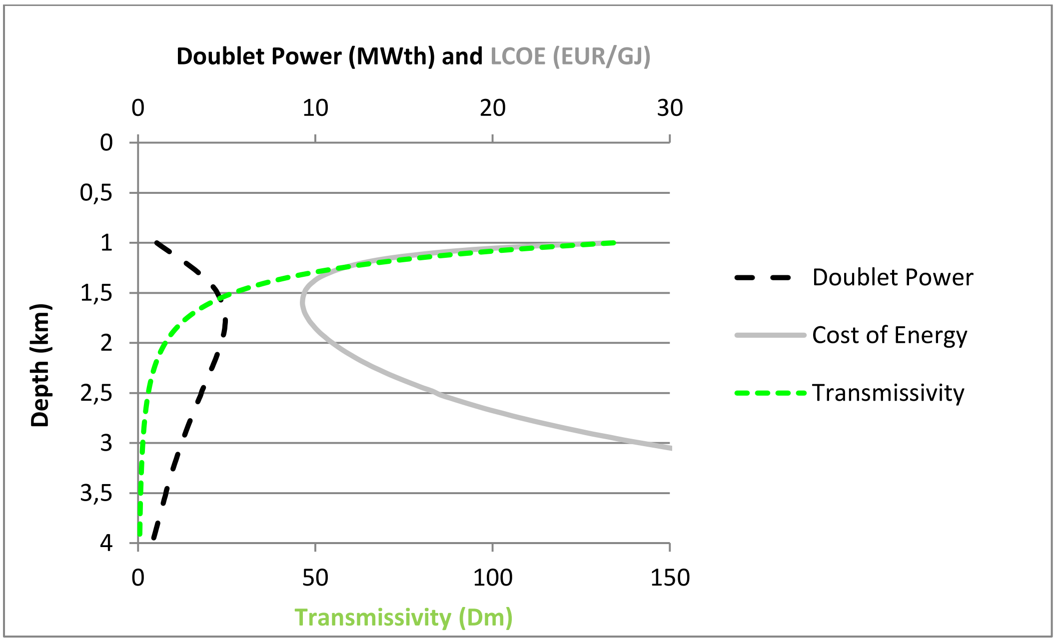


Figure 6. Optimal depth in doublet power and LCOE modelled with DoubletCalc for an aquifer in the Rotliegend stratigraphic group.

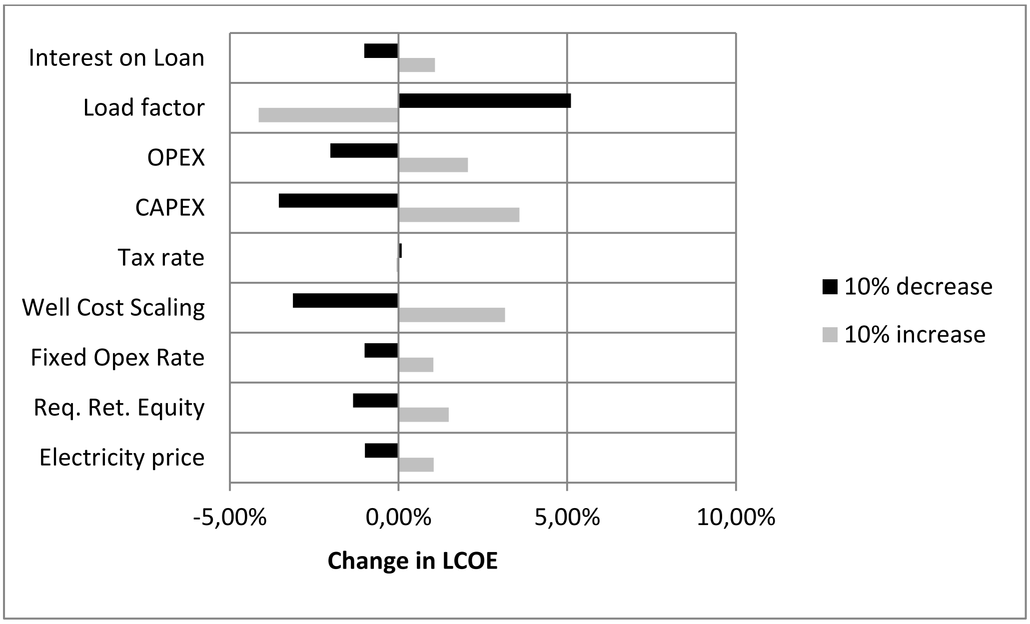


Figure 7. Tornado plot of the one-way sensitivity analysis in ecnomical parameters on performance in LCOE.

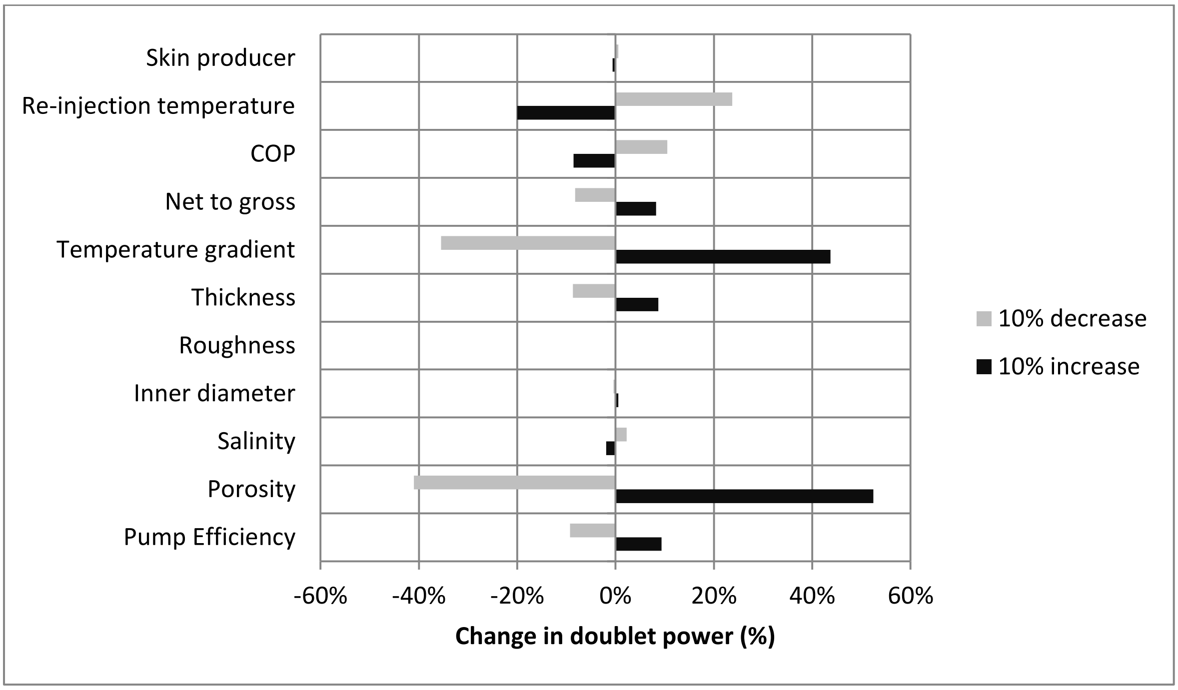


Figure 8. Tornado plot of the one-way sensitivity analysis in geotechnical parameters on performance in doublet power.

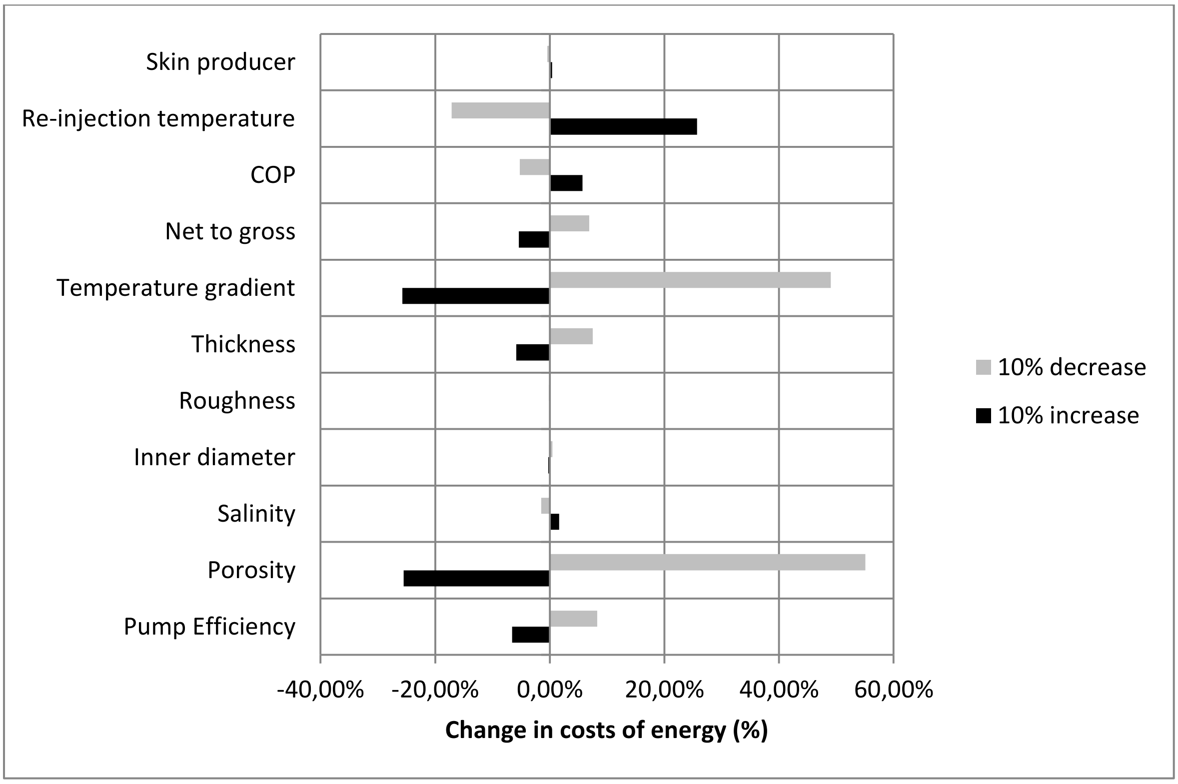


Figure 9. Tornado plot of the one-way sensitivity analysis in geotechnical parameters on performance in LCOE.

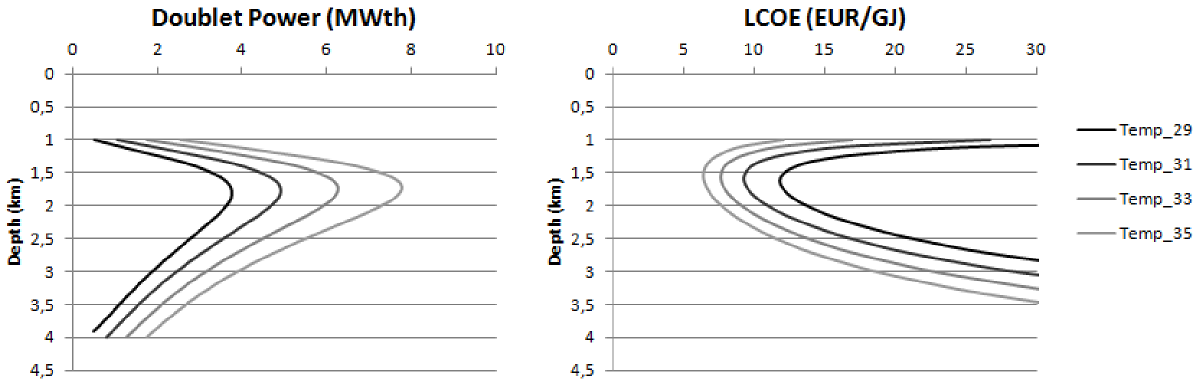


Figure 10. Sensitivity of optimal depth in performance to changes in the temperature gradient between 29 °C/km and 35 °C/km.

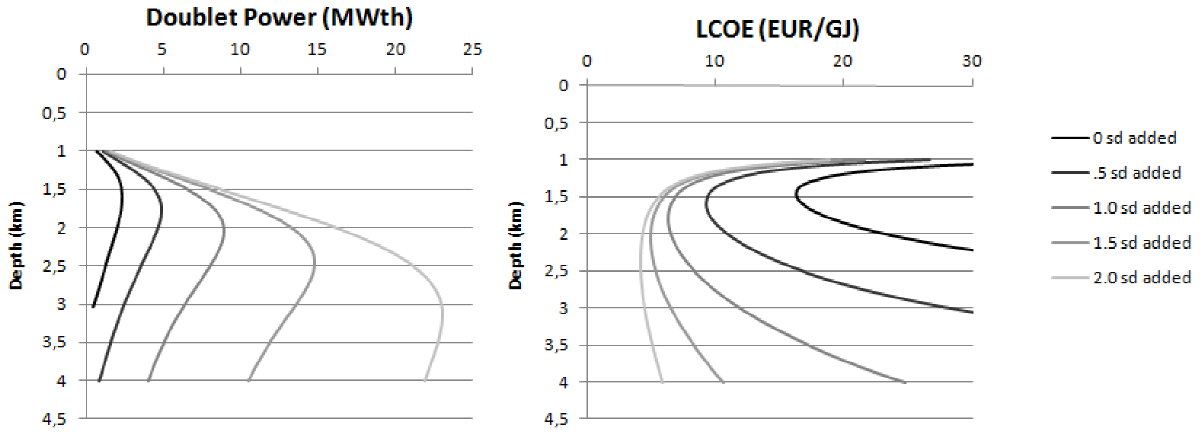


Figure 11. Sensitivity of optimal depth in performance to changes in the porosity-depth relationships with additions of standard deviations between 0 and 2.0.

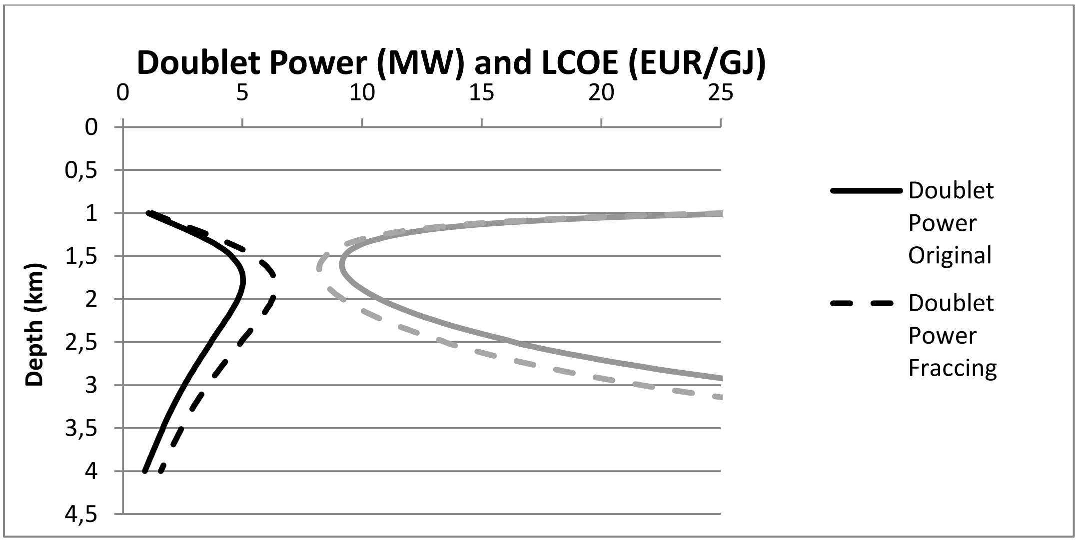


Figure 12. Optimal depth in doublet power and LCOE with hydraulic to enhance permeabilities for a clastic aquifer in the Rotliegend stratigraphic group.

TABLES

Description	**Unit**	**Default value**
Modelling depth	[km]	1-4
Porosity-permeability relationship	k = mD, x = %	$\ln(k) = 0.28x - 0.06$
Porosity-depth relationship	y = %, x = m	$y = (43.4e^{-0.0005*x}) + 2.87$
Economical parameters		
Load factor	[-]	0.6
Interest on loan	[%]	5
Electricity price for operations	[EURcts/kWh]	8
Heat exchanger costs	[mln EUR]	0.1
Well-costs scaling	[-]	1.2
Stimulation and base plant costs	[mln EUR]	0
Injection/production pump initial costs	[mln EUR]	0.5
Fixed OPEX costs	[%]	2
Pump work over costs	[mln EUR]	0.25
Pump replacement	[years]	5
Tax	[%]	25.5
Required Return on Equity	[%]	15
Depreciation	[years]	30
Energy-Investment deduction (EIA)	[%]	41.5
Number of pumps	[-]	1
Coefficient of Performance (COP-target)	[-]	15
Economical lifetime	[years]	30
Technical parameters		
Skin factor injector	[-]	0.5
Skin factor producer	[-]	2
Thermal gradient	[°C/km]	31
Surface temperature	[°C]	10
Production temperature greenhouses	[°C]	45
Re-injection temperature greenhouses	[°C]	35
Inner tubing radius	[inch]	3.5
Tubing's inner diameter	[inch]	7.0
Wells outer diameter	[inch]	8.0
Tubing roughness	[milli-inch]	1.38
Pump efficiency	[-]	0.6
Aquifer thickness	[m]	100
Maximum pump capacity	[m^3/h]	300

Table 2. Default parameters and relationships for the baseline scenario of the Koekoekspolder used in the TEPA-tool DoubletCalc.