POLITECNICO DI TORINO

Master of Petroleum and Mining Engineering

SUSTAINABILITY OF GEOTHERMAL SYSTEMS BASED ON EXERGY ANALYSIS AND EFFECT OF HETEROGENEITY ON HEAT RECOVERY

Supervisor:

Prof. Stefano Lo Russo

Co-supervisor:

Dott.ssa Martina Gizzi

Author:

IBRAHIM Nesrine

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Declaration

I declare that this project is my own work. It is being submitted for the degree of Master of Science in Petroleum Engineering in Politecnico di Torino, Italy. It has not been submitted for any degree or examination in any other university.

Signature of the candidate

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Dedication and acknowledgments

I dedicate this work to my family and friends, for the love, support and the faith they always show in me especially in these hard conditions due to the Covid-19, and most importantly to the explosion in Beirut in 4th of August 2020.

I also present my thanks to my academic supervisor Professor Stefano Lo Russo for his support and help during the project and his faith in me.

In addition, I would like to thank Professor Rouhi Farajzadeh and Professor Hans Bruining from Technical University of Delft in the Netherlands, who have been an excellent reference both in the theoretical field and in helping in accomplishing part of this Master thesis.

Abstract

There is an increasing demand from the society to utilize resources in a sustainable way. Geothermal energy is believed to be one of the renewable and sustainable resources. Geothermal energy has been developed in more than a decade for the several purposes from direct heat use and electricity power generation in more than 20 countries. However, it is still unclear under which conditions geothermal energy could be considered as "sustainable". Recently, a master student De Bruijn tried to answer this question which was the title of her thesis: "Under what conditions is a geothermal system used sustainably?".

The sensitivity of the geothermal system was tested by varying several parameters in the simulations. It was performed on a homogeneous reservoir using SEAWAT, by testing four geological uncertainties and two production parameters. The geological uncertainties are the thickness of the reservoir, the permeability of the confining layers, the thermal conductivity of the reservoir and finally the thermal conductivity of the confining layers. The production parameters are the production rate and the well spacing. It was found that the thickness of the reservoir, heat recharge, rate of production, and permeability are among important parameters in maximizing the heat recovery.

Sustainability meaning is still controversial as there is no global definition and can be defined differently and based on different indicators. De Bruijn used it in the context of longevity of heat production from the geothermal reservoirs. In this thesis, we take an alternative approach and employ concept of exergy analysis to assess life-cycle of heat production using the exergy recovery factor as an indicator. Therefore, the main objective of this thesis is to find out the conditions under which geothermal energy could be considered sustainable from a thermodynamic point of view. Moreover, the exergy analysis used in the thesis also quantifies the CO_2 emissions in kg/ MJ-heat extracted. It was concluded that, although we got a negative exergy recovery factor we can take the system into account since it saves a lot of CO_2 emissions, have a high coefficient of performance. In addition, we found out that the system is sometimes totally insensitive to the parameters due to the simulations of De Bruijn that considered a constant temperature for a long period of time.

Finally, the effect of heterogeneity which was disregarded in the thesis of De Bruijn is also discussed by building a 2D model using COMSOL Multiphysics 5.5. A layered reservoir is modeled considering 10 layers. Each layer will have a permeability value which is assigned based on the Dykstra-Parsons coefficient. Dykstra and Parsons (1950) initially presented the concept of the permeability variation coefficient V_{DP}, which is a statistical measure of non-uniformity of a set of data, and is used to quantitatively describe the degree of heterogeneity within a reservoir. It was concluded that increasing the degree of heterogeneity increases the lifetime of the project. Despite that positive impact, it cannot be concluded that having a more heterogeneous reservoir is better. We need to optimize between the production rate (which is slower) thus leading to a lower energy output and the energy demand of a certain society which has to be fed.

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List of Abbreviations

GHG: Greenhouse gases

NOAA: National Center for Environmental Information

IRENA: International Renewable Energy Agency

V_{DP}: Dykstra-Parsons coefficient

U.S. EIA: United States- Energy Information Administration

SD: Sustainable Development

DAGO: Dutch Association of Geothermal energy

W: Energy

Ex: Exergy

A: Anergy

SLT: Second Law of Thermodynamic

$\dot{E}x$: Exergy flux

$\dot{E}x^{ke}$: Kinetic exergy

$\dot{E}x^{p}$: Potential exergy

$\dot{E}x^{ph}$: Physical exergy

$\dot{E}x^{ch}$: Chemical exergy

ex: Specific exergy

$\dot{m}$: Mass flux

h: Enthalpy

h_0: Enthalpy in dead state conditions

s: Entropy

s_0: Entropy in dead state conditions

C_p: Heat capacity

s: standard deviation

C_V: Coefficient of variation

d: Distance between points

GHP: Geothermal Heat Pump

COP: Coefficient of Performance

$\dot{Q}$: Rate

Ƿ: density

g: Acceleration due to gravity

CS: Carbon Storage

CC: Carbon Capture

CCS : Carbin Capture and Storage

$e_{pp:}$ Specific CO_2 emissions

ExRF: Exergy recovery factor

PDE: Partial Differential Equation

u: Velocity

k: Permeability

ExROI: Exergy Return On Investment.

CHAPTER 1. INTRODUCTION

This chapter provides the necessary background information for this research.

Section 1.1 discusses the global energy challenge. **Section 1.2** gives a general overview of what geothermal energy is and how it can be produced. **Section 1.3** describes the role of geothermal energy in the Netherlands. **Section 1.4** is briefly presenting the concept of renewability and sustainability. **Section 1.5** gives a general overview of what the meaning of exergy by describing the general concept behind exergy analysis and providing the benefits acquired from using exergy analysis concept. **Section 1.6** introduces the importance of considering the heterogeneity in a reservoir and defines the Dykstra-Parsons coefficient and the simulation tool used in this part. **Section 1.7** gives an overview of some similar previous work. **Section 1.8** Thesis outline and Objectives.

1.1 The global energy challenge

The global energy challenge is to mitigate the effects of climate change which is caused by the greenhouse gases GHG that are released and trapped in the atmosphere due to burning the non-renewable fossil fuels to produce energy. According to NOAA (**National Centers for Environmental Information, 2020**), the global average temperature has risen by 1.14˚C above the 20th century average which was 13.9˚C as of January 2020. Certainly, the global temperature of the land and ocean surfaces is expected to raise more if the necessary mitigation measures are not taken. Climate change research started in the late 19th century (**Sawyer, 1972**), but only recently national governments, the energy industry and the public took initiative to ease its onset (**Bolin, 2007**). Carbon taxes, new fuel economy standards, campaigns promoting renewable energies at citizen-level and individuals understanding of energy use and its consequences are the form of initiatives that **de Moor, 2001** and **Walker, 1995** talked about. In December 2015, an agreement was held between countries, in Paris, upon it they have decided to take necessary measures across the globe that will maintain the global temperature below 2˚C to fight the climate change (**United Nations, 2015**). As an example, in order to achieve this vision, the United States will have to radically alter energy sources used in the country since it is still highly dependent on the fossil fuel resources as we can see in **Figure 1**, so an emission reduction will occur only if there is a shift in energy to sources with little GHG emissions. The share of nuclear energy is somehow high in the United States. Although it is a clean source with very little life-cycle emissions ranging from 30 to 60 gCO_2/ kWh according to **Sovacool, 2008**, but the radioactive waste associated with the nuclear energy is very dangerous and hard to dispose due to its adverse harmful effects on the human health (**Bowman et al., 1992**; **Ewing et al., 1995**). Other renewables such as Wind and Solar energies used to produce electricity are variable and fluctuating daily, seasonally and yearly. Unlike all of the above, the geothermal energy, due to the geothermal heat flux that does not vary and that can provide more or less flexibility in energy supply, can match the increase in energy demand. Finally, to shift to these renewable and "sustainable" energy resources requires intensive studies and researches to improve the energy conversion efficiency of renewable resource. In the end, until now, renewable energy will not be able to replace the current dependency on fossil fuels energy **Mackay,2008**.

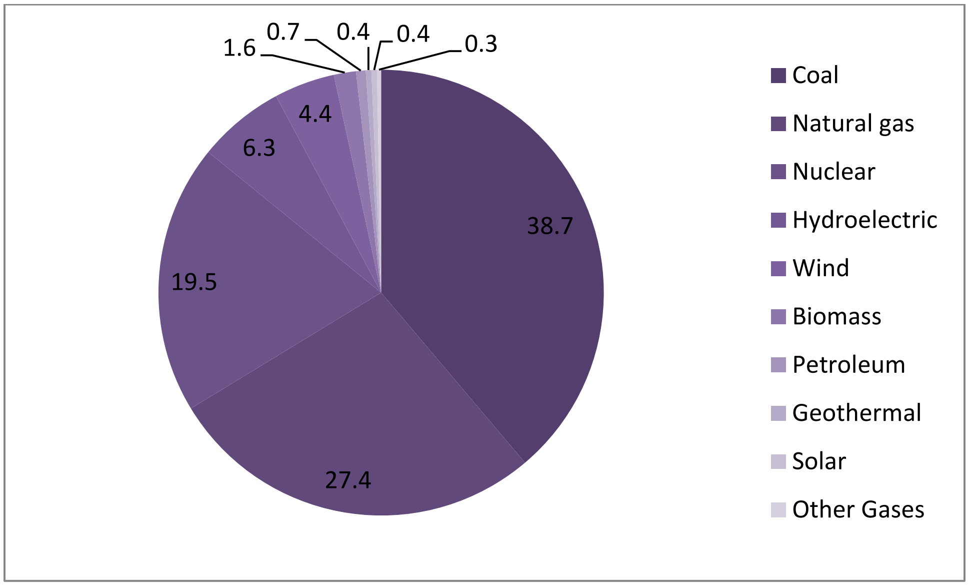


Figure 1- United States total energy consumption (%) - Institute of Energy Research

1.2 Geothermal Energy

The use of geothermal energy has increased over the last decade. However, as we see in **Figure 1**, the geothermal energy use accounts only for 0.4% as of 2015 (**Bertani, 2012**) in the United States which is a leading country in geothermal energy usage according to **National Geographic**. This is negligible with respect to the estimated 10^{13} EJ that are stored in our planet earth (**Rybach, 2007**). It was also estimated that it would take over billion of year to fully cool down the earth if we are only relying on geothermal energy (**Rybach, 2007**).

1.1.1 What is geothermal energy?

The word "geothermal" comes from the mixture of the Greek words gê, meaning Earth, and thérm, meaning heat **(Energy Information Administration EIA, 2019).** Quite literally geothermal energy is the heat of the planet Earth. It is thermal energy generated and stored in the Earth, and a continuous conduction of this thermal energy in the form of heat is derived by the temperature difference between the core and the Earth's surface. The heat originates from the initial formation of the Earth and by radioactive decay of elements in the Earth's core (**Wikipedia**).

Geothermal resources are concentrations of the Earth's heat, that can be extracted and use economically. Geothermal energy is a clean, renewable resource where the heat can be captured and used directly for heating structures such as buildings and parking lots, or their steam can be used to generate electricity (**National Geographic**). It could exist as hot water, as hot dry rock or as steam. In our thesis, we are considering hot water and so hot water can be produced to the surface where it can be used for heating or to generate electricity and this is depending on the temperature of the water (**International Renewable energy Agency-IRENA**, **Unwin, 2019**).

Depending on the temperature of the hot water, geothermal energy can be used directly (heating, cooling...) or indirectly (to generate electricity). A general overview of geothermal energy is presented in **Figure 2**. Direct use of geothermal energy is extracted from shallow targets and often intermediates targets (**Olasolo et al., 2016**). This direct use of geothermal energy has increased though years according to **Fridleifsson et al., 2008** where an increase of 43% was observed from 1999 to 2004. Nevertheless, electricity generation was also proven reliable through the years (**Arslan, 2010**; **Franco et al., 2012**) where the first geothermal power plant to exist was in Italy, Larderello in 1904 and which is still functioning until these days (**Unwin, 2019**).

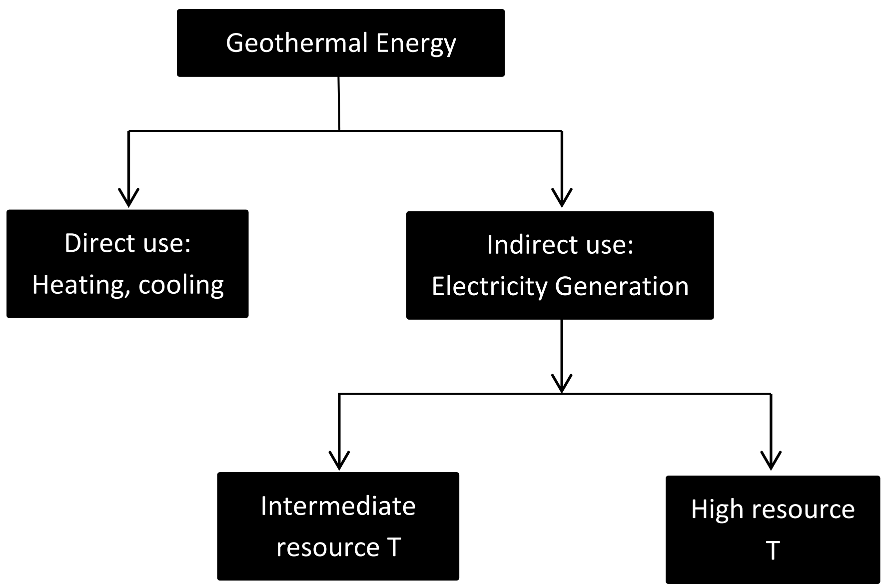


Figure 2-General overview of geothermal energy resource

In the following section we will distinguish between the types of geothermal energy based on one of the classification which is related to depth.

1.1.2 Type of geothermal energy

There are many classifications adopted to describe the geothermal energy and one of them is related to the depth from where we extract it. According to **ThermoGIS** and **Swiss Seismological Service** the geothermal energy can be subdivided into three groups:

i- Shallow geothermal energy

It lies at depth between 300 and 1500 meters where the temperature is low and especially in the Netherlands where the Temperature gradient is approximately 31 ˚C, so at such depths it is between 20 to 50 ˚C.

ii- Deep geothermal energy

It lies at a depth between ~1500 m and ~ 4000 m where the temperature is between 50 and 120 ˚C and where the produced heat can be directly used in heating greenhouses, and sometimes it can be used to heat cities.

iii- Ultra-deep geothermal energy

It lies at a depth between ~ 4000m and ~8000m where the temperature is greater than 120 ˚C which implies that the water is in form of steam and so it is used in industrial applications or for generating electricity.

It is important to know that the subsurface temperature for countries lying on the margins of the tectonic plates where a high heat flux is observed such as Italy (**Minissale, 1991**) and Iceland (**Whaley, 2016**) have higher temperature than those observed for the Netherlands and Switzerland cited in the previous paragraph. In other words, in Italy or Iceland a shallow aquifer of 1000 m could produce a steam at 200˚C to 300˚C, whereas in the Netherlands or Switzerland, at comparable depth, temperatures in the range of 40 °C are measured (**Oxburgh R., 1976**).

In the following section, after having an idea of what a geothermal energy is and how can we classify it, we will present the production technique

1.1.3 Geothermal energy production technique

A typical geothermal system consists of a production and an injection well as illustrated in **Figure 3** and each production and injection well together form a doublet. The geothermal energy in the form of hot water is extracted from a rock which has to be sufficiently permeable. As a consequence, the pressure in the reservoir near the production well will drop similarly to what happens in oil and gas reservoirs. Then, to enhance heat recovery, avoid early thermal breakthrough while maintaining pressure balance in addition to avoiding the contamination of surface waters or shallow aquifers with high salt loads or even toxic fluid constituents, re-injection of cooled water is proven to be a good strategy since discharging it at the surface is prohibited (**Agemar et al., 2014**).

As we said we produce hot water, then a heat exchanger extracts the heat from the water at the surface. Afterwards, the cooled water is re-injected back in the reservoir to prevent earthquakes or subsurface subsidence like we have said before. As a consequence, the temperature of the produced water will decrease with time. Thus, this will lead to a lower heat extraction with time. This is described by a cold front which will form and will move gradually from the injection well towards the production well. When this cold front reaches the production well, the production temperature will decrease (**Ganguly & Kumar, 2014**). The moment this happens is called thermal break-through.

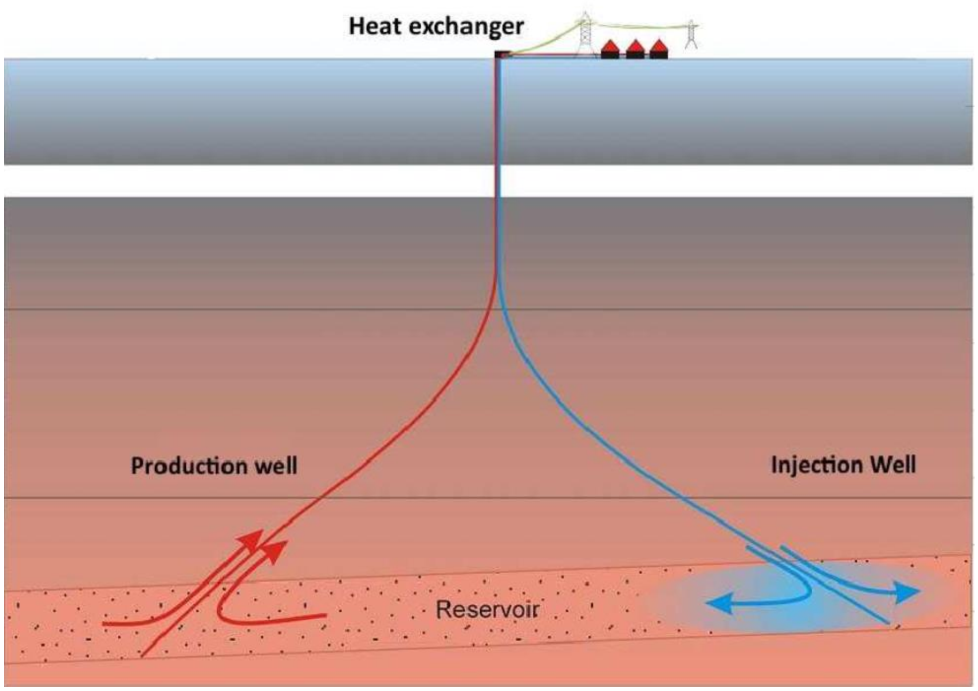


Figure 3-General Layout of a geothermal doublet (T&A Energy, 2010)

In the following short part, we will briefly summarize the necessary and sufficient conditions to consider a geothermal reservoir as a promising resource for economic use.

1.1.4 Conditions to consider a geothermal reservoir:

There are three important conditions that should be satisfied to consider the aquifer in question as a promising aquifer to produce geothermal energy. They can be summarized as follow: 1) high temperature, 2) highly porous and permeable rock, 3) sufficient fluid in the subsurface (**Office of Energy Efficiency & Renewable Energy**).

1.1.5 Geothermal Heat Pump

In this paragraph, we will describe briefly the geothermal heat pump. A geothermal heat pump, also known as the ground source heat pump, is a highly efficient renewable energy heating technology that is acquiring wide acceptance for both residential and commercial buildings especially in Europe (**Office of Energy Efficiency & Renewable Energy**, **Rybach, 2010**). The benefit of ground source heat pumps is that they use naturally existing heat, rather than producing heat through the combustion of fossil fuels and use the constant temperature of the earth as the medium where heat is exchanged instead of the outside air temperature (**Energy Saver**) and which is believed to be a promising strategy for achieving environmental protection in compliance with the principles of sustainable development and the respect of CO_2 emissions.

GHPs come in various configurations, which are installed horizontally and vertically and they exist in four types from which three of them are closed loop and one is the open loop option which is our case and the four configurations are present in **Figure 4** (**Energy Saver**). The type chosen depends upon the soil and rock type at the installation, the land available and/or aquifer

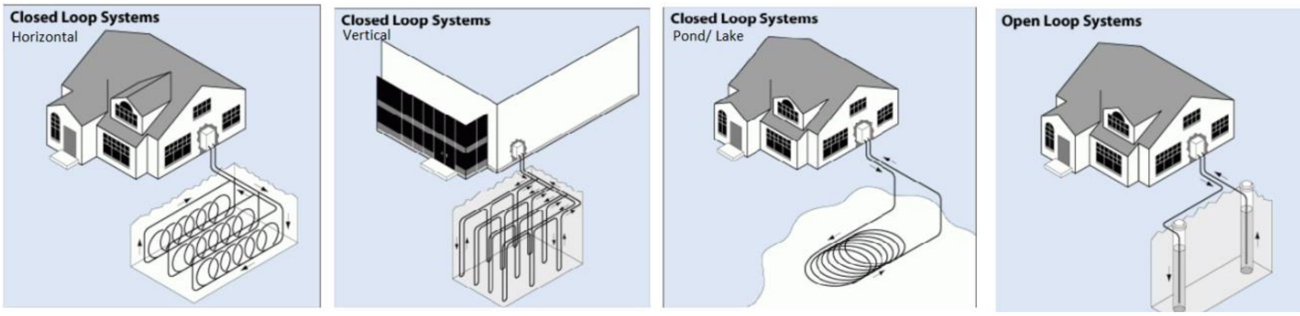


Figure 4-Different configurations of GHPs

The closed loop horizontal systems are effective for residential installations, especially the new ones and when sufficient land is available. The vertical closed loop is for large commercial buildings and schools since a very large land would be needed for the horizontal loop. The third system, is used when an acceptable water body is available where this closed loop pond/lake system will be the most effective. Finally, the open loop system like in our case is used when there is an adequate supply of relatively clean water (**Energy Saver**, **Conserve Energy Future**).

The heat pump (HP) relies on additional power to achieve the temperature rise needed in the system. In most cases, HPs are driven by electric power (natural gas, oil coal, solar power plants).

The property that describes the efficiency of a heat pump system (i.e. the ratio of heat output to electric energy input) is defined by the Coefficient of Performance, COP. It is another parameter that can be used to compare the heating systems that we will use later on in the chapter. The higher the COP, the better the heating system since more heat can be provided per unit of electricity input (**Rybach, 2010**) and a COP over 1 means your heat pump is performing very efficiently and your heating bills will be low. We will also use the concept of Exergy return on Investment ExROI which is the ratio between the exergy of an energy resource and the amount of exergy invested to produce that energy (**Chen, 2019**) and which is an important figure of importance for energy alternatives' viability evaluation(**Mansure, 2011**).

The main objective of the thesis is to assess the sustainability of a selected system by performing an exergy analysis since the term sustainability has an integrative use and meaning. Dictionaries define sustainability as the capacity of a system to stand and maintain itself. So in the next part we will address the meaning of sustainability which is still in question and which indicator we will be using briefly.

1.1.6 Sustainability of geothermal energy is still questioned

The main goal of a geothermal project is to sustainably use the available geothermal system, to optimize the lifetime the project. There're still conflicting opinions about both the sustainability and renewability of a geothermal system (**Basu et al., 2015**).A lot of uncertainties about to what extent a geothermal system can produce and to what extent the geothermal energy is renewable are still present.

Previous work discusses these two aspects. (**Axelsson, 2012**) and (**Steingrímsson et al., 2006**) have done research to investigate how reservoir management can contribute to guarantee a sustainable production from a geothermal system. **Poulsen et al. (2015)** emphasizes the huge potential and the long lifetime of a geothermal system as a result of thermal recharge during production phases. However, due to the lack of hard evidence regarding the lifetime of a geothermal project, it could also be that a geothermal system cannot be used sustainably and has a production lifetime similar to that of fossil fuels.

Thus, due to the unclear conditions related to the sustainable use of a geothermal reservoir, this thesis try to answer this issue from an exergetic point of view. Among the indicators of the effectiveness of the geothermal energy extraction process, we choose to work with the exergetic recovery factor. This indicator uses the concept of exergy (**Szargut, 1988**) which is based on the laws of thermodynamics. Based on the use of exergetic recovery factor, we are going to discuss the conditions under which the geothermal system can be considered sustainable: we started from the results of the analysis done by **De Bruijn, 2020** where the temperature decline in the production wells was considered and an exergy analysis was applied. Thus, this study addresses the sustainable use of geothermal energy from a homogeneous geothermal system but also emphasizes the effect of heterogeneity by 1) building a model using COMSOL multiphysics 5.5 with ten layers having different permeability and 2) performing a sensitivity analysis on Dykstra Parsons Coefficient V_{DP} which is an important parameter that is a measure of the degree of heterogeneity.

1.3 Geothermal Energy in the Netherlands: Current Situation

The Dutch government considers geothermal energy to be part of the solution for the energy transition and has one of the most ambitious targets for climate-change mitigation. According to the **Ministry of Economic Affairs and Climate Policy**, one of the new measures to reach the goal of CO_2 emission reduction indicates that no natural gas will be supplied to the new buildings as of 2020, and the residential heating systems will be gradually replaced by electricity-driven heat pumps or geothermal heat (**Wim van 't Hof,2018**). Renewable and sustainable energy in the Netherlands comes mostly from biofuels, waste, and wind, whereas geothermal, solar and hydro energy play only a minor role in the country (**Sanchez Nicalos, 2020**) and that accounts only for 7.4% (**Eurostat, 2020**, **U.S. EIA,2016**) of the total energy used in the Netherlands as seen in **Figure 5**. Thus, based on **Eurostat**, the Netherlands is the furthest from achieving the goals of the EU' regulations which was set to be 14% at least by the end of 2020 (**Sanchez Nicalos, 2020**).

However, In the Paris agreement of 2015, the Dutch government agreed to reduce the CO_2 emission in the coming years where emissions must be reduced by 49% and 95% compared to 2015 in 2030 and 2050 respectively (**Wim van 't Hof,2018**). Thus, the energy supply in the Netherlands needs to shift from fossil fuels to sustainable and renewable sources.

So, in addition to renewable energy that are modestly used in the Netherlands, geothermal energy is believed to be one of the energy sources that is generally considered to be a renewable option (**Energy Information Administration EIA, 2019**).

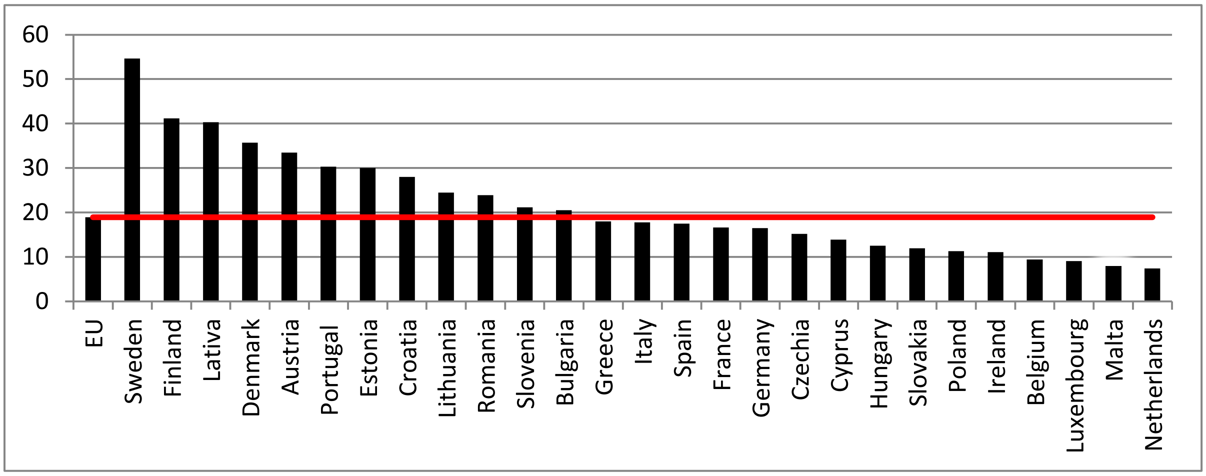


Figure 5-Share of renewables in EU countries- Eurostat

Geothermal energy is relatively new to the Netherlands. In recent years, the profile of geothermal energy in the Netherlands has increased. The first deep geothermal well was drilled in 1986 in Asten but didn't result in the success of a doublet (**ThermoGIS**). After 20 years, in Bleiswijk, a second exploration well was drilled and which has given good fortune to the industry as after this well, all the drilled well were also successful. Furthermore, the exploration for deep target that has larger potential is still limited since the heat is not equally distributed over the Earth's surface. Netherlands is contrary case with respect to Italy or Iceland ones where a shallow aquifer of 1000 m could produce a steam at 200˚C to 300˚C s as we have said before, whereas in the Netherlands, at comparable depth, temperatures in the range of 40 °C are measured (**Oxburgh, 1976**). Thus, to be able to produce the same temperature form the Netherlands subsurface, a very deep well of 8000 m should be drilled since the average temperature gradient is about 31˚C/km, and this target is still uneconomically feasible (**Tester et al., 2016**).

And as it is known, geothermal energy offers a promising and "sustainable" alternative for heating buildings, greenhouses and for applications in industry. According to the **Dutch Association of Geothermal Energy (DAGO)**, the use of geothermal energy has increased by 51% compared to 2019 and this is due to the increase in the number of doublets. At the end of 2019, the Netherlands had 24 doublets shown in **Figure 6** where 20 of which are active. Most importantly to highlight, the use of geothermal energy in the Netherlands in 2019 saved 168 million cubic meters of natural gas due to the production of 5.6 PJ heat from geothermal energy

Figure 6-A map view of the installed geothermal doublets in the Netherlands. (ThermoGIS – Map viewer).

and this is equivalent to a CO_2 reduction of 300,000 tons (**DAGO**). The goal is for geothermal energy to meet 5% of the total energy demand for heat in 2030 and 23% in 2050. The ambitions are set at 50 PJ in 2030 and 200 PJ in 2050 (**Provoost et al., 2019**).

1.4 Renewability and Sustainability

In order to see whether an analyzed system can be considered sustainable/ renewable, we need to have a clear understanding of both terms. In this thesis, sustainability is only under study but we will give the general concepts behind the two terms.

These two concepts, renewability and sustainability are of importance in this discussion. As there seems to prevail some confusion about the meaning of these concepts, it is appropriate to clarify the author's understanding of their definitions. We will briefly discuss first renewability and then proceed to the meaning of sustainability.

The author needs to know that the two terms are not comparative. Renewable describes a property of the energy resource, whereas sustainable describes how the resource is utilized, i.e the production process (**Cataldi, 2001**).

1.5.1 Renewability

Initially, there was a debate whether geothermal energy can be considered a renewable resource (**Ledingham, 1998**) since temperature decline can be seen over time in a geothermal system. According to **Axelsson et al., 2001** a renewable energy source can be defined as follows: "The energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy and the replacement takes place on a similar time scale as that of the extraction".

Stefansson, 2000 studied the concept of renewability of a geothermal system and concluded that the rate of energy recharge to geothermal systems is the most critical aspect for the classification of the geothermal energy as a renewable energy source. The recharge of energy takes place by advection of thermal water at the same time scale as the production from the resource.

1.5.2 Sustainability

Sustainability is a concept describing "how" natural resources are invested and used by man; therefore, sustainability is not related to any intrinsic characteristic of any natural resource. It only reflects human decisions on how to use a certain resource in a given period of time, which means for example choosing best production rate and technology to be applied to the process (**Cataldi R., 2001**). The concept of sustainable development is a difficult concept to define and it depends on the process it is used for.

The general definition of Brundtland of SD (**World Commission on Environment and Development, 1998**) has led to intensive researches that define sustainability in a more explicit way and for specific applications. According to **Bromley et al. 2006**, "sustainable production of a geothermal heat consists of extracting heat at the same rate as heat renewal to maintain a consistent level of production for a long time."

Rybach, 2007 confirms that geothermal energy can be used in a sustainable way, which means that the production system is able to sustain the production level over long times. He also claims that the longevity of production can be obtained and that sustainable production is achieved by optimizing production rates which take into account the local resource characteristics or by choosing the best well spacing.

De bruijn, 2020 followed the same concept of **Rybach L, 2007** and assessed the sustainability of a geothermal doublet in the context of longevity of heat production from the homogeneous geothermal reservoir model built using SEAWAT. In our thesis, as we said before, we will take an alternative approach and try to assess the conditions under which the geothermal system built by **De bruijn, 2020** is sustainable form an exergetic point of view. The following section gives a general overview of what the meaning of exergy by describing the general concept behind exergy analysis and providing the benefits acquired from using exergy analysis concept.

1.5 Exergy

Exergy is the only part of energy available to do work. The amount of exergy in energy carriers is very different as Exergy is a measure of energy quality. Energy is always conserved and can neither be produced nor consumed. Whereas, exergy can be very easily converted in anergy through irreversibilities in the conversion processes (**Novak P., 2017**).

Rant in 1956 first introduced the word "exergy". The present common definition is: "exergy of a system in a certain environment is the amount of mechanical work that can be maximally extracted from the system in this environment".

According to Rant's definition the energy W is a sum of exergy Ex and energy of environment A:

$$\boldsymbol{W = Ex + A} \qquad \text{eq.(1)}$$

Exergy in the system, like energy, can be also quantified into several types of exergy, such as: chemical exergy, nuclear exergy, physical exergy, potential exergy, radiation exergy… Exergy is always lost in a real energy conversion process due to irreversibility and conserved during ideal processes: as a consequence, exergy cannot be balanced and it is considered as a close system.

1.5.1 Exergy Analysis: General Concept

Exergy analysis is a thermodynamic analysis technique based on the second law of thermodynamics SLT. It provides an alternative and illuminating means of assessing and comparing processes and systems rationally and meaningfully (**Dincer et al., 2007**).

As we know, thermodynamics describes the behavior, performance, and efficiency for systems for the conversion of energy from one form to another. Conventional thermodynamic analysis is based on the first law of thermodynamics, which states the principle of conservation of energy. The thermodynamic losses that occur within a system often are not accurately identified and assessed with energy analysis (**Terzi, 2018**).

From here comes the concept of an exergy analysis that complements and supplements an energy analysis. It involves the application of exergy concepts, balances, and efficiencies to evaluate and improve energy and other systems. Thus, it is a powerful tool for developing, evaluating, and improving an energy conversion system. Due to the growing energy supply and demand, an interest toward the plant equipment efficiency and the optimization of existing thermal power plants is created and this optimization can be done using exergy analysis (**Kotas, 1980**).

Therefore, the exergy concept has gained great interest within the thermodynamic analysis of thermal processes and systems since it has been demonstrated that the conventional thermodynamic analysis has been insufficient from an energy performance point of view and that the system energy balance is not sufficient for the possible finding of the system imperfections (**Terzi, 2018**).

In order to understand, exergy is defined as the amount of work (which is equal entropy-free energy) that a system can perform when it is brought to thermodynamic equilibrium with its environment which is also known as dead state. The exergy of a substance is function of the material's temperature, pressure and composition, and also a function of the average temperature, pressure and composition of its surrounding dead state. It can also be a function of location (potential exergy) and velocity (kinetic exergy). These terms are defined later in this section (**Farajzadeh et al., 2020**).

First we need to define the dead state conditions. Conventionally, the benchmark temperature is 298.15 K (25℃), and pressure is 0.1 MPa (1bar) (**Song et al.,2018**). In the following, we denote the exergy by Ex [J] and its rate by Ėx [J/s].

According to **Farajzadeh et al., 2020**, the exergy transfer rate associated with the material streams is given by:

$$\dot{E}x = \dot{E}x^{ke} + \dot{E}x^{p} + \dot{E}x^{ph} + \dot{E}x^{ch}\text{ ; where} \qquad \text{eq.(2)}$$

-$\dot{E}x^{ke} = \frac{\dot{m}V_0^2}{2}$ is the kinetic exergy rate (where V_0 is the velocity of the stream, with flow Q [m^3/s] relative to the earth surface and $\dot{m}$ is the mass flow rate of the material stream in [kg/s]);

- $\dot{E}x = \dot{m}gZ_0$ is the potential exergy rate (where g is the acceleration due to gravity and Z_0 [m] is the stream altitude above sea level);

- $\dot{E}x^{ph}$[J/s] represents the physical or thermo- mechanical exergy based on the temperature and the pressure difference between the stream and the dead state;

- $\dot{E}x^{ch}$[J/s] is the chemical exergy based on the difference between the chemical potentials of the components in the stream and the dead state.

The thermo-mechanical or the physical exergy is the work that can be obtained by taking the substance through a reversible process from its initial state (T,P) to the state of the environment (T0,P0). The specific exergy is then defined by $ex = \frac{\dot{E}x}{\dot{m}}$ [J/kg], where $\dot{m}$ is the mass flux.

Thus, the specific physical exergy is written as:

$$ex^{ph} = h - h_0 - T_0(s - s_0) \qquad \text{eq.(3)}$$

For solids and liquids assuming a constant heat capacity c [J/ (mol K)] the physical exergy can be calculated from:

$$ex^{ph}_{liq-sol} = c\left[(T - T_0) - T_0 ln\frac{T}{T_0}\right] - \upsilon_m(P - P_0); \qquad \text{eq.(4)}$$

where υ_m [m^3/mol] is the molar volume of the substance at temperature T_0.

The specific chemical exergy at T_0 and P_0 can be calculated by bringing the mixture component into chemical equilibrium with the environment. Practically, it is more convenient to use the chemical exergy of the elements to calculate the chemical exergy of pure components. Using the standard chemical exergies of the elements, the standard chemical exergy of compounds can be calculated from:

$$\dot{E}x^{ch,0} = \Delta_f\dot{G}^0 + \sum_{el} n_{el}\,\dot{E}x^{ch,0}_{el}; \qquad \text{eq.(5)}$$

where $\Delta_f G^0$ [J] is the standard Gibbs energy of formation of the compound, n_{el} is the number of moles of the element per unit of the compound, and $\dot{E}x_{el}^{ch,0}$ [J/mol] is the standard chemical exergy of the element.

1.5.2 Exergy analysis benefits:

There has been an increasing interest in using energy and exergy modeling techniques for energy utilization assessments in order to attain energy and financial savings (**Ediger et al., 2007**) but there are still few studies on advanced exergy-based analyses of power-generating systems in the open literature (**Rosen, 2001**, **Rosen et al., 2003**).

Exergy analysis has several advantages when it is compared to energy analysis and among the different approaches existing to improve industrial processes, the exergy analysis appears as one of the most promising one. In the following, the more important benefits are summarized according to **Terzi, 2018**, **Tsatsaronis & Cziesla, 2009** , and **Gourmelon et al., 2013**:

1- Exergy efficiencies are the measures of the border to true ideality and when assessing the performance of energy systems it provides more meaningful information;

2- An exergy analysis identifies the location, the magnitude and the causes of thermodynamic inefficiencies and enhances understanding of the energy conversion processes in complex systems;

3- Exergy methods can help evaluate the thermodynamic values of the product energy forms in complex systems with multiple products (e.g., cogeneration and trigeneration plants);

4- Exergy-based principles can be used to improve economical and environmental assessments;

5- Exergy can improve understanding of terms like energy conservation and energy crisis;

6- Exergy-based methods can also be used in optimization procedures and in developing new concepts;

7- Exergy analysis enables to: evaluate the inefficiency of the process then translate all kinds of inefficiency to the primary fuel consumption and finally propose hints to reduce these inefficiencies;

After having a general overview of the exergy analysis concepts and benefits we will introduce the importance of considering the heterogeneity in a reservoir and we will define the Dykstra-Parsons coefficient and the simulation tool used in this part.

1.6 Effect of heterogeneity: Introduction

As we have seen the effect of heterogeneity was disregarded in the thesis of **De Bruijn, 2020** where she considered a homogeneous reservoir having a permeability of 200 mD. In the oil and gas production, the permeability has a large impact on production and always high permeability is mostly preferable. In low permeability reservoirs we always face high pressure drop near well bore zone. This is proven by Darcy's equation where the permeability and pressure drop are inversely proportional. (**Solomon et al., 2010**, **Zhao et al., 2018**)

Thus, the permeability, which is always known to be an important parameter also in geothermal reservoirs (**Economides, 1985**) is tested using COMSOL 5.5 by building a model of ten layers, and performing a sensitivity analysis on the degree of heterogeneity described by the Dykstra–Parsons coefficient.

Over the last decades, numerical models became an important tool to estimate risks by performing parametric studies within reasonable ranges of uncertainty. In the next section we will show what is Dykstra–Parsons coefficient and the tool used to perform the simulations.

1.5.1 Dykstra–Parsons coefficient

Dykstra–Parsons (V_{DP}) coefficient is an excellent tool for indicating the degree of reservoirs heterogeneity. The term V_{DP} is also called the Reservoir Heterogeneity Index (**Tiab, 2012**). This index ranges between 0 and 1 which is between an ideal homogeneous reservoir and perfectly heterogeneous reservoir.

•$0<V_{DP}<0.25$, slightly heterogeneous, can be approximated by a homogeneous model in reservoir simulation with minimal error.

•$0.25<V_{DP}<0.50$, heterogeneous reservoir

•$0.50<V_{DP}<0.75$, the reservoir is very heterogeneous

•$0.75<V_{DP}<1$, the reservoir is extremely heterogeneous

The permeabilities in the field are normally distributed according to (**Male et al., 2020**). P-normally distributed is between 0 (normally distributed) and 1 (log-normally distributed). Log normally distributed means that the logarithm of the permeability (lnk) is normally distributed (**Bruining, 2020**), and we can see this through equations:

$$Pln(k)d\,lnk = \frac{1}{\sqrt{2\pi s^2}}\, e^{-\frac{(lnk-m)^2}{2s^2}\,d\,lnk}\ , \qquad \text{eq.(6)}$$

$$P(k)dk = \frac{1}{\sqrt{2\pi s^2}}\,\frac{1}{k}\,e^{-\frac{(lnk-m)^2}{2s^2}\,dk}\ , \qquad \text{eq.(7)}$$

Where he used the fundamental transformation law of probabilities which states that:

$$|p(y)dy| = |p(x)dx|, \qquad \text{eq.(8)}$$

$$p(y) = p(x)\left|\frac{dx}{dy}\right|, \qquad \text{eq.(9)}$$

Where m denotes the average of the logarithm of the permeability, s denotes the standard deviation of the logarithm of the permeability.

According to **Bouquet, 2017**, for a log-normal permeability field, with a mean m of $log\ (k)$ and a standard deviation s of $log\ (k)$, we can define the Dykstra-Parsons coefficient as follows:

$$V_{DP} = \frac{e^m - e^{m-s}}{e^m} = 1 - e^{-s} \qquad \text{eq.(10)}$$

It can be written also a:

$$s = -\,log(1 - V_{DP}) \qquad \text{eq.(11)}$$

Accordingly, we will use this coefficient to indicate a heterogeneous reservoir. We chose a V_{DP} value in the range of 0.5-0.8 in addition to the homogeneous case with a mean value of the permeability that is representative of the Netherlands subsurface. For each V_{DP} we generated ten permeability fields using the free Microsoft Excel spreadsheet available online. We call this realization, i.e., we generated 10 realizations for each V_{DP} chosen.

According to **Farajzadeh et al., 2010**, $(10C_V)^2$ realizations are needed to obtain a more representative result, where $C_V = \sqrt{\left(e^{d^2} - 1\right)}$ is the coefficient of variation (average/standard deviation), where d is distance between points. However, this is time consuming and technically impossible thus we stick to ten realizations per case to obtain a general overview of the outcome from these variations.

In the following section, we will describe the simulation tool used which is COMSOL Multiphysics 5.5.

1.5.2 Simulation tool

This study uses COMSOL Multiphysics 5.5 to simulate the production from a geothermal reservoir. COMSOL is a platform finite element analysis software founded by Svante Littmarck (CEO of the COMSOL Group) and Farhad Saeidi (President of COMSOL AB) in 1986 in Stockholm, Sweden.

In general, by COMSOL we can develop mathematical modeling software that drives new breakthroughs in physics and engineering. COMSOL Multiphysics® is used in all fields of engineering, manufacturing, and scientific research for modeling multiphysics systems. It is used to understand, predict, innovate, and optimize product designs and processes (**COMSOL**).

In COMSOL, you can start by a predefined physics. Almost all of the processes (**Brun, 2011**, **Jahanbakhsh et al., 2016** & **Daanen 2012**) involved in the various geothermal applications could be modeled with the Subsurface Flow Module in porous medium and coupling it with heat transfer, which determine the thermal development of the subsurface due to geothermal heat production. In our thesis, we will implement partial differential equations in weak formulations to simulate the results. The detailed equations are presented in section 2.3.1.

1.7 Previous work

In last decades, the research concerning geothermal energy has increased by using the concept of exergy analysis. **Dincer, 2002** reported the link between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in details and more other links. In order to highlight the importance of the exergy and its essential utilization in numerous ways he summarized its importance in several point, one of them was that the exergy is a key component in obtaining a sustainable development and it is one of the most suitable technique for furthering the goal of more efficient energy‑resource use.

In the paper of **Hepbasli, 2008** the sustainable use of geothermal resource from exergetic point of view is elaborated. He based his analysis on the evaluation of the system performance from the exergetic point of view: the geothermal brine exergy inputs from the production field and exergy destructions in the system, taking place as the exergy of the fluid lost in the heat exchanger, the natural direct discharge of the system (pipeline losses), and the pumps play an important role in the whole system. He calculated the exergy destruction and performed a mass balance. Then he calculated the exergy efficiency that varies according to several parameters and especially the dead state conditions. In this thesis, we are going to perform an exergy analysis based on the exergy recovery factor which is among most important indicators to assess the sustainability of a certain system.

A recent paper of **Pandey et al., 2018**, on geothermal reservoirs coupled thermo-hydro-mechanical-chemical approaches shows that the impact of reservoir heterogeneity on performance of doublets is less studied. Most of the studies on performance of low enthalpy systems, have considered homogeneous systems or simple lithographical variations. Only few existing researches deal specifically with heterogeneity for geothermal doublet systems.

Very recently, **Babaei et al., 2019** demonstrated, based on 2600 simulations using ECLIPSE 300, that the lifetime of the project is shorter with increasing heterogeneity. They claim that the heterogeneity can have a positive impact: the cold waterfront diverts and so moving slower to the producer or a negative impact by anticipating the thermal breakthrough. This depends on the on the anisotropy and isotropicity of the correlated heterogeneity. Furthermore, **Talebian et al., 2020** studied the impacts of horizontal permeability anisotropy deducted from pressure-interference tests on geothermal doublets performance in the Netherlands. He demonstrated the importance of considering the permeability anisotropy in the horizontal plane in predicting the lifecycle, that have received less attention, by modeling a three-dimensional thermal reservoir simulator of a reservoir in the West Netherlands Basin. What he meant by lifecycle is determined by the cold-temperature breakthrough of an existing doublet and in optimally designing the second doublet in the same licensed area.

De Bruijn,2020 considered a homogeneous reservoir, an oversimplified reservoir model, and disregarded the effect of the permeability on the heat recovery. Therefore, we will assess the effect of the permeability on the heat recovery using COMSOL 5.5 by performing the sensitivity analysis on two parameters: permeability and the degree of heterogeneity.

1.8 Research Objective

The aim of this study is to examine what role geothermal energy can play during the energy transition and if it can be a strong alternative to fossil fuels in the future. Therefore, the sustainable use of a geothermal system will be investigated from an exergy point of view, in addition to the effect of the heterogeneity that will be also assessed. The main objective can be summarized by this question:

Under which conditions a geothermal system is sustainable based on exergy analysis and what is the effect of heterogeneity on the heat recovery from a geothermal reservoir?

In order to answer this question, the result of the sensitivity analysis done by **De Bruijn, 2020** will be used to evaluate the sustainability from a thermodynamic point of view. We took the temperature decline in the production well from her thesis. Then, we followed the sensitivity analysis performed on a set of geological uncertainties and production parameters. In the second part of the thesis, we will investigate the effect of heterogeneity using COMSOL Multiphysics 5.5 where we will study its impact on heat recovery from geothermal reservoirs for a fixed V_{DP} and an average permeability. For each V_{DP} value, we will generate 10 permeability fields. The conclusion will be based on the variation of the lifetime of the project and the energy produced.

In the second chapter, we will describe the methodology used in the two different parts. First, we will present the base case study used by De Bruijn which was a reference for comparing the results of the performed sensitivity analysis. Then, we will describe the geothermal production technique based on which the system and its boundary is defined for the exergy analysis assessment and which will also let us define the material and work streams. Subsequently, the indicator, on which our assessment is based on, will be defined. In addition to that, we will also define the Dykstra-Parsons coefficient which will be used to generate the permeability fields that will allow us to investigate the effect of heterogeneity. A Base Case as a reference for the other cases where we changed the V_{DP} will also be chosen.

Finally, the results are shown and discussed in chapter 3.

CHAPTER 2: METHODOLOGY

This chapter addresses the method used to assess the sustainability of a pre-existing geothermal model, and the simulations performed to study the effect of heterogeneity on the heat recovery.

Section 1 describes in detail the model with its input parameters, the equation used and defines the system and its boundaries to which exergy analysis will be performed.
Section 2 presents the indicator that will account for the effectiveness of the geothermal system.
Section 3 presents the geometry of the model built by COMSOL to assess the effect of heterogeneity on the heat recovery, the equations used in the simulations and the Base Case for this study.

2.1 Exergy Analysis

This section describes the methodology used to assess the sustainability of a given system which was defined by **De Bruijn, 2020**.

As we have said before, the temperature decrease is taken from **De Bruijn, 2020**, the pressure drop during the production wasn't simulated so we assumed a pressure drop of 1.5 bar each year for a production rate of 150 m^3/hr, 2.5 bar for 250 m^3/hr, 4 bar for 400 m^3/hr and finally 6 bar for 600 m^3/hr.This assumption is nothing else than an increase of pressure drop proportionally to the increase in rate. The maximum allowable pressure at each well is equal to the initial pressure in the reservoir +50 bar (($\Delta P_{fracturing}$=50 bar) to avoid inducing hydraulic fractures. At this threshold, stimulation is performed. The rest of the parameters and assumptions are cited in the following sections in this chapter.

2.1.1 Pre-existing model parameters

In this part, we will describe briefly the system used by De Bruijn 2020 with all the parameters used for the Base Case. De Bruijn2020 used SEAWAT to build up her model that represents a geothermal system consisting of an injection well and a production well. A Base Case was constructed at first and served as a reference for other cases in which the parameters have been varied to test the sensitivity of the model to that particular parameter. In **Table 2** is represented the input and setup parameters.

2.1.2 System definition

Choosing the boundaries is the most important step in life-cycle analysis in any system. The selected system is shown in **Figure 7** and includes the exergy analysis of the main stages of a geothermal doublet consisting of a production and injection well. The temperature of the aquifer is set to be 90 ˚C and so the geothermal system under study is a shallow aquifer considered as a low temperature reservoir (**O'Sullivan, 2014**). The threshold temperature of geothermal reservoirs varies from one resource to another. **Table 1** represents different classification of the low, medium and high geothermal resources.

	Muffler and Cataldi, 1978	Hochstein, 1990	Benderitter and Cormy, 1990	Nicholson, 1993	Axelsson and Gunnlaugsson, 2000	Helston, 2012	Akar et al., 2016	Water encycolpedia, 2020
Low enthalpy resources	< 90	< 125	< 100	≤ 150	≤ 190	<149	< 90	< 100
Media enthalpy resources	90- 150	125- 225	100- 200	-	-	-	>90	100- 150
High enthalpy resources	>150	>225	>200	>150	>190	>149	>90	>150

Table 1- Classification of the geothermal resources based on the temperature in ˚C.

Parameter	Value
Dimensions	
Reservoir thickness	50m 100m 200m
Top reservoir depth	2475m 2450m 2400m
Bottom reservoir depth	2525m 2550m 2600m
Over and under burden thickness	800m
Well data	
Well distance	1200m
Injection temperature ˚C	35˚C
Injection rate	150 m^3/hr
Production rate	150 m^3/hr
Temperature & Pressure data	
Initial average reservoir temperature	90 ˚C
Surface pressure	1.03 bar
Pressure gradient	10 MPa/ km
Reservoir	
Porosity	20%
Permeability	200 mD
k_v/k_h	0.1
Confining layers	
Heat conductivity	2 W/m/K
Permeability	0.01mD
Fluid properties	
Density	1085 kg/m^3
Salinity	0.12 kg/kg
Viscosity	$6.8*10^{-4}$ kg/m.s

Table 2- Input parameter for the Base Case

The analyzed system with a temperature of 90 ˚C is considered to be a low-temperature geothermal energy. The associated geothermal resource will be used for heating homes, apartment and office buildings, public facilities and farms by means of the use of geothermal plant (**Planete Energies, 2015**).

Ultimately, in the selected system consisting of a doublet, the water is produced in the producing well, where heat is extracted at the surface using a heat exchanger unit. Before re-injecting the cooled water, at the chosen temperature and pressure, it is treated to meet the required quality. Pumps are used to inject and produce water. But it is important to note that, the circulation of hot water from the well can be either self-flowing or by artificial lift which means to force circulation by pumps. Self-flowing is of course the most attractive production mode provided it can supply target flow rates without excessively depleting well head pressures (**Grant et al., 2011**). Generally, many lower-temperature geothermal wells are not self-energized and must be pumped (**Finger, 2010**). Therefore artificial lift is usually the rule in geothermal, low grade heat, direct uses(**Grant et al., 2011**). Whereas, higher-temperature wells are normally self-energized and produce without stimulation (**PetroWiki, 2015**).

At Melun, which is a doublet, located in South Paris, and due to exceptional reservoir performance, artificial lift was no longer required and, instead, self-flowing at high production rates prevails. The well, put on line on late March 1995, demonstrated high productivity, producing about 70°C fluid at a rate of 200 m^3/ hr at 2.5 bars well head overpressure (**Ungemach, 2001**).

In particular, we will consider the types of geothermal plant where we perform artificial lift by a pump placed at the producer and a case in which we consider that the pressure inside the reservoir is sufficient so that water is produced without the aid of a pump. Based on all of the above we can now define the system used and its boundaries to be able to define the input and output streams from the system.

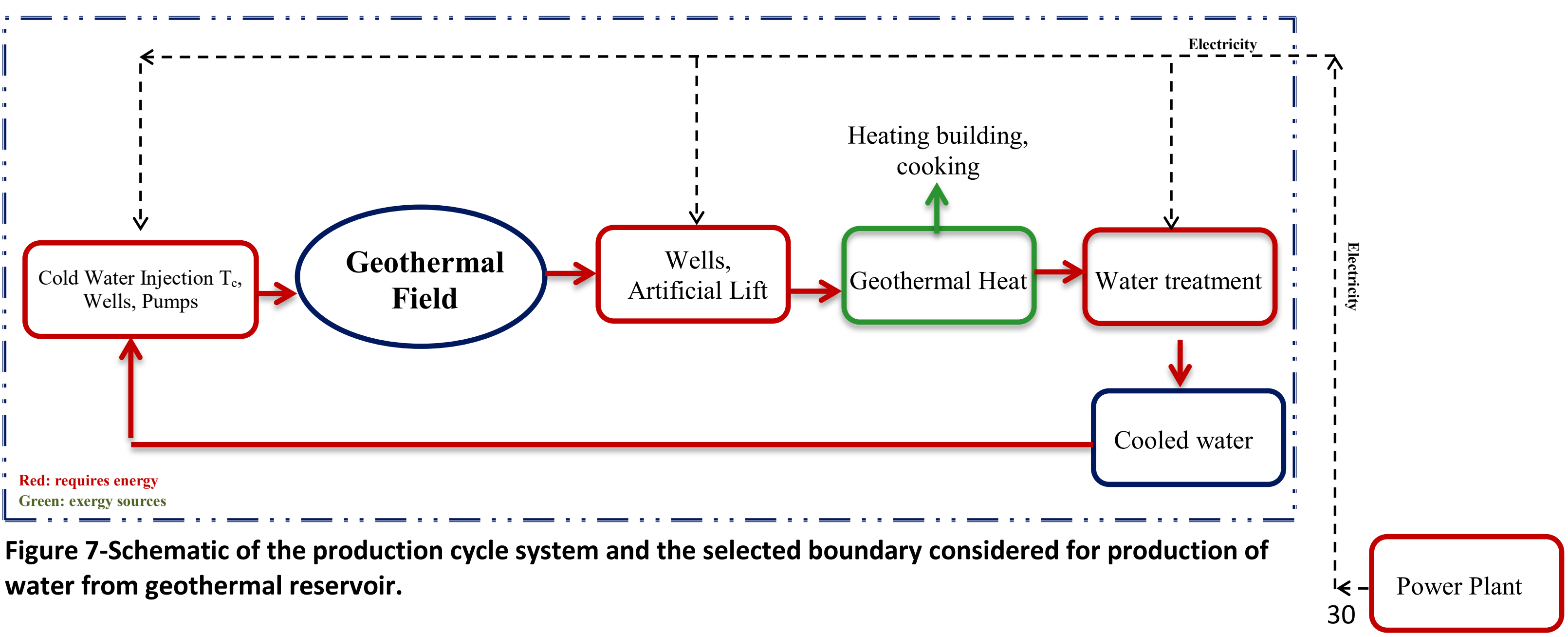


Figure 7-Schematic of the production cycle system and the selected boundary considered for production of water from geothermal reservoir.

As pumps are used to produce and inject water and usually, they require energy and thus are denoted by red arrows. Before being injected, water is treated to meet the minimum requirement. As this also requires energy, it is denoted by red arrows. The produced water is the exergy source and so it is denoted by green arrows. The production and re-injection pumps are driven by electricity that comes from different power plants, e.g. natural gas, oil, coal, solar power plants.

2.1.3 Exergy streams

The exergy analysis of the system defined in **Figure 7** is performed by considering the material (shown by green arrow) and work (red arrows) streams. The chemical exergy value of the produced water is calculated in the following section. As it was mentioned before, the dead state is assumed to be at a temperature and pressure of 298.15K and 1 atm (101.325 kPa), respectively. Potential and kinetic exergy were assumed to be negligible in comparison with the chemical and physical exergy in this study. In the following part we will present the equation used for our calculations.

2.1.3.1 Material stream

The chemical exergy of hot water, when neglecting potential and kinetic exergy can be written as:

$$\dot{E}x_{ressource,t}(T,P) = Q_w \rho_w [\left(h_{T,P} - h_{T_{ref},P_{ref}}\right) - T_{ref}\left(s_{T,P} - s_{T_{ref},P_{ref}}\right)]; \qquad \text{eq.(12)}$$

where h [J/kg], s [J/(kg.K)] and ρ_w [kg/m3] denote the specific enthalpy, specific entropy and mass density respectively. T_{ref} [K] and P_{ref} [Pa] are the reference temperature and pressure of the dead state.

Then, The exergy flux of the geothermal reservoir [J/s] is calculated at the T and P of the produced water which is usually re-injected into the reservoir at a temperature and pressure (T_{inj} [K] and P_{inj} [Pa]) higher than the dead state; therefore, the exergy flux of the re-injected water must be subtracted from the extracted exergy to calculate =>

$$\dot{E}x_{resource,t} = \dot{E}x_{ressource,t}(T,P) - \dot{E}x_{resource}(T_{inj}, P_{inj}) \qquad \text{eq.(13)}$$

The injection temperature is already chosen and fixed at 35 ˚C. Regarding the injection pressure we will follow the **Protocol for determining injection pressures for geothermal energy extraction** imposed by the State Supervision of Mines SSM which consider that a guide value for an acceptable limit value for the liquid pressure in all applications height of the top of the reservoir is a gradient of 0.135 bar / m * the depth (of the injector) to top reservoir. To be more specific in the case of water injection with different salinity the injection pressure can be determined by:

$$THP_{max} = Dt * (0.135 - Grad.Inject.Water)\ in\ bar; \qquad \text{eq.(14)}$$

where THP_{max} is the maximum Tubing Head Pressure on the injection well; Dt is the depth of the injection well from ground level to the top of the reservoir; Grad.inj,water = Hydraulic Gradient of the local injection water as a function of the salinity and it has a range of 0.103-0.108 bar/m in the Netherlands.

For the calculation of the physical properties of the fluids (water), we use the free software package CoolProp (**Bell et al., 2014**), which implements the IAPWS formulation for water (**Wagner, et al., 1995**).

2.1.3.2 Work Streams

Injection Pump. The theoretical pumping exergy rate of the injected water is:

$$\dot{Ex}_{liquid}^{theoretical,pump} = Q\Delta P \qquad \text{eq.(15)}$$

where $\dot{E}x$ is the exergy rate, $\dot{Q}$ (m^3/s) is the rate of the injected water and ΔP [Pa] is the pressure difference between the injection and production wells. The practical pumping exergy is calculated by including the mechanical efficiency of the pump (80%), efficiency of the electrical driver (90%), and the efficiency of the power plant which is 50%, 40 % and 34% for a natural gas an oil-fired and coal power plants respectively (**Mirage Machines, 2018**).

$$\dot{Ex}_{liquid}^{practical,pump} = \frac{\dot{E}x_{liquid}^{theoretical,pump}}{\eta_{pump}\,\eta_{driver}\,\eta_{powerplant}} = \frac{Q\Delta P}{\eta_{pump}\,\eta_{driver}\,\eta_{powerplant}} \qquad \text{eq.(16)}$$

Artificial lift. The rate of exergy to lift the liquids from the well was calculated from the following equation:

$$\dot{Ex}_{liquid}^{theoretical,lift} = Q\rho_w gh; \qquad \text{eq.(17)}$$

where h is the depth of the reservoir. The same pump efficiency was assumed in the calculations.

Drilling process. Here, we consider the energy requirement for drilling, and the cement and steel requirements for the piping and cementing of the wells.

Drilling Exergy is 70 000 KJ/m.

$$Ex_{drilling}^{practical}\,[kJ] = ex_{drilling}^{pr} * well\ length \qquad \text{eq.(18)}$$

For the cementing and piping**,** we simply multiply the mass of the pipe and cement that is required for an injection and a production well by the exergy values of steel and cement, respectively.
Practical exergy values of steel and cement are taken directly from **Eftekhari, et al., 2012**, where practical specific exergy for cement and steel is 6165 kJ/kg and 58667 kJ/kg respectively.

$$Ex_{cement,steel}^{practical} = ex_{cement/steel}^{pr} \, V_{cement/steel} \, x \, \rho_{cement/\,steel} \qquad \text{eq.(19)}$$

where Portland cement is used with average density of 2870 Kg/m^3 (**Bett, 2010**) and steel density is 7855 Kg/m^3 (**Engineering ToolBox**).

Furthermore, we assume that the casing steel pipe has an inside diameter of 200 mm with a thickness of 6.4 mm and 15 mm of space between the pipe and the hole wall that is to be filled with cement. All the final values are presented in **Table 3**.

Water treatment. As we have mentioned before, the produced water requires further treatment to meet some specifications since meeting water quality specifications for injection or re-injection is essential for protecting the permeability of a reservoir to avoid plugging (**Oil and Gas Online**). Obviously, components of produced water vary from one location to another depending on geological formation and condition. Four methods of produced water treatment before re-injection have been proposed, i.e. physical, chemical, biological and membrane-based treatment (**Ahmadun et al., 2009**). The energy consumption for treatment of the produced water can vary between less than 1 (floatation, filtration, adsorption methods) to more than 100 kWh/m3 (e.g. multi-stage flash distillation method) depending on the applied technology (**Farajzadeh et al., 2019**). Among all the technologies, membrane is considered as an attractive technology in various processes including in water and wastewater treatment (**Khoiruddin et al., 2017**) due to its ability of producing a high quality product along with relatively lower cost, lower energy and chemical consumption, smaller footprint, more intensive process, easy to scaleup, and flexible to operate (**Makertihartha et al., 2017**). Membrane separation processes operate without heating that's why use less energy than conventional thermal separation processes such as distillation, sublimation or crystallization and without the addition of chemicals. The membrane separation process is based on the presence of semi permeable membranes, so it relies on a membrane barrier to filter or remove particles from water.

The principle is actually simple: the water flow through the membrane which acts as a very specific filter, and while water is flowing it catches suspended solids and other substances. There are various methods to enable substances to penetrate a membrane such as the applications of high pressure, the maintenance of a concentration gradient on both sides of the membrane and the introduction of an electric potential (**Lenntech**). In our study, fluid passes through the membrane because of the pressure difference between one side of the membrane and the other. Furthermore, if we inject under matrix injection conditions, higher water quality and thus higher energy is required, where the energy consumption is 5 kWh/m3 (18 kJ/kg) is assumed. Whereas, for the injection under fracturing conditions the water quality can be relaxed, thus the energy consumption is considered to be 1 kWh/m3 (3.6 kJ/kg) (**Farajzadeh et al., 2019**). It is important to know that 52% of the energy usage in water treatment is coming from electricity (**Singh et al., 2012**).

Stimulation. Scaling from geothermal fluids has been recognized as a major problem in the development of geothermal energy (**Andritsos et al., 2002**) which was concluded according to

(**Antics et al., 2015**) that it is due to CO_2 degassing that occurs during production in the production well. Furthermore, if scaling is allowed to form without intervention, it will limit production, resulting in abandonment of the well (**Petrowiki, 2018**). Accordingly, based on the chemical composition of the produced water, Calcium, Iron or Lead can be precipitated causing the clogging of pores therefore an additional pressure drop. The most common salt is Calcium carbonates in low enthalpy reservoirs (**Andritsos et al., 2002**). Thus, one mitigation of several mitigation techniques to this scaling problem is to perform acidification by injecting an acid such as HCl (**Gray et al., 2018**, **Antics et al., 2015**).

The stimulation exergy is the result of the summation of the injection exergy and the chemical exergy of the acid used in the stimulation**.**

$$\dot{E}x_{simulation} = \dot{E}x_{injection} + \dot{E}x_{chemical} \quad \text{eq.(20)}$$

$$\dot{E}x_{injection} = Q\Delta P \quad \text{eq.(21)}$$

$$Ex_{chemical} = \frac{ex_{ch}}{MW} * \rho_{acid} * V_{acid} \quad \text{eq.(22)}$$

In this work, we will consider hydrochloric acid HCL having a specific chemical exergy of 84.5 kJ/mol (**Szargut, 2007**) to which we add the manufacturing energy of HCl which is 408 kJ/mol (**Boustead, 2005**) and a density ρ_{HCl} = 1185 kg/m^3 at 25 ˚C and with 40% w/w concentration (**HandyMath**), and a Molecular weight MW= 36.46 g/mol for the stimulation process.

According to a real case in the Netherlands (**Antics et al., 2015**) the stimulation recovery is 50% and can reach 65% and after each stimulation we have a more severe pressure drop. Thus, in our calculation we will consider 65% recovery and a factor of 0.5 of additional pressure drop with respect to the previous one before the last performed stimulation.

Finally, the extraction exergy of the system which is the exergy invested along all the lifecycle of the system is calculated by the summation of the pumping, drilling, piping, cementing, stimulation exergy values;

$$Ex^{j}_{extraction} = Ex_{pump} + Ex_{art_{lift}} + Ex_{driling} + Ex_{steel} + Ex_{cement} + Ex_{waste} + Ex_{stimulation} \ [\mathrm{J}]; \quad \text{eq.(23)}$$

$\dot{E}x_{waste}$ is by assuming a heat loss of 10% $X_{loss} = 10\%$,

$$Ex_{waste} = X_{loss} Ex_{resource} \ [\mathrm{J}] \quad \text{eq.(24)}$$

Moreover, we will consider **carbon capture and storage** process where the exhaust gas coming from the above-mentioned power plants are transferred to the carbon capture (CC) and carbon storage (CS) units to make electricity production zero-emission. The exergy values for carbon capture and storage (CCS) to each type of power plants are extracted directly from (**Farajzadeh et al., 2020**).

Finally, the abatement exergy (here only for CO_2 emission) is estimated by:

$$Ex_{abatement} = C_{total} ex_{ccs}, \quad \text{eq.(25)}$$

where ex_{ccs} [J/kg CO_2] is the CO_2 capture and storage exergy requirement summarized in **Table 4**, and C_{total} is the CO_2 emission [kg CO_2/s] of the process calculated by :

$$C_{total} = \left(Ex_{drilling} + Ex_{pump} + Ex_{art_{lift}} + Ex_{steel} + 0.5\, Ex_{cement} + 0.52\, Ex_{waste} + Ex_{stimulation} \right) e_{pp}; \quad \text{eq.(26)}$$

Where e_{pp} is the specific CO_2 emission from the fuel-fired power plant which is summarized in **Table 4**.

Material/ Work Streams	Practical specific exergy	Unit
Drilling exergy	70 000	kJ/m
Steel	58 667	kJ/kg
Cement	6 165	kJ/kg
Injection pump	**eq.(16)**	kJ/s
Artificial lift	**eq.(17)**	kJ/s
Water treatment	3.6	kJ/kg
Other processes	10% of the total resource exergy	kJ/s
Exergy resource	**eq.(13)**	kJ/s
Stimulation	**eq.(20)**	

Table 3- Summary for the required exergy for work streams

Fuel	Actual storage exergy MJ/kg	Specific CO_2 emission kgCO_2/MJ: e_{pp}
CH4	7.88	0.055
CH2	9.19	0.073
CH	10.6	0.088

Table 4- Summary of the CCS requirements and specific CO_2 emissions (Farajzadeh et al., 2020)

2.2 Recovery factor

The exergy recovery factor, ExRF, is defined as the ratio between the produced exergy and process exergy requirements for its extraction and the gross exergy of the source,

$$ExRF = \frac{Ex_{net}}{Ex_{ressource}} = 1 - \frac{Ex_{extraction} + Ex_{waste}}{Ex_{ressource}} \quad \text{eq.(27)}$$

A negative recovery factor indicates that the process is not feasible. This is the theoretical exergy recovery factor, by including efficiencies of the pump and power plant we will get the practical exergy recovery factor $ExRF^{pr}$,

$$ExRF^{pr} = \frac{Ex^{pr}_{extraction} + Ex_{waste}}{Ex_{ressource}} \qquad \text{eq.(28)}$$

Finally, if we want to capture the carbon and store it we calculate the zero-emission recovery factor $ExRF^0$by including the abatement exergy in the process:

$$ExRF^0 = \frac{Ex^{pr}_{extraction} + Ex_{waste} + Ex_{abatement}}{Ex_{ressource}} \qquad \text{eq.(29)}$$

2.3 Effect of heterogeneity

In this section we will describe the model and its parameters built to assess the effect of heterogeneity based on the Dykstra-Parsons coefficient that is a measure of the degree of heterogeneity.

"The COMSOL Multiphysics finite element package is designed to combine physical equations. The package has a very strong grid building tool that is flexible" (**Daanen, 2012**). COMSOL allows conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs).

2.3.1 Model equations

For the simulation of temperature in the reservoir COMSOL use an algorithm based on PDE in the weak formulations which is an important tool for the analysis of mathematical equations that permits to solve problems in fields other than linear algebra such as partial differential equations. It is important to note that in the following equations we will see a function called "Test()" since in weak formulations an equation doesn't hold totally and has instead weak solutions with respect to certain test functions.

Temperature equation in the whole domain *Ω*, in the weak formulation

$$\int [C_{p-r} Test(T)\partial_t T + C_{p-w}\frac{k(x,y)}{\mu(T)}\,\partial_x PT\ test(T_x) + C_{p-w}\frac{k(x,y)}{\mu(T)}\partial_y PTtest(T_y) + \lambda\partial_x T\ test\ (T_x) + \lambda\partial_y T\ test\ (T_y)]d\Omega = 0, \qquad \text{eq.(30)}$$

where C_{p-r} is rock heat capacity in J/m^3/K, C_{p-w} is the water heat capacity in J/m^3/K, T is the temperature in K, λ is the conductivity in W/m/K, μ(T) is the water viscosity in Pa.s, k(x,y) is the permeability in the x and y-directions.

Darcy's velocity in the weak formulation

$$\boldsymbol{\nabla}\cdot(\overrightarrow{u})=0\text{, i.e., incompressible fluid} \quad \text{eq.(31)}$$

$$\frac{-k(x,y)}{\mu}\,\partial_x P\ test(P_x) - \frac{k(x,y)}{\mu}\,\partial_y P\ test(P_y) = 0; \quad \text{eq.(32)}$$

where P is the pressure in Pa and $\vec{u}$ is the velocity.

Permeability function of x and y-directions

$$k(x,y) = \sum_{1}^{10} k_i e^{\frac{-(y-y_i)^2}{\Delta}} \quad \text{eq.(33)}$$

where Δ is the smoothing parameter, k_i is the permeability of layer I & y_i average y position of each layer.

Water viscosity as a function of T:

We chose to have a viscosity that varies as a function of temperature to have more realistic calculations. According to **ResourceSaylor** the equations is as follow:

$$\mu(T) = A * 10^\wedge \frac{B}{(T-C)}; \quad \text{eq.(34)}$$

where A= $2.414*10^{-5}$ Pa.s, B=247.8 K, C= 140 K.

2.3.2 Geometry

A 2D model was built using COMSOL Multiphysics 5.5, with 10 layers having a rectangular shape **Figure 8**. We assumed a structurally simple, synthetic, 2D rectangle for the geological system under study with 500m × 100m lengths in x and y directions. A 2D horizontal geothermal reservoir representing the porous medium is modeled filled with hot formation water. We considered a geothermal reservoir with a distance between the wells equal to 500m and a thickness of 100m with 10 layers having 10m thickness each. The reservoir parameters and fluid properties as functions of temperature are defined. The reservoir depth is not implemented but it is assumed to be 2500m and so where the temperature is 90˚C (**Bonté et al., 2012**). When we start the production the produced hot water is cooled down to 35˚C and re-injected through the injection well.

Each layer will have a permeability value with an average permeability of the layers consistent with the Netherlands subsurface and which is 100mD with a specified Dykstra-Parsons coefficient used to generate the permeability fields.

Thermal breakthrough which is the moment when the extent of re-injected cold water plume reaches the production wells is the used to determine production lifetimes as an indicator for the temperature drop at the boundary. However, the considered area's temperature may not immediately drop to non-economic values when thermal breakthrough occurs at production wells. As a consequence, the project lifetime (how long the doublet can produce economically) is defined as the time when the temperature at the production well reaches 50˚C.

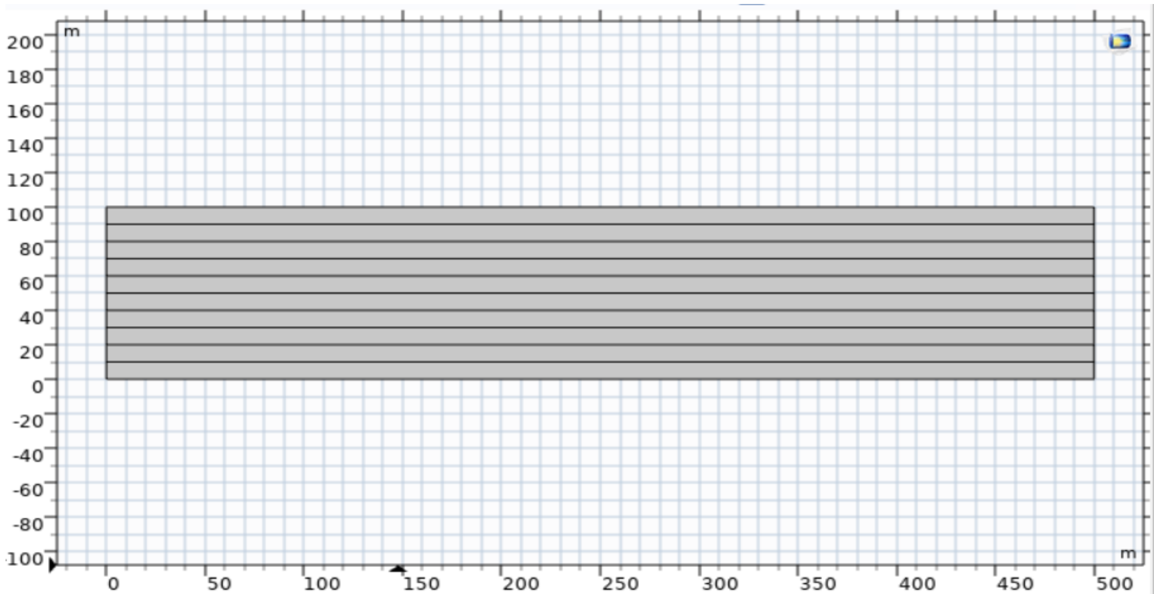


Figure 8- 2D reservoir representation consisting of 10 layers

2.3.3 Model Setup

The COMSOL software is used to set-up a model that is a two-dimensional representation of a geothermal system. First we constructed a Base Case which serves as a reference for other cases in which the permeability in the layers has been varied in the layers to test the sensitivity of the model to the heterogeneity based on a chosen degree of heterogeneity V_{DP} = 0.7.

This section discusses the model input and setup. The parameters used in the Base Case are all grouped in **Table 5**.

Parameter	Value
Dimensions	
Reservoir thickness	100m
Mesh size	Extra fine (10m x 0.0375m)
Well data	
Well distance	500m
Injection temperature ˚C	35˚C
Injection pressure	20 bar
Temperature & Pressure data	
Initial average reservoir temperature	90˚C
Initial average reservoir pressure	100 bar
Surface pressure	1.03bar
Reservoir permeability	
Layer 1	208mD
Layer 2	36.9mD
Layer 3	23.3mD
Layer 4	162mD
Layer 5	82mD
Layer 6	198mD
Layer 7	12.7mD
Layer 8	187mD
Layer 9	22.20mD
Layer 10	9.2mD
VDP	0.7
s	1.2
k_{av}	100 mD
Fluid properties	
Heat capacity	$4.814*10^6$ J/m^3/K
Viscosity	**eq.(34)**

Table 5- Input parameters for the Base Case.

After presenting the methodology used for the two parts in details we move to the next chapter to present the results obtained and discuss them.

CHAPTER 3. RESULTS AND DISCUSSIONS

In this chapter we will present the result and discuss the obtained outcomes.

Section 3.1 discusses the results of the sensitivity analysis based on exergy analysis. **Section 3.2** discusses the results obtained from the simulations using COMSOL.

3.1 Sustainability based on exergy analysis.

In this part we will present the results we obtained from the exergy analysis, applied on the defined system and we will base our conclusion on the exergy recovery factor **ExRF,** the coefficient of performance **COP,** the exergy returns on investment **ExROI and** the **CO_2 footprint**.

3.1.1 Geological Uncertainties

Four geological uncertainties are varied with respect to the base case: the reservoir thickness, the thermal conductivity of the reservoir, thermal conductivity of the confining layers and the permeability of the confining layers. The best conditions that lead to a sustainable production will be chosen. The electricity is generated from a natural gas power plant for all the cases.

Case 1: Reservoir thickness

The reservoir thicknesses tested are 50,100 and 200m, with an injection rate and production rate of 150 m^3/hr.

All the other technical parameters are the same as the Base Case (well spacing, heat conductivity).

Moreover, the pressure drop is assumed to be 1.5 bar each year and a stimulation is performed after 50 bars pressure drop. In total, in the case where we have a rate q= 150 m^3/hr. 7 stimulations are performed and the well is abandoned after 83 years of production since no further stimulation can be performed and the reservoir is totally damaged.

Analysis:

When we exclude artificial lift form the calculations the average CO_2 emission in kg/MJ-heat extracted, for a 200m reservoir thickness for example, is negligible with an order of magnitude of 3 x 10^{-3} kg/MJ-heat extracted. ExRF is positive decreasing from 87.74% to 58.47%. We also obtain high COP for all three cases which is 20.68, 21.04, and 21.15 for a 50m, 100m and 200m thickness respectively and finally a high ExROI with an average 2.4. As a consequence, we almost have a perfect scenario and all the numbers show that with an increase in the thickness the system is more sustainable. Unfortunately, as we said before an artificial lift is needed and in very few special cases the reservoir is self-energized so we are going to show the result for the system but when including the artificial lift in the calculations. When artificial lift is included the following results are seen.

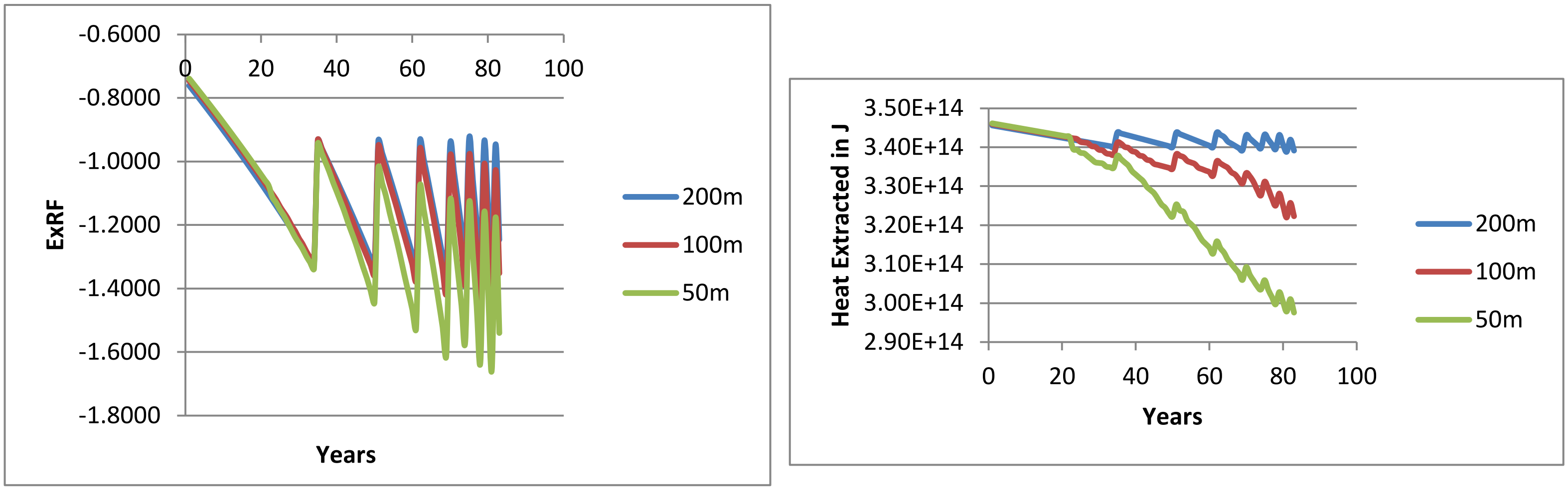


Figure 9- Graphs representing the exergy recovery factor and the heat extracted in J for a 50m, 100m & 200m thickness over 83 years.

The obtained shape in all the graphs is due to the stimulation performed through the lifetime of the project.

Despite the difference between the numbers is moderate, as we can see from the graphs, the parameters plotted versus time show that from an exergetic point of view the higher the thickness is, the more heat we can extract, the less CO_2 emissions we will have and higher is the ExRF. Even though the exergy recovery factor is negative for all three cases and which indicates that the system is unfeasible, the system can be taken into account since the CO_2 emissions are very small compared to a system powered by a Natural gas power plant with a maximum value of 0.020 kg/MJ-heat extracted through the 83 years.

The exergy analysis that we did by using the concept of recovery factor does not consider the fact that "heating" only destroys exergy. Therefore, having a negative recovery factor is not necessarily a negative result. To avoid this awkwardness, the term coefficient of performance (COP) is used for heat pumps, defined as the ratio of product thermal energy to input driving energy. In order to see the status of geothermal energy system, the COP of geothermal energy must be compared with alternative heating methods such as heat pumps using this coefficient. The average coefficient of performance for geo heat pumps is 2, heat pumps is 1, and finally natural gas burners which is 0.8 respectively (**Self et al., 2013**). However, these are just average values serving as a tool to be able to compare with the performance of geothermal energy, but they can vary seasonally for example by increasing or decreasing.

Thus, if we look at **Table 6** where the average values of COP, CO_2 emissions and ExROI is presented. A reservoir with a 200m thickness has a slightly higher average COP than the other cases. Not to mention also the ExROI which is 0.65% higher than that of the 100m thickness and 3% higher than the case of a 50m thickness. Having a low ExROI, not even reaching 1, is explained by the negative ExRF. Considering a system with a low ExROI, there must be strong reasons for it. But in any case always an ExROI higher than 1 is desired and which is not our case. The only parameters that proved one positive side of this system is the high COP and low CO_2 emissions for all cases but slightly better for an increase in thickness compared to the alternative heating methods. As it is seen even with a moderate variation but the reservoir thickness has somehow a large impact on the results. This is expected since with a larger thickness more heat can be produced. Moreover, based on the calculation that we made, we could say that an increase in thickness will lead to a more sustainable production. Yet, we didn't take into account the recharge concept that favors thinner reservoirs (**De Bruijn, 2020**).

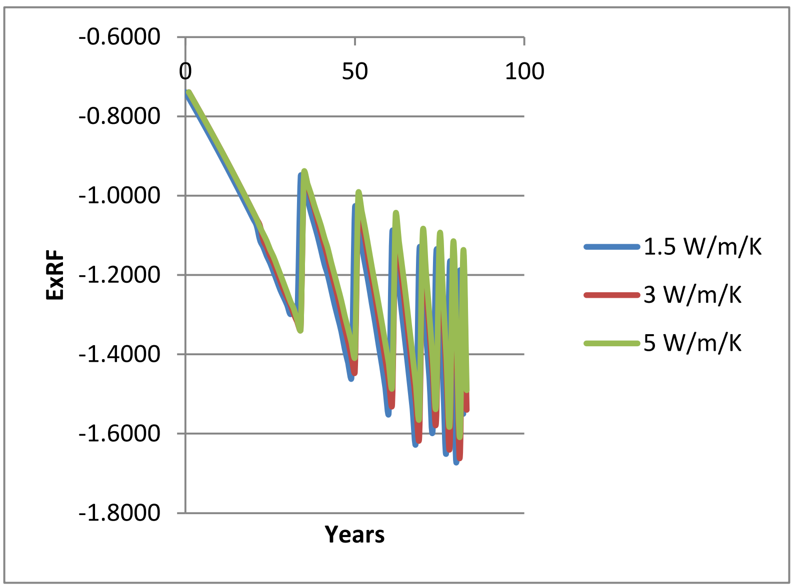
	COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
50m	2.86	0.0192	0.3253
100m	2.95	0.0186	0.3342
200m	2.99	0.0183	0.3364

Table 6- Summary of the average COP, CO_2 emissions and ExROI for the three cases

Case 2: Thermal conductivity of the reservoir

In this case, we also keep the same production parameters while the only parameter that is changing is the thermal conductivity of the reservoir which is varying between 1.5, 3 (base case) and 5 W/m/K.

Since we're still considering the production rate which is equal to 150 m3/hr, the lifetime of the project is still 83 years and the number of stimulations performed is 7. In the following figures, the results are shown for a 50m thickness.



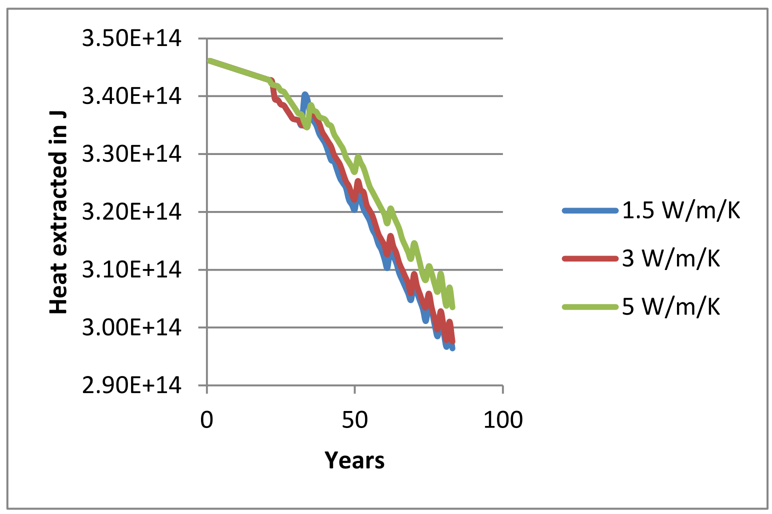


Figure 10- Graphs representing the sensitivity on the thermal conductivity of the reservoir for a 50m thickness over 83 years

The higher the thermal conductivity of the reservoir is, the higher are ExRF, and the heat extracted for the same thickness, although we couldn't see a change for 200m thickness in terms of heat extracted and ExRF. This is due to the almost constant temperature for the whole period of time: as with a high thermal conductivity the temperature doesn't decrease a lot and we will have a constant temperature for a longer period of time, the heat will travel faster in the reservoir, producing more heat per unit time.

Table 7 summarizes the result of the sensitivity on the thermal conductivity for 50m and 200m reservoir thickness in terms of COP, CO_2 emissions and ExROI.

		COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
50m	1.5 W/m/K	2.86	0.0193	0.3244
	3 W/m/K	2.86	0.0192	0.3253
	5 W/m/K	2.89	0.0190	0.3281
200m	1.5 W/m/K	2.98	0.0183	0.3363
	3 W/m/K	2.99	0.0183	0.3364
	5 W/m/K	2.99	0.0183	0.3365

Table 7-Summary of the average COP, CO_2 emissions and ExROI for a 50m & 200m thickness

The COP increases slightly with increasing thermal conductivity for a given thickness. CO_2 emission decreases. This can be seen clearer for a thinner reservoir.

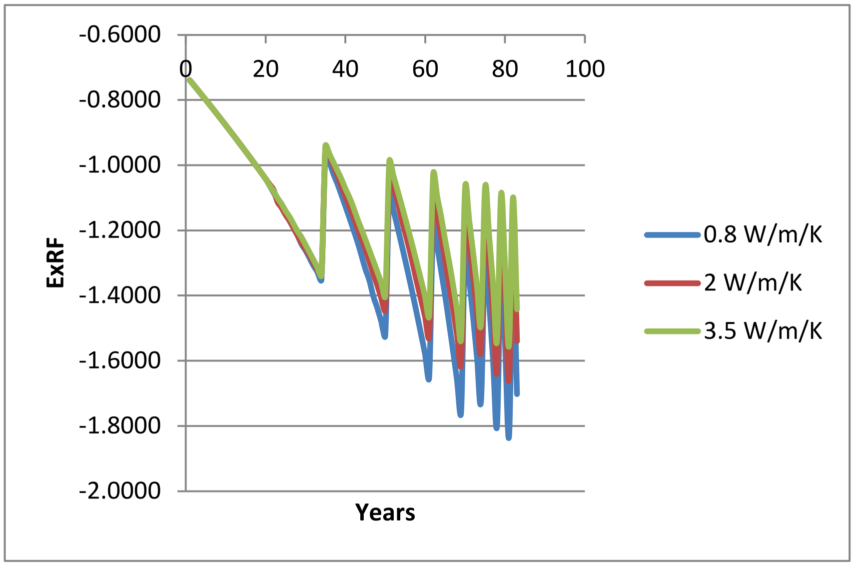
As we can see from the summarized average COP, CO_2 and ExROI, by considering higher values of thickness it is possible to have slightly better results. We couldn't assess the effect of thermal conductivity due to the almost constant and equal temperature in all cases.

If we look at the amount of heat extracted in J, the higher thermal conductivity values have slightly higher heat extracted which is also an indicator that having high thermal conductivity is always desired.

Like before a negative ExRF means that the system is unfeasible and in addition to the ExROI which is lower than 1 which means that we are investing more than we are benefitting from the system. The only advantage is the low CO_2 emissions compared to a traditional heat pump and the high COP which is higher than the alternatives.

Case 3: Thermal conductivity of the confining layers

In this case, we also keep the same production parameters and the only parameter that is changing is the thermal conductivity of the reservoir which is varying between 0.8, 2 (base case) and 3.5 W/m/K. Since we're still considering the production rate which is equal to 150 m3/hr., the lifetime of the project is still 83 years and the number of stimulations performed is 7.



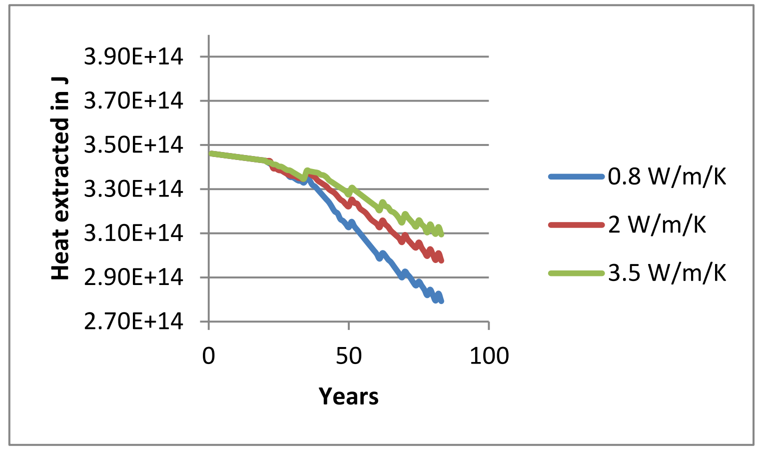


Figure 11- These graphs show the exergy recovery factor and the heat extracted in J for a 50m reservoir thickness for different thermal conductivity of the confining layers.

As we can see from the graphs, the higher the thermal conductivity is, the higher the ExRF and the heat that can be extracted are. As it is known, the confining layers provide the thermal energy that is used for the recharge. Thus, a larger thermal conductivity will allow a higher heat flow to the reservoir and this will delay the temperature decline that's why more heat is extracted and it can be seen in the graphs.

For 200m, the result is insensitive since for this period of time which is 83 years the temperature decline is almost constant. In addition to that, if we look at **Table 8**, for 200 m reservoir thickness the COP, CO_2 emissions and ExROI are not varying but for 50m thickness, the COP is slightly increasing with increasing thermal conductivity and CO_2 emissions are decreasing with increasing thermal conductivity. Thus, the higher the thermal conductivity in the confining layer the more heat is moving towards the reservoir the more the temperature is constant the better the results we could have even though the variations are conservative.

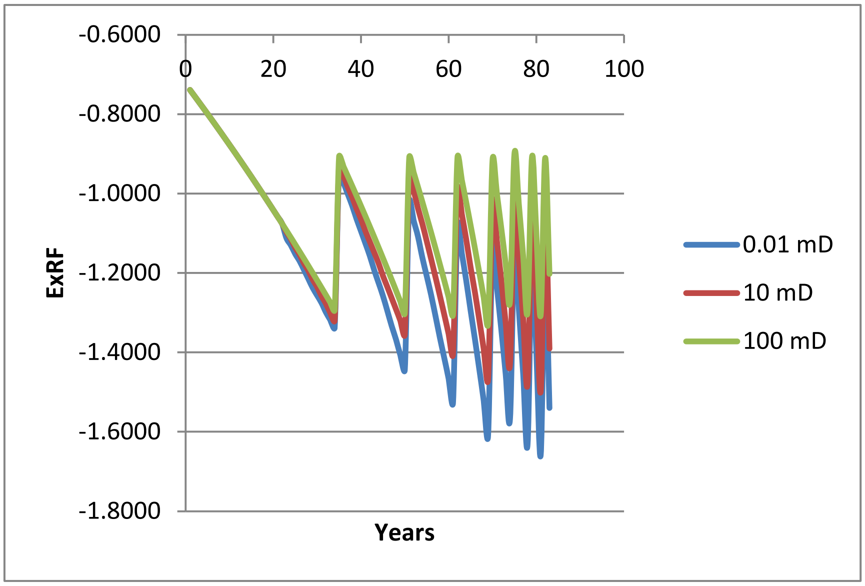
		COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
50m	0.8 W/m/K	2.80	0.0197	0.3183
	2 W/m/K	2.86	0.0192	0.3253
	3.5 W/m/K	2.90	0.0189	0.3296
200m	0.8 W/m/K	2.99	0.0183	0.3364
	2 W/m/K	2.99	0.0183	0.3364
	3.5 W/m/K	2.99	0.0183	0.3364

Table 8-Results for the study on the sensitivity of the production process to the thermal conductivity of the reservoir rock for a 50m & 200m reservoir thickness.

We can notice that the thermal conductivity of the confining layers has a larger impact than the thermal conductivity of the reservoir which is seen clearly for a reservoir thickness of 50m.

Case 4: Permeability of the confining layers

These tests examine the sensitivity of the production process to a change in the permeability of the confining layers. The Base case that is used as a reference has a permeability of 0.01mD in the confining layers. This section presents the results of two other scenarios where the horizontal permeability in the confining layers is 10 mD and 100 mD. The permeability in the reservoir is kept constant at 200 mD, and the vertical- horizontal permeability ratio (k_v/k_h) remained at 0.1, for the entire model. For a reservoir with the thickness of 50 meters, and 200 meters the effect of this parameter is reviewed.



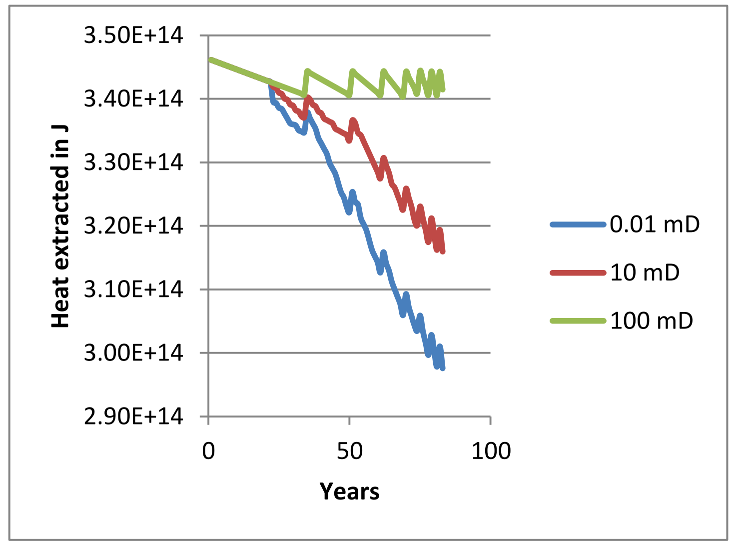


Figure 12-These graphs show the exergy recovery factor and the heat extracted in J for a 50m reservoir thickness for different permability of the confining layers.

As we can see in the graphs, an increase in the permeability leads to a higher ExRF and more heat that can be extracted. This effect is larger for a thinner reservoir as for 200m: we can barely see the impact, and this is again due to the temperature that remains constant for all the lifetime of the system. As we said before, the confining layers provide the thermal energy that is used for the recharge. Thus, a larger permeability in the reservoir rock will allow a faster heat flow to the reservoir and this will delay the temperature decline that's why more heat is extracted and it can be seen in the graphs.

		COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
50m	0.01 mD	2.86	0.0192	0.3253
	10 mD	2.93	0.0187	0.3329
	100 mD	2.99	0.0183	0.3410
200m	0.01 mD	2.99	0.0183	0.3364
	10 mD	2.99	0.0183	0.3365
	100 mD	2.99	0.0183	0.3365

Table 9- Results for the study on the sensitivity of the production process to the permeability of the reservoir rock for a 50m & 200m reservoir thickness.

Moreover, with increasing permeability, a higher COP and lower CO_2 emissions can be observed. The same for the ExROI but which is unfortunately lower than 1.

So it can be seen from Case 2, 3 and 4 that the confining layers has a large impact on the reservoir and in our project lifetime restricted by the stimulation concept this can be seen more on the thinner reservoir.

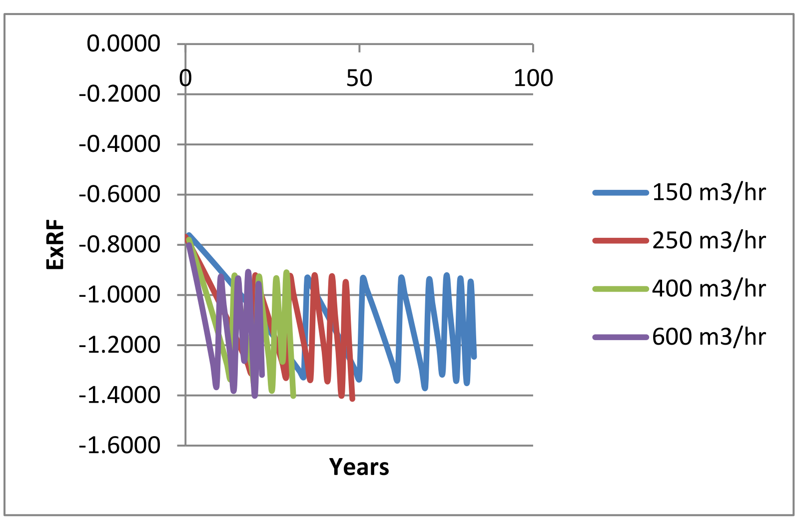
As it is noticed the reservoir thickness has the largest impact on the results from a thermodynamic point of view. For a thinner reservoir the temperature decreases faster in the production well. As a consequence, during the lifetime of the project, we could notice a slight change in the calculated parameters when performed a sensitivity analysis on the system. Whereas, when we perform a sensitivity analysis on the system with 200m reservoir thickness, we can barely see a variation in the calculated parameters due to the constant temperature in the producer. However, all the calculations showed that higher reservoir thickness has better results.

3.1.2 Production Parameters

This case investigates the sensitivity of the system due to a change in the production rate and the effect of well spacing. Unlike the geological uncertainties which were discussed the production parameters can be adjusted and optimized to the best production strategy.

Case 5: Production rate

The production rate is varied between 150 m^3/hr which is the Base Case, 250 m^3/hr, 400 m^3/hr & 600 m^3/hr. As we said before, the pressure drop during the production wasn't simulated so we assumed a pressure drop of 1.5 bar each year for a production rate of 150 m^3/hr, 2.5 bar for 250 m^3/hr, 4 bar for 400 m^3/hr and finally 6 bar for 600 m^3/hr with a fracturing pressure drop of 50 bar. Thus, this leads to a decrease in the lifetime of the project with an increase in the rate. The lifetime of the projects is 83, 49, 31 & 22 years respectively. So this decrease in the lifetime is the first negative conclusion concerning the increase in rate since the main purpose is to produce for a longer period of time which indicates a more sustainable system and this purpose is lost here.



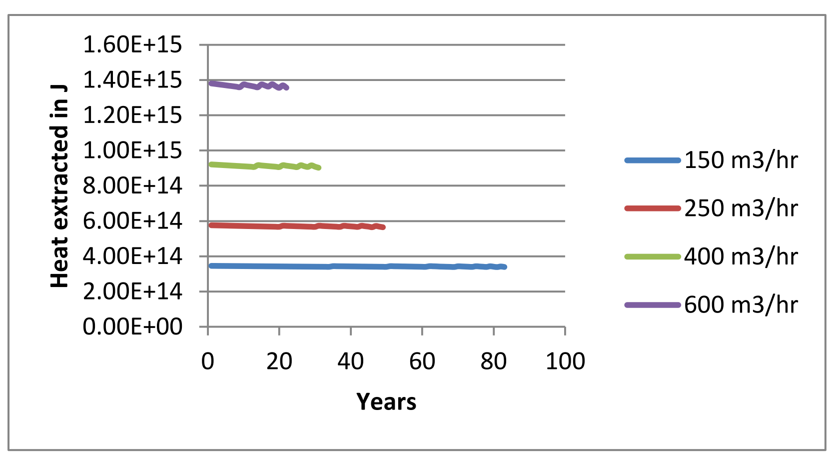


Figure 13- These graphs show the exergy recovery factor and the heat extracted in J for a 200m reservoir thickness for different production rate.

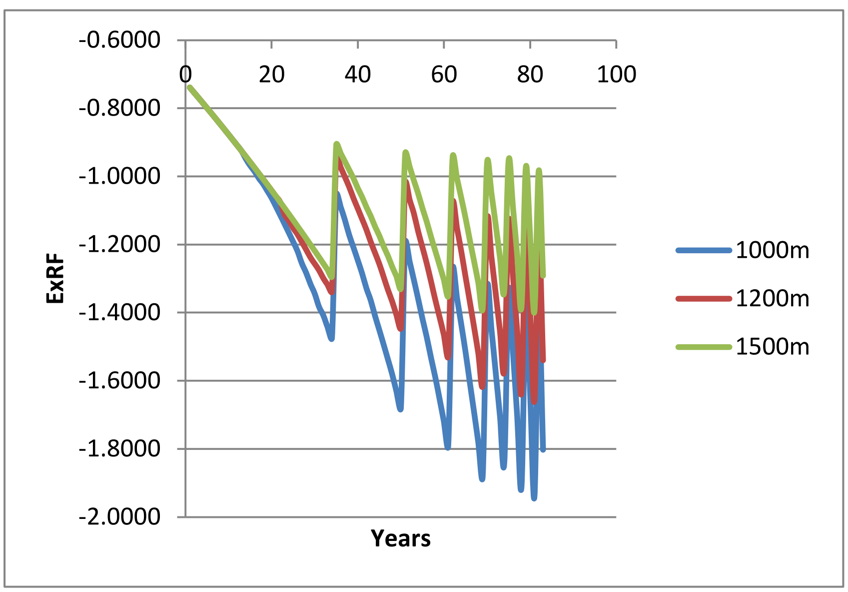
As we can see form the graphs approximately 66.5 %, 166%, & 298% more heat is extracted with respect to the base case which is 150 m^3/hr, with an increase in rate from 250 to 400 to 600 m^3/hr respectively. Although we have this increase in the heat extracted, the lifetime is shorter, the COP is slightly lower, CO2 emissions are also slightly higher. The impact is not seen clearly since we are working with a 200m thickness and the lifetime of the project decreases when we increase the rate so approximately the temperature is the constant or decreases slightly within the lifetime chosen for each rate. Accordingly, we can see that producing with a lower rate is more sustainable. Yet, we need to choose the rate in a way that will let the system feed the required energy demand by a certain society. As a consequence, we need to balance between producing in the most sustainable way and the energy demand.

	COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
150 m3/hr	2.99	0.0183	0.3364
250 m3/hr	2.99	0.0184	0.3362
400 m3/hr	2.98	0.0184	0.3349
600 m3/hr	2.97	0.0185	0.3335

Table 10- Results for the study on the sensitivity of the production process to the production rate for a 200m thickness

Case 6: Well spacing

The well spacing is varied between 1000m, 1200m which is the Base Case and 1500m.



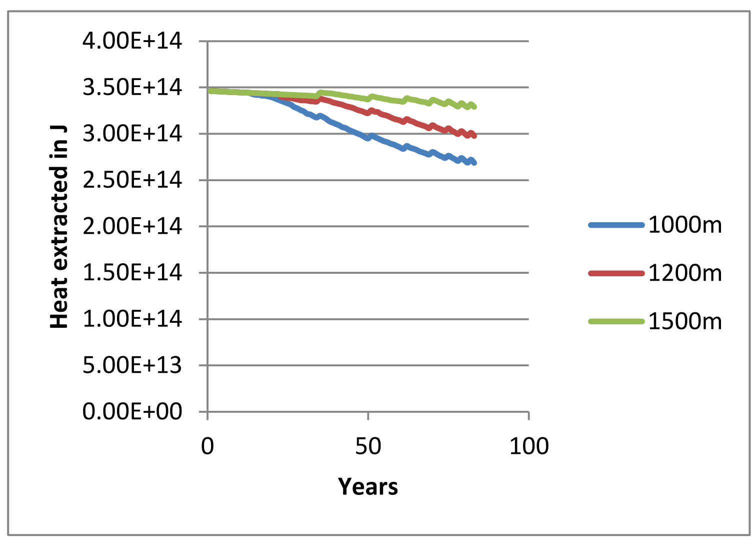


Figure 14- These graphs show the exergy recovery factor and the heat extracted in J for a 50m reservoir thickness for different well sapcing.

By looking at these graphs we can directly recognize that the well spacing has the largest impact on the results since we can clearly see the results of the sensitivity analysis on the distance between the injection and the production well. The larger the well spacing is, the higher are the

ExRF, and the heat extracted for the same thickness although we couldn't see a change for 200m thickness in terms of heat extracted and ExRF. This is due to the almost constant temperature for the whole period of time. As a consequence, having a higher well spacing seems to be the best strategy for a sustainable production. Moreover, for 50m thickness, with an increase in the well spacing, we could notice a decrease in the CO_2 emission, an increase in the COP and an increase is the ExROI which stays lower than 1.

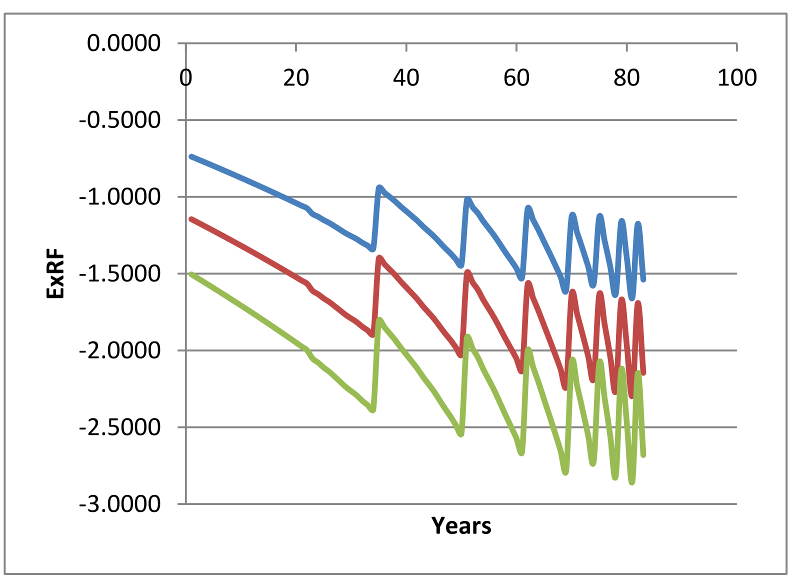
		COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
	1000m	2.72	0.0204	0.3083
50m	1200m	2.86	0.0192	0.3253
	1500m	2.97	0.0185	0.3376
	1000m	2.97	0.0184	0.3343
200m	1200m	2.99	0.0183	0.3364
	1500m	2.99	0.0183	0.3365

Table 11-Results for the study on the sensitivity of the production process to the well spacing for a 50m & 200m thickness.

3.1.3 Switching power plants

We are not going to present all the calculations, but as a general conclusion when switching from a natural gas to oil then to coal- fired power plant which means to a less efficient power plant: 50%, 40%, 34% respectively we will notice that the ExRF is lower (also negative) whereas CO_2 emission is higher. However the heat extracted is not affected by the change since it is only function of the temperature which is not changing for the same chosen case.

As an example, we will take the Base Case with different power plants that drive the geothermal system and see the effect for a 50m thickness since the impact of the parameters are more visible for a thinner reservoir.



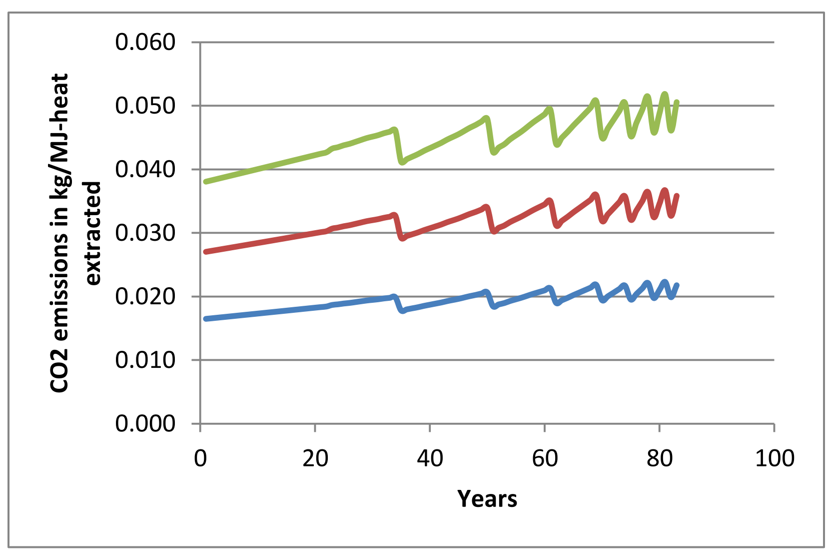


Figure 15- These graphs show the exergy recovery factor and the CO_2 emissions in kg/MJ-heat extracted for a 50m reservoir thickness.

As we can see in **Table 12**, the COP decreases, CO_2 emissions increase and ExROI decrease when moving to a less efficient power plant as expected.

	COP	CO_2 emissions in kg/MJ-Heat extracted	ExROI (including exergy abatement)
Natural Gas	2.86	0.019	0.3253
Oil	2.31	0.032	0.2256
Coal	1.98	0.045	0.1669

Table 12- Summary of the COP, CO_2 emissions & ExROI for the different power plants

It is important to note that the system emits less CO_2 in all the cases compared to 0.055 kg/MJ-CH_4, 0.073 kg/MJ-CH_2, 0.088 kg/MJ-CH for a fully electricity driven heat pump by natural gas, oil-fired and coal fired power plant respectively.

In the end a general conclusion will be elaborated in chapter 4.

3.2 Effect of heterogeneity on heat recovery

In this part we will present the results we obtained from the model we built using COMSOL Multiphysics 5.5.The model is a layered reservoir consisting of 10 layers to which is assigned a certain permeability based on a certain V_{DP}. The sensitivity of the system to a change in V_{DP} followed by a change in the average permeability will be studied. The conclusion will be based on the lifetime of the project and the energy produced and whether the heterogeneity has a negative or positive impact on the heat recovery. We will study the effect of heterogeneity by changing the V_{DP} values between 0.5, 0.7, 0.8 and for a homogeneous reservoir having a V_{DP}= 0 for a fixed average permeability: $k_{av} = 100m$. Afterwards, we will change the permeability values between 100mD, 200mD and 300mD.

3.2.1 Fixed average permeability

In this part we will vary the Dykstra-Parsons coefficient between 0, 0.5, 0.7 (Base Case) and 0.8 for a fixed average permeability of 100mD.

Case 1.1: V_{DP}= 0.7

For V_{DP}= 0.7 (Base Case), 10 realizations were generated in addition to the Base Case which are represented in **Table 13**.

Base Case	Realiz. 1	Realiz. 2	Realiz. 3	Realiz. 4	Realiz. 5	Realiz. 6	Realiz. 7	Realiz.8	Realiz. 9	Realiz.10
208	33.5	84.9	170	40.6	74.2	98.5	5.52	16.3	8.64	4.12
36.9	283	12.4	9.05	63.9	12.8	11.7	62.6	75.7	221	83.7
23.3	147	43.2	62.5	25.1	73.1	25.9	2.47	33.1	62	178
162	7.53	14.8	22.8	130	544	63.7	95.2	101	70.9	246
82	133	15.3	6.3	208	38.6	201	9.52	47.3	95.5	43.1
198	19.8	16.9	37.7	61.1	32.8	352	135	78.8	94	27.9
12.7	6.36	90.3	217	8.14	52.9	306	297	101	39.9	46.3
187	290	22.8	79.1	219	39	108	46.9	340	24.1	7.31
22.2	24.8	628	191	125	11.2	186	150	13.5	116	11.4
9.2	83.7	24.9	83.3	181	7.4	285	313	16	70.7	35.5

Table 13- Permeability values for the 10 realizations in mD for 10 layers

Based on the lifetime of the project and on the energy produced we will base our comparison between the cases. The project lifetime (how long the doublet can produce economically) is defined as the elapse time from the start of the project to the moment that the temperature in the production well decreases up to 50˚C. After that time, the production is stopped to take its time to recharge again. In **Table 14** we can see the different lifetime of the 10 realizations with a highest value of 7.89 years and a value that reaches 2.85 years. Thus, we can say that 4.94 years ≈ 5 years is the average lifetime for a geothermal reservoir with a degree of heterogeneity of 0.7.

We focus for example on the Base Case and realization 2, we can notice that the main difference between them is that in the Base Case we have high permeability in certain layers with respect to the other layers for the same field (one order of magnitude higher than the other layers) whereas in the realization 2 all the permeabilities have the same order of magnitude. The cold water front travels slower in the realization 2 than the water front travelling in the base case so the thermal breakthrough is anticipated when we have a higher permeability even in one layer and this will anticipate the temperature decrease in the production well. As we can see in **Figure 16**, after 3.17 years we can notice that the temperature is still high in the layers having lower peremabilities.

	Lifetime in years	Energy produced in W/m^2
Base Case	4.02	9.84E+04 – 7.15E+03
Realization 1	4.15	1.08E+05 – 9.58E+03
Realization 2	6.97	1.01E+05 – 4.71E+03
Realization 3	5.13	9.11E+04 – 9.08E+03
Realization 4	3.64	1.11E+05 – 6.11E+03
Realization 5	6.46	9.12E+04 – 3.98E+03
Realization 6	2.85	1.68E+05 – 9.68E+03
Realization 7	4.75	1.15E+05 – 5.91E+03
Realization 8	4.72	2.71E+05 – 6.39E+03
Realization 9	3.83	8.71E+04 – 8.63E+03
Realization 10	7.89	7.37E+04 – 4.22E+03
Average	**4.94**	**1.20E+05 – 6.86E+03**

Table 14- Lifetime and energy produced during the lifetime of the project in years and W/m^2 respectively

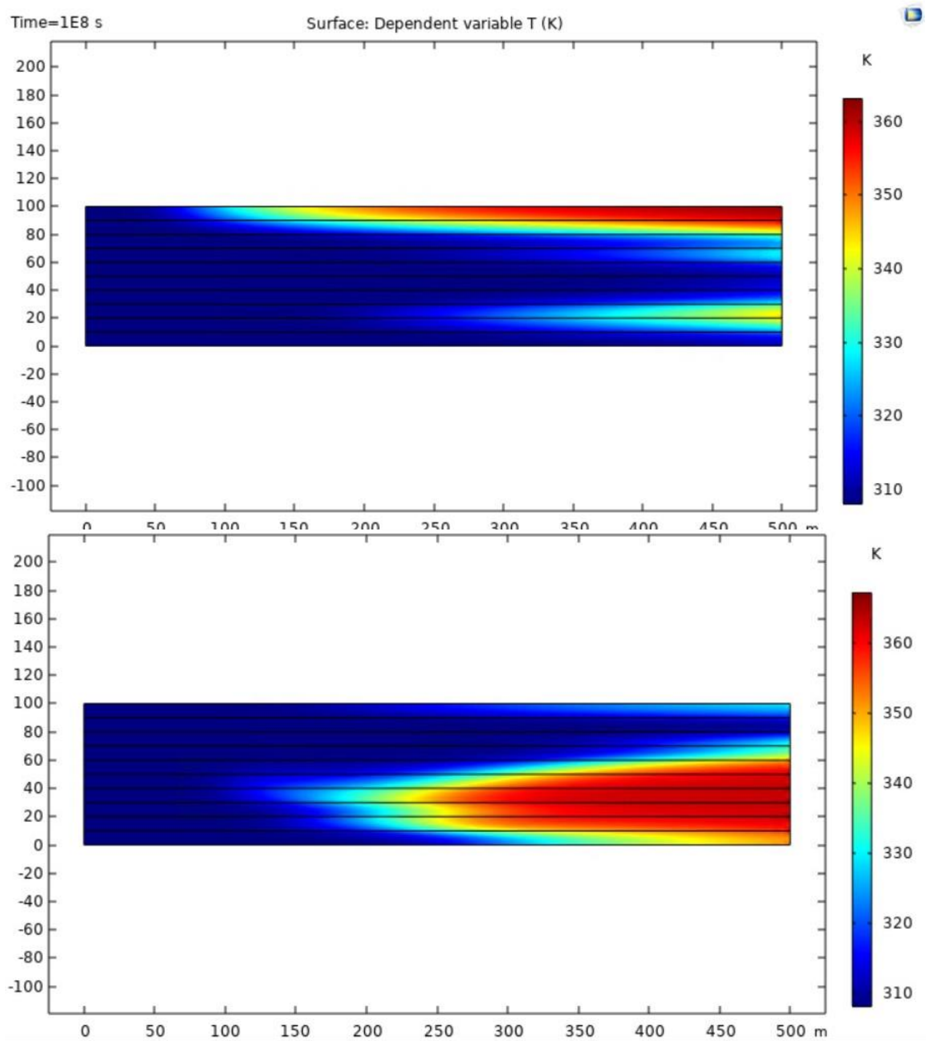


Figure 16- Temperature's 2D distribution for the Base Case and Realization 2 respectively at 1.00E+8 s ≈ 3.17 years.

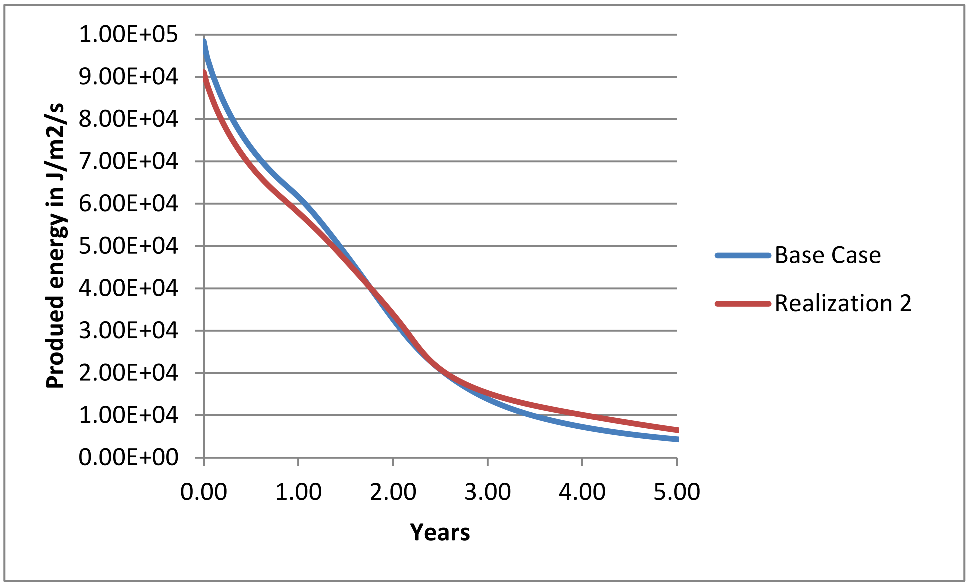


Figure 17- Graph representing the energy produced in W/m^2 over 5 years.

Finally, for the first 1 year the Base Case had higher energy output and this is because of the higher permeability layers which lead to a higher rate as we see in **Figure 18**. The flow move faster to the producer and more heat can be produced per unit time.

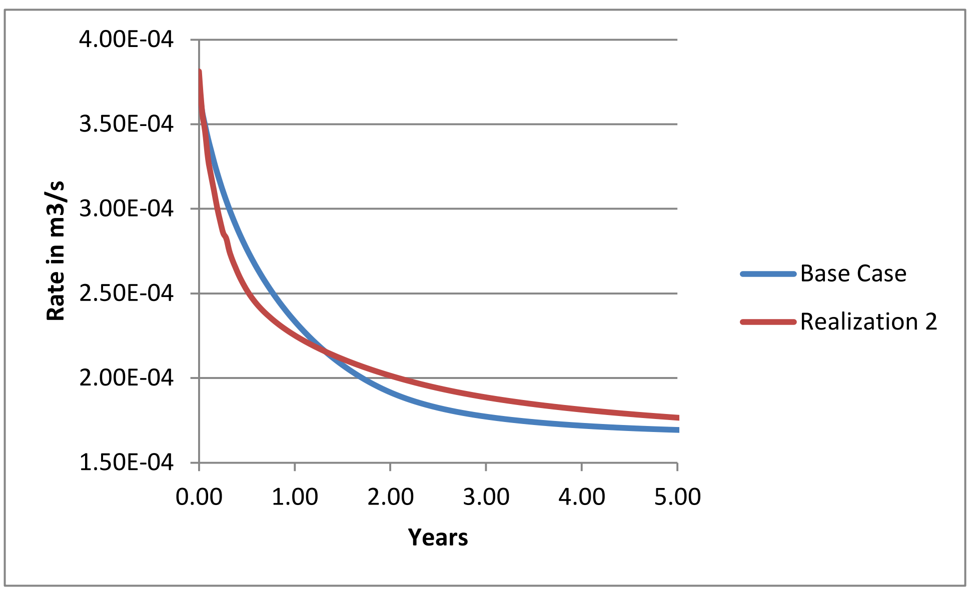


Figure 18- Graph representing the production rate in m^3/s over 5 years

We chose 2 random cases each having one value of V_{DP}. As we can see in **Figure 18** the production rate in realization 2 is slower than that in the Base Case for the first 1.Then, there's a crossover point where the production rate in the Base Case becomes lower. Thus, more heat can be produced per unit time for the Base Case at first then for the realization 2.

This will be clearer when we change the degree of heterogeneity by increasing and decreasing it.

Case 1.2: V_{DP}= 0.8

Base Case	Realiz. 1	Realiz. 2	Realiz. 3	Realiz. 4	Realiz. 5	Realiz. 6	Realiz. 7	Realiz.8	Realiz. 9	Realiz.10
11.1	14.1	85.3	4.06	12.1	4.84	5.59	263	23.47	96.91	30.57
10.8	3.08	19.30	10.90	4.81	2.80	190	11	2.1	167.58	17.91
35.5	7.37	2.58	51	41	290	0.64	18.30	44.24	50.22	53.17
19.5	47.7	145	203	1.63	43.7	46.8	313	4.03	103	102.61
21.8	116	8.47	98.5	102	23.2	28.9	100	116.8	340.46	3.39
52.4	18.2	22	4.1	48.4	101	3.73	10.4	41.7	100.46	2.84
621	824	142	2.17	104	75.5	1.09	2.12	260.56	1.7	76.07
38.8	1.26	16.1	14.7	5.76	35.4	12.6	49.4	108.37	56.12	2.44
71.6	4.93	11.6	25.7	38.9	237	9.78	3.39	157.4	23.08	73.88
21.7	20.4	5.13	11.3	18.1	67.5	8.55	4.62	1.43	13.53	5.62

Table 15- Permeability values for the 10 realizations in mD for 10 layers

In **Table 16** we can see the different lifetime of the 10 realizations with a highest value of 20.72 years and a value that reaches 4.15 years. Thus, we can say that 10.36 years ≈ 10 years is the average lifetime for a geothermal reservoir with a degree of heterogeneity of 0.8. When increasing the degree of heterogeneity we could notice that the average lifetime of 10 realizations has doubled with respect to previous one which is 5 years. This positive impact of increasing heterogeneity can be explained by the retardation of the cold water front in some layers which will slower the temperature decrease in the production well and therefore increasing the lifetime of the whole project.

	Lifetime in years	Energy produced in W/m^2
Base Case	10.65	4.07E+04 – 3.03E+03
Realization 1	13.06	1.12E+05 – 2.74E+03
Realization 2	9.06	4.96E+04 – 3.49E+03
Realization 3	15.02	4.56E+04 – 2.54E+03
Realization 4	8.90	9.90E+04 – 3.49E+03
Realization 5	4.15	1.76E+05 – 6.43E+03
Realization 6	20.72	3.39E+04 – 1.63E+03
Realization 7	10.24	8.70E+04 – 2.84E+03
Realization 8	7.61	8.00E+04 – 4.31E+03
Realization 9	5.39	9.88E+04 – 5.30E+03
Realization 10	9.16	3.83E+04 – 4.02E+03
Average	**10.36**	**7.83E+04 – 3.62E+03**

Table 16- Lifetime and energy produced during the lifetime of the project in years and W/m^2 respectively

By looking at **Figure 19**, we can notice also that the energy output is more in the case where VDP= 0.8 up to a certain time where the majority of the heat volume in the reservoir is discharge. After the crossover point, more heat is produced from the reservoir having a degree of heterogeneity equal to 0.7.

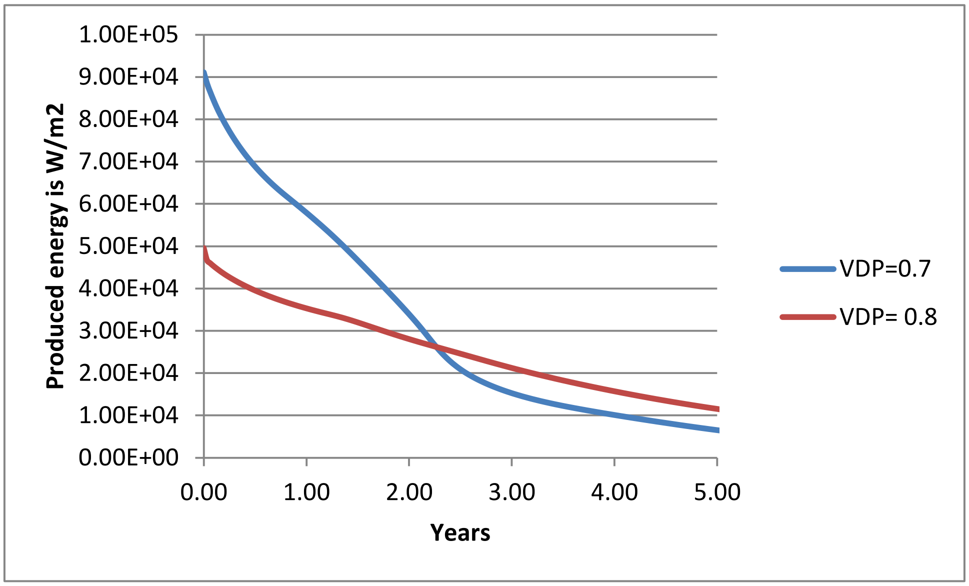


Figure 19- Graph representing the power output per unit area for two different degree of heterogeneity.

Case 1.3: V_{DP}= 0.5

In this case, we decreased the degree of heterogeneity. The following tables show the permeability fields, the lifetime and energy produced for each realization.

Base Case	Realiz. 1	Realiz. 2	Realiz. 3	Realiz. 4	Realiz. 5	Realiz. 6	Realiz. 7	Realiz.8	Realiz. 9	Realiz.10
72.57	32.08	114.51	40.40	139.65	17.53	78.24	87.28	252.52	49.57	43.35
124.31	66.32	39.04	83.81	362.71	126.54	34.22	123.08	66.18	94.37	20.72
40.18	288.07	40.53	275.61	93.35	31.92	125.50	28.93	66.25	102.99	182.63
33.16	39.17	62.89	145.69	72.81	112.97	154.17	32.47	38.85	84.18	91.82
78.10	64.06	54.11	71.77	38.01	50.95	77.25	73.33	65.69	67.16	89.19
98.05	45.69	175.94	64.75	71.74	23.81	56.51	26.98	88.69	39.70	160.21
60.61	139.01	27.21	104.05	23.47	32.47	124.24	117.45	126.46	137.23	45.80
124.40	88.73	98.22	200.43	72.82	116.64	73.70	151.07	75.69	151.84	92.08
75.27	65.37	323.63	92.84	21.30	156.48	184.56	108.80	86.33	35.16	101.33
54.32	92.38	39.07	25.55	46.57	124.72	50.29	24.68	53.21	169.39	153.93

Table 17-Permeability values for the 10 realizations in mD for 10 layers

	Lifetime in years	Energy produced in W/m^2
Base Case	3.80	8.23E+04 – 8.57E+03
Realization 1	3.45	9.60E+04 – 9.51E+03
Realization 2	3.68	1.34E+05 – 9.00E+03
Realization 3	3.39	1.16E+05 – 1.08E+04
Realization 4	4.50	1.00E+05 – 7.32E+03
Realization 5	4.53	9.46E+04 – 7.45E+03
Realization 6	3.11	1.02E+05 – 1.11E+04
Realization 7	4.47	1.23E+05 – 7.79E+03
Realization 8	3.42	9.89E+04 – 9.23E+03
Realization 9	3.26	9.69E+04 – 9.99E+03
Realization 10	3.30	9.56E+04 – 9.35E+03
Average	**3.72**	**1.04E+05 – 9.10E+03**

Table 18- Lifetime and energy produced during the lifetime of the project in years and W/m^2 respectively

We can witness that the average lifetime of the project is lower than that of the Base Case (V_{DP}= 0.7).

Case 1.4: V_{DP}= 0

In this case, we changed the model to a homogeneous model and set an average permeability value of 100mD. The results showed that after 2.12 years the temperature in the producer reached 50˚C. The energy produced decreased from 1.34E+05 to 1.62E+04 W/m^2. We can see the Temperature and Energy produced during this period in **Figure 20**.

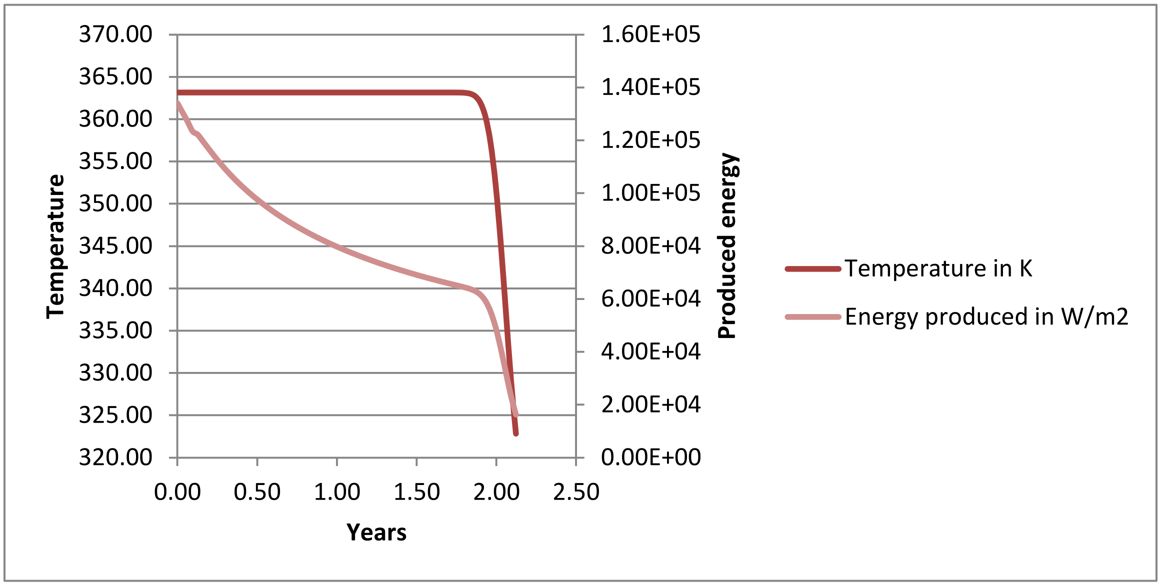


Figure 20- Graph representing the temperature and produced energy as a function of the project lifetime.

A general conclusion will be elaborated in chapter 4.

3.2.2 Fixed degree of heterogeneity

In this part we will vary the Dykstra-Parsons coefficient between 100mD (Base Case), 200mD and 300mD for a fixed Dykstra-Parsons coefficient of 0.7.

Case 2.1: K_{av}= 0.2 D

In this case, 10 realizations were generated in addition to the Base Case which are represented in **Table 19**.

Base Case	Realiz. 1	Realiz. 2	Realiz. 3	Realiz. 4	Realiz. 5	Realiz. 6	Realiz. 7	Realiz.8	Realiz. 9	Realiz.10
340.73	114.39	214.08	468.01	69.55	146.20	42.82	51.95	232.44	159.97	116.54
52.27	124.13	103.55	138.28	9.73	60.66	1.82	413.92	342.15	15.96	225.86
40.05	63.30	547.03	19.89	209.50	109.31	77.90	57.59	789.13	69.02	60.73
89.29	470.01	17.49	53.60	943.91	411.70	72.70	159.12	60.54	372.74	214.29
114.37	196.30	278.01	581.92	69.08	130.79	54.39	66.96	38.68	30.81	371.39
438.83	364.35	77.32	21.66	80.21	57.13	307.32	125.14	17.00	438.44	59.53
103.61	129.26	59.79	165.32	80.75	126.84	53.85	24.61	50.68	301.11	599.60
62.39	122.36	121.79	83.48	76.42	54.97	416.01	66.07	62.14	55.22	218.63
507.43	311.01	134.40	87.38	122.11	96.31	476.54	814.49	40.36	237.66	13.10
74.03	91.84	22.45	292.31	35.06	749.92	585.33	97.06	72.92	61.26	37.89

Table 19- Permeability values for the 10 realizations in mD for 10 layers.

	Lifetime in years	Energy produced in W/m^2
Base Case	2.28	2.44E+05 – 1.39E+04
Realization 1	1.68	2.37E+05 – 1.96E+04
Realization 2	2.31	1.74E+05 – 1.25E+04
Realization 3	2.06	2.02E+05 – 1.47E+04
Realization 4	3.01	1.79E+05 – 1.05E+04
Realization 5	2.09	2.51E+05 – 1.60E+04
Realization 6	3.07	2.19E+05 – 8.25E+03
Realization 7	2.38	2.17E+05 – 1.37E+04
Realization 8	4.15	1.76E+05 – 7.84E+03
Realization 9	2.22	1.87E+05 – 1.46E+04
Realization 10	1.87	2.15E+05 – 1.27E+04
Average	**2.47**	**2.09E+05 – 1.31E+04**

Table 20- Lifetime and energy produced during the lifetime of the project in years and W/m^2 respectively.

As expected the higher the average permeability is, the lower the lifetime of the project and the higher the average power output are. We took two random realizations having two different permeabilities: 100mD (Base Case) and 200mD. The energy outputs for the two cases are plotted in the following graph.

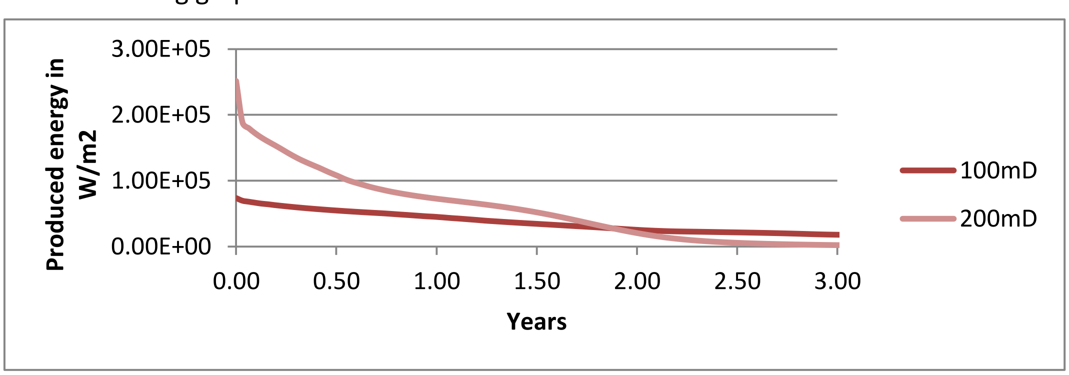


Figure 21- Graph representing the temperature and produced energy as a function of the project lifetime.

Case 2.2: K_{av}= 0.3 D

In this case, 10 realizations were generated in addition to the Base Case which are represented in **Table 21**.

Base Case	Realiz. 1	Realiz. 2	Realiz. 3	Realiz. 4	Realiz. 5	Realiz. 6	Realiz. 7	Realiz.8	Realiz. 9	Realiz.10
203.38	110.61	436.38	68.19	231.02	24.79	27.41	218.47	56.75	112.45	143.99
714.76	116.41	156.68	453.18	106.61	114.53	319.57	424.84	103.06	680.77	16.41
30.96	113.01	234.23	80.59	35.44	58.28	208.15	379.32	328.25	73.01	1212.91
1151.00	30.48	51.45	156.57	217.20	74.31	136.68	7.61	209.24	123.35	214.65
25.19	237.98	68.94	78.88	219.70	761.58	42.36	115.16	278.92	761.73	122.90
20.49	61.78	199.13	603.81	323.94	113.67	602.71	1209.14	53.43	37.04	81.36
83.01	1322.46	979.25	679.06	35.52	58.20	486.73	187.07	53.09	11.53	692.81
64.42	795.71	13.02	51.03	428.38	180.95	617.78	151.55	188.29	24.68	343.12
301.64	22.74	155.89	441.95	1321.05	146.95	166.50	118.92	303.25	817.04	187.70
166.98	40.15	528.26	610.40	52.58	1376.93	26.81	135.29	1327.49	61.33	16.70

Table 21- Permeability values for the 10 realizations in mD for 10 layers.

	Lifetime in years	Energy produced in W/m^2
Base Case	1.96	2.86E+05 – 1.51E+04
Realization 1	1.52	3.07E+05 – 4.09E+04
Realization 2	1.39	2.95E+05 – 2.18E+04
Realization 3	1.30	3.32E+05 – 2.52E+04
Realization 4	1.52	3.25E+05 – 2.07E+04
Realization 5	2.22	3.01E+05 – 1.33E+04
Realization 6	1.55	2.79E+05 – 1.59E+04
Realization 7	1.36	3.14E+05 – 2.26E+04
Realization 8	1.62	4.03E+05 – 1.72E+04
Realization 9	2.06	2.85E+05 – 1.40E+04
Realization 10	1.71	3.24E+05 – 1.68E+04
Average	**1.66**	**3.14E+05 – 2.04E+04**

Table 22- Lifetime and energy produced during the lifetime of the project in years and W/m2 respectively.

As expected the higher the average permeability is, the lower the lifetime of the project and the higher the power output are.

A general conclusion is elaborated in chapter 4.

CHAPTER 4. CONCLUSION

One of the objectives of the thesis was to assess the sustainability of the pre-defined model built by **De Bruijn, 2020** by following the sensitivity analysis performed on some geological uncertainties and production parameters from an exergetic point view. The main was to examine whether geothermal energy can play an important role during the energy transition and if it can be a strong alternative to fossil fuels in the future.

The geological uncertainties examined were the reservoir thickness, the thermal conductivity of the reservoir, the thermal conductivity and the permeability of the confining layers. The production parameters tested were the production rate and the well spacing.

While performing the exergy analysis, the system was insensitive in some cases especially for the 200m reservoir thickness. So we presented the results for a 50m thickness to be able to see the effect of the parameters with respect to the Base Case, even though the values are also barely changing.

In general, when excluding the artificial lift, the scenario is almost perfect and the system is considered sustainable since we obtain: 1) a positive decreasing exergy recovery factor through the lifetime of the project, 2) a convenient exergy return on investment around 3, 3) a very low CO2 emission with an average of 2.78×10^{-3} kg/MJ-heat extracted and 4) a very high COP with an average around 20 for all the cases and when the power plant that generates the electricity is a natural gas power plant.

When including the artificial lift, for all the cases considered, a negative exergy recovery factor is seen, which indicates that the system under study is unfeasible and an exergy return on investment lower than 1 is obtained. This indicates that we are not even benefiting from the system as much as we are paying for it. Thus, from an exergetic point of view the system is unsustainable in all the studied cases.

Despite that and since a negative exergy recovery is not necessarily a negative result and to avoid this inconvenience in the results we chose to calculate the COP and compare its value with alternative heating systems. The result showed that the COP of our system is between 2.5 and 3, between 2 and 2.5 and between 1.5 and 2.5 for a natural gas, oil and coal power plants respectively and which is higher than the alternative heating system chosen which are geo-heat pump, heat pump and natural gas burners having a COP of 2, 1 and 0.8 respectively. This is summarized in **Figure 22**.

Despite we got a negative exergy recovery factor with a low exergy return on investment, in addition to the negligible difference between the numbers we could compare the results by choosing the best conditions and best production strategy that could leads to a slightly more “sustainable” production or to be more accurate to a better situation since if we want to stick to the exergy recovery factor the system is unsustainable.

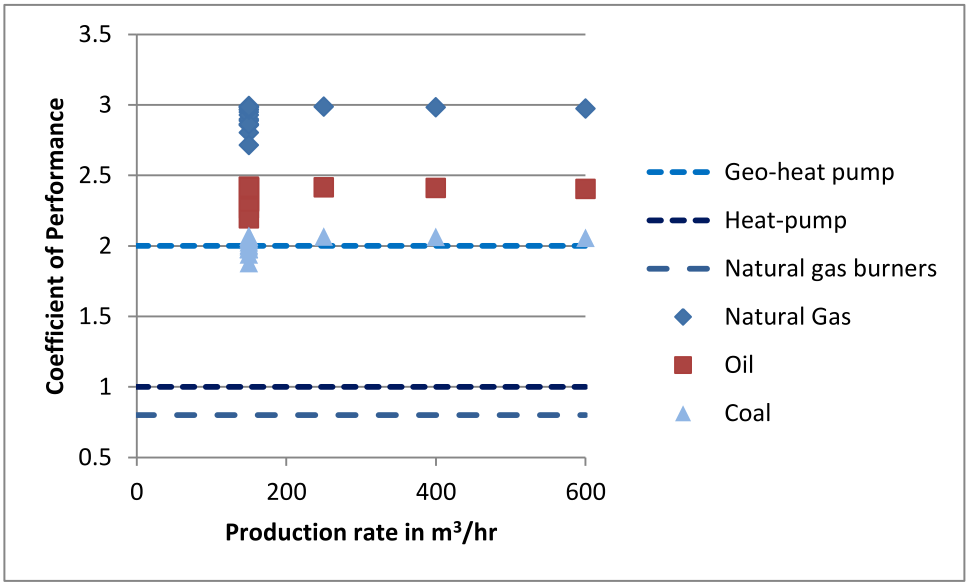


Figure 22- Graph representing the values for COP for a geothermal system powered by different power plants. The dashed lines show the average coefficient of performance for the alternative heating systems.

Both production parameters tested has a large impact on the overall production. Obviously, we can produce more heat with increasing rate but unfortunately when increasing the rate the lifetime of the project decreases 73% with respect to the lowest rate which is 150 m^3/hr. This is trivial as cold water front reaches the producer well earlier (in addition to the pressure drop). One main purpose from the sustainable development is to produce along a longer period of time. Producing with a lower rate gives less energy per unit time but produces for a longer time.

We need to optimize between the energy demand and the sustainable development of a system since a low rate could be a droplet of water each second, for example. The lower the rate is, the more sustainable the system is but the less energy output per unit time alongside a slight increase in COP, slight decrease in CO_2 emissions. A larger well spacing leads to a more constant temperature in the production and therefore to more energy output from the system alongside a reduction in CO2 emissions and an increase in COP.

Moreover, the two geological uncertainties that have the largest impact on the production according to our calculations are **the thickness**, since for a larger thickness we witnessed a constant heat production through time, and the **parameters of the confining layers**. The effect of the confining layers is larger on a thinner reservoir.

The production parameters could be chosen or adjusted in contrary to the geological uncertainties. Subsequently, the best strategy to have a sustainable production was found to be with a low rate that is chosen according to an optimization between the sustainable production and providing the sufficient energy demand, and with a larger well spacing. Moreover, a higher permeability and thermal conductivity in the confining layers that will ensure the recharge of the reservoir are desired alongside a high thermal conductivity in the reservoir. Finally, since for a given formation we are constrained by the geological parameters, we focus on choosing the best production parameters that leads to a more sustainable production.

The second objective of the thesis was to assess the effect of heterogeneity on the heat recovery from a geothermal system. The Dykstra-Parsons coefficient is used. We changed the degree of heterogeneity for a fixed average permeability then we varied the permeability for a fixed V_{DP}. It is important to note that the number of realizations needed is a lot more than 10 (see section 1.6). We will base our conclusion on 10 realizations only. However, they could be considered not enough to have a representative conclusion. It is important to note also that the production process is simulated without any confining layers which govern the heat recharge of the aquifer during the production and after it has stopped.

For the first part, we concluded that when we increase the degree of heterogeneity, the lifetime of the project increase. More power is produced during the lifetime of each case.This can be seen **Table 23**. In **Figure 23**, we chose four random realizations each one having different Dykstra-Parsons coefficient. The power output over years is plotted. We can notice that when increasing the degree of heterogeneity, at first less energy is produced. At certain time, we will have more power output for the more heterogeneous system.

	Average lifetime in years	Average power output in W/m^2
V_{DP}= 0	2.12	1.34E+05 – 1.62E+04
V_{DP}= 0.5	3.72	1.04E+05 – 9.10E+03
V_{DP}= 0.7	4.94	1.20E+05 – 6.86E+03
V_{DP}= 0.8	10.36	7.83E+04 – 3.62E+03

Table 23- Average lifetime and power output for the different degree of heterogeneity.

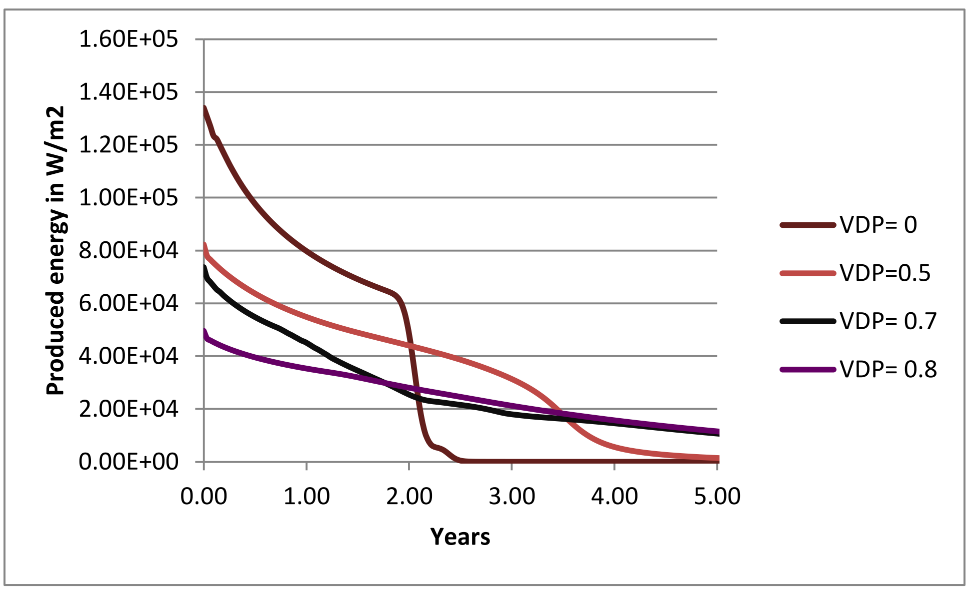


Figure 23- Energy output in W/m^2 for four random realizations with different V_{DP}.

For the second part, we concluded that when we increase the permeability, the lifetime of the project decrease and less power output we will have during the lifetime of each case. This can be seen **Table 24**. In **Figure 24**, we chose four random realizations each one having different average permeability. The power output over years is plotted. We can notice that when increasing the average permeability, at first more energy is produced. At a certain time, we will have less power output for the more permeable system.

	Average lifetime in years	Average power output in W/m^2
K_{av}= 100mD	4.94	1.20E+05 – 6.86E+03
K_{av}= 200mD	2.47	2.09E+05 – 1.31E+04
K_{av}= 300mD	1.66	3.14E+05 – 2.04E+04

Table 24- Average lifetime and power output for the different average permeabilities.

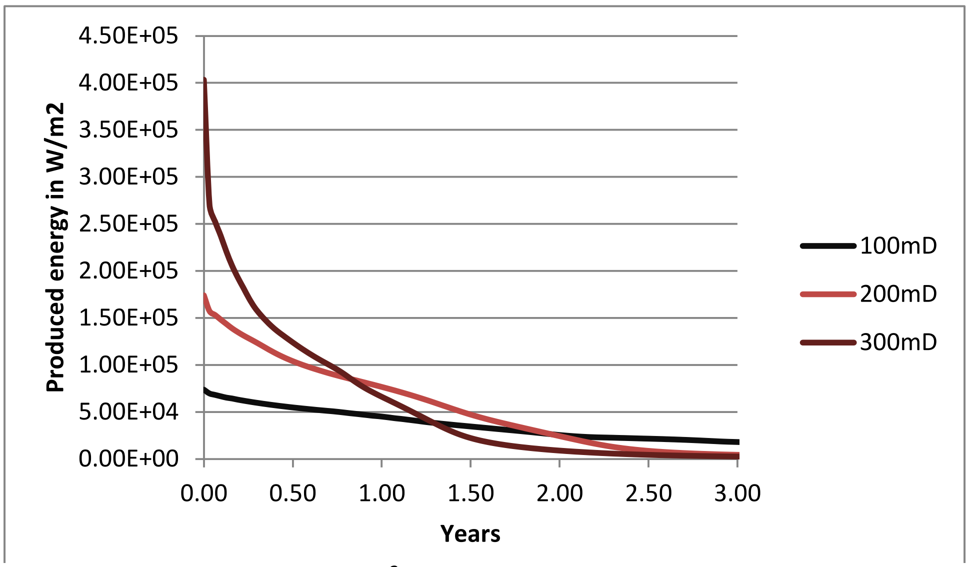


Figure 24- Energy output in W/m^2 for four random realizations with different V_{DP}.

When increasing the degree of heterogeneity, very different permeabilities will be assigned for the different layers, mostly with different order of magnitude. As a consequence, cold water plume reaches the production well in some layers late. Thermal- breakthrough occurs, but the temperature of the licensed area still didn't totally decreased to uneconomical values. This will retard the temperature decrease in the producing well for a more heterogeneous system. The lifetime will increase. The less heterogeneous system produces more power for a certain period in its lifetime. In the less heterogeneous case we have more permeable layers, as a consequence, when we start the production the heat will travel faster in the reservoir, producing more heat per unit time. When we increase the permeability, the lifetime decreases but more heat can be produced up to a certain time.

Despite that the lifetime is increasing, it cannot be concluded that having a more heterogeneous reservoir is better. The same for the increase in permeability which leads to a lower lifetime. We need to optimize between the production rate (which is slower for a more heterogeneous system) thus leading to a lower energy output and the energy demand of a certain society which has to be fed.

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