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The Thermal Interference Effect of Neighbouring Geothermal License Areas – a Parameter Modelling Study

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The Thermal Interference Effect of Neighbouring Geothermal License Areas – a Parameter Modelling Study

By

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TU Delft

Preface

This thesis is the final project to obtain a Master degree in Applied Earth Science track of Petroleum Engineering and Geosciences, and marks the end of my studies at Delft University of Technology. This project has been presented in European Geothermal Workshop 2020. This project has been a challenging but worthwhile experience, which I could not have done without some help and support along the way. I would like to thank my supervisors for their excellent guidance and assistance during this process. Thank you to Prof. David Bruhn, who gave me this exciting project and valuable experience in the Larderello field. He has extensively supported me in academic and non-academic. I have been fortunate to be supervised by caring and supportive supervisor who always pay a lot of attention to my work and promptly answer all my questions. For Dr. Sanaz Saeid and Dr. Alexandros Daniilidis. I am very grateful for your continuous support and encouragement throughout this thesis period. Especially for Dr. Sanaz Saeid, it is not easy to find a great supervisor to look up to, so it has been a valuable experience to work with her. Thanks for helping me and being patient to make me an expert in this study. I learn a lot from you.

I want to dedicate this achievement to my beloved family for their unconditional support at all times. My parents: Iskandar Muda and Nia Kurnianingsih, who raised and supported me until getting to this position. For my wife: Resti Sandy Tias, for her love and constant support, for all the late nights and early mornings, and for keeping me sane over the past few months. And my sister: Hafizhah, and Syarafina Shadrin, thank you for supporting me in everything, and many thanks for being such a good girl always cheering me up.

Also, I would like to thank the Indonesian Endowment Fund for Education (LPDP) for allowing me to study at TU Delft by financially supporting me during the study.

Last but not least, this thesis work is, however, still far from perfection. Any comments and criticism are kindly welcome to improve the quality of the thesis work.

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Aldyth Alem
Delft, November 2020

Nomenclature

Symbol	Description	Unit
α	Thermal diffusivity	[m²/s]
Cp	Rock specific heat capacity	[J/kg-K]
Cp_w	Water specific heat capacity	[J/kg-K]
E	Produced energy	[Mw]
g	gravity	[m/s²]
k	Permeability	[mD]
P	Pressure	[MPa]
ρ_m	Rock density	[kg/m³]
ρ_f	Fluid density	[kg/m³]
ρ_{f_o}	Initial fluid density	[kg/m³]
Q	Specific volumetric source term	[Kg/s]
T	Temperature	[°C or °K]
T_o	Initial temperature	[°C or °K]
ΔT	Temperature different	[°C or °K]
t	Time	[second or year]
μ_f	Fluid viscosity	[cP]
${\mu_f}_o$	Initial fluid viscosity	[cP]
Ø	Porosity	
λ_m	Rock thermal conductivity	[W/m-K]
λ_f	Fluid thermal conductivity	[W/m-K]

Abstract

In a future scenario, the successful development of geothermal industry will result in the large-scale deployment of new deep geothermal projects. In highly populated areas, such as the Netherlands, such a development will lead to a dense grid of neighbouring licenses. In such a situation a new project requires careful design and planning as the available subsurface space can become scarce, leading to the potential thermal interference with the neighbouring licenses and competing usage of the resources. Interference can cause the reduction of lifetime, produced energy, and the profitability of neighbouring projects. Therefore, it becomes important to consider the thermal interference while designing these systems in such dense areas to be able to obtain maximum energy and profit without hindering neighbours.

This research project assesses the question of thermal interferences in neighbouring geothermal systems using a numerical simulation approach regarding what parameters are ideal for optimisation in neighbouring systems and what parameters should be monitored.

To generate a numerical model capable of describing and predicting the effect of thermal interference the software package COMSOL Multiphysics 5.4 was used. The physics of fluid flow and heat transfer in porous media is applied to the reservoir model, and the finite element method is used to approximate the solution of these equations. Sensitivity analyses are performed on all input parameters as a post-processed simulation to control their influence on the output performance. The input parameters are divided into two categories; first, operational-controlled parameters: start time, injection temperature, injection/production flow rate, well spacing, well distance to the license border, and second, natural-controlled parameters including permeability and its anisotropy as kx/ky ratio. At the end of the parametric sensitivity analysis, an economic model is used as an instrument to evaluate how these input parameters can affect the long-term project feasibility.

In this study, we present the results of global comparisons between each parameter while incorporating all measurement control (lifetime, cumulative energy and NPV). The results from the 3D qualification, the correlation between measurement controls and the reference base case study are used as background for this comparison. Our results show that the injection temperature and well spacing are ideal designed parameters to optimise profitability because the negative effect on the neighbour is only 1% for every 10°C reduction injection temperature and increasing 300 m of well spacing. On the other hand, injection / production flow rate is the most influential parameter that must be monitored in neighbouring production areas.

Contents

1 Introduction

1.1 Direct Use Geothermal Systems in the world

The energy transition, a pathway to zero carbon emissions by 2050, is major challenge, especially for urban areas (IRENA, 2018). To meet the goals of decarbonisation and climate mitigation set out in the Paris Agreement, renewable energies must expand significantly as a source for direct use, including electricity and direct heat (IRENA, 2018). Geothermal energy can play a significant role in the energy transition, the ability to provide both electricity and heat in most regions of the world making it suitable for answering the future energy demand. Moreover, geothermal energy has a mature history of reducing greenhouse gas emissions and sustainable use for power generation that has been provided for 50–100 years in several locations (Fridleifsson, 2001), e.g., in Italy, New Zealand and the United States (Bromley & Mongillo, 2013) .

Geothermal power plants are currently operating in 29 countries with a total installed power generation capacity of 15,4 GW by the end of 2019. IRENA (2019) and the global geothermal capacity is expected to reach 17 GW by the end of 2023 (Aruvian Research, 2020). However, there is still an enormous potential for direct use geothermal, between 125 and 1793 exajoule/yr (equivalent to 34,722 TWh to 498,055 TWh) of geothermal energy resources, based on an assessment of global geothermal resource for direct heat (Limberger et al., 2018)

To support the significant progress of renewable energy, several governments provide incentive such as market financing for geothermal energy (Dumas & Garabetian, 2019). According to “Report reviewing existing insurance schemes for geothermal” (2019), few countries (France, Germany, Iceland, The Netherlands and Switzerland) have developed risk mitigation funds for geothermal energy development. An integrated action plan between the national government and organisations (universities, research institutes, companies, public institutions and associations) will boost progress of geothermal development.

In the future scenario, where the successful rate of developing geothermal industry increases, more projects will be realised. A significant increase of new projects will require careful planning, as the available subsurface space can become scarce, leading to potential interference of projects and competing usage of the resources. The density of projects in one area will eventually lead to a reduction in temperature in the subsurface where the geothermal wells are placed (FascÌ et al., 2019). Reduction of life time would occur as a result of thermal interference with other geothermal systems/doublets in the area. Therefore, it becomes important to consider the thermal interference while designing these systems in such areas to prevent excessive exploitation and over-use of the resource with the resulting economic consequences.

1.2 Geothermal Energy in the Netherlands

Geothermal energy has been developed rapidly in the Netherlands. Since the first producing doublet in 2007 (Vrijlandt et al., 2019), the rate of development has gradually increased. As of January 2017, there are a total of fifteen geothermal installations that produce heat from the deep subsurface (TNO, 2017), and in 2020 there are a total of 24 geothermal production installations as reported on 1 January 2020 (TNO, 2020). This is also followed by an increase in the number of exploration licenses as shown in Figure 1-left. The ambition of the Dutch government is to provide 50 petajoules in 2030, and more than 200 petajoules in 2050 from geothermal energy (Stichting Platform Geothermie, 2018)

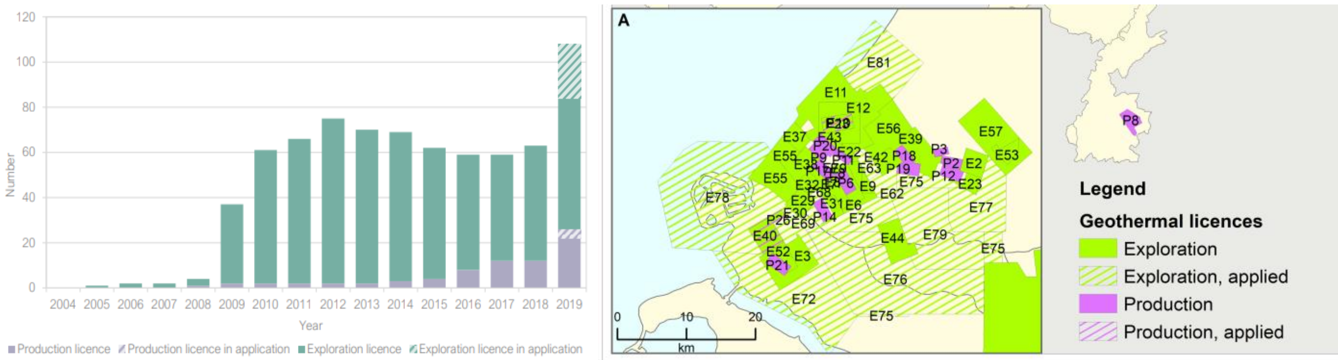

Figure 1. Left: Number of licences for geothermal energy per year.(TNO, 2020)*, Right: Geothermal licence situation as at 1 January 2020 in WNB*

In the last decade, there has been a rapid growing interest in geothermal energy exploration in the Netherlands (Békési et al., 2020), (Lochem et al., 2020) . The West Netherlands Basin (WNB) has become a favourable setting for geothermal developments, which has seen a rapid expansion there (Willems et al., 2020). This is also because the entire WNB is covered by 3D-seismic surveys (nlog, 2020) and it is well investigated, as documented by the wealth of published literature (den Hartog Jager, 1996)(Racero-Baena & Drake, 1996)(Jager & Amsterdam, 1996). So far 12 geothermal well doublets have been placed in this area (Willems et al., 2020) and more doublets might be expected due to geothermal potential (Donselaar et al., 2015). The future expansion of WNB geothermal exploitation can be seen from the current accepted exploration license as in Figure 1. This situation raises awareness of the problem of over-exploitation in an area.

1.3 License Area

The exploration and production of geothermal energy in the Netherlands require a license from the Minister of Economic Affairs and Climate Policy (Mining Act, article 6) and a license is only granted if the production within the area of the license to be applied can be economically recovered. (Minister of Economic Affairs and Climate Policy of the Netherlands, 2020). A license can contain area size, start time and duration of extraction. An example of the shape of neighbouring licenses in the Netherlands presented in Figure 2 .

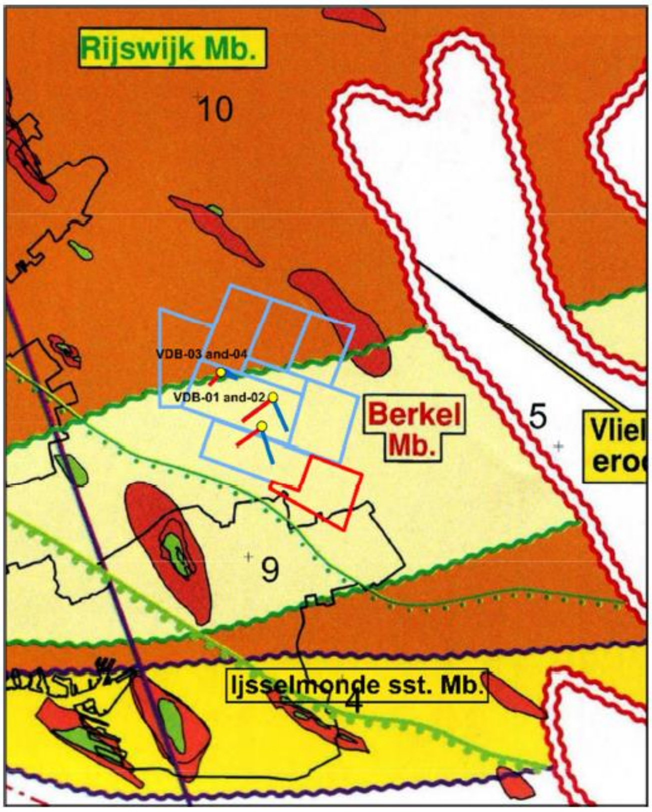

Figure 2. Example of shape of neighboring licenses (in The Netherlands). (PanTerra Geoconsultants, "Project report: G1330c", March 2018)

To date, there are no clear regulations for the placement geothermal well-doublet in neighbouring systems. Misplacement of well-doublet, especially in dense neighbouring areas, can cause interferences and decrease production performance.

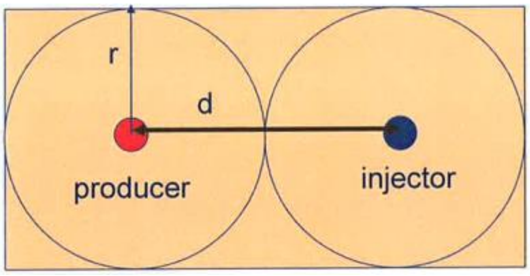

Figure 3.Location of injection and production well at reservoir. The well spacing is the diameter (d) and the two circles coincide at the radius (r) distance from each well (H. F. Mijnlieff & Van Wees, 2009)

A study has been suggested to determine the size of exploration licenses using doublets influence areas. An influence area is defined by two circles with a radius equal to half the distance between the wells at the reservoir level. (H. F. Mijnlieff et al., 2009)

1.4 Previous work

A dense license area can cause problems between adjacent doublets, especially when they belongs to different owners. A case study in the Delft area by Reinhard (2019) explained the pressure and temperature interferences between three neighbouring doublets. The study found that the total energy production of these three doublets decreased by 3% due to pressure and temperature interferences (compared to when the doublets were running in a stand-alone configuration). Also, the reservoir pressure decreases at the injector when a neighbouring production well starts producing. This allows the injector to inject at a higher flow rate. For this case study, the increase in flow rate can reach up to 24 m^3/h. However, several variables still need to be observed and adjusted due to the effects of interference, such as the effect on lifetime and economic models.

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Several comprehensive research studies have addressed thermal interferences in geothermal operations. For instance, the study of optimization of well spacing to minimize the interference effect between two doublets in homogeneous (Willems et al., 2017) and in heterogeneous reservoir scenarios (Babaei & Nick, 2019). The study found that reducing well spacing can lead to an increase in NPV of up to 15% and the suggested well spacing should be between 1000 and 1500 m. In addition, there is a more extensive study of thermal interference by Daniilidis (2020) with the scenario of geothermal doublets across a fault under subsurface uncertainty. This study found that the sufficient lifetime and NPV can be obtained with a well spacing of 1000 m and a rate of 400 m^3 / hr; and with a well spacing of 800 m and a rate of 250 m^3 / hr or lower and a distance to a fault greater than 200 m.

To our knowledge, there is no published work about a comparison of all relevant parameters affecting thermal interference between neighboring licenses. Research addressing such a comparative analysis is important because some parameter might have more influence than another. We therefore decided to look at such a comparison as a basic idea for this MSc thesis.

1.5 Research Question and Objective

This research project aims to assess the effect of thermal interference in neighbouring geothermal systems as well as possible solutions for the long-term efficiency in geothermal energy provision. The main research question of this project can be formulated as follows:

How to identify and mitigate thermal interference and its effects on long term efficiency in densely spaced geothermal licence areas?

This research is fully based on numerical modelling experiments. Numerical modelling uses mathematical models to describe the physical conditions of a reservoir using numbers and equations (Ismail-Zadeh & Tackley, 2010). With numerical models, a method such as the finite element method can approximate the solution of these equations (Logan, 2017; Reddy, 2006). In this study, COMSOL Multiphysics 5.4 was used to generate a numerical model that is capable to predict and analyse the effect of thermal interference.

Sub-questions

The following three research questions will be answered to address the main research question:

A. **What are the possible indicators to measure the effects of thermal interference?**
   Three measurement controls were investigated in this study. First, the lifetime was assessed by using the breakthrough time of reservoir temperature. Second, the cumulative energy produced that was determined from the generated power over the project lifetime, and the last one is the economic viability. Economic ability is not only essential for the sustainability of a project, but it is also important to get license approval. A production license will only be issued if it is applied for economically extractable energy (Minister of Economic Affairs and Climate Policy of the Netherlands, 2020).
   In this study, we used the Net Present Value (NPV) as economic indicator.

B. **What is the most influential parameter that affects the profitability of a project?**
   Seven parameters from operational control and natural control were evaluated by using sensitivity analyses and were assessed by using three measurement controls (lifetime, cumulative energy and NPV). Based on this intensive parameter study, we expected to find the most influential parameter that can provide profitability and long-term production efficiency in neighbouring systems.

C. **What parameters should be controlled to avoid thermal interference between neighbours?**
   During the sensitivity analysis, we studied the effect on another doublet in the neighbouring system for each parameter change. Based on the three measurement controls, we can calculate how much the parameter changes affect the neighbouring doublet and determine the implications.

The main objective of this research is to develop a simulation model that is capable to capture thermal interference issues in neighbouring systems. Thus, energy production can be maintained efficiently in terms of economic costs. All necessary input in the numerical model is derived from literature data.

2 Model Description

2.1 Model Geometry

The model geometry has dimensions of 6400m width, 5200m length and 650m height. Located at a depth of 2300 m from the surface, the model was chosen as it represents a common geothermal system in the Netherlands (Affairs & Policy, 2017). The geometry is divided into three layers; Overburden and underburden with a thickness of 300 m each and a reservoir layer with 50 m thickness. Overburden and underburden are considered as impermeable zone with a permeability of 0.55 mD and a porosity of 0.001.

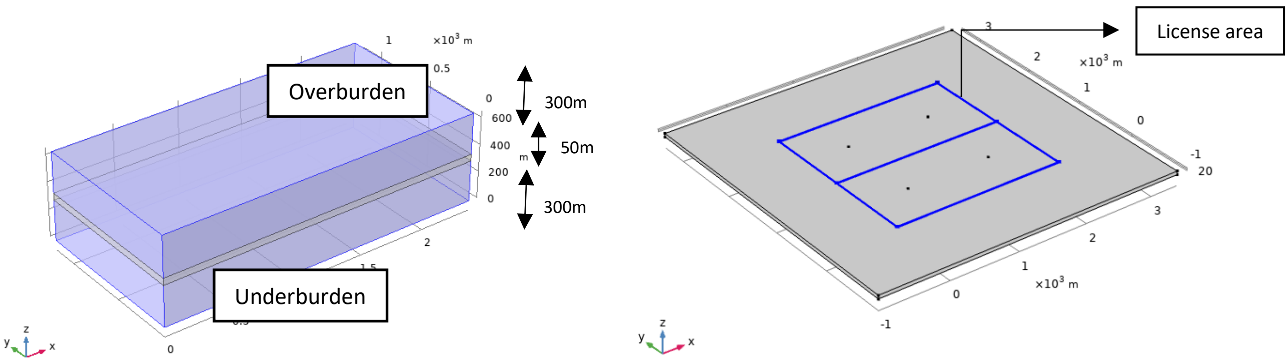

Figure 4. Geometry Model (Left) and License Area (Right)

This geometry consists of 2 license areas with each license having an area of 2400 m width and 1200 m length. Areas outside the license areas are assumed to have the same characteristics as the license area of the base case, but there are no wells that are actively producing or injecting. In each license area wells are placed at 600 m from the common license border, and the well spacing between injection and production wells is 1200 m. Both wells are perforated along the reservoir thickness (50 m) and each well has a diameter of 0.22 m. The summary of the model dimension can be seen in the following figure.

Table 1. Geometry Model Dimension

Geometry Model	Value
Width	6400 m
Length	5200 m
Width of each license area	2400 m
Length of each license area	1200 m
Reservoir Thickness	50 m
Underburden & Overburden Thickness	300 m

2.2 Reservoir Model & Properties

One of the main processes in modelling the geothermal systems is creating a reservoir model. It is designed to represent the given reservoir based on geological, geophysical and petrophysical properties. These properties are obtained from reservoir characterization studies in which geoscientists and engineers gather all data and extrapolate those values throughout the reservoir. In this thesis a conceptual reservoir model is used for reservoir simulation in order to evaluate thermal behaviour when 2 neighbours produce under variable conditions.

The main rock properties to be considered are permeability, which is related to the capacity of the formation to transmit fluid, thermal diffusivity (α), thermal conductivity (λ), density (ρ) and the specific heat capacity (C_p). These thermal properties are related by the following expression:

$$\alpha = \frac{\lambda_m}{\rho_m\, C_p} \tag{1}$$

where thermal diffusivity is the rate of heat transfer of a material from the hot end to the cold end, thermal conductivity is the ability of material to conduct heat, and heat capacity is the amount of heat energy required to raise the temperature of a substance per unit of mass. These properties have specific values dependent on the material.

The rock properties used for the model are shown in Table 2. These properties are based on data from the prototype design of deep low-enthalpy geothermal systems in the work of Saeid et al. (2015). The reservoir properties are assumed to be homogeneous in the whole domain.

Table 2. Rock Properties

Parameter	**Symbol**	**Value**	**Unit**
Isotropic Permeability	$k_{xx} = k_{yy} = k\_zz$	200	mD
Porosity	φ	15	%
Rock Matrix Density	ρm	2650	$kg.m^{-3}$
Rock thermal conductivity	λm	3	$W.m^{-1}.K^{-1}$
Rock Specific heat capacity	Cp	980	$J.kg^{-1}.K^{-1}$

The fluid properties to be considered here are density and viscosity, including their dependence on temperature variations because they have a significant effect on thermal transport in geothermal systems, as also shown experimentally by Saeid et al.(2014). The density and viscosity can be described as:

$$\rho_f = \rho_{fo}\, e^{-\beta(T-T_o)} \tag{2}$$

$$\mu = \mu_{fo} e^{-\theta(T-T_o)} \tag{3}$$

where ρ_{fo} and μ_{fo} are the initial density and viscosity of the fluid at an initial temperature, T_o , and β is the fluid thermal expansion. Moreover, the thermal conductivity of water is influenced by the temperature (Schön, 2011), which can be described by:

$$\lambda_{water} = 0.56 + 0.002(T) - 1.01.10^{-5}.(T^2) + 6.71.10^{-9}.(T^3) \tag{4}$$

2.3 Model Assumption

Inevitably, simplifications and assumptions must be used to adapt the complex geological model to this conceptual numerical simulation. The assumptions and simplifications for the model can be summarized as follows:

- Neglecting the presence of hydrocarbons in the reservoir, as solution gas, similar to Mijnlieff (2020).

- Neglecting any skin factor around the well bore that can be formed by mineral precipitation during geothermal production due to highly saline geothermal fluid, as shown by Regenspurg et al. (2015).
- Thermal conductivity and heat capacity of rocks and fluid are defined as homogeneous throughout the model. Generally, rocks are made up of mineral assemblages in varying compositions and structures causing heterogeneity on the sub millimetre to centimetre scale. This may result in a strong internal variation of thermal conductivity across the entire porous medium, as shown in a laboratory study by Jorand et al. (2013).
- Permeability is defined as isotropic homogeneous throughout the reservoir. In nature, permeability in Dutch geothermal resources is dominated by matrix porosity, but karst, fracture or fault permeability also play a significant role (Mijnlieff, (2020).
- Production is assumed to have 100% up-time. During the production, a geothermal system might have uptime around 68% to 79% (Rijksdienst voor Ondernemend Nederland, 2019), due to maintenance or other reasons, such as reduction of injectivity (V.D.Hulst, 2019).

2.4 Governing Equations

The numerical model is solved by using the finite-element method (FEM) with COMSOL Multiphysics 5.4. The subsurface flow and heat transfer modules are used to couple fluid flow and heat transfer in the porous medium. The heat transport in the subsurface due to geothermal heat production can be described as:

$$\left(\rho\, C_p\right)_{eq}\frac{\partial T}{\partial t}+\rho\, C_p q\,.\nabla T=\nabla\,.\left(k_{eq}\,\nabla T\right)+Q \tag{5}$$

Where T (C) is the temperature, ρ (kg/m³) the mass density, C_p (J/(kg K)) the specific heat capacity, q (m/s) the Darcy velocity and k (W/(mK)) thermal conductivity.

Equation (5) states that change in temperature (∇T) is caused by conductive and convective processes.
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2.4.1 Heat Transfer in Porous Media

The conductive process is defined as transfer of heat occurring through direct contact.
The following equations are used to represent the heat transfer between the rock matrix and the fluid (1-Porosity (φ).

The effective volumetric heat capacity ($\rho\ C_p$) can be described as:

$$\left(\rho\, C_p\right)_{eq}=\varphi_s\,(\rho\, c_p)_s\,+(1-\varphi_s)\left(\rho C_p\right)_f \qquad \frac{J}{kg.K} \tag{6}$$

And the thermal conductivity (k) becomes:

$$k_{eq}=\varphi_s\,k_s+(1-\varphi_s\,)k_f \qquad \frac{W}{m.K} \tag{7}$$

Where f and s refer to the fluid and the solid matrix respectively

2.4.2 Fluid Flow in Porous Media

Solving the heat transport properly requires incorporating the flow field. Generally, Darcy's law is used for fully-saturated and pressure-driven flow in deep geothermal modelling to describe the flow mathematically. The velocity field (q) of equation (5) was implemented by adding the flow field as described by the equation below

$$q=-\frac{k}{\mu}\nabla P$$

$$(8)$$

Where the velocity field (q) depends on the permeability (k) and the fluid's dynamic viscosity (μ) and is driven by a pressure gradient (∇P). Darcy's law is then combined with the continuity equation (9). Thus, the solution of Darcy's Law is expected to be continuous along the boundary between adjacent elements.

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla.(\rho q) = Q \tag{9}$$

2.4.3 Initial and Boundary Condition

The initial temperature and pressure (at time=0) are defined as the steady state conditions, using temperature and pressure gradients with depth. They can be calculated by:

$$T_{initial\ (x,y,z)} = T_{surface} + T_{grad} \tag{10}$$

$$P_{initial\ (x,y,z)} = P_{surface} + P_{grad} \tag{11}$$

Where the average surface temperature level in the Netherlands is 10.5° C and the geothermal gradient T_{grad} is 0.031 °C/m (Bonté et al., 2012) and surface pressure is assumed at 1.01325 bar with pressure gradient 0.1 bar/m (Daniilidis et al., 2016).

For the boundary conditions we assume that a porous medium is bounded by an impermeable surface in the top and bottom layers as shown in Figure 4, while the other boundaries are open to flow.

Additional boundary conditions such as pressure or mass flow rates around the reservoir are required when production and injection wells are placed and operated in the geothermal reservoir. In this model, injection wells are controlled by fix pressure and production wells are controlled by flowrate, described as:

$$P_{bottomhole(inj)} = P_{hydrostatic} \tag{12}$$

$$Q_{bottomhole(prod)} = Q \tag{13}$$

the thermal boundary condition at both injection wells is defined by:

$$T_{bottomhole\ (inj)} = T_{injection} \tag{14}$$

2.5 Mesh Study

A simple mesh may not only produce inaccurate simulations but can also cause the solver to produce errors due to instability, while a complex mesh model may provide very accurate results, but the solution can take hours and up to days (high computational cost). The objective of this study is to find the optimum mesh that can balance between accuracy and computational cost.

This study uses a single license area with a geometry dimension as in section 2.1, but the length of the geometry is adjusted to 3200 m. The license area uses the physical mesh category that has the maximum and minimum element size characteristics of 242 m and 17.6 m respectively, and the element growth rate is 1.4. This mesh study focuses on the area around the producer and injector wells as shown in Figure 6

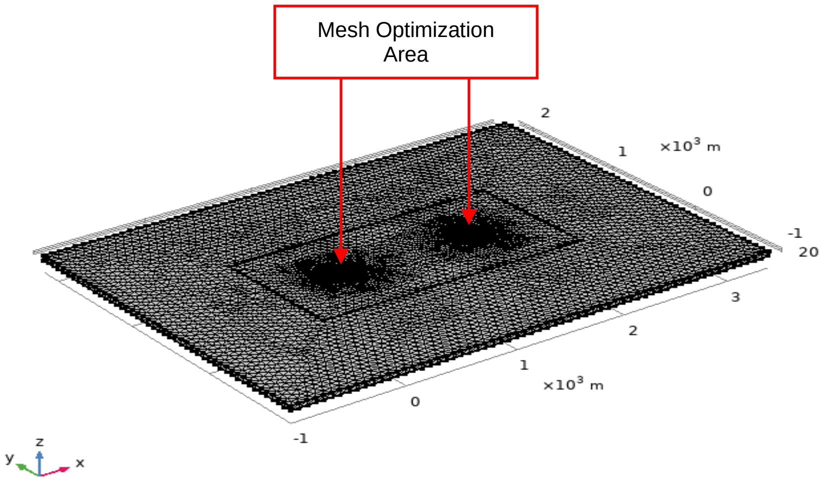


Figure 5. Mesh Size Optimization Area

An iterative method is used in this study. We start by increasing the number of elements along each side and solve. Then, we record the complexity of the model and the result. The complexity of the model means the element size and element growth of the model, and the result means the variation of breakthrough time (when the reservoir temperature decreased by 7% of the initial temperature (82°C)) and solution time of simulation. The table below represents the mesh characteristics and results of our study:

Table 3. Mesh Sensitivity Study Result

	Mesh Categories	**Extremely Coarse**	**Extra Coarse**	**Coarser**	**Normal**	**Finer**	**Extra Fine**	**Extremely Fine**
Mesh Characteristics	Max. Element Size	156	94.5	61.4	31.7	17.5	10.9	6.14
	Min. Element Size	33.1	23.6	18.9	9.45	1.89	0.709	0.0945
	Element Growth Rate	1.4	1.3	1.25	1.15	1.1	1.08	1.05
	Number of Elements	680	1958	3803	11819	27674	51945	146594
Result	Breakthrough time	42	43	44	45	46	46	46
	Solve Time (hh:mm:ss)	00:00:05	00:00:09	00:00:11	00:00:25	00:00:45	00:01:22	00:04:10

The results are plotted together with the number of elements as shown in Figure 6

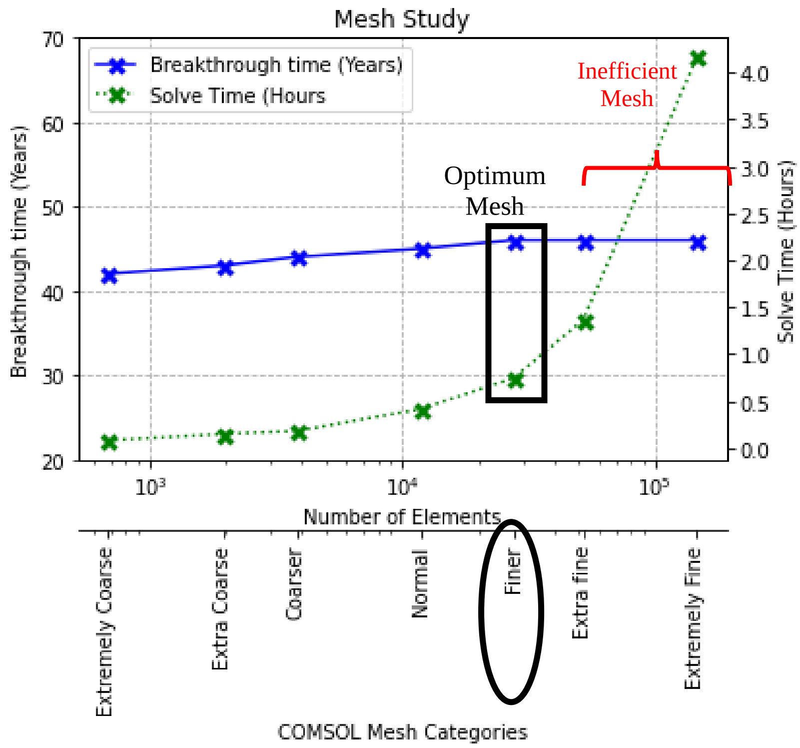


Figure 6. Mesh Study

As shown in Figure 6, the breakthrough time does not change anymore (stable result achieved) from mesh category finer to extremely fine. It means that increasing element between this category, the results become independent of mesh sizing (results converge to constant value), or it can be explained, the mesh category passing through finer mesh is an inefficient mesh because the converging solution is accompanied by an increase in the solve time

Based on this study, this category of mesh and its characteristics are implemented throughout the research as this mesh is sufficiently dense but not very demanding on computing resources.

3 Research Strategies

3.1 Pre-Study

3.1.1 Defining Parameter

Two main parameter controls are studied; operational-controlled parameters and natural-controlled parameters. Operational-controlled parameters are controllable parameters that can be set up before or during field operations. In contrast, a natural-controlled parameter is a natural property of a reservoir that cannot be altered, but it might have a high impact on the field operation.

The operational-controlled parameters in our model cover the following aspects:

- Starting Time
  The differences of starting are standard in neighbouring geothermal operations. In one area, for example, a geothermal operator can start in 2020, while other operators start 2 or even 5 years later. Thus, it is important to study the effects of operations in neighbouring geothermal systems that started at different times.

- Flow rate injection
  Flow rate is perhaps the one of controllable parameter in geothermal system. This is due to the operator's ability to control the production and injection flow rates by changing the pump rate from the surface. Furthermore, the flow rate is also a determining factor for calculating the energy that can be produced (17)

- Injection Temperature
  The re-injection process is an important factor to maintain reservoir pressure in the geothermal system. In this process, cooled water is re-injected into the reservoir. The difference in injection temperature can cause different production results. Thus, studying this parameter has to be considered.

- Well spacing
  In a doublet system, injection and production wells must be located at an optimal distance from each other. Large well spacing may result in better lifetime, but more fluid losses can occur due to geological uncertainties such as variations in porosity, permeability, fractures and channels, while smaller well spacing can reduce geological uncertainty it may result in a shorter lifetime. This parameter is interesting for a thermal interference study between two neighbouring system.

- Well-distance to license border
  In the future, geothermal licenses in an area might be getting more crowded due to increased demand for geothermal resources. Placing the well regarding the distances to license borders can bring benefits or drawbacks. This study will analyse what is the impact of well distance to the license border.

And the natural-controlled parameters included in our model are:

- Permeability
  Permeability represents the ability of a porous material to transmit fluid. As discussed in chapter 2.4.2, permeability is related to the fluid flow capacity. Also, permeability can represent the fluid pathways for the injection fluid. This means that permeability plays an important role in extracting heat energy from rocks through the use of fluids. For this reason, permeability is one of the natural-controlled factors that need to be considered in neighbouring systems.

- Anisotropy of permeability (Kx/ky ratio)
  Generally, within a formation, permeability can vary between the vertical and horizontal planes. The variation of permeability in different directions is known as anisotropic permeability. Anisotropic permeability is another essential parameter that needs to be studied because flow can occur in both vertical and horizontal planes.

3.1.2 Well Positioning

The objective of this section is to determine the effective well position for the study of thermal interference between neighbouring wells.

This study uses two adjacent geothermal licenses. Four scenarios are carried out, which consist of two tramline and two checker-board configurations. The tramline configuration refers to the injector and producer being aligned, whereas the checkerboard refers to an alternating pattern of injector and producer. Figure 7 and Figure 8 show a schematic of these four scenarios.

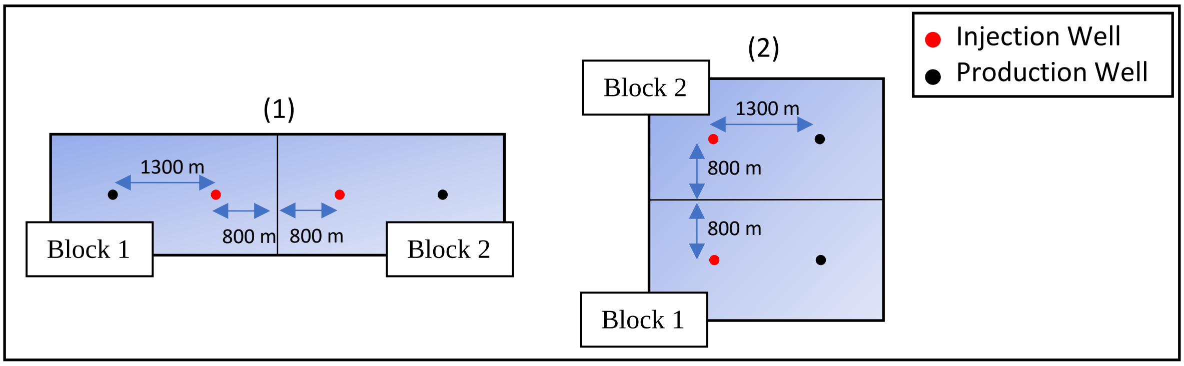


Figure 7. (1) Horizontal Tramline, (2) Vertical Tramline

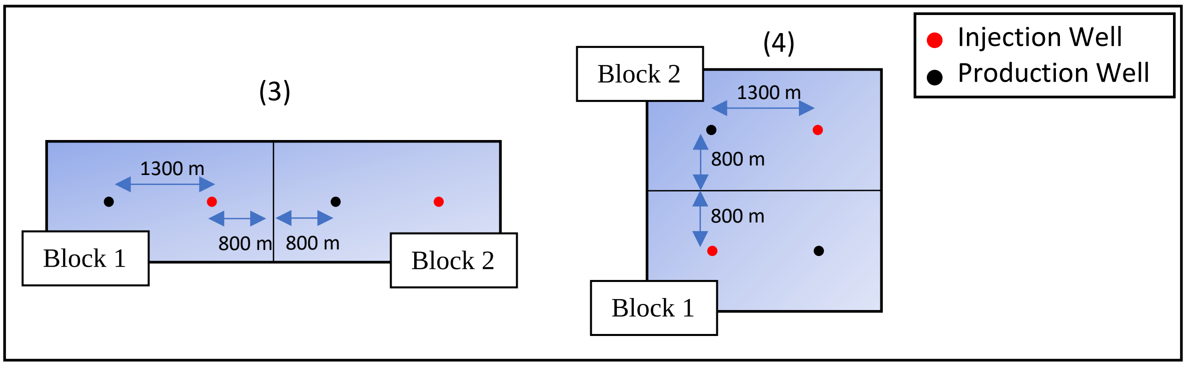


Figure 8. (3) Horizontal Checkerboard, (4) Vertical Checkerboard

These 4 scenarios will be examined to determine which one has the strongest impact on the neighbouring systems when they are produced simultaneously. The selected scenario will be used as a model for the geothermal neighbouring system in this research study.

3.2 Parameter Analysis

Parametric sensitivity is a series of analyses to measure how the input parameter can control the output performances. In most analyses, parametric sensitivity is divided into local and global sensitivity analysis. Local sensitivity analysis is a one-at-a-time (OAT) technique that focuses on analysing the impact of one parameter and keeping the other parameters fixed. In contrast, a global analysis examines the sensitivity of the entire parameter distribution. This study focuses on local sensitivity analysis to assess all of the input parameters.

In this study a geothermal doublet without neighbours (single system) is assumed as the reference. In chapter 4, the effects of two neighbouring systems (licenses) on each other’s lifetime, energy production and NPV are studied.

The principal concept of this study is using the constant (base case) parameter in Block 2 and the sensitivity parameters are conducted in Block 1. The following figure shows the overall concept of this parametric study:

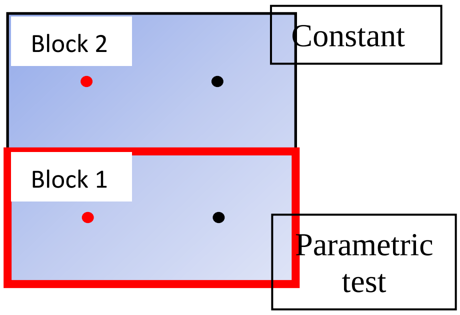


Figure 9. The Concept of parametric sensitivity analysis

Several parameter variations were tested using parametric sensitivity in single and neighbouring systems. In the two-neighbour system (Figure 9), we perform the sensitivity analysis in Block 1, while Block 2 is kept constant similar to the base case. The parameters that changed during the sensitivity analysis and their ranges of change are listed in Table 4. In this way, we study how two neighbouring licenses affect each other's heat production when each has different natural or operational parameters. Moreover, in each sensitivity study we compare the behaviour of neighbours with a single case (no neighbours).

Table 4. Parameters for Sensitivity Analysis. The green blocks present the parameters of the base case.

Test Seq / **Parameter**	**1**	**2**	**3**	**4**	**5**
Starting Time	0	10 years	15 years	20 years	25 years
Flow rate	50 m³/h	100 m³/h	150 m³/h	200 m³/h	250 m³/h
Temperature Injection	10 °C	20 °C	30 °C	40 °C	50 °C
Well Spacing	600 m	900 m	1200 m	1500 m	1800 m
Well Distance to border	400 m	600 m	800 m	1000 m	1200 m
Permeability	100 mD	200 mD	300 mD	400 mD	500 mD
Anisotropy of Permeability (Kx/ky Ratio)	200 md / 20 md	200 md / 100 md	200 md / 200 md	200 md / 400 md	200 md / 2000 md

* The highlight is showing the base case parameters

3.3 Post-Processed

The output of the sensitivity analyses is evaluated and assessed based on lifetime, cumulative energy produced and economic feasibility (NPV). This chapter explains the calculations and the assessment of the related economic implications.

3.3.1 Lifetime

The breakthrough time is chosen as the estimation of the doublet lifetime. This is defined as the time when the reservoir temperature is decreased by a specified percentage of its initial value. In this study, the breakthrough temperature is set as a 7% decrease of its initial value (in °C).

$$T_{bt} = 0.93\, T_0 \tag{15}$$

Where T_{bt} is the breakthrough temperature in°C and T_0 is the initial temperature in°C

3.3.2 Cumulative Energy Produced

The amount of energy produced at timestep *i* is calculated from the doublet power produced at timestep *i*, multiplied by the time difference between timestep *i* and the previous timestep *i* (Doddema, 2012). Thus, the cumulative energy produced can be obtained as:

$$Cum.\, Energy\, produced = \sum (P_{doublet}\; x\; \Delta t) \tag{16}$$

where Δt is the time difference (hours) between t_i and t_{i-1} and $P_{doublet}$ is the doublet power produced (Watt) which is obtained by:

$$P_{doublet} = q * \Delta T * C_{brine} \tag{17}$$

where q is the flow rate (m³/s), ΔT is the temperature difference between injection and production well (°C, and C_{brine} is volumetric heat capacity (J/K.m³) defined by

$$C_{brine} = C_p * \rho_{brine} \tag{18}$$

where Cp is the specific heat capacity (J/kg.K) and ρ_{brine} is the density of the fluid (kg/m³).

3.3.3 Economic feasibility

The economic model is inextricably linked to the reservoir simulation. The optimisation of the parameters depends on the lifetime and the cumulative energy produced. But, optimal indicators are determined based on economic factors. From an economic perspective, the feasibility of geothermal projects depends on many factors such as geological uncertainties, cost differences at each phase of the project, and government policies (Planbureau voor de Leefomgeving, 2019).

This chapter describes the development of an economic model based on previous studies (Daniilidis et al., 2017; van Dongen, 2019). It includes an overview of the economic input parameters, followed by project expenditures and project revenues. Then, it finalizes with calculation of economic indicators (cash flow and NPV).

3.3.3.1 Economic Input Parameters

The economic input parameters used in this study are based on the Development of an economic model under the Dutch fiscal conditions by Zaal et al. (2020) .

Table 5. Economical Parameters Input (Zaal, 2020)

Parameter	Value	Unit	Sample Frequency
Production time	30	years	-
No. of Doublets	1	-	-
No. of Wells	2	-	-
Exploration costs	460,000	€	Once
ESP costs	800,000	€	Every 5 years
Power facility	1,500,000	€	Once
Drill location	300,000	€	Once
Unforeseen costs	5	% of construction costs	Once
ESP downtime	15	Days	Every 5 years
ESP efficiency	55	%	-
Electricity price	0.071	€/kWh	-
Gas price	0.016	€/kWh	-
Fixed OpEx	5	% of CapEx	Annually
Drill insurance	7	% of maximum compensation available	Once
$/€ conversion	0.90	-	-
AbEx single well	1,275,500	€	Once
Market value of equity	0.3	-	-
Market value of debt	0.7	-	-
Cost of equity	14.5	%	-
Cost of debt	2	%	-
Corporate tax	25	%	-

3.3.3.2 Project Expenditure

To build an economic model, we need to calculate project expenditures that reflect all costs incurred during the project. We consider the following three components of project expenditure:

- Capital expenditure (CaPex)
  Capital expenditure is the cost that occurs when a new project is started. CapEx accrues from three phases: exploration, development, and unforeseen development costs.

  Exploration phase
  The cost components of the exploration phase are shown in the following table (van den Bosch et al., 2013)

Table 6. Exploration Phase Cost

	Minimum Costs (€)	Maximum Costs (€)
Quick Scan	10,000	20,000
Geological Research	25,000	250,000
Permit requests and requires research	30,000	70,000
Drill design documentation and research	70,000	120,000

Based on these data, the costs in the exploration phase range from €135,000 to €460,000 euro

<u>Development phase</u>
Development costs cover all expenditures for the preparation, drilling, and installation of drilling equipment and sites. In the Netherlands, most geothermal projects have an initial cost (preparatory) between €150,000 and €300,000 (van den Bosch et al., 2013). This includes a location on the surface where the production facilities are placed. However, the cost may vary depending on the geothermal project goal, drill rig used, and the trajectory of the well (deviated or vertical).

In drilling, the costs depend on the specific depth. The deeper the target location, the higher the costs incurred. This is calculated as follows:

$$Wellcosts = 375000 + 1150 * depth + 0.3 * depth^2 \tag{19}$$

The costs are given in euros and based on one well. Thus, in a doublet geothermal system, the cost must be doubled.

In terms of equipment costs, a Dutch geothermal project consists of some standard necessary equipment. It includes equipment for the circulation of water, filters and screens, injection pumps, Electrical Submersible Pump (ESP), and heat exchangers. The ESP cost estimation is based on the pump capacity in a unit of kilowatts which is shown in the following table:

Table 7. ESP Cost based on Capacity (kW)

ESP capacity (kW)	Estimated costs (k€)
250-500	300
500-800	600
800-1000	800
1000-1200	1000
>1200	1200

The total costs for this surface facility range from €500,000 to €1,500,000 (van den Bosch et al., 2013)

<u>Unforeseen development costs.</u>
Any unexpected problems might occur during the development process, and additional costs will arise. These additional costs need to be considered as unforeseen costs and are calculated as 5% of construction costs (Zaal, 2020)

❖ Operational Expenditure

Operational cost is the cost incurred during production. However, the total OpEx consists of the variable OpEx and the fixed OpEx. The variable OpEx is a cost that depends on the energy required to extract geothermal energy and is related to the price of electricity. This cost changes over time.

The calculation of required energy is given by:

$$Required\ Energy\ =\ P_{pump}\ x\ \Delta t \qquad (20)$$

where Δt is the time difference (hours) between t_i and t_{i-1} and P_{pump} is the pump power required (Watt) which is given by equation (21) (Ungemach, 2016)

$$P_{pump} = \frac{q * \Delta P}{n} \qquad (21)$$

where P_{pump} (W) is power required by pump, q (m^3/s) is the flow rate, ΔP (Pa) is pressure difference between injector and produce, and n is pump efficiency 55%

The amount of required energy is multiplied by the electricity price and the tax. The electricity price is very volatile due to many factors, such as gas prices, fluctuations in energy demand, as well as national and international energy policies. In this study, the fixed electricity price is assumed to be 0.071 euro/kWh (CBS, 2020). The electricity use tax in industry is 0.01421 euro/kWh (Belastingdienst, 2012).

Fixed OpEx is the cost that represents the maintenance and workover costs, rental facilities, employee payments, and insurance costs. These costs do not change over time. The fixed OpEx is an annual cost and calculated at 5% of CapEx.

❖ Other expenditure

Other expenditures come from abandonment and insurance. The abandonment consists of plugging and closing the wells and returning the production site to its original state. The minimum abandonment and plugging can cost around EUR 1,078,000 per well (Osundare et al., 2018). The insurance is based on the drilled depths, which is EUR 11,050,000 for depths between 2000-3500 and EUR 18,700,000 for depths deeper than 3500 (Garantieregeling, n.d.).

3.3.3.3 Project Revenue

The project's revenue is obtained from delivered energy and the subsidy (SDE+).

❖ Delivered energy

Delivered energy is calculated from the amount of energy produced multiplied by the heat price. The energy produced is obtained from chapter 3.3.2 by calculating energy produced per-year, and the heat price is assumed by using Low Heating Value (LHV) of gas at the price of 0.014 euro/kWh (CBS, 2020).

❖ Subsidy

The subsidy is calculated by using SDE+ 2019 schemes. This subsidy is obtained from the base amount of the energy and the correction amount (Rijksdienst voor Ondernemend Nederland, 2019).
The base amount is the production cost, which is fixed over the period of the subsidy. The correction amount is the market price of energy. It can be revised annually, depending on the market price. These two variables are obtained based on the depth and type of the wells, as shown in the following table:

Table 8. SDE+ 2019 prices (Rijksdienst voor Ondernemend Nederland, 2019)

Geothermal Project 2019	> 500 m	> 500 m, use of oil/gas well	> 500 m, extra well	> 4000 m
Base Amount (€/kWh)	0.052	0.052	0.052	0.052
Base Energy Rate (€/kWh)	0.013	0.013	0.013	0.013
Correction Amount (€/kWh)	0.019	0.019	0.019	0.019
Full capacity hours per year	6000	6000	6000	6000
Maximum subsidy duration (years)	15	15	15	15

Furthermore, this subsidy only covers a maximum period of 15 years, with 6000 to 7000 hours per year as an annual full capacity production (Rijksdienst voor Ondernemend Nederland, 2019). If there is a calculation difference in the annual evaluation, the operator will have to pay back.

3.3.3.4 Economic Indicator

- Cash Flow (Ct)
  Cash flow is calculated to measure the amount of cash and cash equivalents received and disbursed by a business in a specific period of time. It is calculated by combining the total money earned and spent during the project.

- Present Value (PV) and NPV
  PV represents the current value of money or future cash flows at a specified discount rate. The present value depends on the time interval between the current time and the cash flow. It also depends on the discount rate. The discount rate is important because the value of money changes constantly. Therefore, we use the discount rate to get a better perspective on how much it is worth in present value. PV calculations can be obtained using the following formula:

$$PV = \frac{Ct}{(1+r)^t} \tag{22}$$

Where, Ct is Cashflow generated at time t (Euro), r is Monthly discount rate, and t is Elapsed time since project start (30 days assumed in this thesis)

Net present value (NPV) applies to a series of cash flows that occur at different times. It is calculated by generating cumulative PV during the project. This NPV represents how much the project will benefit. In simple terms, if the NPV is positive, the project is profitable. In contrast, if the NPV is negative, the project will suffer a loss.

4 Result

As discussed in chapter 3.2, this chapter will present the results of each parameter and range of sensitivity analysis. The reservoir model is simulated over 100 years of production. All results are analysed to understand the effect of changing parameters under several conditions: First, in a single doublet system (without any other neighbour), second, in two neighbouring doublets (two blocks).

In the second scenario (Figure 9), Block 1 will change parameters for each sensitivity study. However, the parameters of Block 2 will always be constant as for the base case. The idea here is to study how variation of different operational or natural parameters in one neighbour (Block 1) can affect the heat production and economic profitability of the other neighbour (Block 2).

This chapter is divided into three sections. It begins with a discussion of well positioning as a pre-study. This is followed by an evaluation of the lifetime and energy produced based on an intensive sensitivity analysis. Finally, the optimization is found by using an economic model as an assessment instrument.

4.1 Pre-study – Well Positioning

This study is based on chapter 3.1.2. Four difference scenarios are simulated to evaluate the effect of changing the well positions. Figure 10 shows the lifetime and cumulative energy produced when Block 1 and Block 2 use the same parameter values, similar to the base case.

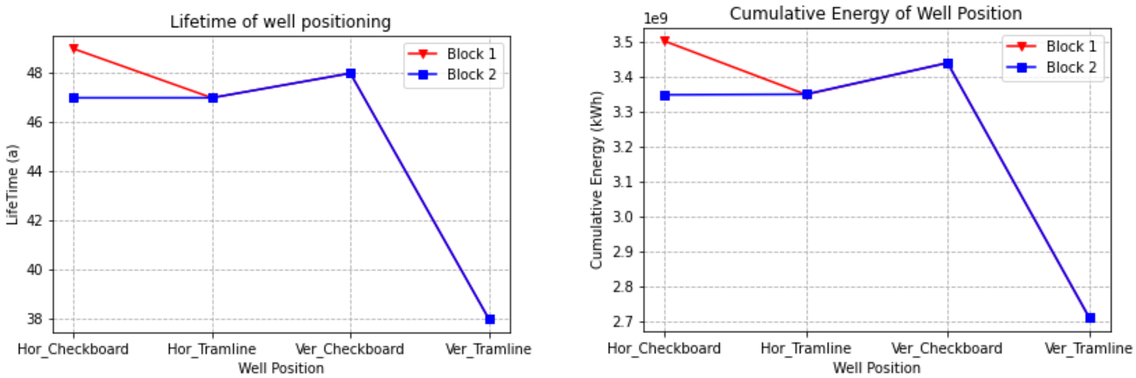


Figure 10. Lifetime & Cumulative energy of well position

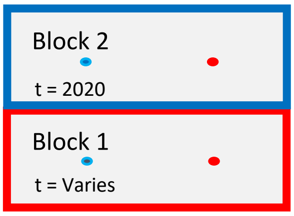
As shown in Figure 10, the lifetime curve has a linear relationship with the cumulative produced energy. The first three types of well positions show the same results between Block 1 and Block 2. The results only show different outcomes on the horizontal checker-board type, where Block 1 has a greater lifetime and energy than Block 2. This study also finds that the vertical tramline scenario has the strongest negative impact compared to all the other scenarios. It shows a 23% difference in result compared to the average results of the other three scenarios. This strongest impact is the most sensitive scenario for well position in a neighbouring system. For this reason, we used the vertical tramline position to observe all parameters in the sensitivity analysis study.

4.2 Lifetime and Energy Produced

4.2.1 Start time

In this part, Block 2 is assumed to start injection and production from 2020, while operations in Block 1 started 10 to 25 years later. The details of this sensitivity analysis can be seen in the Table 9 and the 3D simulation results can be seen as Figure 11.

Table 9. Starting Time Configuration



	Starting Time Configuration 1	2	3	4	5
Block 2	0 (2020)	0 (2020)	0 (2020)	0 (2020)	0 (2020)
Block 1	0 (2020)	10 years (2030)	15 years (2035)	20 years (2040)	25 years (2045)

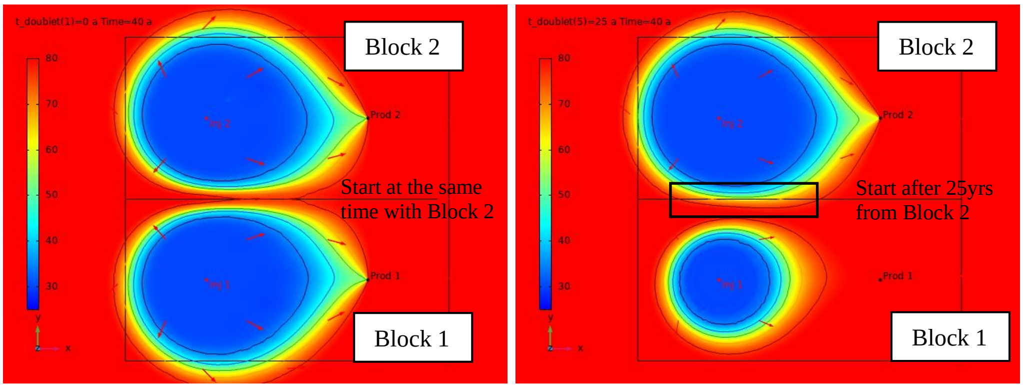


Figure 11. Cold front propagation for neighbours at year 2060. Left: both blocks start production at the same time (2020). Right: Block 1 starts 25 years later than Block 2.

Figure 11 shows the effect of the different starting times in 2060. Figure 11-left, shows the cold front distribution when both blocks start injection/production at the same time. As can be seen a symmetrical cold front shape around the common border of 2 blocks is shaped. Figure 12 left and right, show similar lifetime and similar produced energy for such a case.

Figure 11-right, shows the cold frond propagation when Block 2 starts production at 2020 while Block 1 starts 25 years later. As can be seen the cold front from Block 2 has a chance to enter other license area and take heat from neighbouring license when Block 1 starts operating very late.

To look at the effect of the difference in starting time in more detail, the following figures are plotted to show the effect on lifetime and produced cumulative energy.

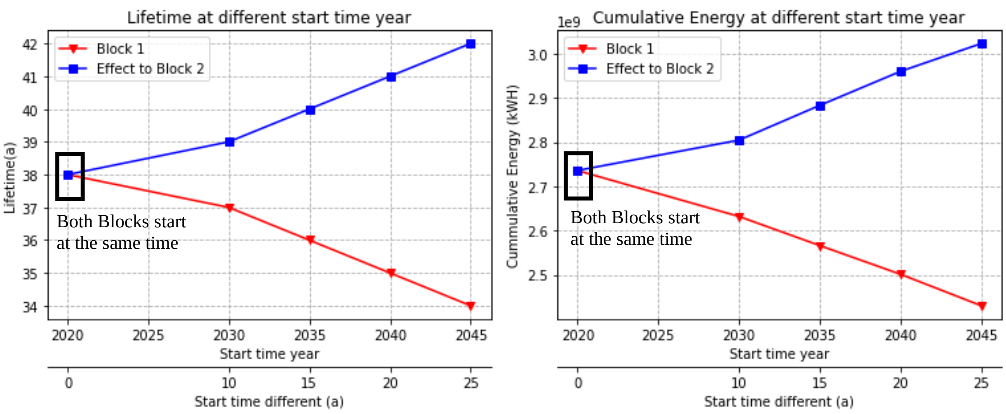


Figure 12. Sensitivity analysis of Starting time Vs lifetime (Left) and Cumulative Energy (Right) for starting time sensitivity analysis.

The figure above indicates the effect of starting time on the produced energy and lifetime. As can be seen the lifetime and consequently the produced energy of Block 1 decrease linearly with increasing delay in starting time with respect to Block 2, while Block 2 shows a linear increase in both lifetime and produced energy. This difference is due to the longer access of Block 2 to the whole resource area, as Block 1 starts later.

Figure 12 suggest that the start time effect between 2030 and 2045 has a linear relationship to lifetime and cumulative energy. For Block 1, this relationship can be described as

L (ST) = -0.2 ST + 37 (eq number for all)

$$CE(ST) = -10^7 ST + 3.10^9$$

For Block 2 can be describe as

L (ST) = 0.2 ST + 39

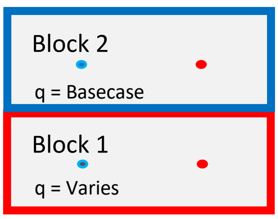
$$CE(ST) = 10^7 ST + 3.10^9$$

where L indicates lifetime in years. ST shows the starting time in year and CE indicates cumulative energy in kWh. The positive and negative sign indicate the increasing and decreasing trend respectively.

4.2.2 Injection/Production Flow rate

To study the effect different injection/production flow rates in the two neighbouring blocks, flow rates in Block 1 were changed in the range of 50 m³/h to 250 m³/h in 50 m³/h intervals, while it was kept constant at 150 m³/h in Block 2 (similar to the base case). The results are also compared with a single block (without neighbours) as a reference study. The variations of flow rate can be seen in Table 10 and the 3D simulation results are shown in the Figure 13.

Table 10. Flow rate configuration



	Flow rate injection 1	2	3	4	5
Block 2	150 m³/h	150 m³/h	150 m³/h	150 m³/h	150 m³/h
Block 1	50 m³/h	100 m³/h	150 m³/h	200 m³/h	250 m³/h
Single Block	50 m³/h	100 m³/h	150 m³/h	200 m³/h	250 m³/h

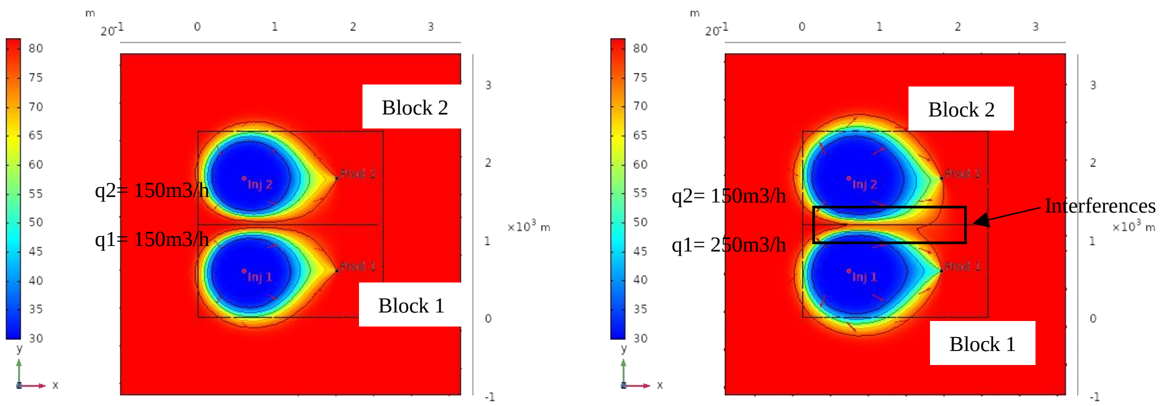


Figure 13. Cold front propagation for neighbours as the effect of injection/production flow rate in 30 years of production. left: Both 2 Blocks have the same flow rate at 150 m³/hr. Right: Block 1 has flow rate 250 m³hr and Block 2 has 150 m³/hr

Figure 13-left indicates the cold front propagation when both blocks have the same flow rate. This figure reveals that after 30 years of production no interference occurs.

Figure 13-right shows that increasing the flow rate to 250 m³/hr in Block 1, will create interference between the two blocks after 30 years of production. Compared to the left figure, the cold-water plume of Block 2 (flow rate as a base case,150 m³/hr) was getting bigger due to the effect of interferences from Block 1. This can cause a decrease in the production performance of Block 2.

The following figure (Figure 14) shows the effect of changing flow rates on the lifetime and cumulative energy in the neighbouring system. The variation of flow rate in a single block is also plotted in these graphs for comparison.

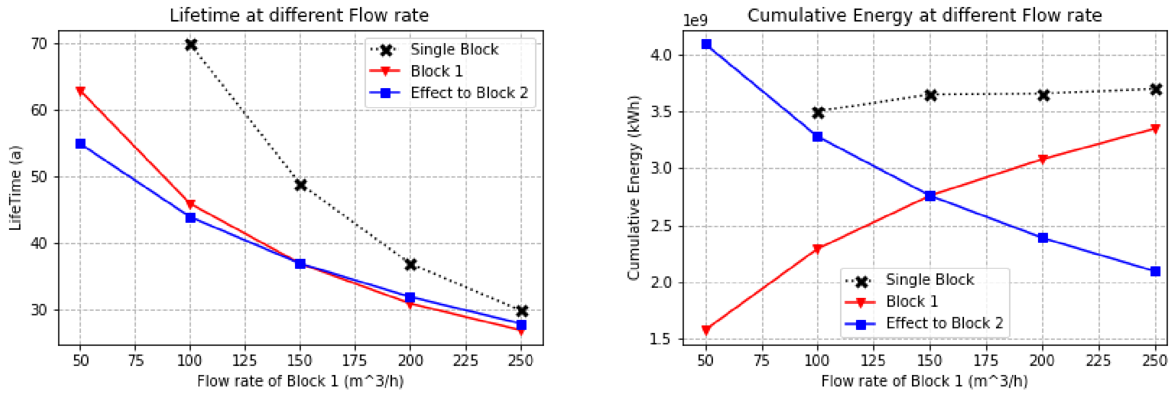


Figure 14 Sensitivity analysis of flow rate Vs lifetime (Left) and cumulative energy (Right). The result of 50 m³ / h in the single block is not visible because it exceeds the simulation time

Figure 14 shows the effect of flow rate variation in the single block (black dashed line) compared to the effect of flow rate in the neighbouring system in Block 1 and its effect on Block 2. Based on the single block, with a varying flowrate range of 100 m³/hr to 250 m³/hr, it is concluded that increasing the flow rate can decrease the lifetime by up to 40% while increasing the cumulative energy by 1.67% for every 50 m³/hr increase. Compared to the neighbouring system, with a range of 100 m³/hr to 250 m³/hr, increasing the flow rate in Block 1 can decrease the lifetime by up to 23% but can obtain up to 17% more energy for every 50 m³/hr increase.

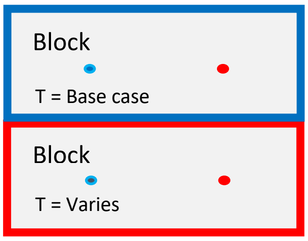
Increasing the flow rate in Block 1 will not only decrease its lifetime, but also reduce the lifetime of its neighbour, Block 2. For example, from the rate of 150 m³/hr to 200m³/hr, it can be seen that the lifetime of Block 1 decreases by 16%. Block 2 also experienced a decrease by 15% due to the negative impact of interference.

Increasing the flow rate in Block 1 will also negatively affect the energy produced of the neighbour block (Block 2). For example, as shown in the right side of Figure 14, when Block 1 increases the flow rate from 150 m³/hr to 200 m³/hr, there is an increase in the energy produced by 13%. However, its neighbour (Block 2) experienced a decrease in the energy produced by 15%.

4.2.3 Injection temperature

Five different injection temperatures were tested from 10 °C to 50 °C with intervals of 10 °C. The injection temperature in Block 1 was changed within the mentioned range, while the injection temperature in Block 2 was kept constant as the base case at 30°C. This injection temperature sensitivity was also compared with a single block as reference study. The variation of injection temperature can be seen in Table 11 and the 3D visualisation results can be seen in the Figure 15.

Table 11. Injection Temperature Configuration



	Temperature injection				
	1	2	3	4	5
Block 2	30 °C	30 °C	30 °C	30 °C	30 °C
Block 1	10 °C	20 °C	30 °C	40 °C	50 °C
Single Block	10 °C	20 °C	30 °C	40 °C	50 °C

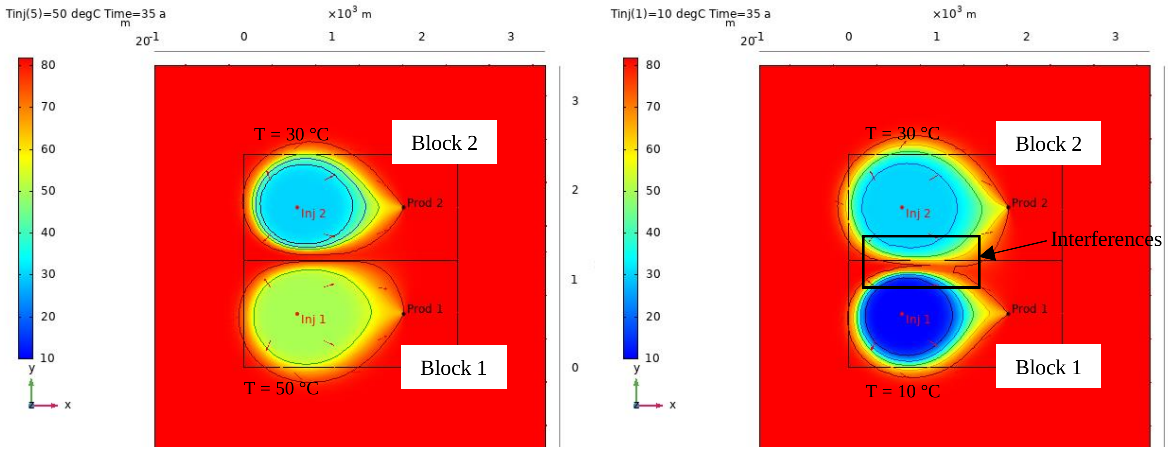


Figure 15. Cold front propagation for neighbours as the effect of injection temperature in 35 years of production. Left: Injection temperature in Block 1 (50°C) is warmer than Block 2 (30°C). Right: Injection temperature in Block 1 (10°C) is colder than Block 2 (30°C)

Figure 15 shows the propagation of cold fronts in the neighbours at different injection temperatures after 35 years of production. Figure 15 -Left illustrates the injection temperatures of 50°C in Block 1 and 30°C in Block 2. Based on this figure, the cold front in Block 1 has bigger propagation in the reservoir than in Block 2. This is due to the effect of higher hydraulic conductivity (lower viscosity) of water at higher temperatures (Saeid et al., 2014)

In the same production year as the left figure, Figure 15-right shows that interference occurs when Block 1 has an injection temperature of 10 °C and Block 2 has an injection temperature of 30 °C. The difference between the sizes of the plumes is caused by the different hydraulic conductivity in each Block due to different temperatures, as shown by Saeid (2014, 2015). This figure indicates the interference between the two blocks increasing the volume of cold-water plume in Block 2, while decreasing the volume of cold-water plume in Block 1. Consequently, this results in a decrease in the lifetime of Block 2 and an increase in the lifetime of Block 1.

The following figure (Figure 16) shows the effect of changes in injection temperature between the neighbouring systems. Variation of injection temperature in a single block is also shown for comparison.

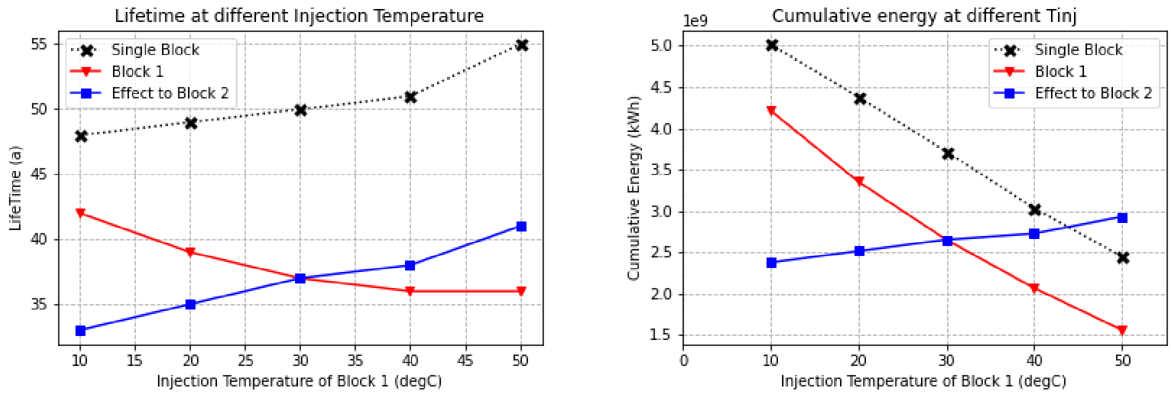


Figure 16. Sensitivity Analysis of Injection Temperature Vs lifetime (Left) and Cumulative Energy (Right).

Figure 16 shows the effect of injection temperature variations in a single block (black dashed line) and in neighbouring systems. In Figure 16-left, a 10°C increase in injection temperature will increase the lifetime of a single block by almost 1 year. The increase in lifetime is even longer, around 4 years, when injection temperature is increased from 40°C to 50°C. However, this can decrease the cumulative energy produced by around 14% to 20 % for every 10°C increase in temperature (Figure 16-Right).

As an effect of thermal interference in neighbouring systems, decreasing every 10°C of the injection temperature in Block 1 will increase the lifetime by maximum 7% but will decrease neighbour's (Block 2) lifetime by around 6% (Figure 16-left). This is because injecting colder water in a neighbouring system will slow down the move of cold-plume to the production well.

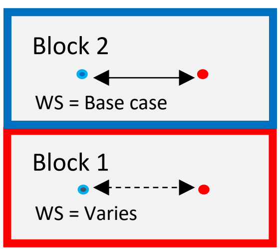
For the cumulative energy in Block 1 (Figure 16-Right), every 10°C decrease in injection temperature will increase the cumulative energy by more than 25%. In contrast, the cumulative energy of the neighbouring block (Block 2) will decrease by around 2% to 7%. The reason for that is because the cold-plume in Block 1 received support from the neighbour's block because of its lower injection temperature.

Based on this study, the injection temperature should be lowered to obtain more cumulative energy produced. However, this parameter doesn't harm a lot the cumulative energy of the neighbouring block.

4.2.4 Well Spacing

The sensitivity in the distance between the injector and the producer (well spacing) was evaluated from 300 m to 1500 m with intervals of 300 m. The well spacing of Block 1 was changed over the range as mentioned above, while the well spacing of Block 2 was kept constant at the base case of 1200 m. This study was also compared with a single block (without any neighbour) as a reference study. Details of parameter variations are shown in Table 12 and the 3D visualisation results can be seen in the Figure 17

Table 12. Well Spacing Configuration



	Well Spacing Between Injector and Producer 1	2	3	4	5
Block 2	1200 m	1200 m	1200 m	1200 m	1200 m
Block 1	600 m	900 m	1200 m	1500 m	1800 m
Single Block	600 m	900 m	1200 m	1500 m	1800 m

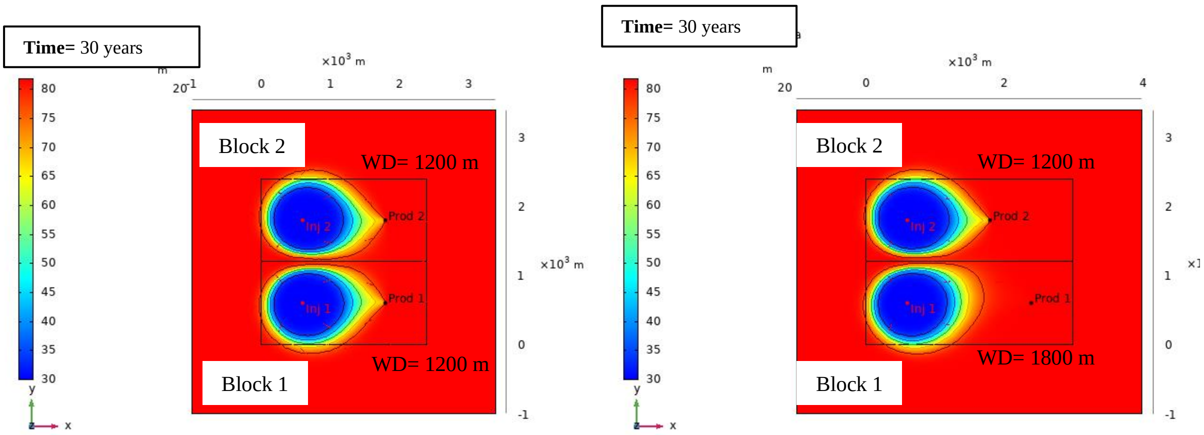


Figure 17. Cold front propagation for neighbours as the effect of well spacing in 30 years of production. Left: Both 2 Blocks have the same well spacing of 1200 m. Right: Block 1 has longer well spacing with 1800 m and Block 2 has 1200 m

Figure 17 shows the cold front propagation in neighbours with different well spacing after 30 years of production. Figure 17-left shows that, when they have the same well spacing, the cold-plumes have the same shape due to the same pressure difference in the two blocks.

Figure 17-right demonstrates a case where well spacing in Block 1 is 1800 m and 1200m in Block 2. As can be seen, the cold front in Block 1, after about 30 years, starts moving towards production well of Block 2 as it is a closer pressure sink point. This causes longer lifetime for Block 1 and relatively shorter for Block 2. This can also clearly be seen in Figure 18-left.

Figure 18 shows the effect of well spacing in neighbouring system with comparison to single block (without any neighbour block) as a reference.

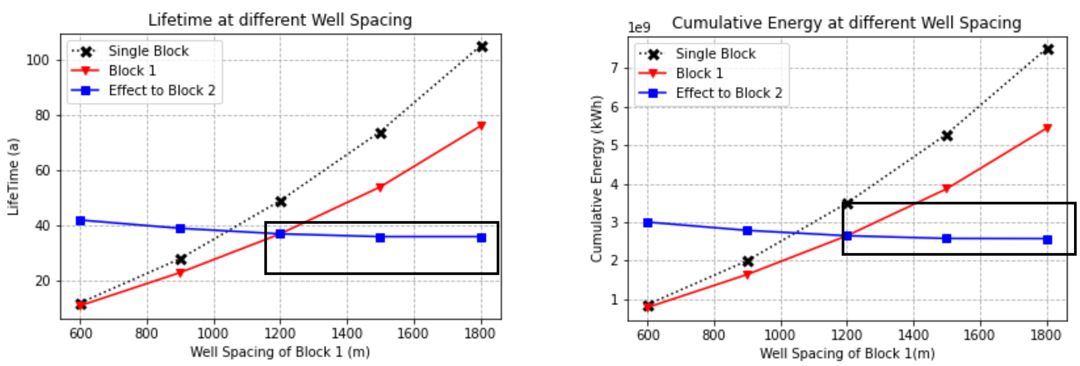


Figure 18. Sensitivity Analysis of Well Spacing Vs lifetime (Left) and Cumulative Energy (Right).

Figure 18 shows the effect of lifetime and cumulative energy at different well spacings. These figures illustrate that the lifetime has the same trend with the cumulative energy as a result of increasing well spacing. Based on the single Block, a longer well spacing will increase the lifetime and cumulative energy. In contrast, a shorter well spacing will decrease the lifetime and cumulative energy.

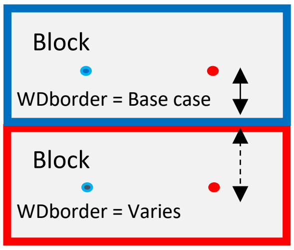
Block 1 has the same trend as the single block, but has a difference of more than 27% for wells spacing above than 1200. This is because the single block has a larger area to extract compared to the neighbouring block. Having a larger well spacing such as from above 1200 m (above the base case), will increase the lifetime and amount of energy produced. However, this could hinder the neighbour, Block 2. When the well spacing in Block 1 is increased from 1200 m to 1800 m, the lifetime and cumulative energy of Block 2 (Blue line) decrease by approximately 3%. This is because the cold-water from Block 1 moves to a closer pressure sink point, which is the producer of Block 2.

In the cases of well spacing below the base case (1200), Block 1 will reach breakthrough faster than Block 2. This results in a smaller amount of energy that can be produced. In general, the shorter the lifetime, the less energy can be obtained. In the case of a smaller well spacing in Block 1, Block 2 as neighbour does not seem to be affected by an interference

4.2.5 Well-distance to license border

In neighbouring system study, Block 2 is placed at a distance of 600 m from the common border between the 2 blocks while Block 1 is placed at variations (200 m interval) of the distance to the border. The details of sensitivity analysis can be seen in Table 13 and the 3D simulation results are shown in the Figure 19

Table 13. Well-distance to license border Configuration



	Well Distance to License Border				
	1	2	3	4	5
Block 2	600 m	600 m	600 m	600 m	600 m
Block 1	400 m	600 m	800 m	1000 m	1200 m
Single Block	400 m	600 m	800 m	1000 m	1200 m

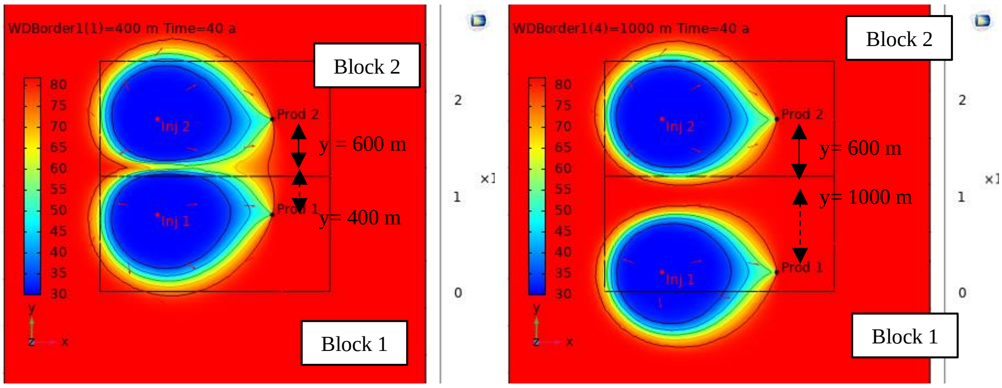


Figure 19. Cold front propagation for neighbours as the effect of well distance to border in 40 years of production. Left: Block 1 has 400 m distance to border. Right: Block 1 has 1000 m distance to border. Block 2 in both left and right figure has 600 m distance to border.

Figure 19 shows the cold front propagation in neighbours with different well-distance to border after 40 years of production. Block 1 close to the license border causes interference between the two blocks (Left figure), while placing Block 1 far from the license border avoids interference (Right figure). Figure 20 shows the effect of well-distance to the border in neighbouring systems by comparing to a single block as a reference (without neighbouring blocks).

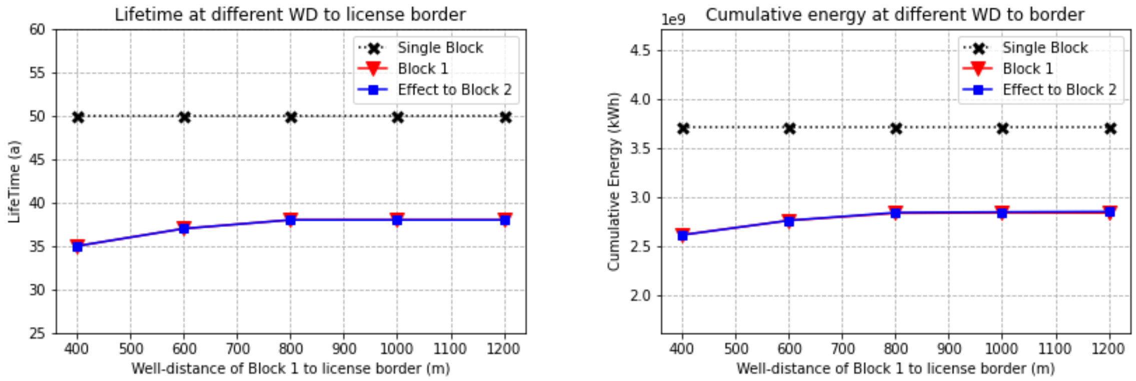


Figure 20. Sensitivity Analysis of Well distance to border Vs lifetime (Left) and Cumulative Energy (Right).

Figure 20 shows the effects on lifetime and cumulative energy with different well distances to the license border. As the single block is not influenced by any other licenses, the lifetime and cumulative energy are constant in one value which is equivalent to 50 years of lifetime with 3,718 GWh as the cumulative energy.

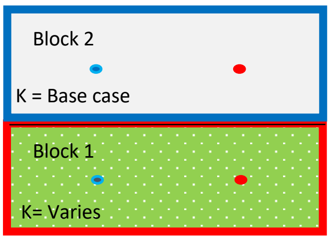
In the study of neighbouring systems, both blocks (Block 1 and Block 2) show similar results for the lifetime and cumulative energy in all sensitivity ranges. It means that they produce an equivalent amount of energy with a similar lifetime. In the range of 400 m to 800 m, a 8 % increase in the lifetime and cumulative energy is indicated for every 200 m increase in well distance to border. By increasing the distance further from the license border, such as in the range between 800 m and 1200 m, the lifetime and cumulative energy remain stable at 38 years and 2,840 GWh.

Overall, it can be said that the distance of every neighbour to the border will affect both neighbours equally. This is an important design parameter and needs to be chosen carefully based on all existing neighbours.

4.2.6 Permeability

For this sensitivity analysis, five different permeabilities were assumed from 100 mD to 500 mD with an interval of 100mD. In the study on neighbouring systems, the permeability in Block 1 was changed over the mentioned ranges above, while the permeability in Block 2 was kept constant as the base case 200 mD. The permeability variation was also compared with a single block as a reference study. This can be seen in Table 14 and the results of 3D visualisation can be seen in the Figure 21.

Table 14. Permeability Configuration



	Permeability 1	2	3	4	5
Block 2	200 mD	200 mD	200 mD	200 mD	200 mD
Block 1	100 mD	200 mD	300 mD	400 mD	500 mD
Single Block	100 mD	200 mD	300 mD	400 mD	500 mD

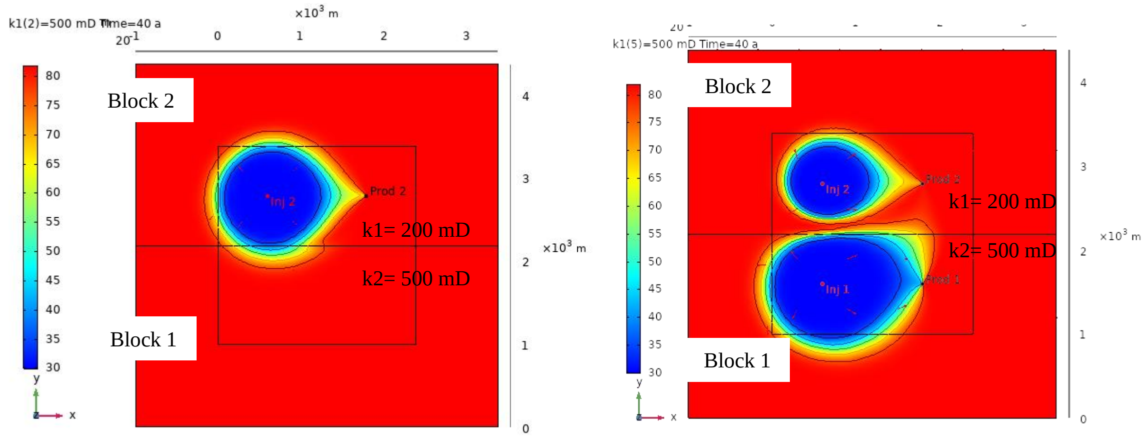


Figure 21. Cold front propagation for neighbours as an effect of different permeability in 40 years of production. Block 1has 500 mD of permeability while Block 2 has 200 mD. Left: If Block 2 produces, without neighbour. Right: both neighbours produce together at the same time

Figure 21 shows the cold front propagation in neighbours with different permeabilities after 40 years of production. The left figure shows that Block 1 has permeability of 500 mD, and Block 2 has permeability of 200 mD, but only Block 2 was operated. Based on this figure, we know how big the cold-water plume should be after 40 years of production. Also, it can be seen that the cold-water plume will be getting bigger after propagating to higher permeability regions (Block 1).

Figure 21-right shows that Block 1 has a permeability of 500 mD, and Block 2 has a permeability of 200 mD (similar to the figure in the left), while both blocks are operated. By looking at the right figure, the high permeability in Block 1 cause faster cooling in Block 1, which will also cause more lateral sweep, due to the fix flow rate boundary condition. Hence the cold front will reach Block 2 and its pressure sink production well 2. As the cold front in Block 1 reaches the middle border, it starts to penetrate the neighbour (Block 2), which has lower permeability; hence, it caused the cold-water plume in Block 2 to get smaller compared to the time when the Block 2 operates without any neighbour (left figure). This is due to the small pressure drop in Block 2 when Block 1 operates at the higher permeability. (Appendix F)

Figure 22 shows the effect of permeability difference in neighbouring systems compared to a single block as a reference (without neighbouring blocks).

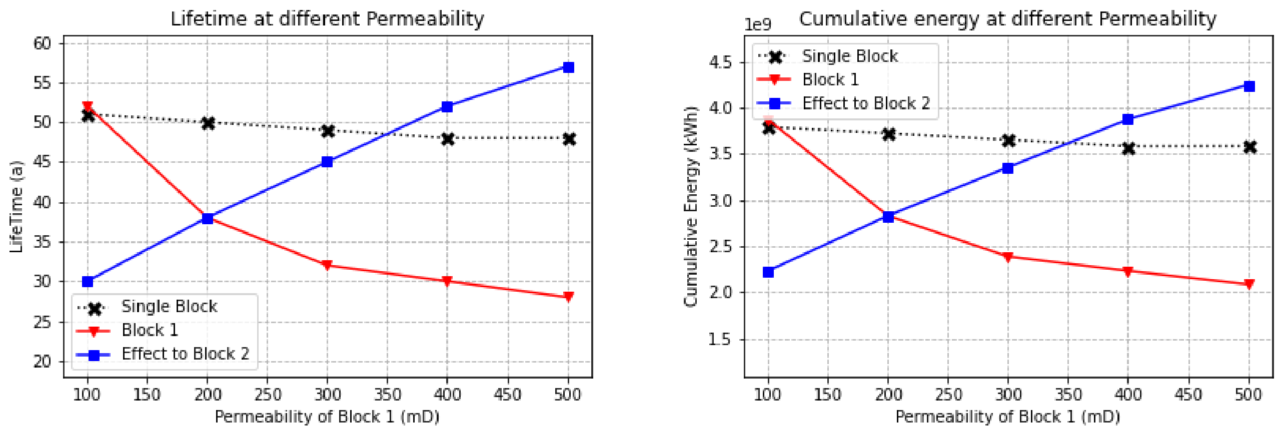


Figure 22. Sensitivity Analysis of Permeability Vs lifetime (left) and Cumulative Energy (right).

Figure 22 shows the variation of lifetime and cumulative energy as an effect of permeability differences. In the figure above, the lifetime has the same relation to permeability as cumulative energy. Based on the calculations for the single block, increasing permeability by 100 mD can decrease the lifetime and the cumulative energy produced by 2.6%.

In the neighbouring system, the sensitivity to permeability is high when production is from two blocks. Block 1 has higher reduction in lifetime and produced energy compared to a single block with increasing permeability. As an example, for a permeability increase from 200 mD to 300 mD, lifetime and cumulative energy produced in Block 1 decrease around 16% compared to the single block, where the decrease is only around 2.6%. With active operation in the neighbouring block with lower permeability, the cold-water plume will confine for a longer period in its area, especially with high permeability differences. As a result, the reservoir temperature will be cooling down quickly. The higher the difference in permeability, the faster the reservoirs cool down and the higher reduction in a lifetime and cumulative energy. This can be seen for a permeability of 500 mD in Block 1, where the lifetime and cumulative energy are falling.

In contrast, Block 1 has a positive effect on Block 2 with high permeability. First, it helps to avoid the impact of thermal interference because the less propagation of cold-water plume from Block 1 (high permeability) to Block 2(small permeability). Second, Block 2 has less pressure drop compared to a Block who does not have neighbour block with big permeability (Appendix F) This can be seen when the permeability of Block 1 is 300 mD, the lifetime and energy produced of Block 2 will be 20% bigger compared to Block 1 with a permeability of 200 mD.

4.2.7 Anisotropy of permeability

This study discusses the variation of permeability in different directions known as anisotropic permeability.
In neighbouring blocks, the anisotropy of horizontal to vertical permeability is varied in Block 1 from the ratio 1:0.1 to the ratio 1:10. In Block 2 permeability is unchanged with the base case ratio of 1:1 between vertical and horizontal permeability. This model is also compared to production from a single block (as a reference study) which can be seen in Table 15 and Table 16 and the 3D visualisation results can be seen in the Figure 23.

Table 15. Anisotropic Permeability Configuration

	Kx/ky ratio				
	1	2	3	4	5
Block 2	1:1	1:1	1:1	1:1	1:1
Block 1	1: 0:1	1: 0:5	1:1	1: 2	1: 10
Single Block	1: 0:1	1: 0:5	1:1	1: 2	1: 10

Table 16. Interpretation kx/ky ratio to permeability direction

	Kx/ky ratio in Single Block and Neighbouring Block 1	
	Kx (mD)	Ky (mD)
Large ratio (1:0.1), Kx/ky=10	200	20
Small ratio (1:0.5), Kx/ky=2	200	100
Base case ratio (1:1), Kx/ky=1	200	200
Small ratio (1:2), Kx/ky=0.5	200	400
Large ratio (1:10), Kx/ky=0.1	200	2000

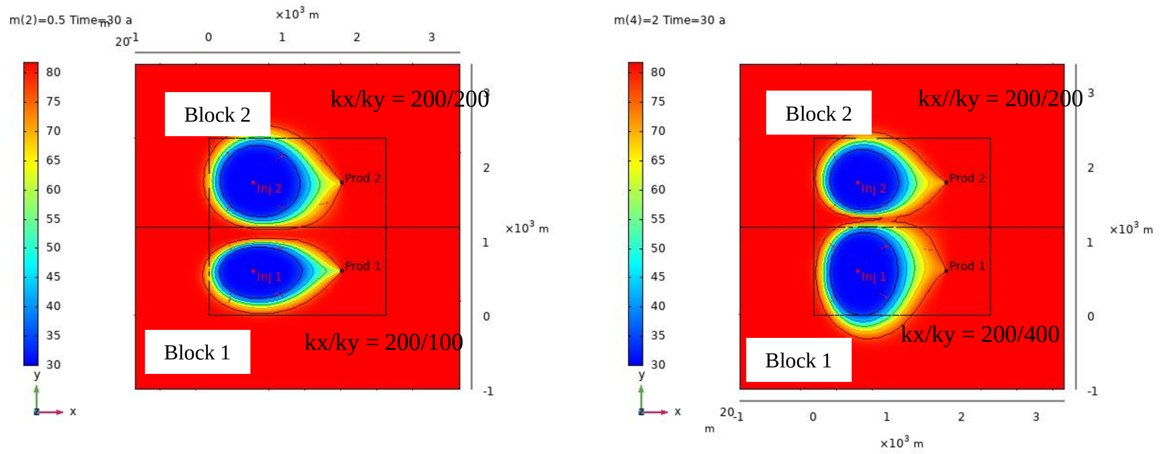


Figure 23. Cold front propagation for neighbours as the effect of anisotropic permeability in 30 years of production. Block 2 has isotropic permeability ratio 1:1 (kx=ky=200). The differences are Left: Block 1 has Kx/ky >1. Right: Block 1 has Kx/ky < 1

Figure 23 depicts the propagation of cold front in the neighbours for different Kx/ky ratios after 30 years of production. The left figure shows the cold front of Block 1 spread from the west to east when Kx/ky > 1. Interference did not occur after 30 years of production because the cold front of Block 1 moves faster to producer well.

The right figure shows that interference occurs when Kx/ky < 1 in Block 1. At this ratio, the cold-front of Block 1 spreads from the south to the north. In this case, the interference occurs after 30 years of production. Additionally, the cold-water plume in Block 2 is getting smaller with a decreasing ratio of Kx/ky from Block 1

The following figures show the effect of this sensitivity analysis in the neighbouring system in comparison to a single block as a reference (without neighbouring blocks).

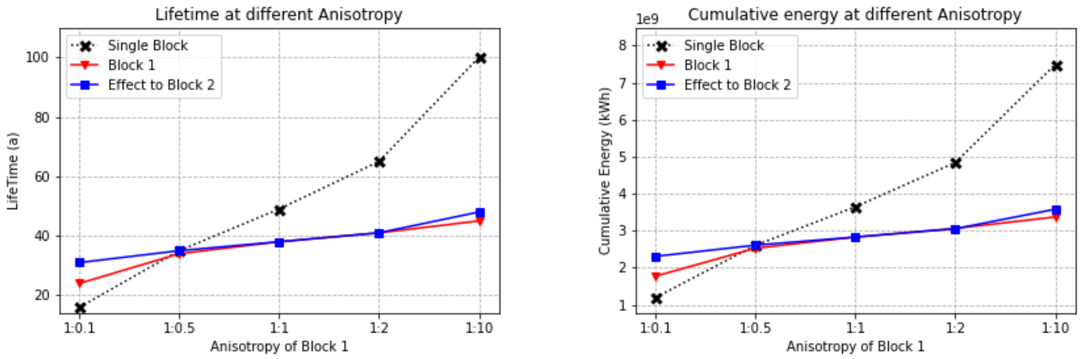


Figure 24. Sensitivity Analysis of Anisotropic permeability Vs lifetime (Left) and Cumulative Energy (Right).

Figure 24 shows the result for lifetime and cumulative energy with the variation of Kx/ky ratio. With a decrease in Kx/ky, the lifetime and cumulative energy produced will increase. Based on the single block, the lifetime and cumulative energy have very optimistic results compared to neighbouring blocks, particularly for Kx/ky 0.5 and 0.1. The reason is that the cold front spreads from south to north, and for the chosen well position, the interference will reduce the lifetime and cumulative energy for both blocks. There is a 45% difference at Kx/ky= 0.5 and a 75% difference at Kx/ky= 0.1 between the single block and the neighbouring Block 1. However, at a Kx/ky > 1, the single block has a pessimistic result which is 40 % lower than neighbouring Block 1.

In a comparison between two blocks in the neighbouring system, for a small anisotropy permeability ratio (Kx/ky= 2 and Kx/ky= 0.5) the effect on the lifetime and cumulative energy in Block 1 is the same as in Block 2. But for the larger anisotropy permeability ratios such as Kx/ky= 0.1 and Kx/ky= 10, Block 2 has more benefits for the lifetime and cumulative energy.

4.3 Economic Analysis

In this study, the Net Present Value (NPV) is used as financial tool to measure the economic feasibility of neighbouring systems under the variation of different parameters. According to Gallo (2014), NPV is a widely used tool for financial analysis for two main reasons:

1. NPV considers the time value of money
2. NPV can provide a particular number that many people can use for comparison

In this section NPV is used as a tool to analyse different scenarios economically. Later to be able to evaluate each sensitivity thoroughly NPV will be compared with the lifetime and produced energy for each sensitivity.

4.3.1 Start time

This study is based on the sensitivity analysis from Table 9, the NPV for different starting time shown in Figure 25:

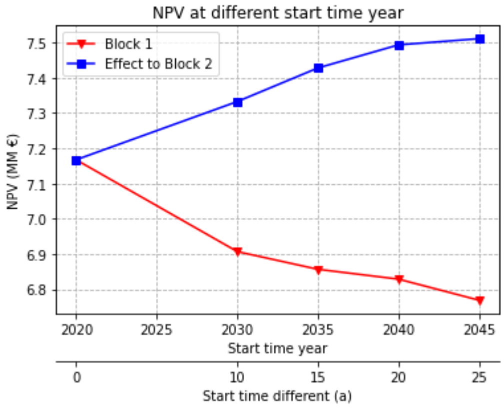


Figure 25. NPV for Different Starting Time in neighbouring systems

Figure 25 shows the NPV performance for different starting time. The NPV can increase or decrease linearly depending on the time when the well starts to extract energy. The increasing/decreasing rate of NPV was indicated by less than 1% for every 5 years different time. Such as, NPV increases by 1% in Block 2 when it starts operation 5 years earlier than Block 1. NPV decreases by 1% in Block 1 when it starts operation 5 years later than Block 2.

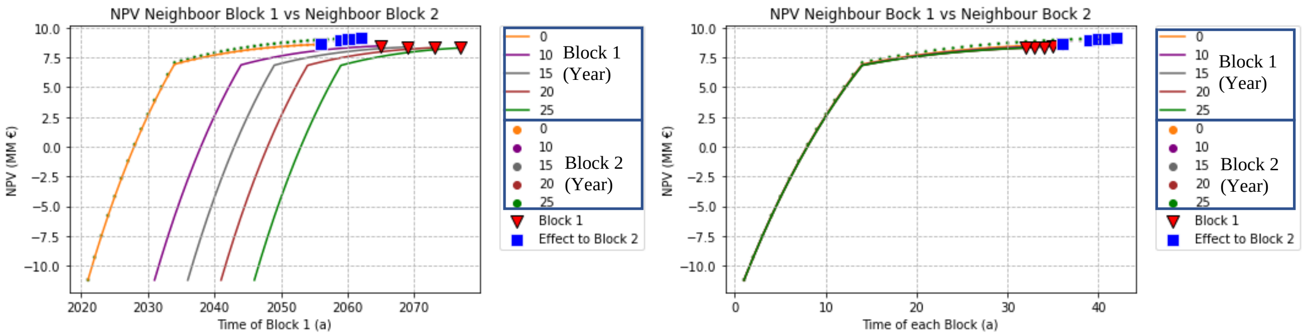


Figure 26. Time evolution of the NPV over the lifetime for different starting times. Left: NPV if we look from the year 2020 when Block 2 start operation. Right: NPV if we look from the year of each block start operation. The solid lines and dotted lines on this figure present the growth of NPV over time. The red triangles demonstrate the lifetime in Block 1, and blue rectangular present the lifetime of Block 2

Figure 26 shows a result of NPV over the lifetime for different start time of a project. In the left figure, by looking only to the year from 2020, Block 1 has less NPV than Block 2, but it has longer in lifetime than Block 2, around 20-30 % difference.

The right figure show NPV vs. the start time difference between Block 1 and Block 2. The solid lines and dotted lines on this figure present the growth of NPV over time. The red triangles demonstrate the lifetime in Block 1, and blue rectangular present the lifetime of Block 2. From the right figure, it can be seen that Block

1 (which started later than Block 2) shows lower NPV and shorter lifetime in comparison with Block 2. From this result, it can be concluded that when an operator (Block 1 in this example) starts later than his neighbours (Block 2), he has a disadvantage in economics and lifetime.

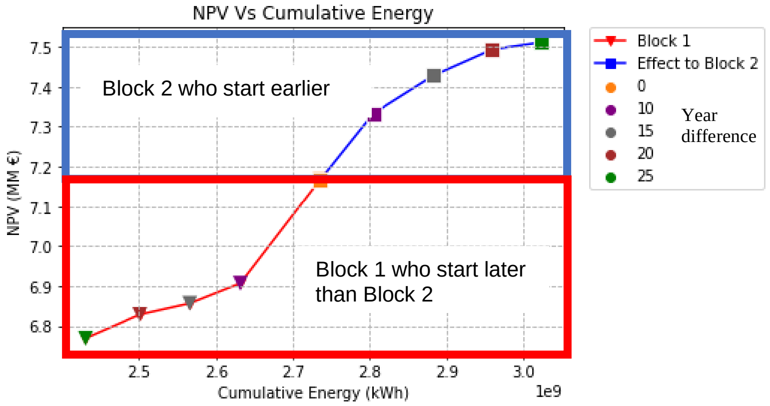


Figure 27. NPV vs Cumulative Energy at Different Starting Time of Block 1. The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of triangles and squares indicate the starting time in Block 1.

Figure 27 shows NPV performance versus cumulative produced energy. The NPV increase in Block 2 depends on how early the operation starts (Blue line). As the operation starts later in Block 1, Block 2 has an advantage with a higher NPV and produced energy. For example, when the difference is 15 years the NPV and cumulative energy in Block 2 increases by 2.8%, and at 20 years difference, it could influence the increase would be approximately 4%.

In contrast, for Block 1 which started late (red line), the NPV and cumulative energy decreases by 1.5% if they started 15 years after Block 2. Even more when they started 20 years after Block 1, the in NPV and cumulative energy will be 3.5%.

4.3.2 Injection/Production Flow rate

This study based on the sensitivity analysis from Table 10, the NPV for different flow rate shown in the Figure 28:

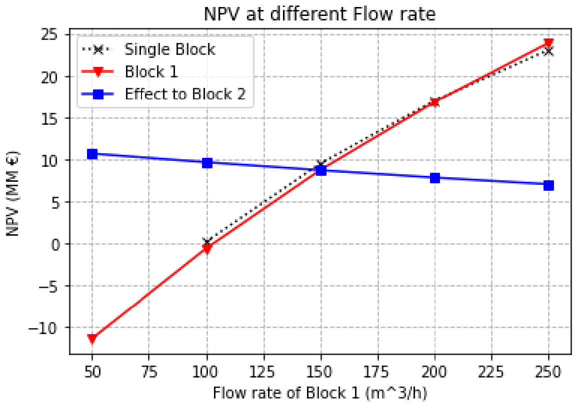


Figure 28. NPV for Different Flow rate in neighbouring systems. The result of 50 m³ / h in the single block is not visible because it exceeds the simulation time

Figure 28 shows the NPV performance at different injection/production flow rates. The flow rate has a huge effect on NPV, which can be seen in single block and Block 1 (in a neighbouring system). The effect shows when increasing the flow rate, NPV will increase linearly by approximately € 8 MM for each 50 m³/hr.

Comparing Single Block and neighbouring systems (Block 1) revealed that Block 1 has around 8% lower NPV than Single Block for the same flow rate. But, at 250 m³/hr, Block 1 has 3% higher NPV than a single block. This is because, at the high flow rate, such as 250 m³/hr, the pressure drop in Block 1 in a neighbouring system is lower than in a single block. The lower pressure drops result in a lower pressure difference. Therefore, the variable OpEx of Block 1 in a neighbouring system is lower than in a single block (Appendix B).

In comparison between two blocks in the neighbouring system, the result of the increased flow rate in Block 1 has a negative effect on its neighbour, Block 2. It relates to the previous study 4.2.2 that increasing flow rate of Block 1 will decrease the cumulative energy in Block 2. An increase of 50 m³/hr in flow rate of Block 1 could reduce the NPV of Block 2 by around 10%.

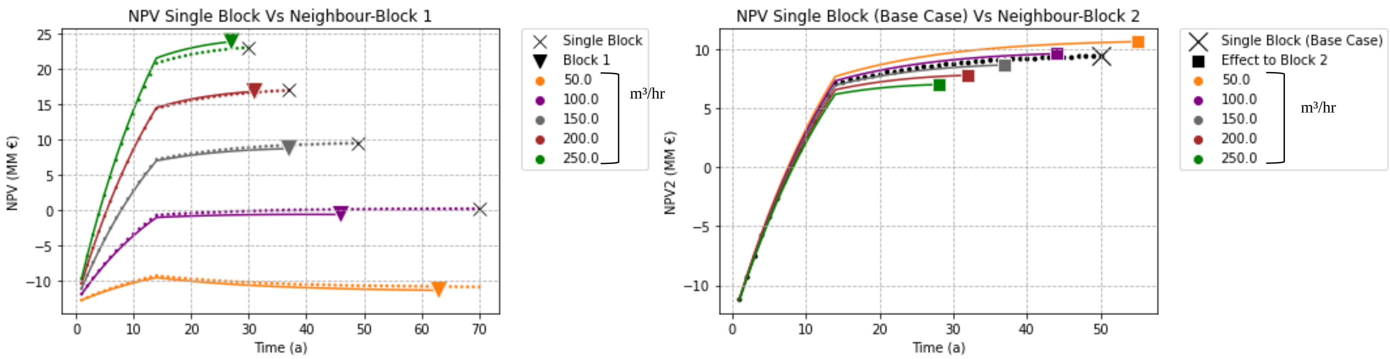


Figure 29. Time evolution of the NPV over the lifetime for Injection/production flow rate. Left: Comparison between Single Block (dotted lines) and Block 1 (solid lines) in various flow rate. Right: Comparison between Single Block base case (dotted lines) and Block 2 (Solid lines) with q=150 m³/hr, but Block 2 was influenced by flow rate changes of Block 1

Figure 29 shows NPV associated with lifetime at different flow rates. The left figure indicates that in Block 1, increasing the flow rate by 50 m³/hr will increase NPV constantly by around € 8 MM and reduce lifetime by ±5 years. For high flow rates, such as from 200 m³/hr to 250 m³/hr, NPV will increase around € 7 MM and lifetime will be reduced by 3 years. This is due to high-pressure drops at this rate. This figure also tells us that the causes of 8% NPV differences between single block and Block 1 (as the previous study) is that there is a big difference in lifetime result between Single Block and Block 1 (up to 30% difference in lifetime).

The right figure indicates a negative effect on NPV for Block 2 due to the increased flow rate in Block 1.
A Single Block base case with flow rate at 150 m³/hr was used as a reference. At the reference flow rate, Block 2 has 8.5% lower NPV. Moreover, the negative effect on Block 2 is getting bigger, by around 10% for every 50 m³/hr increase in flow rate in Block 1.

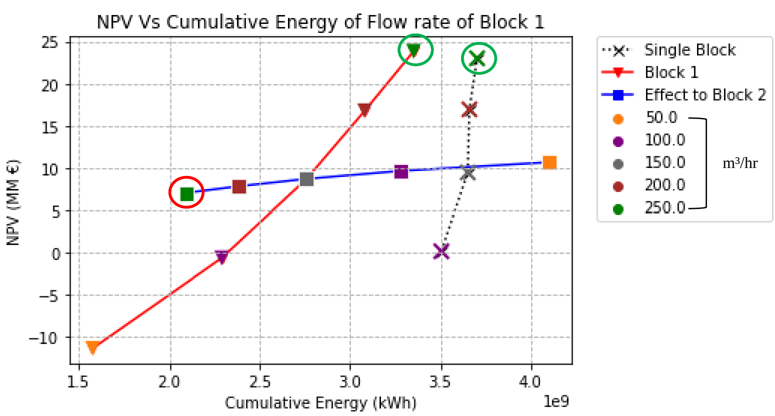


Figure 30. NPV vs. Cumulative energy when flow rate is changing in Block 1. The cross-black dot shows Single Block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the flow rate variation in Block 1.

Figure 30 shows that a single block and Block 1 in neighbouring system, have an improvement of NPV by increasing the flow rate. In a neighbouring system, Block 1 could obtain more than a 30% increase of both cumulative energy and NPV (red line) for a flow rate increase from 100 m³/hr to 250 m³/hr.

In contrast, the negative effect on the neighbour's block is more obvious (blue line). The result of Block 2 is inversely related to what is obtained in Block 1. This is because increasing the flow rate in Block 1 will reduce the energy of its neighbour and increase the pressure drop of its neighbour (Appendix B). This study indicated that every 50 m³/hr increase in the flow rate of Block 1 would be impacting the cumulative energy and NPV in Block 2 by 5% reduction.

4.3.3 Injection Temperature

This study is based on the sensitivity analysis from Table 11. The NPV for different injection temperatures is shown in Figure 31:

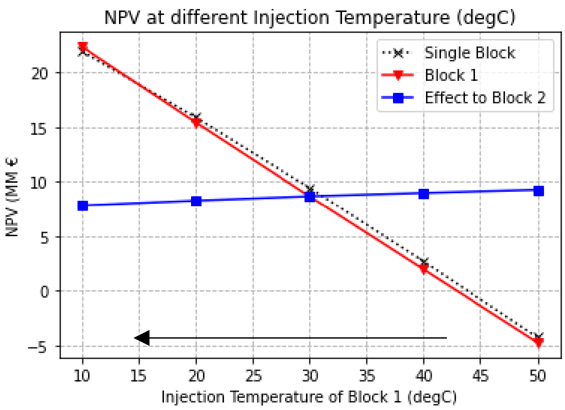


Figure 31. NPV at Different Injection Temperature of Block 1. In this figure, we observed the result from the right axis (every decrease in injection temperature of Block 1)

Figure 31 shows the NPV performance at different injection temperature. The injection temperature is inversely proportional to NPV. It means that decreasing injection temperature can increase the NPV. Based on a single block, reducing injection temperature by each 10°C will result in the linear increase of NPV by € 6MM. The same behaviour was seen in the neighbouring system Block 1 as the effect of changing injection temperature.

Comparing Block 1 in a neighbouring system with a single block shows that Block 1 has 5% lower NPV in for injection temperatures in the range of 20°C to 50°C. But, at 10°C, Block 1 can have a little higher NPV. This arises because at lower injection temperature, the pressure drop in neighbouring system is smaller than Single Block. This pressure drop relates to operational expenditure (OpEx) as part of the NPV calculations (Appendix C)

The decrease in injection temperature in Block 1 has a slightly negative effect on Block 2, with around 3% to 5% decrease in NPV for Block 2 with every 10°C reduction in injection temperature in Block 1.

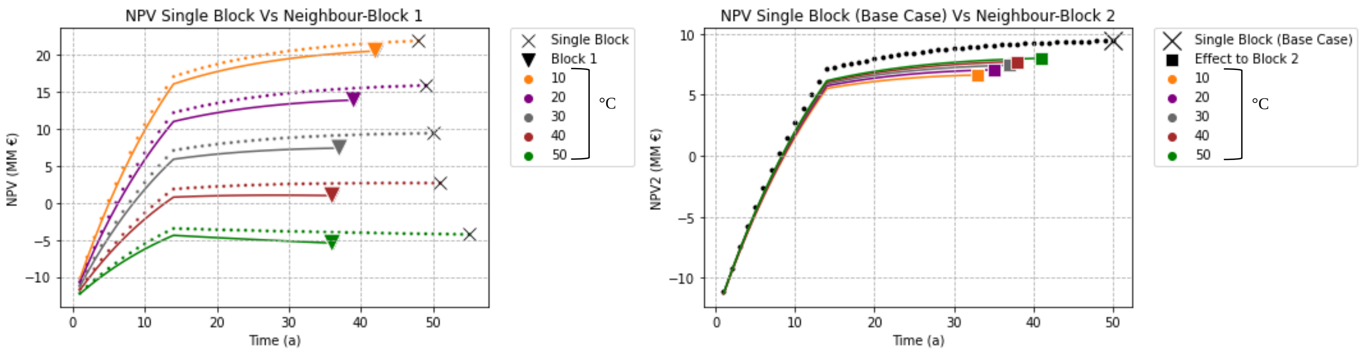


Figure 32. Time evolution of the NPV over the lifetime for Injection Temperature. Left: Comparison between Single Block (dotted lines) and Block 1 (solid lines) in various Injection Temperature. Right: Comparison between Single Block base case (dotted lines) and Block 2 (Solid lines) with t=30°C, but Block 2 was influenced by injection temperature changes of Block 1

Figure 32 shows NPV versus time. Different colours indicate various injection temperatures. The left figure indicates that reducing injection temperature will increase NPV constantly by around € 6 MM for both single Block and Block 1 in a neighbouring system. However, by looking at the lifetime results, single block and Block 1 have an inverse relation.

For example, decreasing injection temperature from 30°C to 20°C will increase the NPV from € 8.2 MM to € 14.3 MM, but reduces the lifetime from 50 to 49 years in a single block. In the neighbouring system, Block 1 can increase NPV around € 7.4 MM to € 13.9 MM, but the lifetime, in contrast to the single block, could increase from 38 to 39 years of production. This is due to the effect of the neighbour (Block 2) and thermal interference in the neighbouring system.

The negative effect is also shown in the Figure 32 –right. A Single Block base case with injection temperature at 30°C was used as a reference. At the same reference injection temperature, Block 2 has 8.5% lower NPV. The NPV in Block 2 will decrease by up to 5.5% for every 10°C injection temperature reduction in Block 1

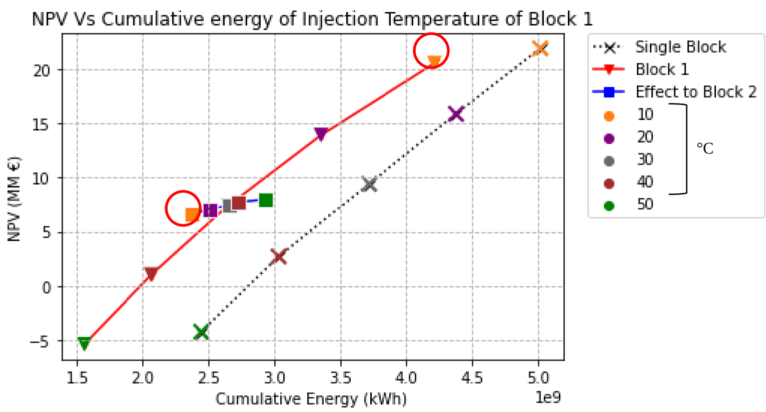


Figure 33. NPV vs. Cumulative energy when injection temperature is changing in Block 1. The cross-black dot shows Single Block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the flow rate variation in Block 1.

Figure 33 shows that reducing injection temperature will increase NPV and cumulative energy both for a single block and Block 1 (in the neighbouring system), however, it has a negative effect on Block 2. In neighbouring system, Block 1 sees an increase of more than 20% for cumulative energy and NPV for every decrease of 10°C in injection temperature. This increase is similar for Block 1 and a single block. The only difference is the amount of cumulative energy and NPV generated. In Block 2, however, NPV decreases around 1% due to reduced injection temperature from Block 1.

Based on this study, decreasing the injection temperature can be a way to improve NPV performance and cumulative energy, while interference only has a minor negative effect.

4.3.4 Well Spacing

This study is based on the sensitivity analysis from Table 12, the NPV for different well spacing shown in Figure 34

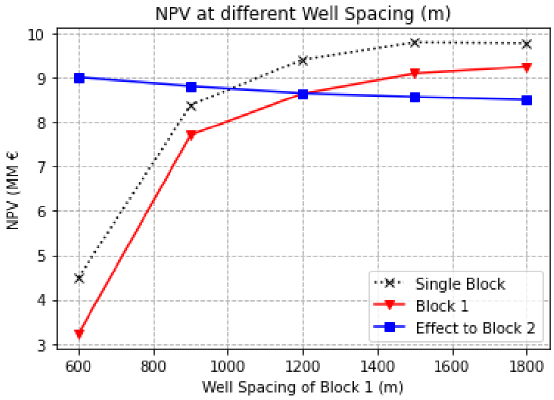


Figure 34. NPV for Well Spacing in neighbouring systems.

Figure 34 shows the NPV performance for different well spacing. Based on a single block, increasing well spacing will increase NPV. NPV shows great sensitivity to well spacing, as can be seen from the variation in 300 m interval. By increasing well spacing from 900 m to 1200 m, NPV increases by 12%. The NPV increase is getting smaller when well spacing increases up to 1500 m and 1800 m. The NPV increases by 4% and 0.3% respectively.

In the neighbouring system, Block 1 has the same increasing trend as the single block. However, the absolute value is about 8% less. This lower NPV of Block 1 is influenced by the effect of heat interference in the neighbour's block (refer to section 4.2.4). The neighbouring block (Block 2) gets a negative impact as a result of the well spacing increase in Block 1. There is a 1% decrease in NPV for every 300 m well spacing increase.

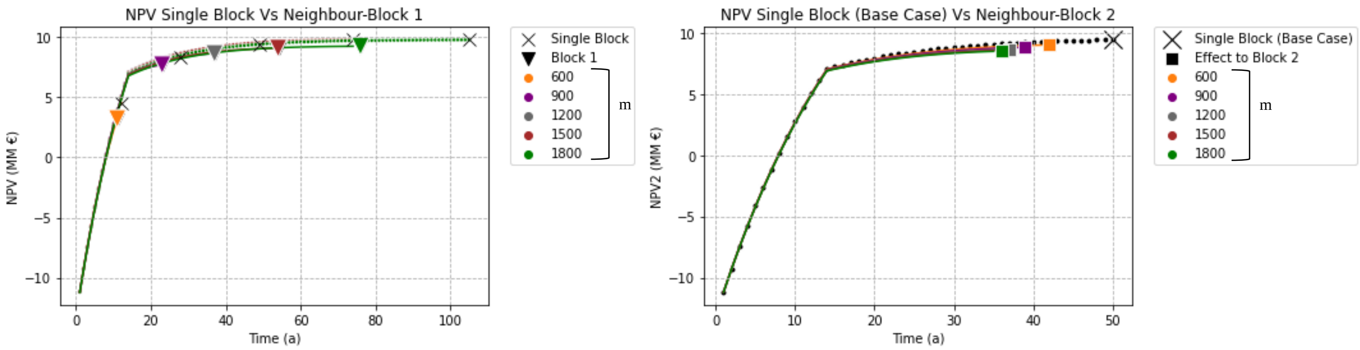


Figure 35. Time evolution of the NPV over the lifetime for well spacing. Left: Comparison between single block (dotted lines) and Block 1 (solid lines) for various well spacings (m). Right: Comparison between the single block base case (dotted lines) and Block 2 (Solid lines) with well spacing=1200 m, but Block 2 was influenced by well spacing changes of Block 1

As in Figure 35-left, increasing well spacing will increase the NPV and lifetime in Block 1. Block 1 and the Single Block (left figure) demonstrate relatively close results. The main difference is in the lifetime factor. In Neighbouring system, particularly Block 1, has shorter lifetime compared to the single block. As a result, NPV of the single block is slightly higher than the corresponding ones in Block 1. Moreover, based on Figure 35-left, the difference in NPV results in Figure 34 between single block and Block 1 in a neighbouring system is due to the lifetime effect.

The parameter's effect on neighbouring block (Block 2) has been studied in Figure 35-right. A single block base case with 1200 m well spacing was used as reference (dotted black line). At the same well spacing with this reference, Block 2 show 8.7% lower NPV. Moreover, every 300 m increase/decrease in well spacing from Block 1 could influence NPV by 1% in Block 2.

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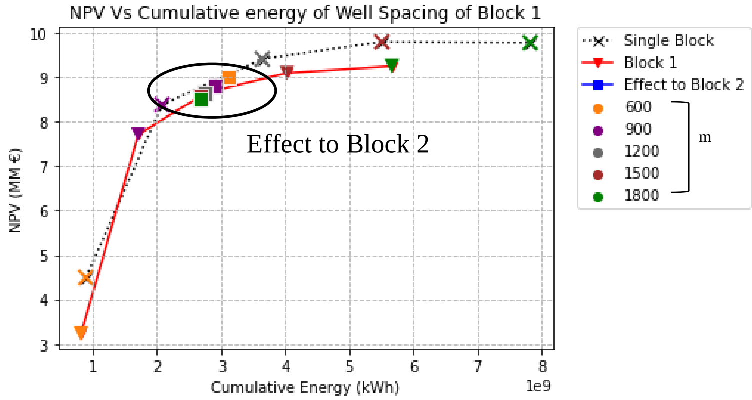

Figure 36. NPV vs. Cumulative energy when well spacing is changing in Block 1. The cross-black dot shows Single Block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the well spacing variation in Block 1.

Figure 36 shows that increase of well spacing can increase NPV and cumulative energy for Block 1 and the single block. The increase of well spacing in Block 1 has a slightly negative effect on both cumulative energy and NPV of Block 2. This can be seen through by the coloured squares marked by an ellipse on Figure 36.

In a single block, the increase of the well spacing from 900 m to 1200 m results in 12% and 65% increase in NPV and cumulative energy respectively. But the increasing rate is getting smaller when the well spacing is getting larger. Increasing well spacing from 1500 m to 1800 m results in only 1.8 % increase of cumulative energy and 44% of NPV.

In the neighbouring system, Block 1 has similar trend with single block. As the increase of the well spacing from 900 m to 1200 m, increases the 61% of cumulative energy and NPV by 12%. This increasing rate is also getting smaller when well spacing is increased from 1500 m to 1800 m, which leads to a 41% increase in cumulative energy and 1.7% of NPV
However, Block 2 does not get much impact on increasing well spacing from Block 1. The limited negative effect can be seen from Figure 36 (black circle) with less than 2% decrease in cumulative energy and NPV when Block 1 increases the well spacing in 300 m intervals.

Based on this study, increasing well spacing in one of the neighbours (Block 1) will increase its cumulative energy and NPV due to increases of its lifetime while having negative effect on its neighbour (Block2).

4.3.5 Well-distance to license border

This study based on the sensitivity analysis from Table 13. The NPV for different well distance is shown in Figure 37:

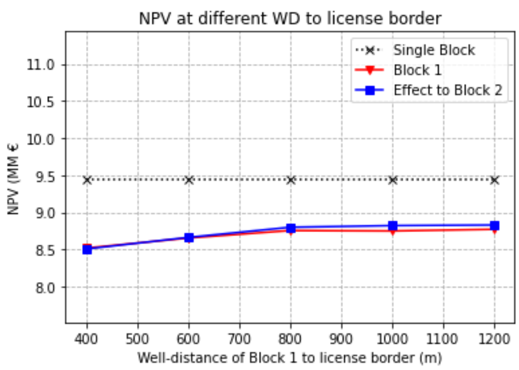

Figure 37. NPV for Well Distance to license border in neighbouring systems

Figure 37 shows the NPV performance at different well distance to license border. In this study, a single block shows almost constant values in NPV as it is not influenced by any license.

In the neighbouring system, the NPV line between Block 1 and Block 2 are overlaying to each other due to the thermal interference in the system. That means both of these blocks produce the same amount of energy with the same lifetime. In Block 1 and Block 2, every 200 m variation in well distance could influence the NPV by up to 1.5%. As the distance to the license border increases, the NPV is getting closer to the NPV reference value (single block) due to the minimisation of thermal interference.

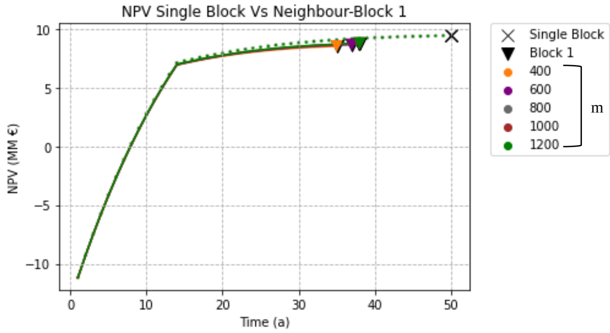

Figure 38. Time evolution of the NPV over the lifetime for Well Distance to Border. Comparison between Single Block (dotted lines) and Block 1 (solid lines) in various well distance to border (m). In neighbouring system, Block 1 and Block 2 have the same result

Figure 38 shows NPV versus time with respect to well distance to license border. First, 400 m distance to the border is sufficient to obtain 35 years of lifetime and the NPV of € 8.52 MM. If the distance to the border increases to 600 m, the lifetime will increase to 37 years with € 8.65 MM of NPV. The lifetime stands at 38 years when the distance to the border increases to above 800 m hence NPV increase to € 8.75 MM. It means that NPV in this sensitivity parameter is strongly related to the production lifetime.

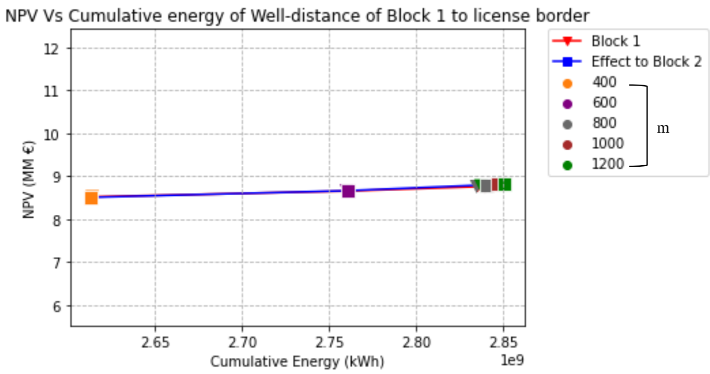

Figure 39. NPV vs. Cumulative energy when well distance to border is changing in Block 1. The cross-black dot shows single block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the well distance to border variation in Block 1.

Figure 39 demonstrates that the linear relationship between cumulative energy and NPV for different well distances to the border. This linear relationship can be described as follows:

$$L\ (WDL) = 1E\text{-}09x + 5.4895$$

where L indicates lifetime in years. WDL shows the Well distance to license border in meter unit and CE indicates cumulative energy in kWh. The positive sign indicates that increasing well distance to license border will increase cumulative energy and the NPV linearly but by a small value. We can obtain up to 2% differences for each 200 m increase of well distance to the border.

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Based on this study, by increasing well distance to the border, NPV will increase since it has a strong relation to lifetime and produced cumulative energy. However, it should be noted that no other neighbours to this licence where considered in this example.

4.3.6 Permeability

This study is based on the sensitivity analysis from Table 14. The NPV for different well spacing is shown in figure 38:

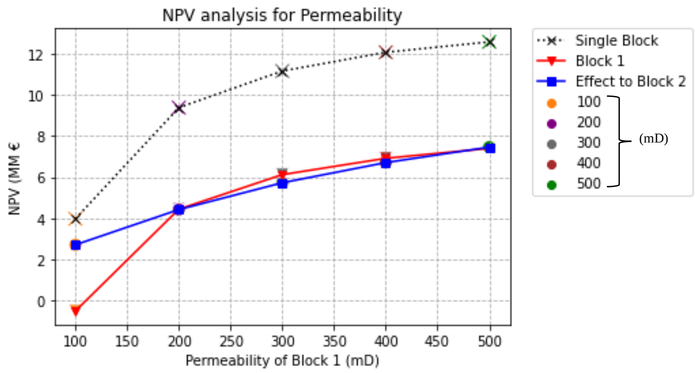

Figure 40. NPV for different permeability in neighbouring systems

Figure 40 shows the NPV performance at different permeabilities of Block 1. The increase of permeability positively affects all systems and all blocks in the neighbouring system. It means that the bigger permeability the higher the NPV. Also, based on this figure, the NPV in the neighbouring system shows a high sensitivity to permeability changes. The difference between NPV in a single block and Block 1 (Neighbouring Block) is more than 50%.

For a permeability of 200 mD to 500 mD in a single block, permeability could influence the NPV up to 31% for each 100 mD increase. Compare to the neighbouring system in Block 1, permeability changes only lead to an increase of NPV of up to 17% for every 100 mD in permeability increase.

In this study, having a neighbouring block with bigger permeability can bring positive results to the adjacent block. For example, when Block 2 has 200 mD permeability and its neighbour (Block 1) has 300 mD permeability, Block 2 will receive a benefit in NPV as a neighbour of Block 1, which results in the increase of NPV from € 3.4 MM to € 4.6 MM.

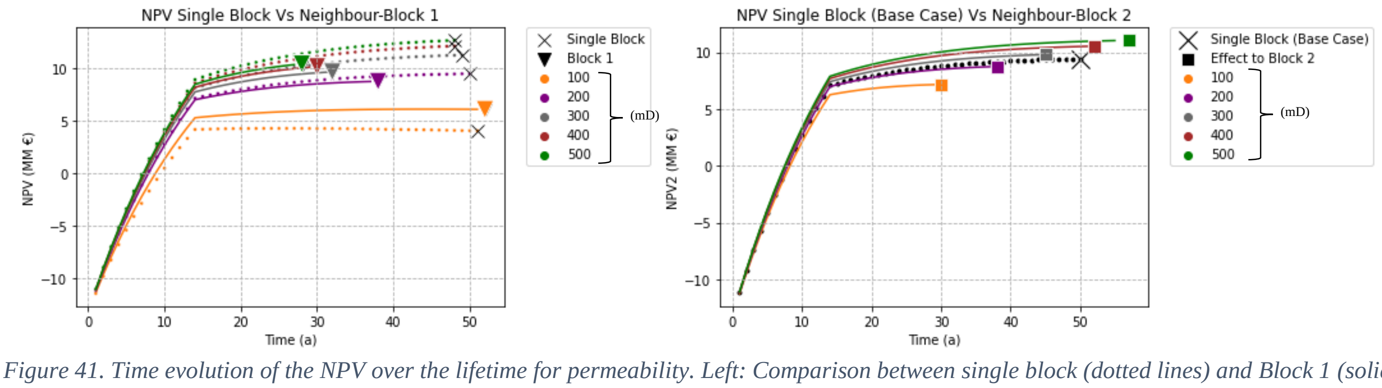

Figure 41. Time evolution of the NPV over the lifetime for permeability. Left: Comparison between single block (dotted lines) and Block 1 (solid lines) for various permeabilities (mD). Right: Comparison between single block base case (dotted lines) and Block 2 (Solid lines) with permeability=200 mD, but Block 2 was influenced by permeability changes of Block 1

Figure 41-left shows increasing permeability will increase the NPV but reduce the lifetime. In a single block, the lifetime is slightly influenced by the permeability value, but the NPV shows more sensitivity when the

permeability is getting bigger. In Block 1 of the neighbouring system, a decrease of lifetime appears, and this also leads to the decrease in NPV of Block 1. This is the reason why the differences between single block and Block 1 (neighbouring block) is more obvious in Figure 40).

Figure 41-right, a single block base case with permeability of 200 mD was used as a reference. At the same permeability as a reference, Block 2 with 200 mD has 70% lower NPV. For every 100 mD permeability increases in the neighbouring block, the NPV of Block 2 increases and approaches the NPV reference (single block base case).

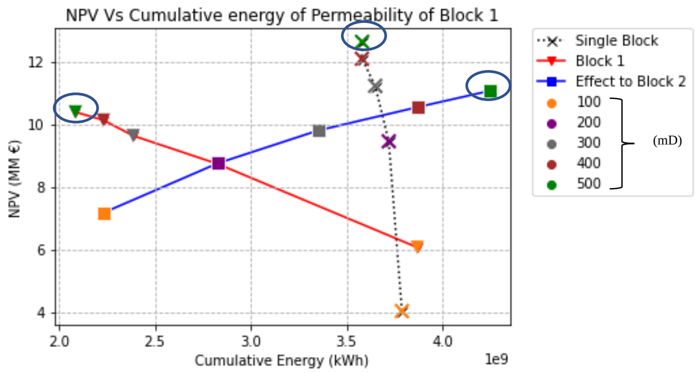

Figure 42. NPV vs. Cumulative energy when permeability is changing in Block 1. The cross-black dot shows Single Block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the permeability variation in Block 1.

Figure 42 shows that increased permeability will increase NPV but might decrease the amount of energy as a consequence. This can be seen in two different systems: Single block and Neighbouring Block (Block 1). In neighbouring blocks, the effect of permeability changes is enormous. Having bigger permeability will jump the NPV, in contrast, it can drop the amount of energy produced. As an example, with permeability increasing from 200 mD to 300 mD, the NPV of Block 1 increased by 31%, but cumulative energy decreased by 16%. This huge drop of cumulative energy is related to the lifetime, as the reservoir reaches temperature breakthrough quickly after 20 years of production.

In contrast, the neighbouring block (Block 2) will benefit from the permeability increase in Block 1. WIth every 100 mD increase in permeability in Block 1, Block 2 will have more than 15% increase in NPV and cumulative energy due to the lifetime and low pressure drop (as discussed in section 4.2.6).

Based on this study, a bigger permeability does not always improve NPV, as it reduces lifetime, and sometimes cumulative energy and NPV. The neighbour's block might have better cumulative energy and NPV when all the other design parameters are identical. Therefore, in such cases tuning the design parameters to obtain higher NPV and cumulative energy is essential.

4.3.7 Anisotropy of permeability

This study is based on the sensitivity analysis from Table 16. The NPV analysis of the anisotropic permeability ratio is shown in Figure 43:

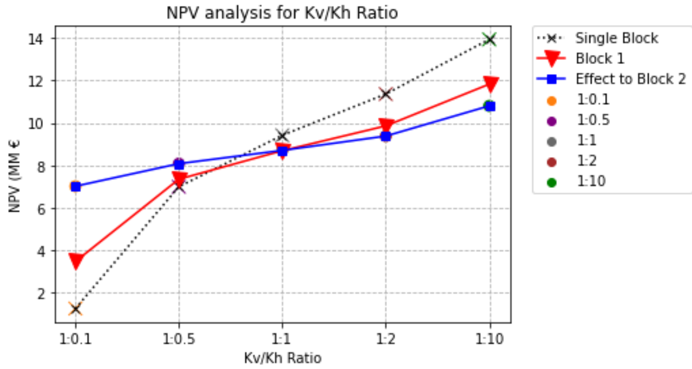

Figure 43. NPV for Well anisotropic permeability ratio in neighbouring systems

Figure 43 shows the NPV performance at different Kx/kyratios (in both blocks). Based on the figure, Kx/ky<1 will result in a higher NPV than Kx / Ky> 1

In the neighbouring system, when Block 1 has Kx/ky<1 and the neighbour has Kx/ky= 1, Block 1 will have a 9% greater NPV. In contrast, at Kx / Ky> 1, Block 1 will have a NPV that is 60% smaller. This means that anisotropic permeability has a strong influence, especially in a large anisotropic permeability ratio.

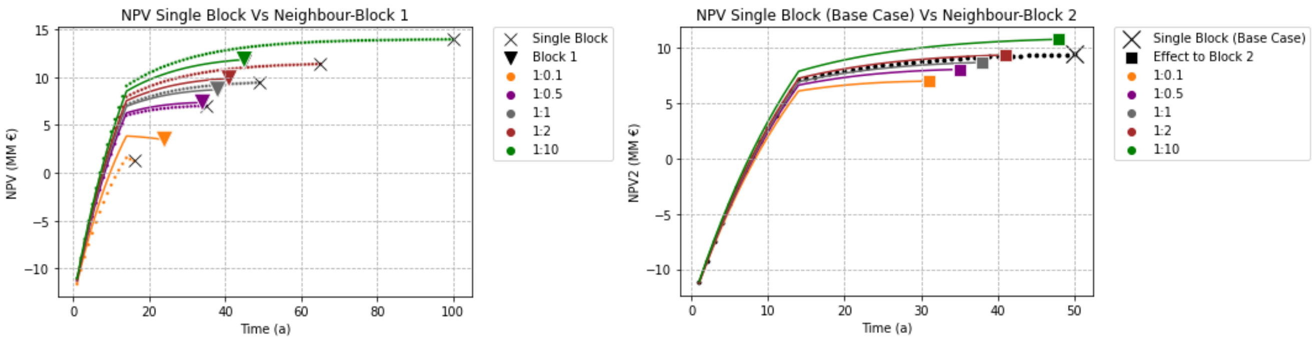

Figure 44. Time evolution of the NPV over the lifetime for Anisotropic Permeability. Left: Comparison between Single Block (dotted lines) and Block 1 (solid lines) in various ratio of anisotropic permeability. Right: Comparison between Single Block base case (dotted lines) and Block 2 (Solid lines) with isotropic permeability ratio kx=ky, but Block 2 was influenced by well spacing changes of Block 1

Figure 44 left shows NPV versus time in term of permeability anisotropy. Overall, the NPV pattern of the single block and Block 1 in the neighbouring block system is quite similar over the year. But the lifetime shows differences, particularly at larger Kx/ky ratio.

The effect of parameters on the neighbouring block (Block 2) has been studied in Figure 44-right. A single block base case with Kx/ky= 1 was used as reference (dotted black line). At the same Kx/kypermeability as this reference, Block 2 in the neighbouring system has an 8% lower NPV. Moreover, a 2-fold increase and decrease in the anisotropy permeability ratio (Kx/ky) for Block 1 results in an increase / decrease in NPV of 7.4% in Block 2.In addition, an increase / decrease in the ratio of Block 1 by 10 times will influence Block 2's NPV by 14%. .

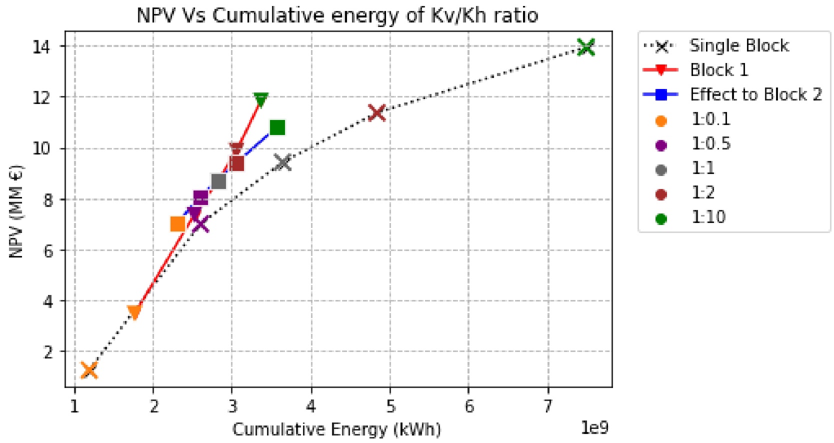

Figure 45. NPV vs. Cumulative energy when anisotropic permeability is changing in Block 1. The cross-black dot shows Single Block, The triangled-red line shows Block 1 and the squared blue line shows Block 2. The colours of shapes indicate the anisotropic permeability ratio variation in Block 1.

Figure 45 displays the NPV and cumulative energy for a single block, Block 1, and the effect on Block 2. The single block shows a very optimistic result with Kx/ky < 1

In the neighbouring system, for Block 1 itself, decreasing the anisotropy permeability of Kx/ky<1 will increase the NPV and the cumulative energy results. For Block 2, it has a slightly positive effect as a decrease in the anisotropy permeability from its neighbour. The impact is less than 1.7% for any decrease in anisotropy permeability in Block 1.

5 Discussion

The results of this study show that every parameter analysed here has a unique effect on the measurement control (NPV, Cumulative energy and Lifetime). For direct comparison, all results from the previous chapter are plotted together to observe the most influential parameter.

Block 1

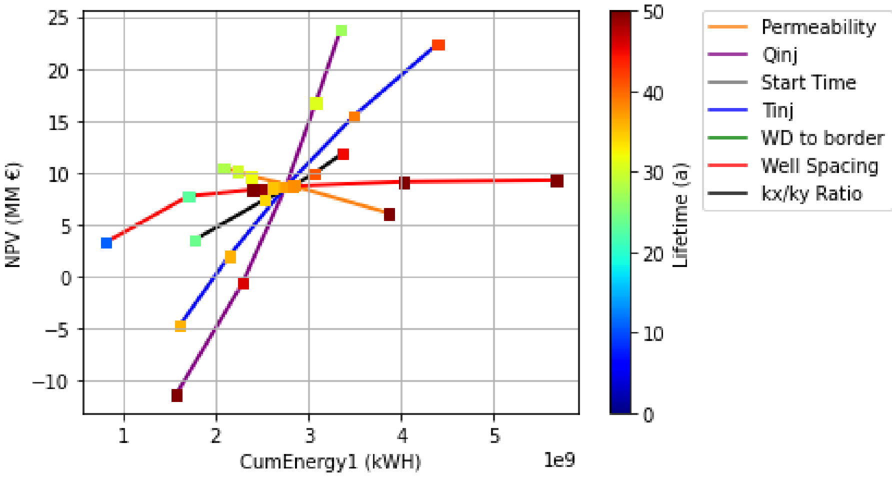

Figure 46. The effect of seven sensitivity parameters to NPV (Y-axis), cumulative energy (X-axis) and lifetime (colored squares) for Block 1

Table 17. Shows the percentage variation of each key indicator parameter (NPV, Cumulative energy and Lifetime) by variation of each parameter for Block 1

	NPV	Cumulative Energy	Lifetime
Start time	0.0086	0.059	0.32
Injection/Production Flow rate	1	0.36	0.55
Injection Temperature	0.76	0.57	0.09
Well Spacing	0.17	1	1
Well Distance to License Border	0.0071	0.046	0.046
Permeability	0.13	0.30	0.30
Anisotropy Permeability	0.23	0.33	0.32

Figure 46 shows that the most influential parameter is Injection/Production Flow rate (Q_{inj}). Q_{inj} (purple line) has a very strong influence on all three measurements controls, this can be seen from the steeper line between the cumulative energy and the NPV. Also, the rapid change in the colour of the square marks indicates that this parameter is sensitive to lifetime. This means that every change of flow rate in one neighbour, will affect a lot its NPV, cumulative energy and lifetime. Based on studies in section 4.2.2 and 4.3.2, the lifetime has an inverse relation with NPV and cumulative energy while flow rate varies in one neighbour. This means increasing flow rate could increase the NPV and cumulative energy, but it can lower the lifetime as a consequence.

The 2nd most influential parameter is Injection Temperature (T_{inj}), Injection temperature has strong influence on the cumulative energy and NPV with the steep line as an indicator. Variation of injection temperature in one neighbour, is less influential on its lifetime as we can see on Figure 46 with the less intense colour of the square mark. Based on sections 4.2.3 and 4.3.3, it can be concluded that is your neighbour using higher injection temperature, you can inject colder fluid back to your system. This not only increase the cumulative energy and NPV, but also avoid the reduction of lifetime (due to injection of colder temperatures). This is because of the thermal interference phenomena between the neighbouring blocks will distribute the drawback from reducing injection temperature (lifetime reduction) to both blocks. As injection of colder water than your neighbour might look interesting and profitable it might also come with several problems. Colder injection temperature will increase the density and viscosity of the water itself. It might burden the pump to deliver the water. Thus, it will increase the minimum required pressure to pumping the water. Secondly, injecting colder temperatures for long periods of time might develop well damage due to precipitation in the future (Mclean & Zarrouk, 2015). This will reflect long term production efficiency.

The 3rd influential parameter is well spacing. It can be seen that however its size, compare to other parameters, has negligible effect on the NPV of the system but has major effect on the produced energy and life time of the system. Based on sections 4.2.4 and 4.3.4, the increasing well spacing could provide better cumulative energy and lifetime, but it does not guarantee to provide higher NPV. By comparing it to other parameters, this minor improvement of NPV might not be interesting for many operators. In addition, increasing of well spacing will also increase the risk of geological uncertainty, such as a temperature difference of several degrees (Bonté et al., 2012).

Affected Neighbour Block (Block 2)

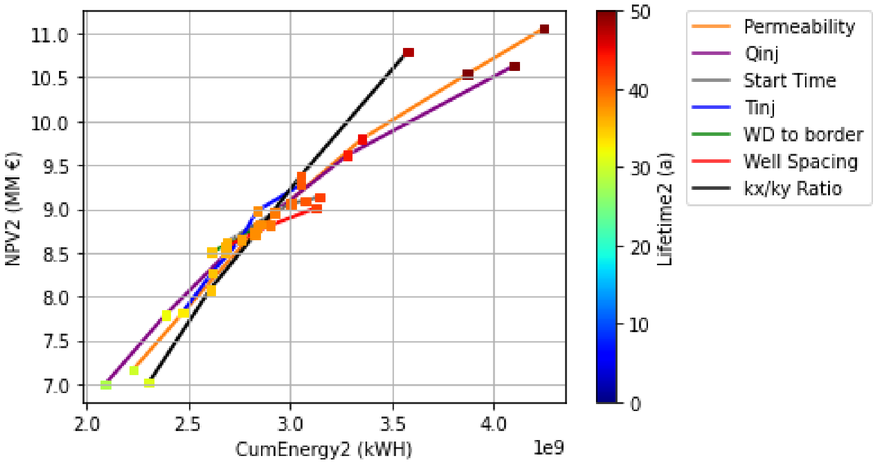

Figure 47. The effect of seven parameters on NPV (Y-axis), cumulative energy (X-axis) and lifetime (square color) to neighbouring block (Block 2))

Table 18. Shows the percentage variation (in decimal) of each key indicator parameter (NPV, Cumulative energy and Lifetime) by variation of each parameter to neighbouring block (Block 2)

	NPV	Cumulative Energy	Lifetime
Start time	0.11	0.16	0.15
Injection/Production Flow rate	0.82	0.71	0.71
Injection Temperature	0.33	0.20	0.21
Well Spacing	0.11	0.15	0.15
Well Distance to License Border	0.073	0.084	0.079
Permeability	1	1	1
Anisotropy Permeability	0.85	0.45	0.44

Looking to Figure 47, it can be seen that the major parameters that can effect a neighbour, Block 2 are permeability, Kx/ky ratio and flow rate of it neighbour (Block 1). Two out of the 3 of these parameters are physics controlled and related to permeability.

Figure 47 shows that parameter affecting interference with the neighbour the most is permeability. The permeability line (orange line) has steeper increase in NPV, longer stretch in cumulative energy, and higher intensity colour of the square marks. This means that every change in permeability from Block 1 has a great influence on the neighbouring block. By looking to sections 4.2.6 and 4.3.6, increasing permeability in Block 1 will increase the NPV, cumulative energy and lifetime of Block 2. So, if your neighbour has higher geological advantages (in terms of permeability) it will also benefit you in long term.

The 2nd influential parameter to neighbour is injection/production flow rate (Q_{inj}). The purple line in Figure 47 indicates that any changes in flowrate from Block 1 will have a major impact on the NPV, cumulative energy and lifetime of its neighbour (Block 2). By looking to section 4.2.2 and 4.3.2, every increase in Q_{inj} in Block 1, the amount of cumulative energy as well as lifetime will drop in Block 2. These two factors resulting in the decreasing the NPV gradually. Therefore, this parameter should be controlled by the regulator to maintain the fairness of production in an area

The 3rd most influential parameter for interference with the neighbour is the permeability ratio Kx/ky. A linearly increasing black line in Figure 47 indicates the high effect of variation of Kx/ky of the Block 1 on its neighbour Block 2. Every step change we chose in the Kx/ky ratio influences the NPV and cumulative energy by around 1.7%. Moreover, high intensity in the colour of square marks indicates that this parameter could affect the lifetime of neighbouring block. By looking to section 4.2.7 and 4.3.6, we found that decreasing Kx/ky from Block 1, will provide the benefit of NPV, cumulative energy and lifetime to its neighbour, Block 2. As Kx/ky ratio decrease the possibility of thermal interference between the 2 blocks minimise and hence their effect on each other become minimum.

6 Conclusion

In this thesis the thermal influence of 2 geothermal neighbouring licenses was studied. A sensitivity study was carried out on some operational (injection temperature, flow rate, well spacing, well distance to the license border, and well positioning) and physical parameters (permeability and its anisotropy as Kx/ky ratio) of the systems. The effects of variation of parameters were evaluated in both neighbours in terms of system's lifetime, cumulative produced energy, and NPV.
To generate a numerical model capable of describing and predicting the effect of thermal interference the software package COMSOL Multiphysics 5.4 was used. The physics of fluid flow and heat transfer in porous media was applied to the reservoir model, and the finite element method is used to approximate the solution of these equations.

The conclusions of this thesis are explained by answering the research questions.

What is the most influential parameter that affects the profitability of a project without hindering the neighbour?
Based on all sensitivity analyses, injection temperature and well spacing could be allowed to increase the profitability of a block. In our study, we found that reducing the injection temperature, in one license area (Block 1), by 10°C can improve its NPV and cumulative energy by up to 20%. While these variations won't hinder the neighbour as NPV and cumulative energy drops only by 1% (depending on the temperature reduction).

Another parameter that can be optimized is the well spacing. Increasing well spacing can increase NPV, cumulative energy and lifetime, however the effect on NPV is less pronounced. Based on our model, the best is that 2 neighbours have more or less similar well spacing, otherwise the one with shorter well spacing can end up with lower NPV, cumulative energy and lifetime.

What parameters should be controlled to avoid thermal interference between neighbours?
This study found that the injection / production flow rate is the most influential parameter that must be considered. In addition, anisotropy and varying permeability (in each license area) can affect the thermal interference between the neighbours. As a consequence, the thermal interference between neighbours will affect their NPV, cumulative produced energy and lifetime. Hence these parameters should be considered and designed carefully in neighbouring licenses.

Based on our study about the distance of well to the borders, having a longer or a shorter well distance to the border will affect the NPV, Cumulative energy and Lifetime of both neighbours equally (when all other parameters are the same). However, it must be noted that as one neighbour places the wells closer to the common license border and hence closer to the neighbouring block, thermal interference will be massive and heat (energy) from the neighbouring block may be used, which must be avoided. It is important that each neighbour produce heat from their own license and don't cross the borders of their license areas. Therefore, this is also an important design parameter to consider and adjust. Similar arguments can be applied for the variation of starting time between the neighbours.

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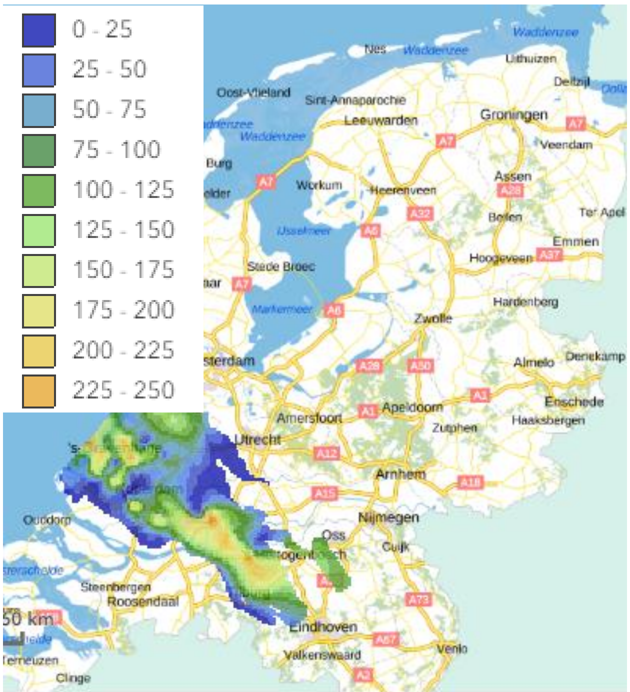
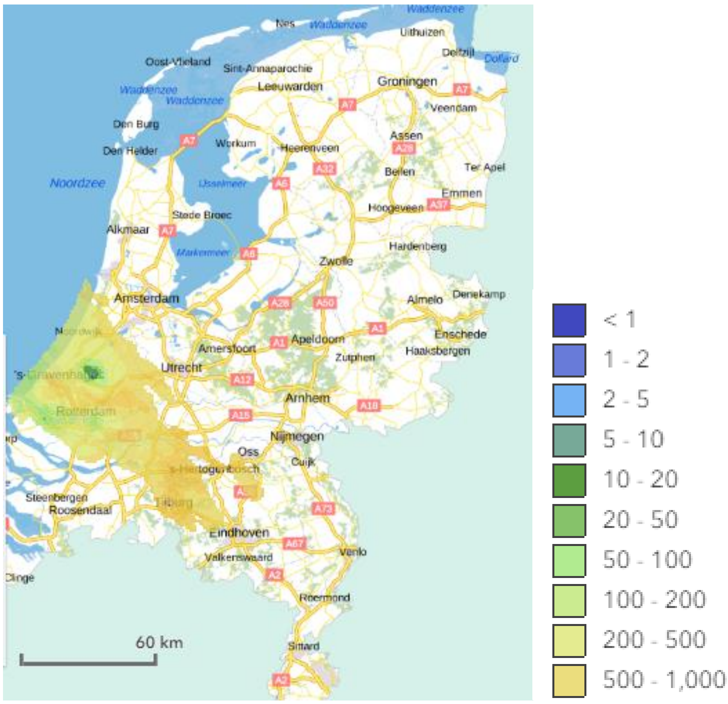
Appendix 1.Aquifer thickness (P50) of Upper Jurassic, aquifer: Delft Sandstone & Alblasserdam (SLDND & SLDNA) (ThermoGIS, n.d.)

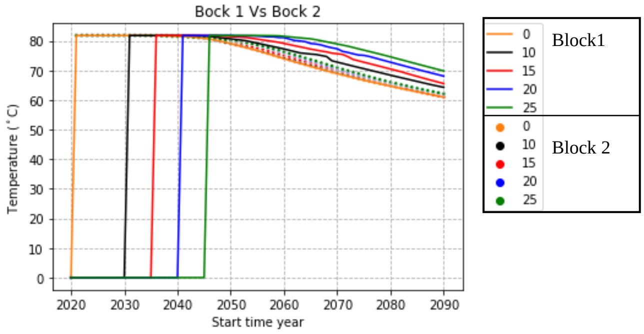


Appendix 2. Permeability distribution (P50) of Upper Jurassic, aquifer: Delft Sandstone & Alblasserdam (SLDND & SLDNA)(ThermoGIS, n.d.)

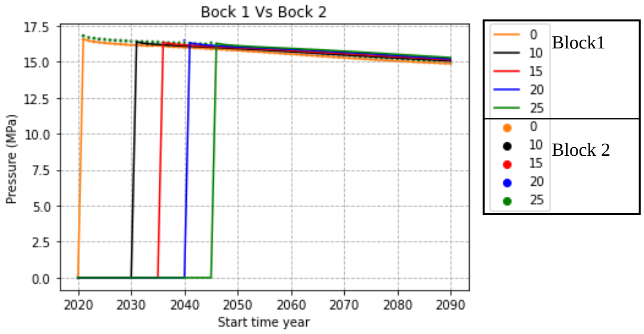


Appendix A. Starting Time

Temperature



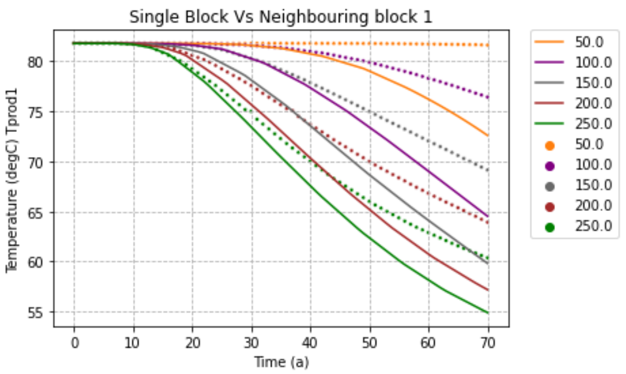
Pressure

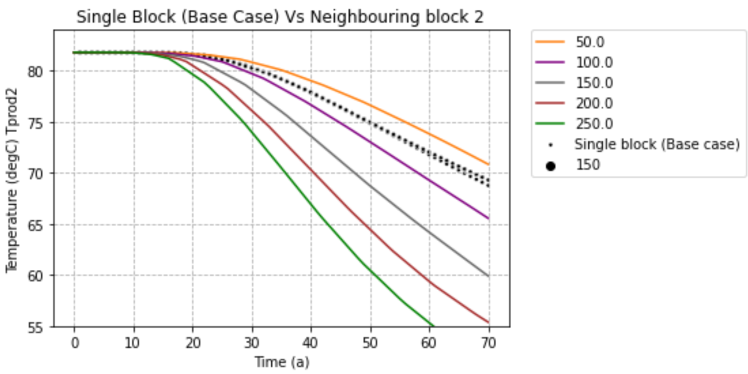


Appendix B. Injection/Production Flow rate

Temperature

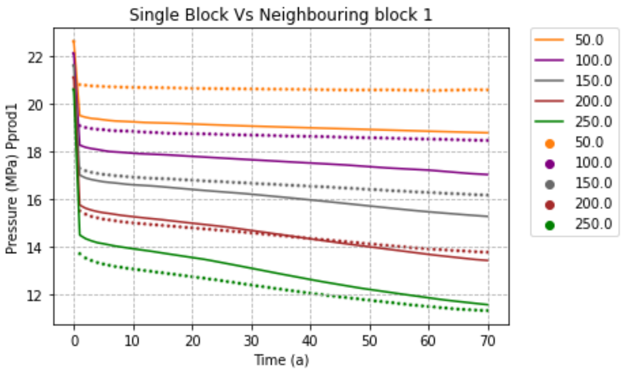
- Is single block

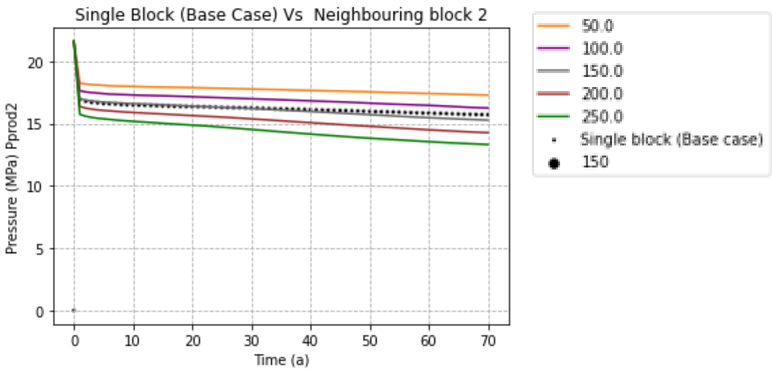




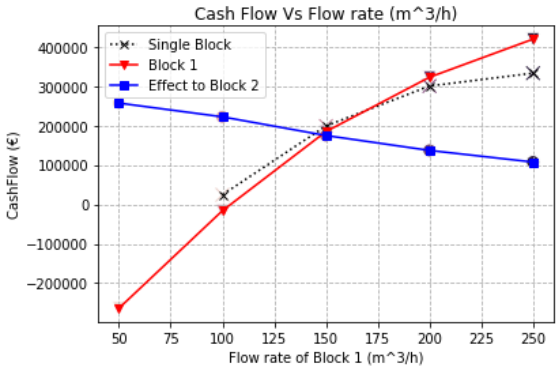
Pressure

- Is single block

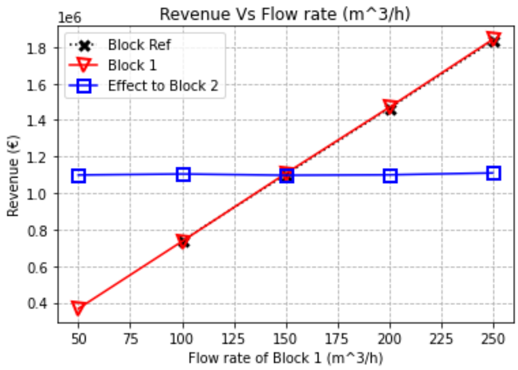


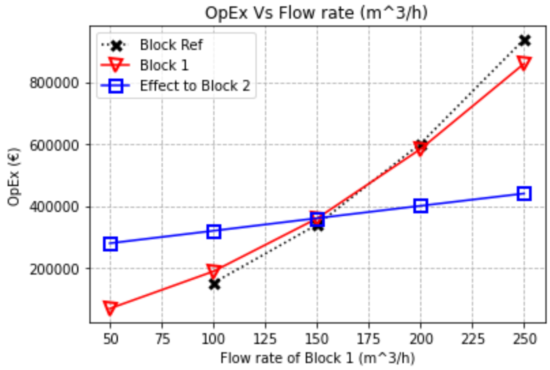


Cash Flow



Revenue – Opex

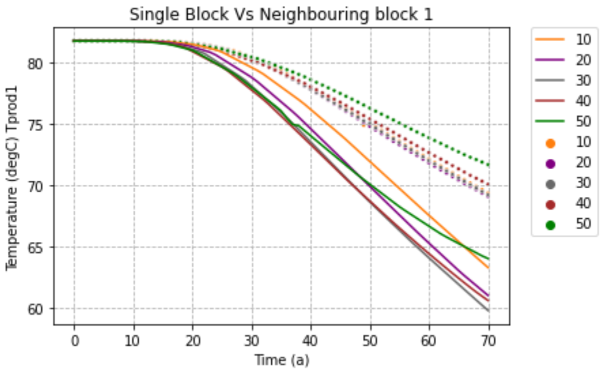


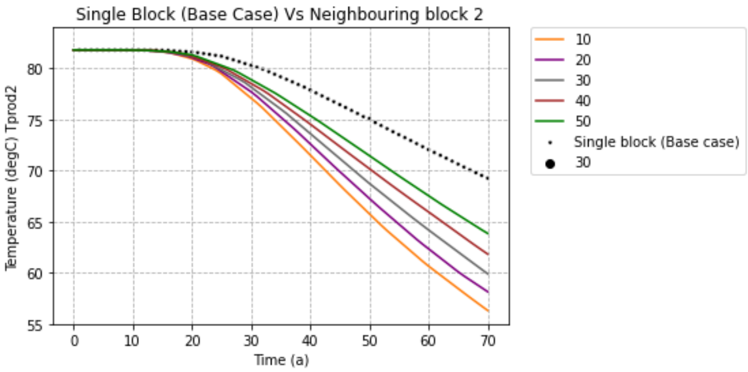


Appendix C. Injection Temperature

Temperature

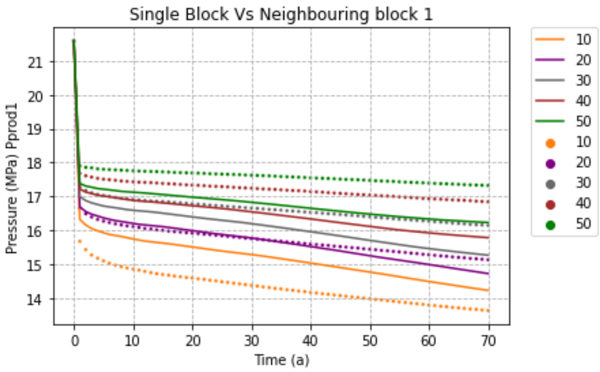
- Is single block

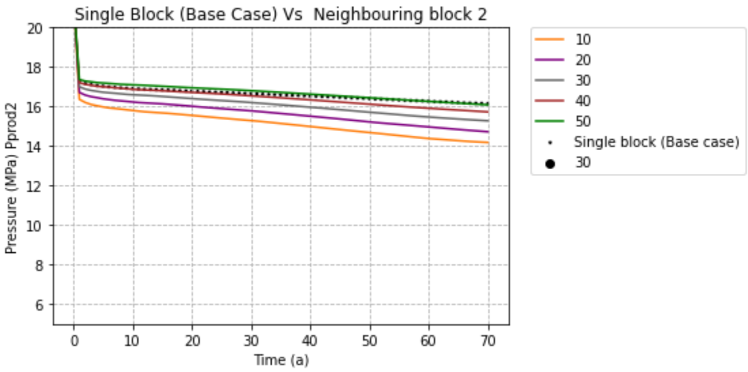




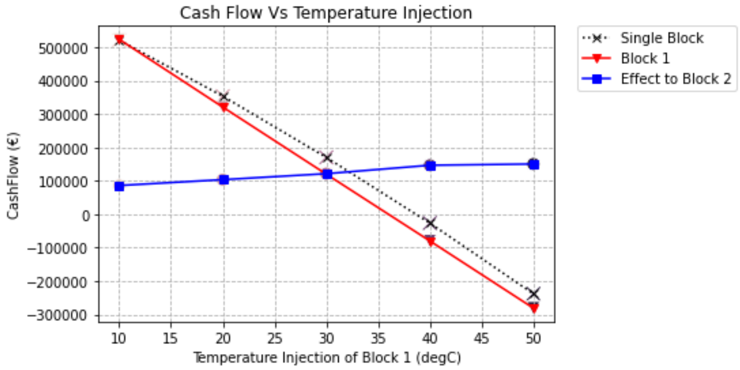
Pressure

- Is single block

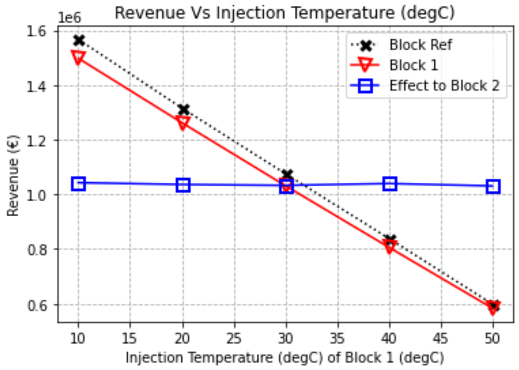


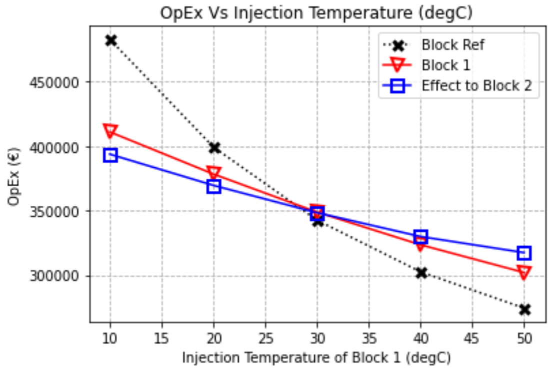


Cash Flow



Revenue – Opex

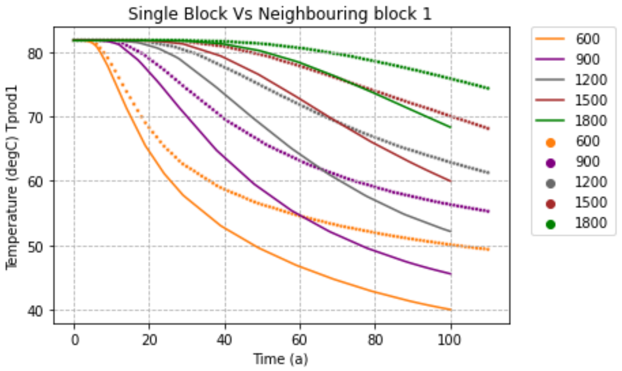


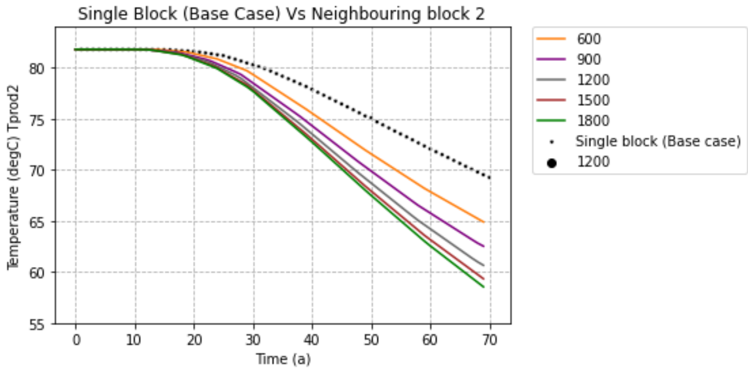


Appendix D. Well Spacing

<u>Temperature</u>

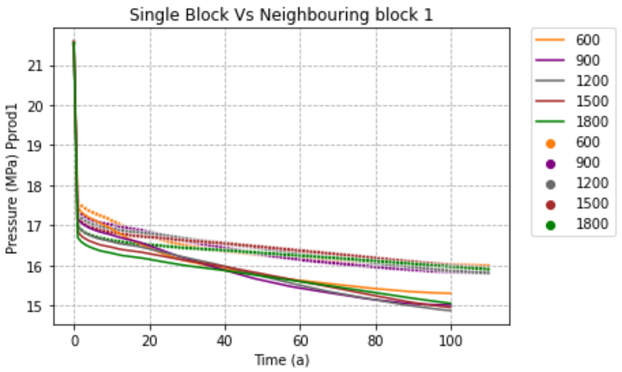
- Is single block

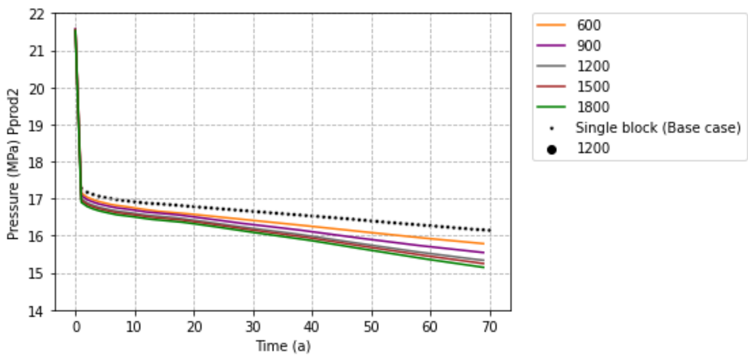




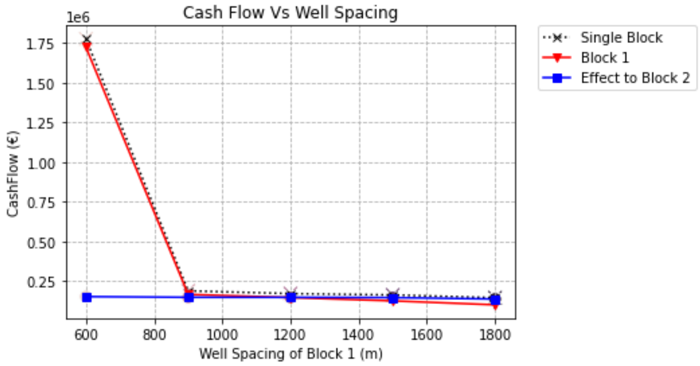
<u>Pressure</u>

- Is single block

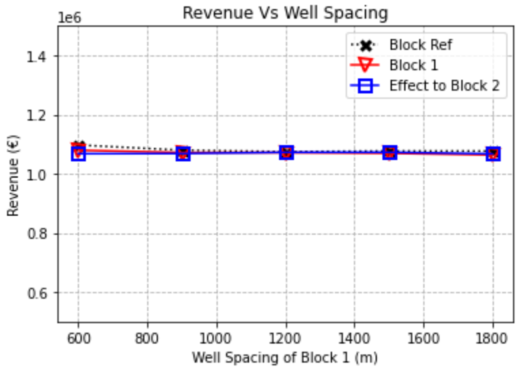


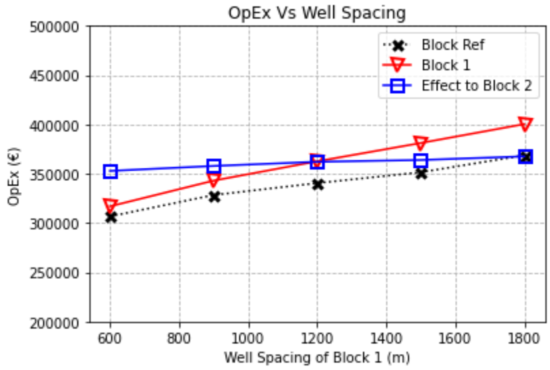


Cash Flow



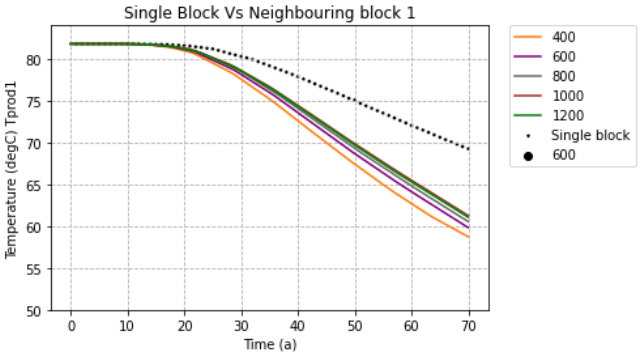
Revenue – Opex

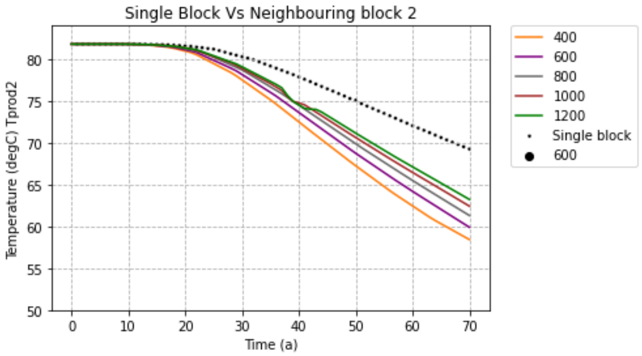




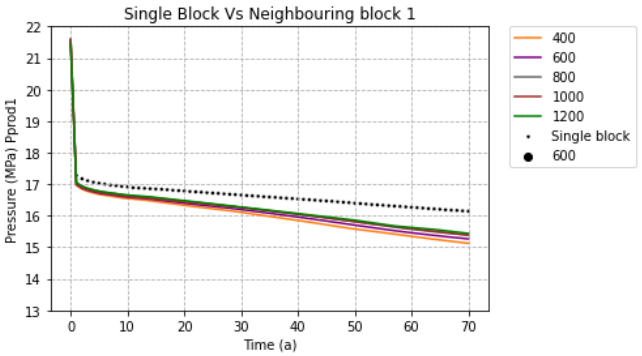
Appendix E. Well-Distance to License border

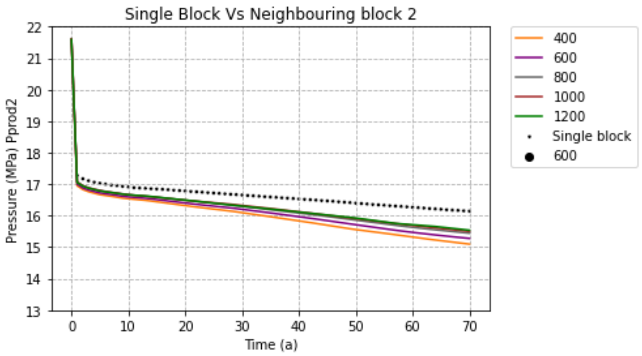
Temperature



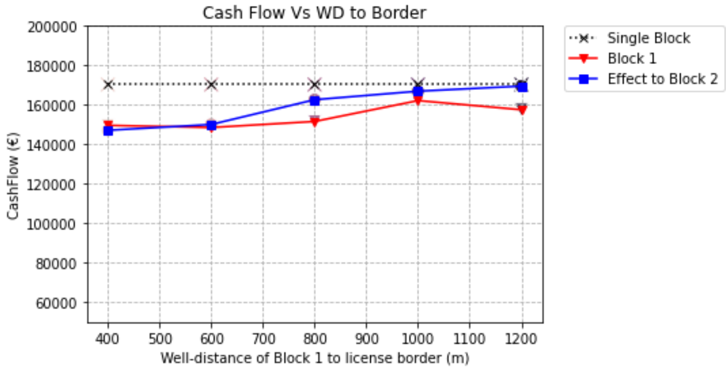


Pressure

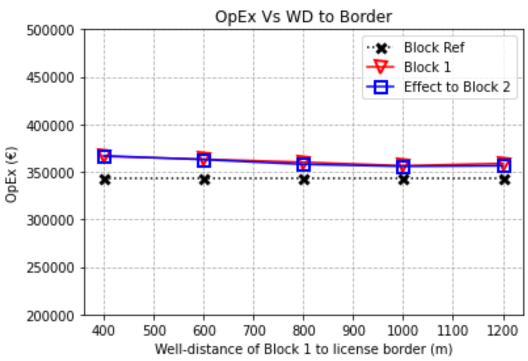


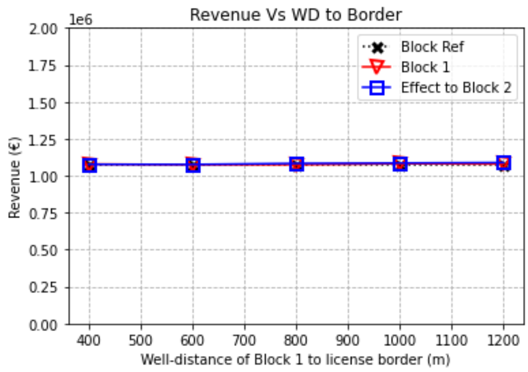


Cash Flow



Revenue – Opex

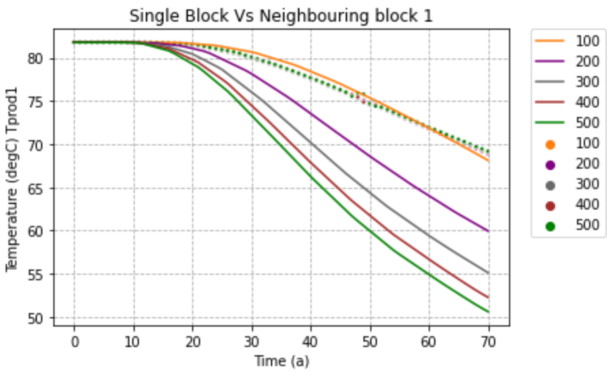


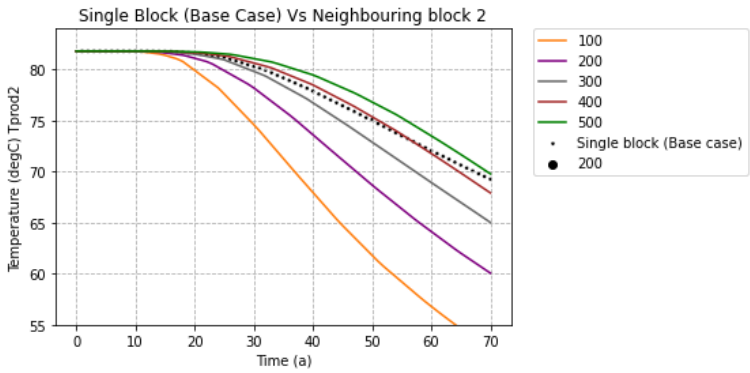


Appendix F. Permeability

Temperature

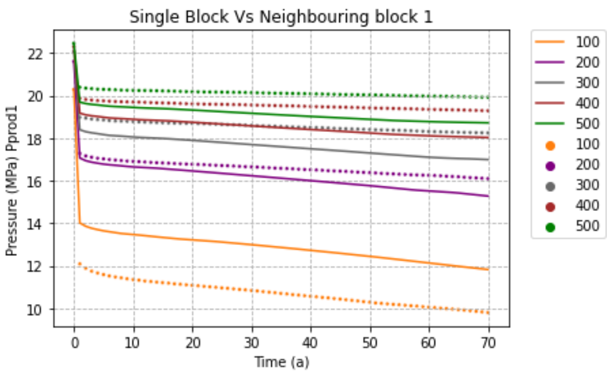
- Is single block

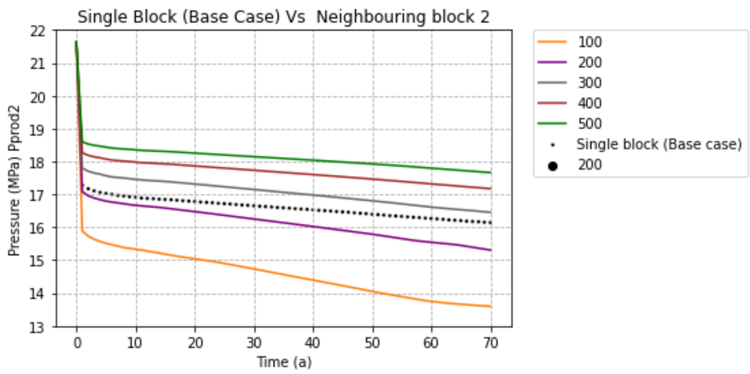




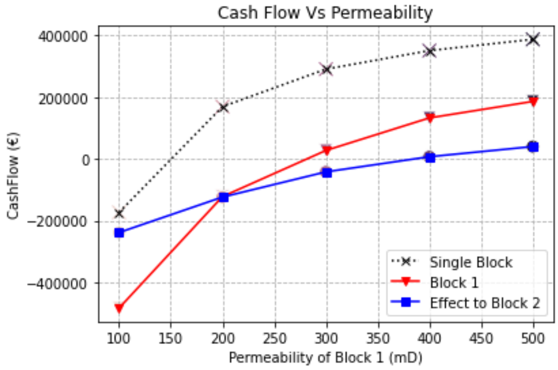
Pressure

- Is single block

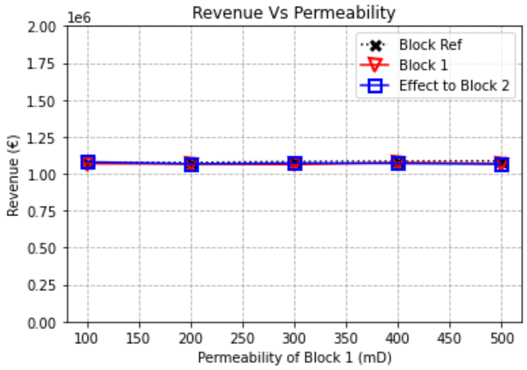


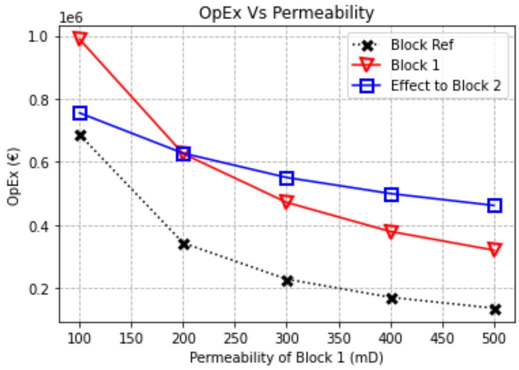


Cash Flow



Revenue – Opex

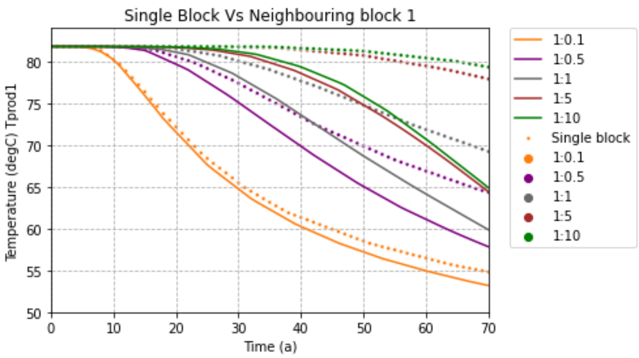


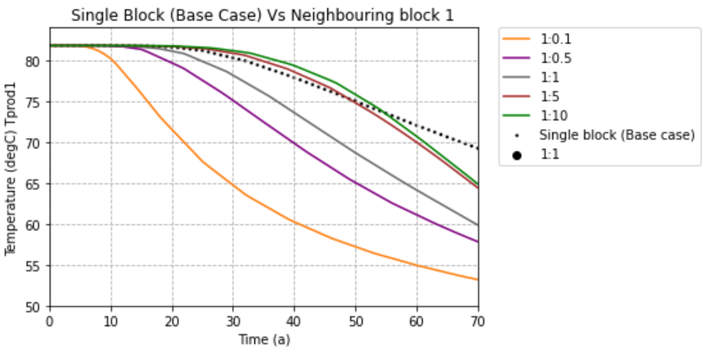


Appendix G. Anisotropy

Temperature

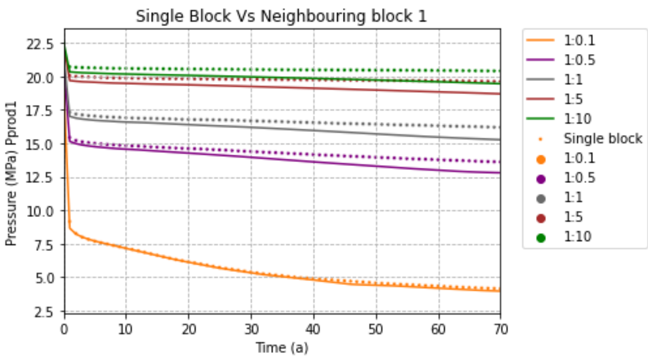
- Is single block

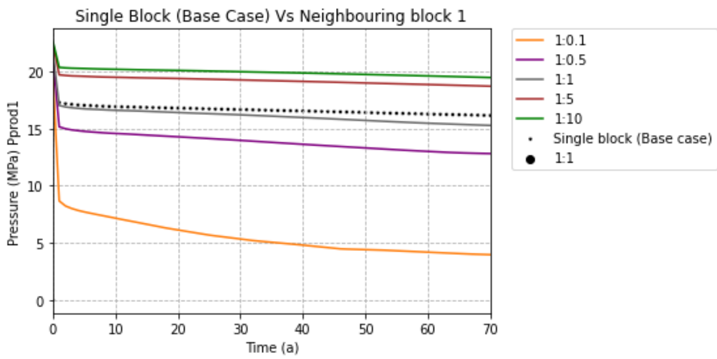




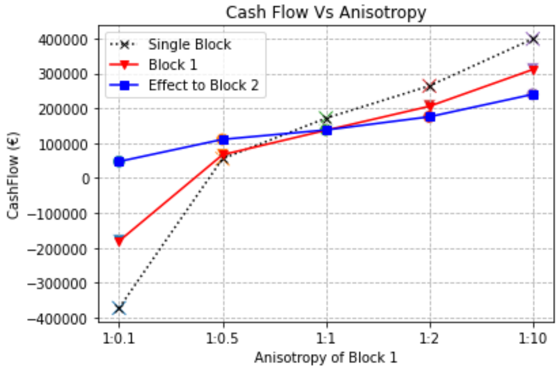
Pressure

- Is single block





Cash Flow



Revenue – Opex