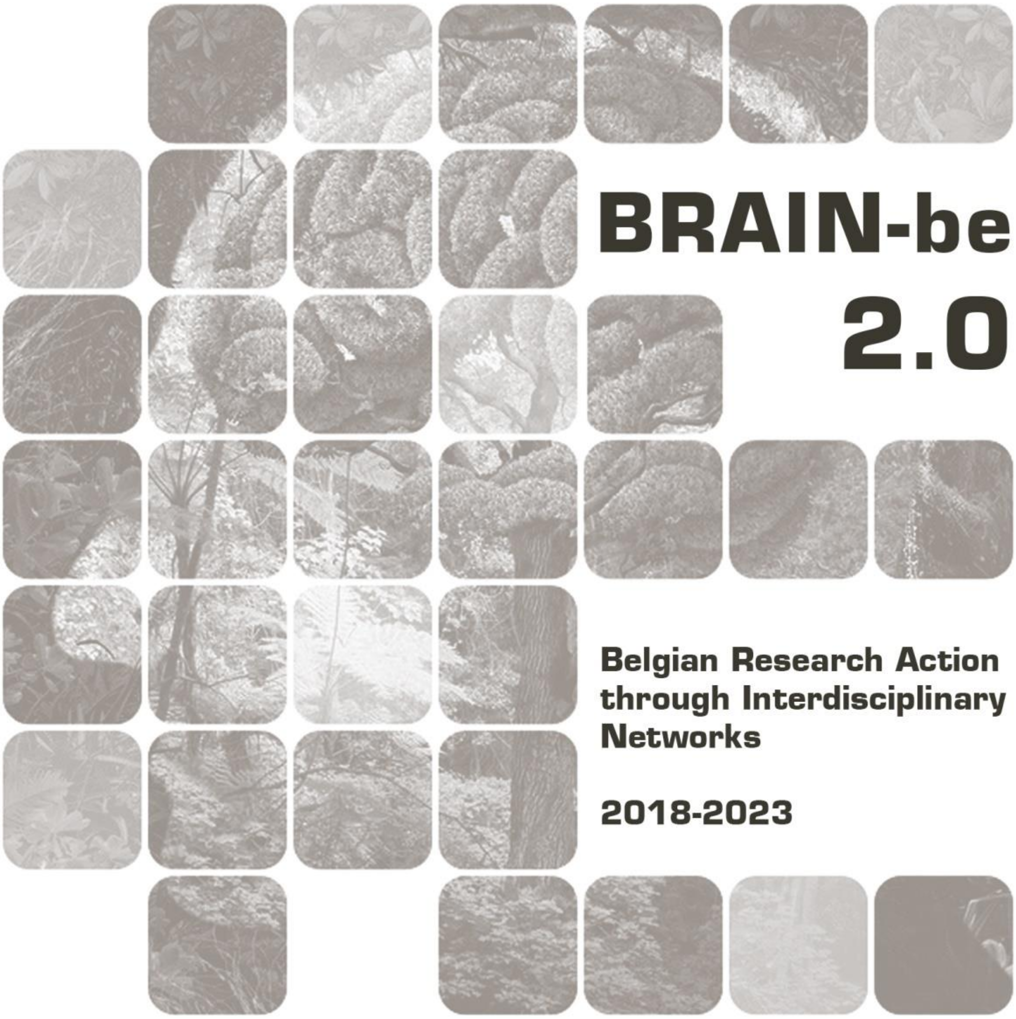

DESIGNATE

Decision Support under Uncertainty for Geothermal Applications

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Pillar 1: Challenges and knowledge of the living and non-living world

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NETWORK PROJECT

DESIGNATE

Decision Support under Uncertainty for Geothermal Applications

Contract - B2/191/P1/DESIGNATE

FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT

Context

In order to meet climate goals and provide energy security, geothermal energy can play an important part in Belgium's energy production portfolio. A major part of the final energy demand is heat, and deep geothermal systems provide thermal energy that can be used directly as a heat source for district heating networks and industrial applications.

Working with deep subsurface data introduces large uncertainties, leading to high financial risks. Considering these risks in decision making at project or policy level is essential but not straightforward. Especially linking numerical geothermal reservoir simulations to economic and environmental assessments, while taking into account uncertainties and flexibilities is challenging.

Objectives

The goal of the DESIGNATE project is to create interdisciplinary tools for integrated forecasts under uncertainty for deep geothermal systems in Belgium, including applications in abandoned mines. More specifically, the objectives are to:

- Develop techno-economic assessment (TEA) tools that incorporate geological uncertainty and are based on real options analysis (ROA) and the PSS simulator.
- Develop a framework for dynamic life cycle assessments (LCA) considering timing of emissions and their effects over time.
- Develop analytical or other fast reservoir simulations that can be directly connected or integrated in the TEAs and LCAs.
- Create a first basis for analysing subsurface interference effects of deep geothermal projects.
- Demonstrate the application of the developed tools and workflows to several case studies within Belgium.

Methods

Five case studies are selected: the Balmatt doublet project in Mol developed by Vito, the Turnhout-NW doublet project which is in early development by the GEO@Turnhout consortium, the hypothetical Deep Mons doublet project, a hypothetical single well application in the Cretaceous in the Flemish Region, and a hypothetical heat-cold storage application in the former Péronnes-lez-Binche coal mines. Geological uncertainties are first characterized, and decision trees are built to map flexibility options.

In order to integrate reservoir simulations in Monte Carlo-based economic and environmental analyses, fast simulation time is needed. An analytical solution for a geothermal doublet is developed and calibrated for the Balmatt project. Lookup tables without and with interpolation are developed for the single well and Deep Mons project, respectively. An operational solution for the mines case is not yet finalized.

After a review of available life cycle assessments of deep geothermal projects, a dynamic LCA method is developed, which takes into account changes in the life cycle inventory and the temporal evolution of the impacts. In parallel, Real Options is applied in a techno-economic assessment of deep geothermal to integrate uncertainty and flexibility in economic analyses. In a final step, the environmental impact is integrated as decision criterion in the ROA-TEA.

The PSS simulator, an ROA-based TEA forecasting simulator for CO_2-storage projects, is adapted for geothermal applications. It is made modular for multiple geothermal applications, connecting with the various reservoir simulation tools that are developed. In particular, realistic project decisions and geological uncertainty evolution are integrated. First developments are also made to model subsurface interferences and surface heat transport.

Simulations are run for several scenarios. These include variations in energy price evolution, decision flexibility, support measures and operation variation.

Results and conclusions

Several interdisciplinary tools and workflows are developed for assisting decision makers in planning deep geothermal projects. Their application is demonstrated with first analyses for multiple case studies and scenarios in Belgium.

The consideration of flexibility to counter investment risk with Real Options Analysis is key when analysing economic performance of projects with large up-front investments and uncertainties such as deep geothermal projects. Similarly, dynamic life cycle analysis and its integration in ROA decision making has major benefits over the industry-standard static LCA for accurately assessing environmental impact and providing decision support. Deep geothermal energy can have an important environmental benefit over alternative heating sources (natural gas or heat pumps), with well construction and pumping operation as first targets for further impact reduction. Including risk and flexibility is also important in designing support measures, to target the correct project phase at an appropriate level.

Geological conditions, especially flow-defining parameters, largely dictate project success regarding economic and environmental impact, emphasizing the location-specific nature of the technology. Considering the current state of knowledge on the deep subsurface in Belgium, a government-led general exploration of the deep subsurface could de-risk the investment. Support measures need to be designed for attaining certain policy and business goals. Of the support measures that were analysed, investment subsidy is identified as a good balance between increasing project value, risk reduction and efficiency.

An optimised design and planning of the full geothermal, including supply, transport and use of heat, has a major influence on the business case. Matching production with demand and increasing operational time by overcoming seasonal changes in demand are key.

An integrated, interdisciplinary analysis is essential to consider all the different-natured impacts that define project decisions, development, operation and success. The developed methods can be expanded even further to achieve a fully a holistic overview by introducing for example the social context.

Keywords

Deep geothermal, mine geothermal, techno-economic assessment, life cycle assessment, analytical reservoir simulation, uncertainty, real options analysis

DELIVERABLES OVERVIEW

D1.1 Progress reports (report)

D1.2 Final report (this report)
+ D1.5 Recommendations for investors and policy makers (this report)

D1.3 Follow-up committee meetings report (report)

D1.4 Communication & dissemination report (report)

D2.1 Reservoir simulation data for Flemish geothermal resources (report)

D2.2 Reservoir simulation data for Walloon geothermal resources (report)

D2.3 Techno-economic database (report/paper)
+ D5.1 Single model results (report/paper)
+ D5.3 Environmental-economic impact (report/paper)

D3.1 Market and policy data (report)

D3.2 Environmental data (report/paper)

D3.3 Scenario definitions (report)

D4.1 Geothermal model concepts (report)

D4.2 Analytical reservoir models (software)

D4.3 Single model (software)

D4.4 PSS Geothermal model (software)

D5.2 PSS Geothermal results (report)

1. INTRODUCTION

The increase of sustainable energy production will help reducing the anthropogenic impact on climate and environment. In its Sustainable Development Scenario, the IEA estimates an increase in worldwide renewable energy production by a factor 2.6 in 2030 and 4.5 in 2040 to counter a reduction in fossil energy use (IEA, 2018). While the EU slightly overachieved on its own goal of reaching a 20% share of gross final energy consumption from renewable sources (at 22%), Belgium needed to use the statistical transfer mechanism to compensate its lower share in other EU countries to achieve the 13% national goal. In addition, in 2020 Belgium had the third lowest share of renewable energy consumption in the heating and cooling sector at 8.4% (Eurostat, 2024). The Belgian nuclear electricity production capacity phase-out is delayed, but it is still anticipated to disappear in 2035. Geothermal energy can provide a renewable and continuous source of energy, especially for heating. Shallow, closed-loop systems can provide a secure low-temperature source for heating in combination with heat pumps. Deeper systems can provide thermal energy that can be used as a heat source for district heating networks, industrial applications and even electricity production. The scope of the DESIGNATE project is geothermal applications that extract heat from deep reservoirs or from abandoned mines. Because of the depth, and the adjoining lower level of exploration, uncertainties about deep resources are much larger than for shallow ones. This makes it difficult to assess the energy output of the system before the wells have been drilled. In addition, uncertainty about the geology results in large financial risks related to drilling, completing and operating the wells and the geothermal plant. These uncertainties hinder investments in deep geothermal projects, much more compared to other energy production technologies. It is important to properly cope with the geological uncertainties during the development of a project, starting from its planning phase.

Risk and uncertainties form an inherent part of dealing with deep geothermal systems but dealing with them for making accurate predictions on their role in the Belgian energy portfolio is difficult. While reservoir simulations can provide output potential and techno-economic models can simulate performance and potential business case, it is challenging to match both approaches, especially concerning uncertainties with respect to geology and (future) circumstances at the surface. Considering the potential increase in geothermal energy developments, concerns about the associated environmental impacts grow too (Tomasini-Montenegro et al., 2017). Geothermal energy production leads to direct and indirect environmental impacts over the lifecycle of the energy generation process. To understand to what extent geothermal energy production forms a sustainable solution and in a next step provide support for strategic planning, these environmental impacts need to be assessed taking into account the total life cycle of the project. Here, also, it is important to consider geological uncertainty (Fridriksson et al., 2016).

2. STATE OF THE ART AND OBJECTIVES

Creating a forecast on the economics and environmental impact geothermal projects demands a specific approach. Welkenhuysen & Piessens (2017) have shown that an integrated approach on uncertainty and investment flexibility is valuable to make reliable assessments on the potential of technologies that rely on deep subsurface resources. As part of the BRAIN-be ALPI project, a cash flow model (techno-economic model, TEA) of a geothermal doublet system was created to investigate the influence of policy instruments on project success and profitability (Compernolle et al., 2019). In the model, uncertainty and uncertainty reduction by exploration are handled by integrating a decision moment for project alterations. Veldkamp et al. (2018) have developed a method for creating a nation-wide geothermal uptake assessment for the Netherlands. Here, learning within geological plays reduces risk when installing multiple projects. It is also shown that development depends on above-ground heat demand and infrastructures. This model, however, develops a fully optimised resource-demand matching without considering changes in time. These issues have been dealt with in the PSS (Policy Support System) suite of simulators, which were developed for the geological storage of CO_2 (Welkenhuysen et al., 2013). The PSS tool matches a geological resource, with above-ground technology in a policy and economic environment over time. Uncertainties of geological, technological and economic origin are integrated, which allows for a realistic representation of investment risk. The applied Real Options Analysis (ROA; Dixit & Pindyck, 1994) is considered as an appropriate way to counterbalance risk generated by uncertainty.

For analysing environmental impact, life cycle assessment (LCA) is considered as the go-to method. Over the past decade, several papers were published presenting the results of LCI (life cycle inventory) and LCA at an individual, local or regional level for deep geothermal technologies (see Marchand et al., 2015 and Fridriksson et al., 2016). The results of these studies are hard to compare as different approaches have been used. In 2018, two EU-wide projects were started come to a widely supported methodology for LCA on geothermal systems and a common understanding of the results: a study on geothermal plant emissions (De Rose et al., 2020), and the Horizon 2020 project GEOENVI (2019) aiming at defining a harmonized LCA methodology. Both projects look at uncertainty at the level of direct and indirect emissions but do not assess temporal and (semi)permanent changes in the deep subsurface. Standard LCAs are static calculations for a single project development pathway, without considering emissions to be released at different times, with an impact that might change over time. In the real world, where decisions can be taken as flexibilities in project development, the time aspect is important to consider.

To integrate reservoir behaviour as much as possible in TEAs an LCAs, a very close connection between the modelling calculations is needed. Preferentially, requests from the TEA or LCA are treated on an automatic ad-hoc basis. If Monte Carlo calculations are involved for dealing with stochastic parameters, the calculation of individual requests needs to be sufficiently fast. In order to account for multiple and large sources of uncertainty, and to be able to run a large number of calculations, analytical solutions or other fast simulation methods are preferred. While these methods typically have a lower level of detail, they can be used for first order planning when considering new targets and help in de-risking by considering multiple decision options.

In addition, while a TEA can provide decision support for investment in deep geothermal energy and an LCA can provide its environmental impact, present-day decision making should consider both aspects. A deep geothermal project is also expected to interfere with other (geothermal) projects in its surroundings. Especially in a limited area such as Belgium this is expected to have an impact on planning and managing future projects. Both these issues are current topics of interest and are identified as research gaps with no available assessment methods (also see Compernolle et al., 2023).

In this context, the goal of the DESIGNATE project is to create interdisciplinary tools for integrated forecasts under uncertainty for deep geothermal systems in Belgium, including applications in abandoned mines (Figure 1). More specifically, the objectives are to:

- Develop techno-economic assessment tools that incorporate geological uncertainty and are based on real options analysis and the PSS simulator.
- Develop a framework for dynamic life cycle assessments considering timing of emissions and their effects over time.
- Develop analytical or other fast reservoir simulations that can be directly connected or integrated in the TEAs and LCAs.
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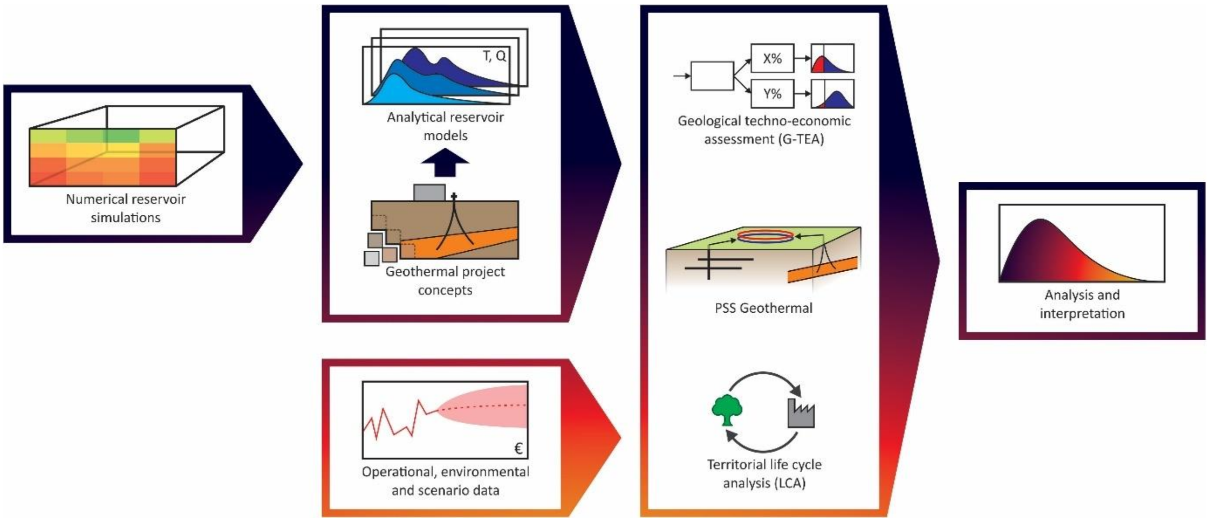

Figure 1. Workflow developed and applied in the DESIGNATE project.

3. METHODOLOGY

3.1 Case definition

Five case studies are defined, with a wide spread in geographical location, geological setting and type of geothermal project (see also deliverable D4.1).

The first case study is based on the Balmatt project by VITO. The geothermal wells at the VITO site were drilled between 2015 and 2016 to the Dinantian or Lower Carboniferous Limestone Group at over 3500m deep, and surface installations for a heat exchanger and connection to an existing heating grid were completed. The project is currently in a testing phase, and many research steps have been taken to understand and optimize the geothermal system. In DESIGNATE, the case study is designed as a commercial project with corresponding cost figures, based on the actual Balmatt project.

The second case study Turnhout NW and adjoining data is delivered by the geothermal development company Hita, and is based on the doublet project of the GEO@Turnhout consortium that is under development at the time of writing. The geological target and setting are very similar to the Balmatt case, but at slightly shallower depth and lower temperature.

The third case consists of a single well application, where two concentric tubes extract and re-inject brine from and to a Cretaceous reservoir at a depth of about 700 m. This is a hypothetical case, which is positioned in the region of Herentals. Radial wells or laterals can increase productivity and delay thermal breakthrough, and a heat pump is used to increase output temperature.

The fourth, Deep Mons case is located in the Hainaut area and targets the Dinantian or Lower Carboniferous limestones. It also involves an open doublet system in a dipping, more permeable layer, at a depth of 2000 m on average. This case too is a hypothetical project, although prospections have been made for very similar projects in this area.

The fifth and last case study is a hypothetical heat-cold storage project in the Péronnes-lez-Binche former coal mine galleries. At depths between 200 and 1000 m, two separate compartments at different depths can be used for seasonal storage of heat and/or cold.

Decision trees are built to serve as a basis for the techno-economic and environmental analyses, with special attention to the decisions and investments in the development phase (Figure 2). The decision trees have a time resolution of one year, with some phases having a minimum duration of multiple years. Decision options include investment, waiting, and decommissioning of installations.

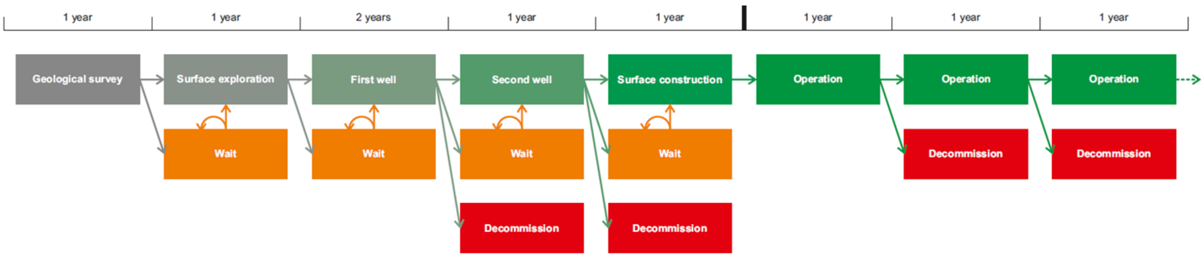

Figure 2. Decision tree developed for the Balmatt case study.

3.2 Uncertainty quantification

Uncertainties are inherent to working with subsurface data. Understanding the source of the uncertainty and correct quantification are vital for making further assessments with the available data. An assessment is made on the uncertainty of depth and temperature of the Dinantian strata of the Carboniferous Limestone Group, one of the main targets for deep geothermal projects in the Flemish Region (see also deliverable D2.1).

When assessing the depth of a geothermal target, a major part of information comes from seismic surveys. An important source of uncertainty here is the conversion from travel time of the seismic waves to depth (velocity model). In addition, different data sets and modelling techniques can result in significantly different depth assessments when interpreting and interpolating data. Firstly, the level of uncertainty depends on location. At greater depth, uncertainty is larger due to scarcity of data, higher uncertainty of seismic data interpretation, and the larger impact of the velocity model that is used. Secondly, it depends on the (amount of) available data: more wells and better seismic coverage lowers uncertainty. This becomes clear when comparing the (newer and more detailed) G3Dv3 geological model (https://dov.vlaanderen.be/page/geologisch-3d-model-g3dv3) with the geological model used in the GeoHeat App (https://publicaties.vlaanderen.be/view-file/25267). A comparison is made with the G3Dv3 model interpretation, applying the GeoHeat App velocity model (Figure 3). The resulting differences in projected depth range between 100 to about 450 m, which is significant in terms of temperature when considering a geothermal gradient of over 30°C/km.

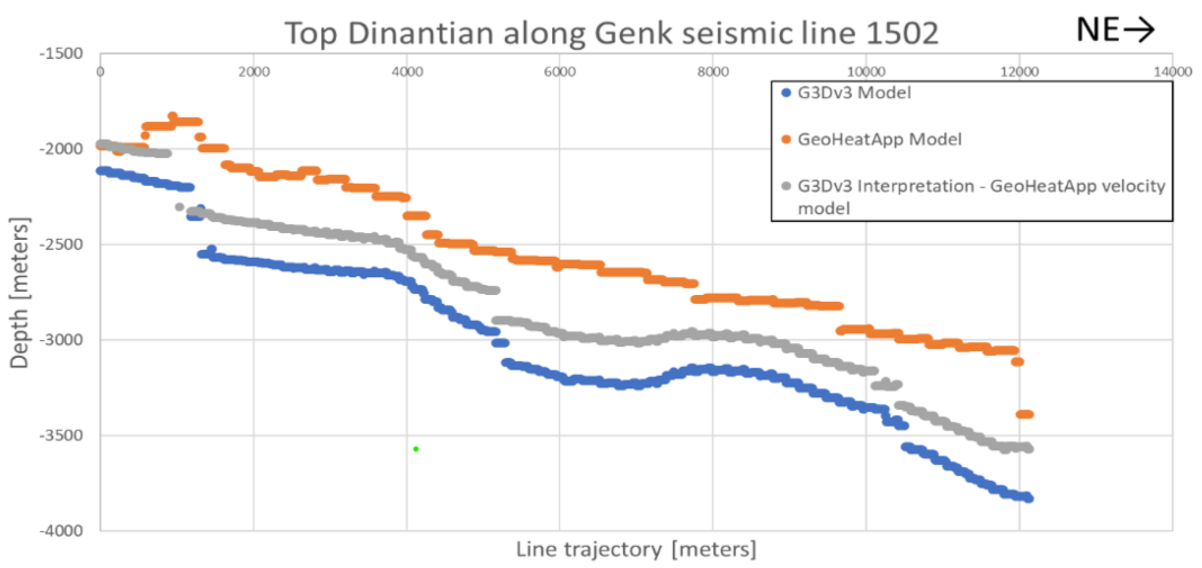

Figure 3. Depth comparison of the top of the Dinantian for several geological models demonstrating geological uncertainty.

The uncertainty on temperature data and geothermal gradient is also analysed, based on the work of Broothaers et al. (2020). The available historical dataset of measured temperatures in wells is very heterogeneous, and every measurement has its own specific accuracy and uncertainty. In general, bottom hole temperature measurements can be used for regional temperature interpretations, although the measured temperature is generally an underestimation. A correction of the bottom hole temperature should therefore be carried out, but there is insufficient metadata available in the historical measurements to apply this to the available dataset. Lowering uncertainty on the geothermal gradient is possible by acquiring more bottom hole temperature data, and doing temperature measurements in drill-stem tests (isolate a specific well section for pressure testing). When recording temperatures, it is important to log specific data to allow for correct interpretation and calibration: circulation time, shut-in time and borehole diameter. And lastly, on individual basis, legacy well data can be corrected when sufficient correctly measure temperature data is available.

Because the impact of temperature uncertainty is smaller compared to depth uncertainty, and considering the available data, a regional geothermal gradient in the Campine Basin of 32.5°C/km can be assumed.

Four key geological parameters are identified to carry the main uncertainty that impacts project development, performance and economics: reservoir top depth, reservoir thickness, permeability and geothermal gradient. Based on expertise, experiences and the uncertainty analysis, the uncertainty evolution/reduction over the development steps in the decision tree of each case are quantified. Each parameter for each case receives a parent distribution, either uniform, normal or lognormal. Before the first development step, the uncertainty range is assumed the largest, at 100%. With every development step, a reduction to a certain percentage is attributed. For the top depth and thickness parameters, uncertainty is assumed to be completely resolved after the second well drilling (for doublet cases). For the permeability and geothermal gradient, uncertainty is strongly reduced after drilling, but it keeps reducing during the operational phase without ever reaching 0%. This mimics the fact that in reality the geothermal system is never completely known.

3.3 Reservoir simulation

The interdisciplinary analysis tools and workflows that are created in the DESIGNATE project rely on repeated Monte Carlo calculations for considering uncertainties. In order to keep model calculation time within reasonable limits, it is necessary to limit reservoir simulation time for single calculations in the order of seconds or less. Typical, numerical, reservoir models of geothermal activities are detailed but require long simulation times. Therefore, new analytical or other solutions are developed, or numerical simulation results are translated so they can be directly connected to or integrated in the techno-economic and life cycle assessments (see also deliverable D4.2 for the models).

3.3.1 Analytical solution for geothermal doublet in the Campine Basin

For simulating the performance of a geothermal doublet in the Campine Basin, an analytical Python model is developed. The proposed solution is based on the Gringarten & Sauty (1975) analytical model for calculating doublet production temperatures. This original model can be applied with the following assumptions:

- The productive layer is horizontal with a uniform thickness.
- The brine and rock are in thermal equilibrium.

- The Péclet number (ration between advection and diffusion) is assumed high, so there is no horizontal thermal conductivity.
- There is steady flow.
- The reservoir has a uniform temperature.
- There is no difference in viscosity and density between the hot and cold fluid.

The first three assumptions are representative for the intended use. However, with seasonal production changes and possible operational decisions made over the course of the project, flow will change over time. In reality, a reservoir doesn't have a uniform temperature distribution, and it was proven that the viscosity and density variation due to temperature changes have a significant impact on reservoir performance.

A comparative simulation was made between the Gringarten & Sauty solution and a numerical TOUGH2 heat and flow simulation for a case equivalent to the Balmatt project. With the standard parameter values, the match between breakthrough time itself of both models is decent when applying a shift of 0.45*log(t_D) cycles, but temperature decline afterwards did not match well. In the Gringarten & Sauty solution, t_D is the non-dimensional time parameters and the lambda parameter specifically determines thermal breakthrough behaviour, which contains a parameter for heat transfer from the overburden to the reservoir (k). When varying this k factor, it appears that the effect on production temperature creates a close match to the TOUGH2 simulations and is thus a good engineering approximation for the change in viscosity due to injection temperature. Especially the long-term behaviour has a decent match for further use in project performance analyses (Figure 4; see also Pogacnik et al., 2023).

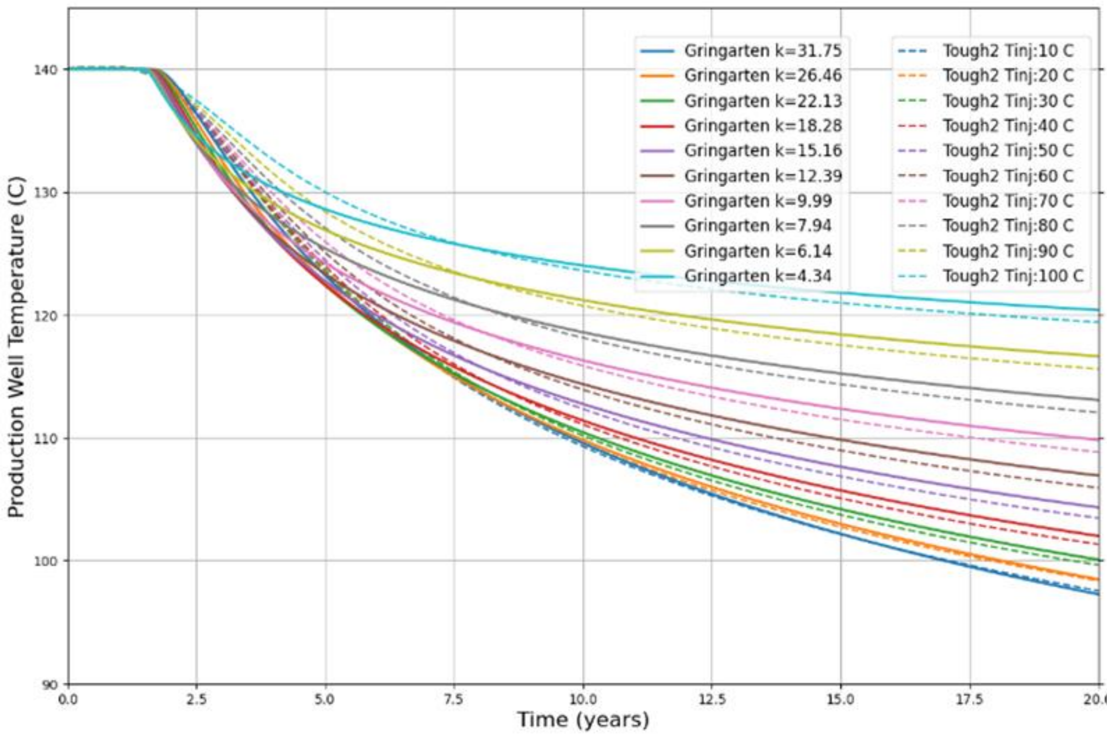

Figure 4. Matching the analytical Gringarten & Sauty solution with numerical TOUGH2 simulations for various injection temperatures by varying the overburden heat transfer parameter (k).

In addition, a solution for varying flow rate is developed by calculating temperature decline curves for each individual flow rate over the full timeline. Matching production temperatures are then retrieved on each curve and time is shifted to stitch the decline curves. This approach can also be applied for varying other parameters in the Gringarten & Sauty solution, such as thickness, reservoir temperature and seasonal flow changes (Figure 5; see also deliverable D4.2 for the model).

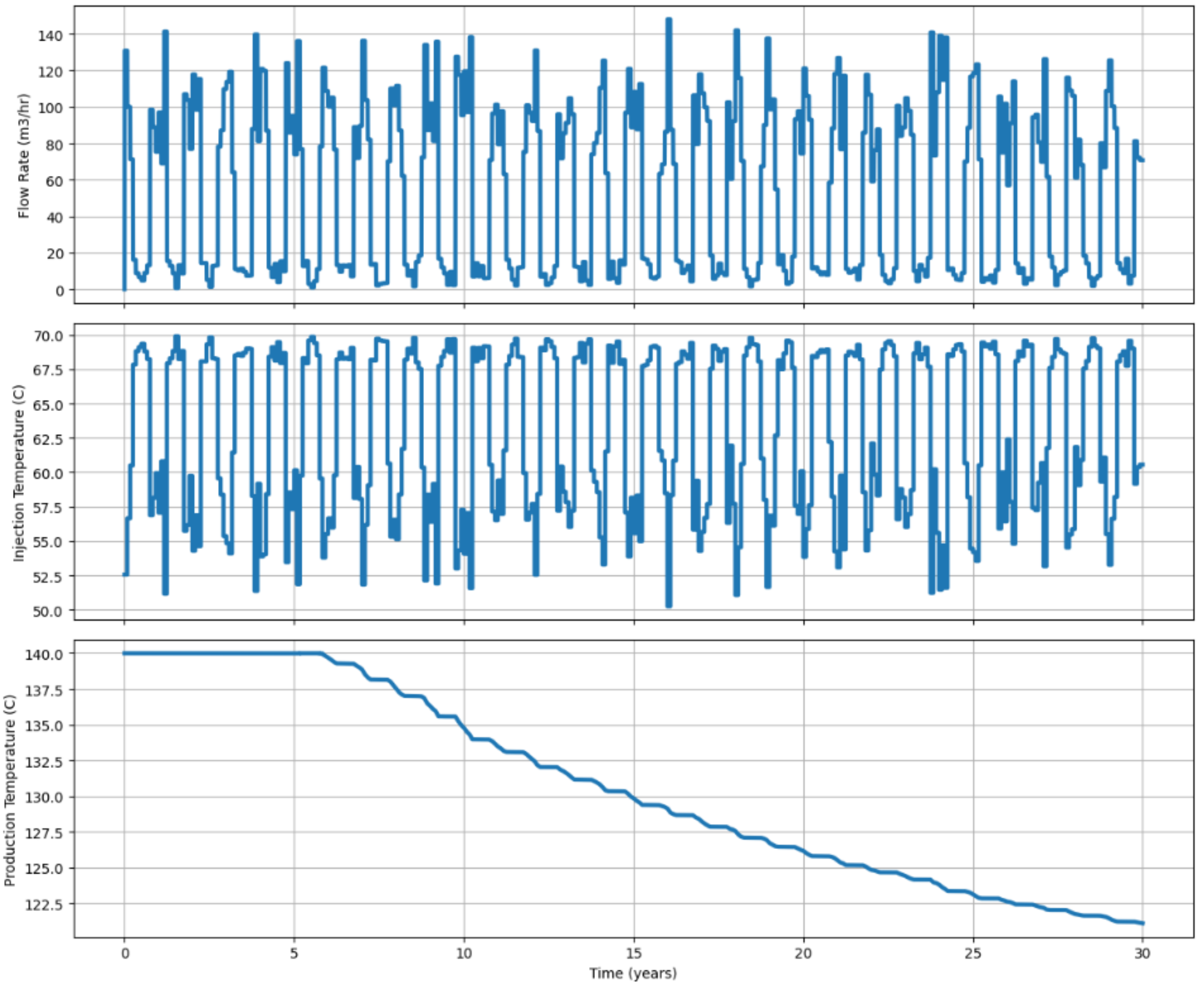

Figure 5. Simulation example of the analytical Python model with varying reservoir temperature and flow. Well spacing is intentionally small to show temperature breakthrough.

3.3.2 Lookup table for single well application

The geological setting for the single well application is the Cretaceous in the Campine Basin, which is a relatively well-known reservoir. The single well technology, however, is new which generates uncertainty on its performance, and simulation is less straightforward compared to the analytical solution for the geothermal doublet in the Campine Basin. A wide range of simulations in COMSOL are made for the following parameter ranges:

- Porosity (0.15-0.25 % in 2 steps)
- Permeability (5E-15-1E-13 in 6 steps)
- Ks (1.5-4.5 in 3 steps)

- W (15-25 in 3 steps)
- Injection temperature (15-25°C in 3 steps)
- Length of lateral wells (1.1-100 m in 5 steps)

Seasonal usage scenarios were also included in the analyses. A lookup table is generated with these results for providing production temperature and pressure change to techno-economic simulation (see also deliverable D4.2 for the model).

3.3.3 Lookup table with multivariate interpolation

The well-known active geothermal projects in the Mons Basin tap into the Lower Carboniferous limestones which has significant thickness of over 2 km in this region and are dipping towards the south (Figure 6). The most prospective layer, however, is a brecciated layer of up to 200m thickness and top depth of 1500-2500 m. The anticipated temperature lies between 60 and 80°C. Because the higher complexity of the geological setting, it was chosen to start building a numerical flow modelling in MODFLOW 6 with the FloPy API, which is a flexible modelling and simulation tool for building and running realistic models: complex geometries and transient simulations are possible. The groundwater flow and solute transport simulation are adapted to heat transport.

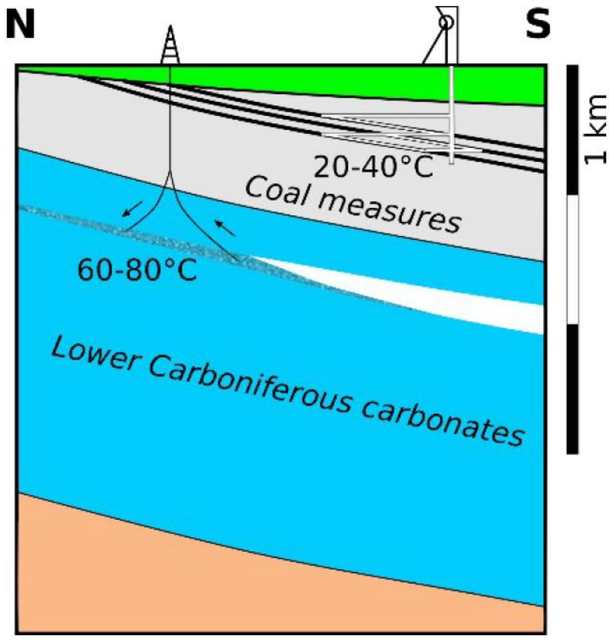

Figure 6. Concept of the Deep Mons and abandoned mines case.

Two model classes are created: a first of the full Lower Carboniferous limestone layer as a homogeneous dipping reservoir in between two aquicludes, and a second with a high-transmissivity layer within the reservoir (Figure 7). Simulations are performed for a timeframe of 26 years of production, considering multiple stochastic parameters:

- Flow (10-300 m3/h in 12 steps)
- Reservoir top depth (1300-2300 m in 11 steps)
- Reservoir thickness (2100-2700 m in 11 steps)

- Aquifer permeability (10-100 mD in 10 steps)
- Geothermal gradient (25-30°C/km in 3 steps)

For the second model class, the high transmissivity layer receives a permeability which is the squared value of the surrounding rock permeability. The high permeable layer thickness is either (thickness of the reservoir rock – 2300) / 2 with a minimum thickness of 5 m. A total of over 50 000 cases was simulated, each with a simulation time of several minutes. A 7-dimensional lookup table is created from the simulation results for use by the techno-economic analysis. A multivariate interpolation function is added to have a higher accuracy in the result. With the possibility to vary flow over time, a solution is developed to obtain accurate results from a static results table: the total heat extracted at the end of a production period is used to match the reservoir state at the start of a new production period. When comparing actual MODFLOW results with the interpolated approximations, even for a varying production rate there is a very close match in temperature (within 1°C) and flow (within a few m³/h over 26 years of production (Figure 8).

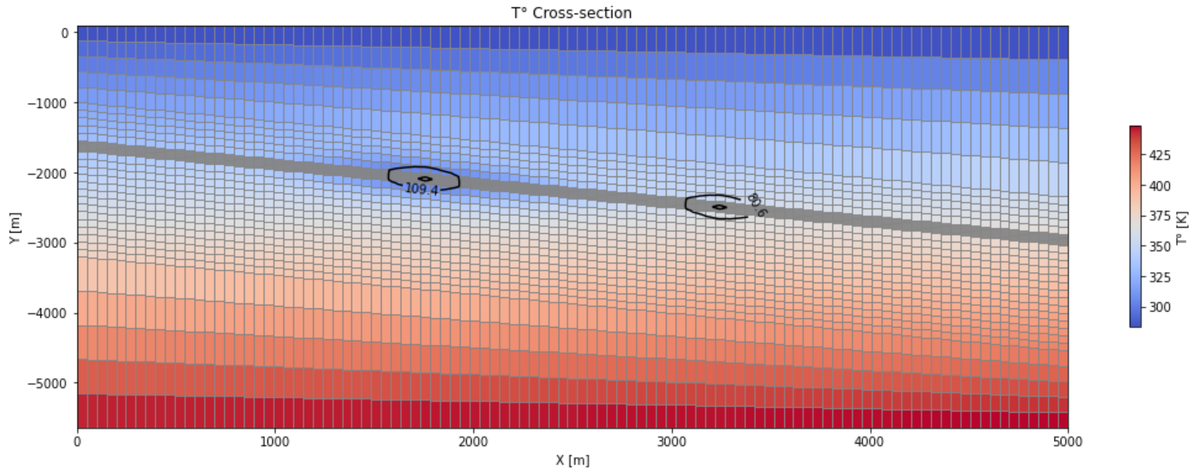

Figure 7. MODFLOW numerical simulation for the Deep Mons case showing the dipping reservoir with high-permeability layer. Doublet wells are indicated (left: injection, right: production).

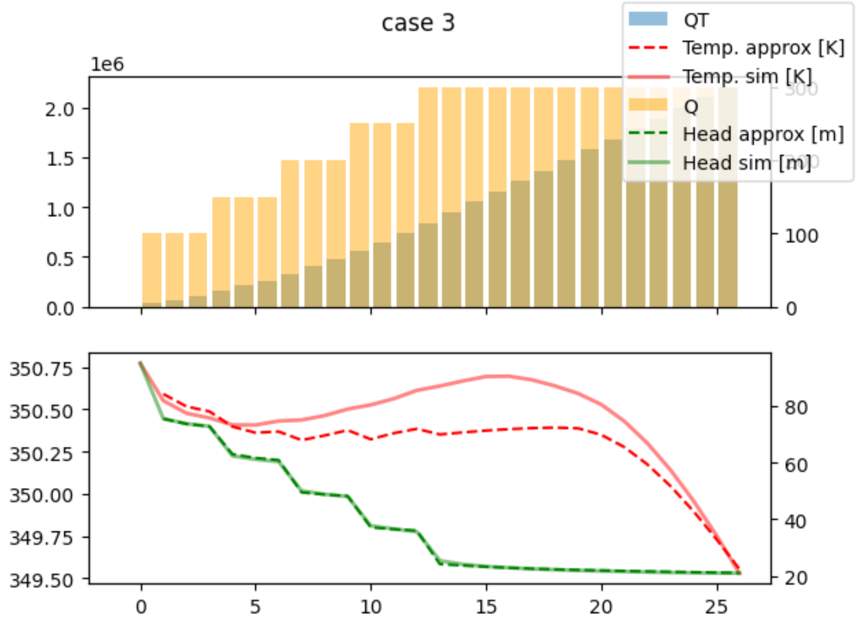

Figure 8. Comparison of the modelling results (sim) with the multivariate interpolation (approx).

In order to distribute the workload of the interpolation function, a remote calculation workflow is developed. An FTP server is set up to act as data transmission for exchanging requests and results as csv files between the techno-economic and reservoir simulation. A centralized task dispatcher monitors new incoming requests, and sends them to one of multiple worker machines that does the actual interpolation and reports back to the dispatcher. After optimization, the simulation time lies below 0.1 second per job (see also deliverable D4.2 for the model and Dupont & Kaufmann, 2024). Future optimizations include machine learning to refine the approximation on variable flows, and to deal with viscosity and density changes in the simulations in function of temperature.

3.3.4 Heat-cold storage in abandoned coal mines

The most relevant parts of the Péronnes coal mine for a mine water geothermal system have been digitized to build a hydrogeological model. This approach proved to be too cumbersome to build a fast and reliable simulation tool for integration with other methods. Therefore, a more generic mine case model is built, to simulate heat-cold storage in a temperature range of 20-40°C at a depth of 200-1000 m. The goal is to produce a multidimensional lookup table with interpolation functionality, similar to the Deep Mons lookup table solution (see also N'depo et al., 2024). Finalization of simulation results is beyond the timeline of the DESIGNATE project, but work is expected to continue in follow-up projects.

3.4 Life cycle assessment

While geothermal energy is considered as a renewable energy source, it still consists of a number of processes and utilises materials that have a certain impact on the environment. In order to understand this impact, a literature review is made on life cycle assessments (LCA) for deep geothermal energy technologies, with a focus on the global warming impact. Environmental impacts appear to vary widely depending on the technology used, site-specific geological conditions, and the assumptions of the study. It also becomes clear that the impact of variability and system dynamics have only been assessed to a limited extent. In a next step, a life cycle inventory (LCI) is created as a database with the emission and scenario data for a geothermal doublet project in the Campine Basin in Belgium (see also Gkousis et al., 2022a and deliverable D3.2). Three projects are analysed in the LCA: a first one considering the Balmatt project, including an ORC unit for power production, a second one with only heat production, and a third one with limited depth, representative for the Turnhout NW case. A hotspot analysis is performed to identify significant impacts, and a global sensitivity analysis is added to quantify the impact of variability and uncertainty (see also Gkousis et al., 2022b and deliverable D3.2).

A standard LCA uses static inventory data and delivers a static impact assessment. In order to calculate a more realistic environmental impact, first a semi-dynamic LCA is developed, where a dynamic inventory data is used, such as an evolution of the electricity mix and a degradation of the geothermal resource over time. Second, a fully dynamic LCA is developed where the dynamic inventory data is coupled with a dynamic impact assessment. Here, it is considered that there is a temporal evolution of the impacts, and that emissions do not cause their impact instantaneously when emitted (Figure 9; see also Gkousis et al., 2022c and deliverable D3.2).

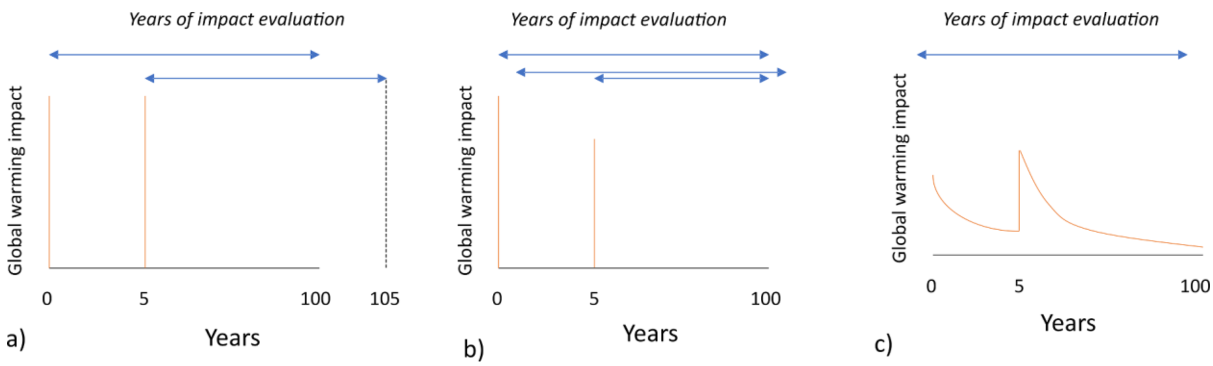

Figure 9. Assessment of the global warming impact, for a time horizon of 100 years of emissions occurring at Year 0 and Year 5 with (a) static, (b) flexible time horizon, (c) instantaneous characterization factors.

3.5 Techno-economic assessment

In a techno-economic model, the components that make up the system that is analysed, are connected trough process flows. By attributing performance and financial parameters to the components a techno-economic assessment (TEA) can be performed. A techno-economic model is built in Python to assess the performance of a geothermal doublet in the Campine Basin, for different price, demand and policy scenarios. The basis consists of the decision tree with multiple development options. A standard Net Present Value (NPV) calculation is insufficient to integrate multiple uncertainties and multiple flexibility options from the decision tree. Real Options Analysis (ROA) takes into account the value of managerial flexibility by adjusting to circumstances and having an outlook on the evolution of uncertain parameters. Both techno-economic and geological parameters are treated as stochastic. A Least Squares Monte Carlo ROA algorithm is used, which calculates values and probabilities from end to start over a project timeline. The TEA model retrieves its reservoir performance data directly from requests to the analytical reservoir model. The eventual economic value of the project, considering the decisions and their probabilities under uncertainty, is then calculated (see also Gkousis et al., 2024a and deliverable D2.3-5.1-5.3).

The developed ROA-TEA model only considers economic performance for decision making. A major driver for investments in renewable energy is the reduced environmental impact. A two-criteria Real Options model is therefore built, which also considers the greenhouse warming impact. An economic threshold is still present, constraining solutions to decision that have a positive expected value. The environmental criterion, however, will drive the decision, and will also provide a threshold to ensure that the greenhouse warming impact is lower than an alternative source of heat, for example natural gas or heat pumps (see also Gkousis et al., 2024b and deliverable D2.3-5.1-5.3).

3.6 Policy Support System

3.6.1 PSS introduction

As part of the Belspo-funded PSS-CCS projects (Policy Support System for Carbon Capture and Storage, 2005-2012), a techno-economic forecasting simulator was created to investigate the deployment of CCS technology in Belgium (Welkenhuysen et al., 2013, 2017). This tool in which input data from mainly Access databases is processed in VBA modules, has been further developed and applied in various CO_2-storage research. PSS version IV serves as a basis for further development, in order to create a tool for geothermal project analysis, integrating reservoir simulation and techno-economic analysis. The resulting PSS V contains multiple major adjustments and expansions that are discussed in the following sections, and is now capable of not only analysing deep geothermal projects (see also deliverables D4.4 for the PSS simulator and D5.2), but is sufficiently modular to accommodate various subsurface activities such as CO_2 storage and hydrogen storage.

3.6.2 Modular activities

All cases for analyses are geothermal projects, but they are very different from each other. They each require a tailored approach for simulating performance and economics in terms of parameters and calculation. The existing PSS versions have activity-specific parameters and calculations. In order to accommodate different geothermal project types, a modular system is developed. Apart from the existing economic and technical parameters, 20 user-assignable input parameters are added that are intended to be used as reservoir parameters (e.g. permeability or geothermal gradient). After reservoir calculation, there are again 20 new user-assignable output parameters (e.g. for flow or temperature). Lastly, three user-assignable commodities can be produced (e.g. heat or electricity). This development provides the needed flexibility for dealing with significantly different types of projects, even beyond geothermal.

3.6.3 Modular reservoir models

Following the previous section, also the calculation of reservoir performance is different for each project or type of activity. In the existing PSS version, there is only a single activity, with one calculation for output. A modular system has therefore been developed to have a user-assignable calculation for each project (Figure 10). Every project can thus be linked to a separate reservoir model. The currently available options are an external analytical Python model for geothermal doublets, its translated internal VBA version within PSS, a local lookup table for single well geothermal, and a remote lookup table with multivariate interpolation for geothermal doublets and heat-cold storage in abandoned coal mines. All connection types are available in the new PSS V, and can be used simultaneously within one simulation.

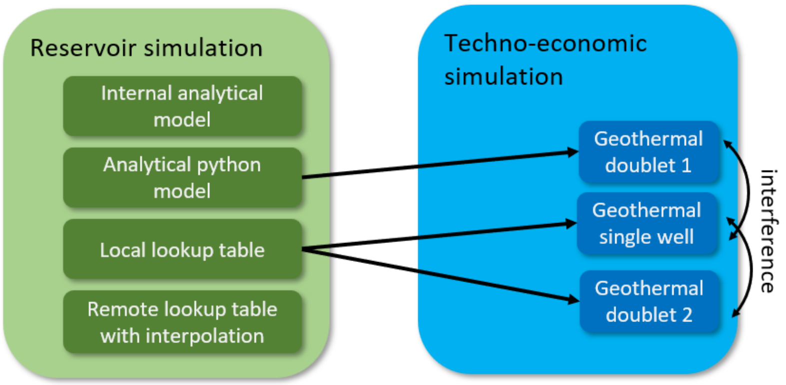

Figure 10. Demonstration of the PSS V flexibility by introducing modular activities and modular reservoir model connections, as well as activity interference.

3.6.4 Reservoir parameter uncertainty

Stochastic parameters have, until now, been modelled as typical economic parameters: with growing uncertainty over time. Geological uncertainty, however, does not change unless research or exploration is undertaken, in which case uncertainty is reduced. Geological uncertainty is therefore now modelled as follows (Figure 11): in the exploration phase, uncertainty is reduced in steps. Each step, e.g. the seismic survey, is assigned a percentage of the original uncertainty range (before any activity) that remains after this step. The operational phase is characterized by a continuous uncertainty reduction that follows a power law learning curve (Henderson's Law). This approach provides a much more realistic geological uncertainty modelling.

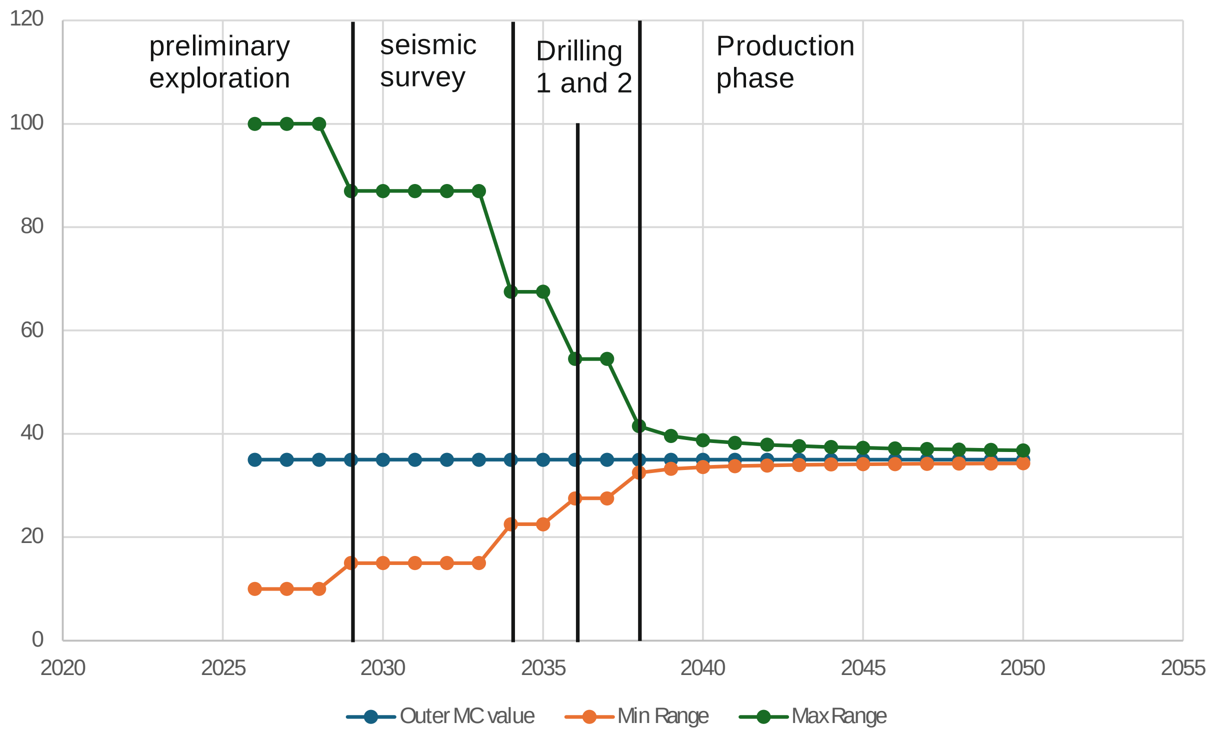

Figure 11. Geological parameter uncertainty reduction for development and operation. The outer MC value represents the value in reality, which is not known exactly when simulating decision making.

3.6.5 Decision tree functionality

In the techno-economic forecasting, the decision tree maps all available options for the project to be developed over time. This optionality provides the decision flexibility to adjust to unforeseen circumstances. In the existing PSS version, there is a fixed 1-year time step between subsequent decisions, which provides insufficient realism for detailed project development modelling. Adjustments have therefore been made to arrive from an options list to a decision tree that is more realistic specifically for the pre-operational phase. For each option, a minimum and maximum phase duration can be defined (including unlimited duration). In addition, each option also has an adjustable step size.

3.6.6 Heat transport

The existing PSS version contains a fully functioning and advanced least-cost pipeline routing algorithm, designed for large-scale pipelines and networks for CO2 transport. While it is not the intention of the DESIGNATE project to create a fully realistic and detailed heat transport network simulation, an attempt is made to transform the existing algorithm to simulate a heat backbone, serving multiple large users and/or substations for further distribution.

Given location of the heat source, users that need to be connected, and a road map (assuming a heat transport network follows this existing infrastructure), the Dijkstra algorithm is used to calculate least-cost routes from all nodes to all nodes. In a next step, the least cost routes are selected from and to the heat source and all users. In a final step, the Kruskal algorithm (minimum spanning tree) is applied to this selection of routes to create a least-cost network between the source and all users. This calculation method is fully developed, but is currently in an early testing phase and has not yet been applied to the case studies.

3.6.7 Interference modelling

Interference of activities in the deep subsurface is a topic recently receiving increased attention due to an increased interest in subsurface solutions for a sustainable society. The DESIGNATE project anticipated to create a first onset towards modelling interference effects, specifically for deep geothermal projects, using box model interactions. Here, individual projects are treated as virtual boxes that create a disturbance (e.g. pressure or temperature changes) at their boundaries with the surrounding environment. Interactions between the boxes is modelled analytically.

A far more advanced interference modelling setup has been developed in collaboration with the FWO-SBO DIAMONDS project, the FWO-Junior MASSIF and the Flemish government assignment on the societal impact of deep subsurface use. The PSS V simulates decision making on multiple (types of) activities in the deep subsurface. A basic influence radius is considered to avoid conflicting activities. Each of these activities provides a minimum and maximum pressure induction over time, which are transferred into a semi-analytical regional groundwater model built in the AnAqSim software. Here, groundwater pressure is modelled regionally (scale of the Flemish Region in this case), including the pressure influence of the activities. The pressure influence and thus interference between activities can be monitored at any location within the model. This workflow reflects actual project decision making, with a prior exclusion zone imposed by regulations, and interference monitoring during actual operation. Workflow and simulation results will be published as part of the three parallel projects (see also Rodriguez et al., 2024).

3.7 Scenario definition

Several scenarios are developed for the techno-economic and environmental simulations (see deliverables D3.1 and D3.3). These scenarios describe the external environment and boundaries of the calculations, and are matched as closely as possible between the different simulation methods.

For defining energy prices and future uncertainty, two methods are employed. The first method relies on the analysis of historical data for deriving a trend and volatility for defining stochastic price processes. Two sets of data are obtained: one considering data until 2020 (pre-covid and Russia-Ukraine conflict) and one until 2022 with higher prices. With the second method, available future projections on energy prices are compiled and averages and spread are used for stochastic price process simulation. A scenario for the current electricity production mix and its future evolution is derived from several data sources.

To investigate possible support measures, four different policy instruments are simulated:

- A heat premium (fixed amount of revenue on top of the commercial heat price).
- A subsidy on the initial investment (reduction of investment cost).

- Carbon benefits (revenues based on avoided CO2 emissions compared to a gas heating solution).
- A risk insurance for the well drilling (partial reimbursement in case of production underperformance, an insurance fee is charged based on drilling cost).

A number of variations in the decisions and operation of a geothermal project are simulated as well:

- A load factor of 50% and 90% to simulate seasonal and full-load operation.
- Variations in the decision tree to reduce the number of calculations while retaining a close approximation of the result.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1 Environmental impact analysis

Thirty LCA studies on deep geothermal energy extraction are reviewed (see also Gkousis et al., 2022a, b, c and deliverable D3.2). It is found that the environmental impact is driven by highly site-specific geological conditions, including reservoir depth, geofluid temperature and composition and the reservoir rock. Design and engineering parameters such as the energy conversion technology, the production flow, and the plant capacity, CF and lifetime also influence the environmental impact. When considering the project lifetime, construction activities such as wells drilling cause a major impact, as well as the plant's pumping need during operation, and the electricity mix supplying the plant. In the available studies, the effect of time is usually not considered, although major variations in impact over time are expected.

A comprehensive but static first environmental assessment is made for three variations of a deep geothermal heating plant in Northern Belgium. The analysis shows that new deep geothermal developments in Northern Belgium have a much lower carbon footprint than the current natural gas dominated heating. Although all three scenarios fall within the reported ranges for Europe, the scenario of the actual Balmatt project appears to have a higher-than average environmental impact. A hotspot analysis shows that the majority of the environmental impact of the DGH plant scenarios investigated is caused by the electricity consumed to run the pumps and the steel, cement and chemicals consumed to construct the wells (Figure 12). For Balmatt, the wells are relatively deep, and due to the limited flow, there is a high energy need for pumping (Figure 13). Future developments are expected to cause lower impacts as they are expected to target locations where the reservoir is shallower and the rock permeability higher. Site-specific analyses are therefore needed, as well as the inclusion of geological and technical uncertainties that influence plant performance in a sensitivity analysis.

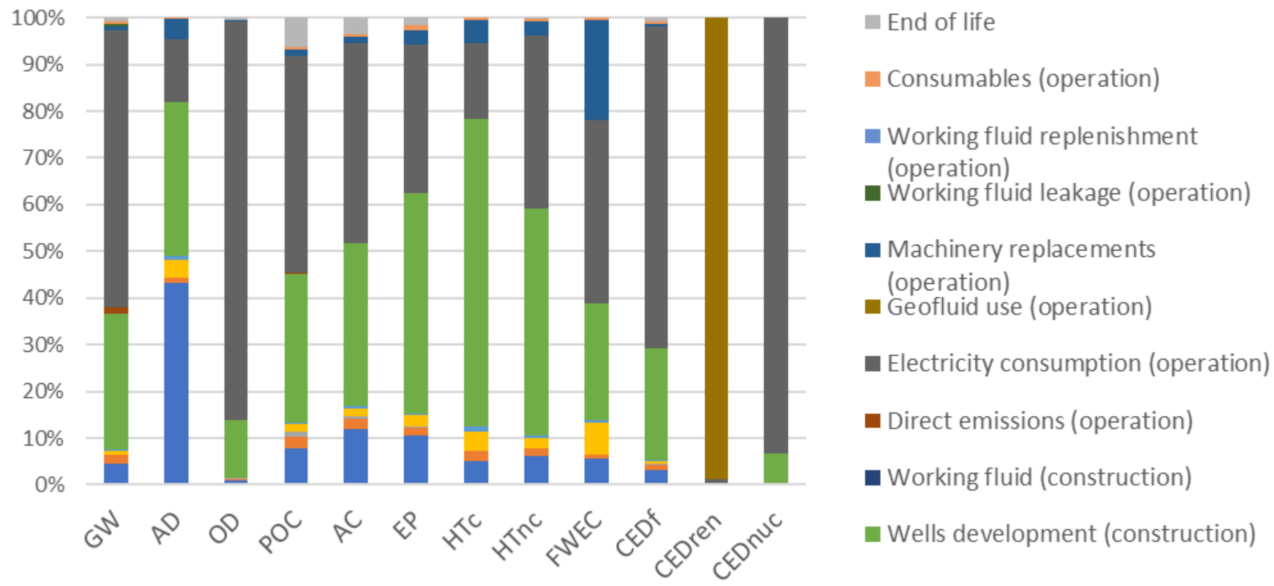

Figure 12. Hotspot analysis for LCA results. GW: global warming, AC: acidification, AD abiotic resources depletion, HTc/HTnc: human toxicity, cancer/non-cancer effects, FWEC: freshwater ecotoxicity, CEDf/nuc/ren: cumulative energy demand of fossil/nuclear/renewable sources, OD: ozone depletion, POC: Photochemical ozone creation, EP: Eutrophication.

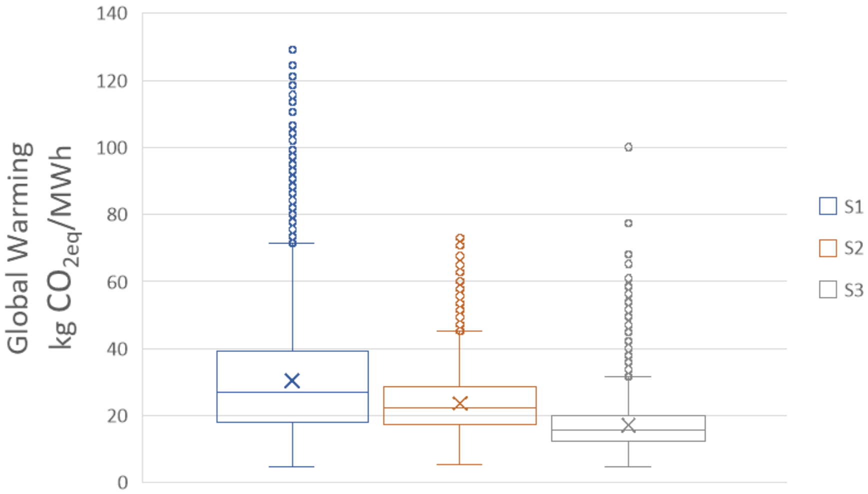

Figure 13. Boxplot Monte Carlo results for the global warming impact of three scenarios. S1: Balmatt case heat + electricity production, S2: Balmatt case heat production, S3: reduced depth and pumping needs.

To investigate the impact of time on environmental impact, a standard (static), semi-dynamic and fully dynamic LCA are developed for the Balmatt case study. In the static LCA, both the lifecycle inventory data and the impact assessment are static. In the semi-dynamic LCA, the inventory data on the electricity mix evolution and a potential decline of geothermal resource temperature is considered, but the impact assessment remains static. In the fully dynamic LCA, the inventory as well as the impact assessment are dynamic. In the dynamic impact assessment, the temporal evolution of the impact and the fact that emissions do not cause their impact instantaneously are considered (Figure 14). When considering changes in the electricity mix, in particular an anticipated closure of nuclear power installations, there is an expected 70 % higher greenhouse warming impact (due to an increase in natural gas-based power production) and a 30 % lower ozone depletion impact in the dynamic analysis compared to the static (Figure 15). A decline on the geofluid production temperature during the plant lifetime leads to considerably higher impacts for all impact categories. In such case, the environmental benefits of geothermal energy can be significantly reduced and rendered irrelevant if continued. Generally, the fully dynamic method presents more accurate environmental impacts; with the static approach, the impacts may be largely over- or underestimated. It also facilitates the interpretation of the results, and comparisons that are made with alternative heating sources.

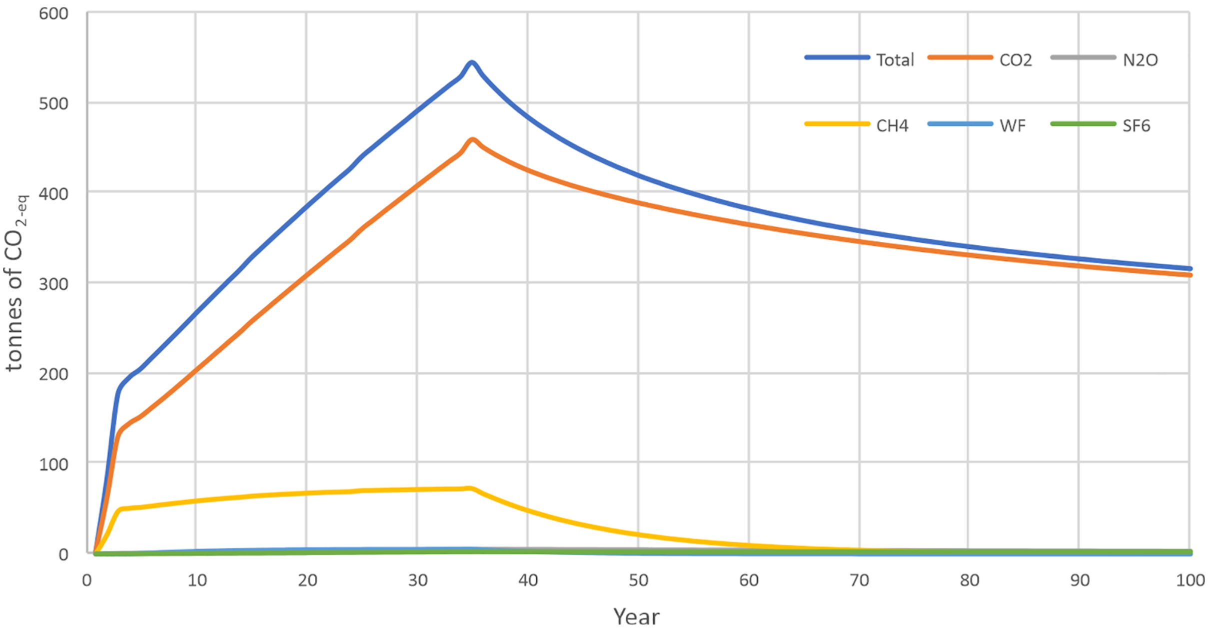

Figure 14. Global warming impact of the Balmatt project caused each year of the time horizon calculated using instantaneous characterization factors.

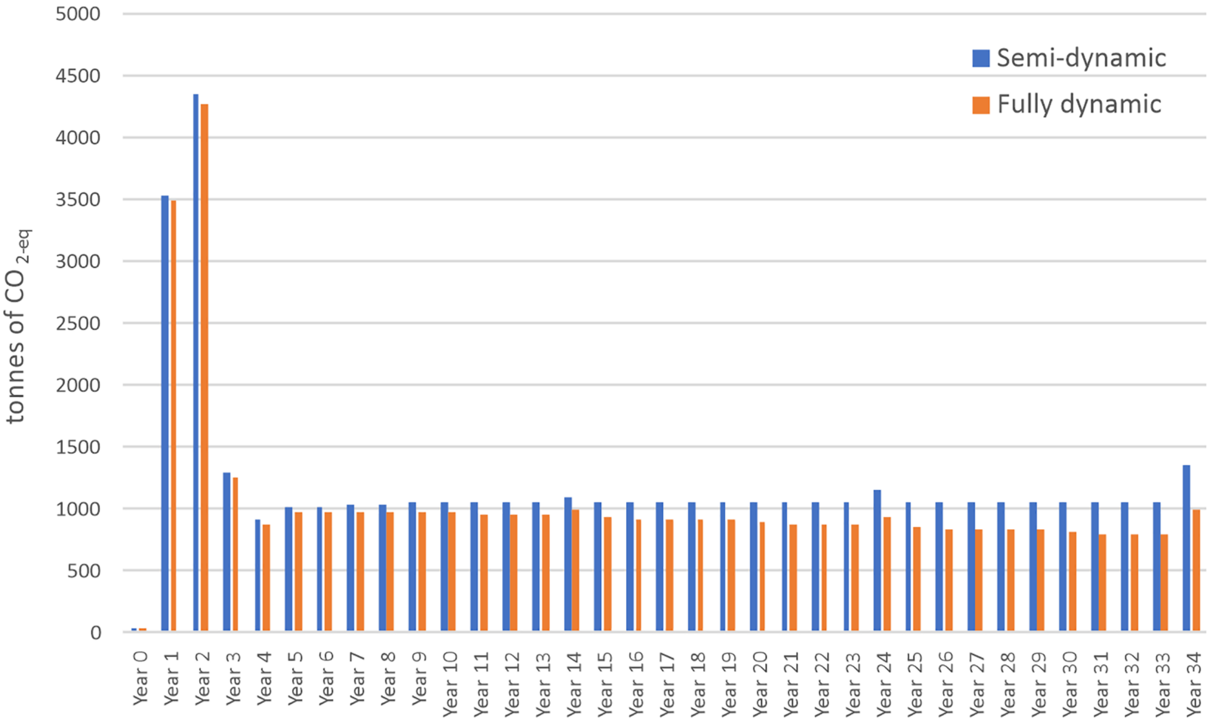

Figure 15. Global warming impact of the Balmatt project caused by the activities taking place each year, calculated using semi-dynamic and fully-dynamic life cycle assessment with flexible time horizon characterization factors.

4.2 Techno-economic analysis

Economic feasibility of deep geothermal energy in the Campine Basin is investigated with a techno-economic analysis (see also Gkousis et al., 2024a and deliverable D2.3-5.1-5.3). To account for flexibility and uncertainty, a Monte Carlo-based Real Options framework is developed. Results show that using a traditional TEA, without decision flexibility, economic performance of the Balmatt case is poor due to low permeability. Including flexibility, large losses are avoided, but average performance is still insufficient for this case (Figure 16). The Real Options approach also allows to determine the optimal timing of investment. In particular, project investment delay is reduced significantly in case the geological conditions are highly favourable. Four government incentives were simulated to support geothermal investment: a heat premium, an investment subsidy, a carbon pricing and a drilling insurance. All incentives are found to increase project value and reduce abandonment rate. Adding flexibility in the analysis is key for designing policy support measures: the incorporation of the flexibility options through the proposed RO framework led to the design of policy measures that cause a 3 to 4 times lower governmental expenditure compared to a traditional techno-economic analysis that neglects any flexibility. Table I shows the level of support needed to increase average project value to zero.

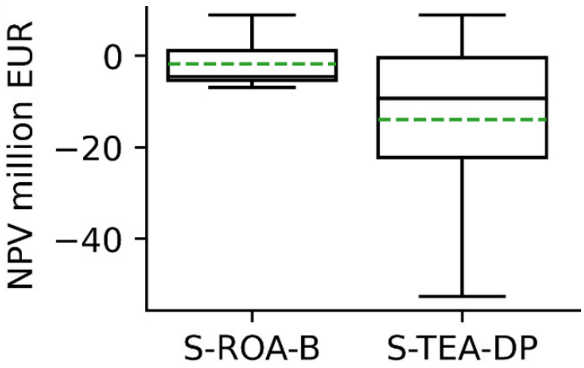

Figure 16. Economic performance of the Balmatt case for the Real Options method (S-ROA-B), the traditional TEA without flexibility (S-TEA-DP).

Table I. Magnitude of policy measures that result to a net present value of the project equal to 0.

Policy measure	Heat premium		Subsidy of capital expenditure		Carbon pricing		Drilling insurance	
Scenario	S-ROA-B	S-TEA-DP	S-ROA-B	S-TEA-DP	S-ROA-B	S-TEA-DP	S-ROA-B	S-TEA
Value that set NPV to 0	8.32	27.3	20	85.5	68	222	*N.A.*	*N.A.*
	EUR/MWh		%		(EUR/t CO_2)		*N.A.*	
Governmental expenditure (EUR/MWh-produced)	8.32	27.3	3.05	13.6	8.33	27.3	*N.A.*	*N.A.*
Development probability (%)	58.9	100	53.7	100	59	100	*N.A.*	*N.A.*
Probability of a project with positive value (%)	40.9	59.8	38.5	60.7	40.7	60.0	*N.A.*	*N.A.*
Mean development time (years)	10.2	4	10.7	4	10.2	4	*N.A.*	*N.A.*

4.3 Combining environmental impact and economic performance

The results of the Real-Options based techno-economic analysis are compared with an expanded model that includes a Global Warming Impact (GWI) criterion (see also Gkousis et al., 2024b and deliverable D2.3-5.1-5.3). Results show that next to increased economic performance, flexibility also adds environmental value (Figure 17). The economic gain of flexibility with the GWI-driven method is comparable too but a little lower than with the NPV-driven method, but the greenhouse warming impact is reduced too. When including GWI as decision criterion, there is a trade-off in economic or environmental impact depending on the priorities of the decision maker. The development probability of the geothermal project is similar for the NPV and GWI-driven decision. The development time, however, is significantly longer for environmentally-driven decisions: development investment decisions are deferred more frequently.

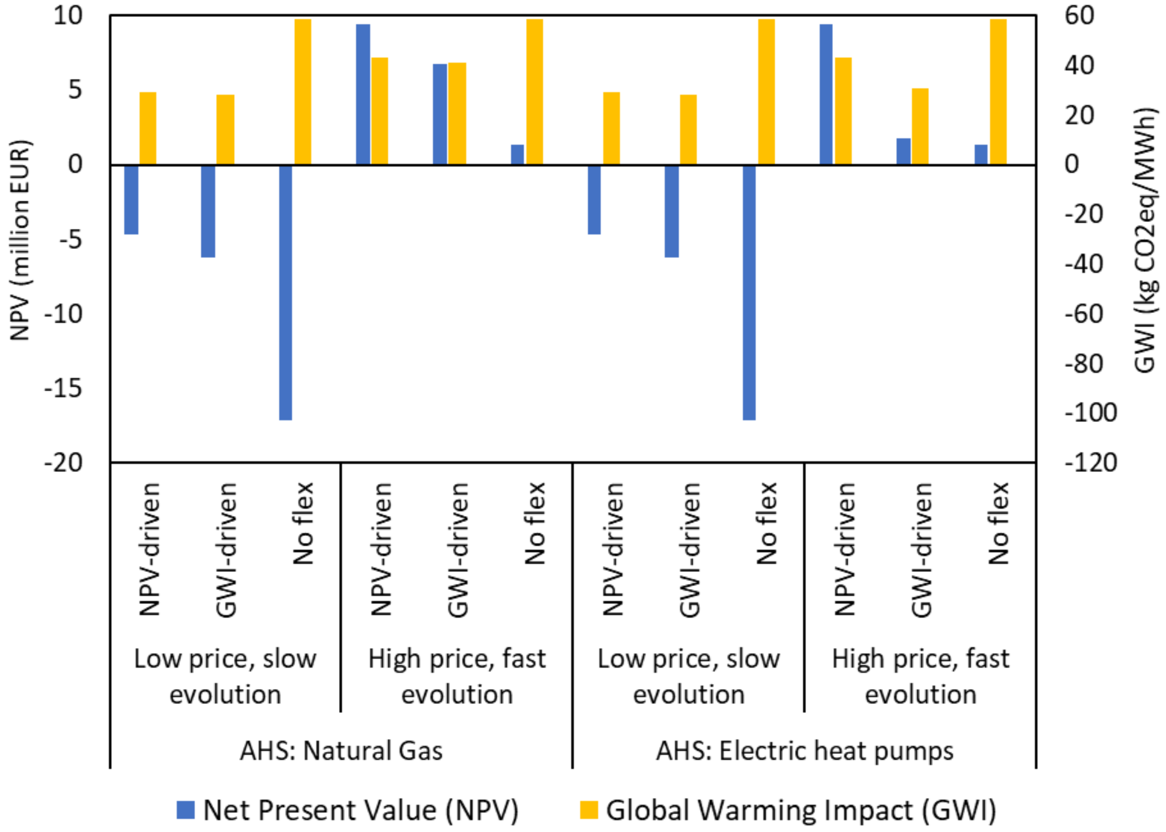

Figure 17. Comparison of the NPV-driven, GWI-driven and no-flexibility analyses for multiple energy price scenarios and alternative heating sources (AHS).

4.4 PSS V simulations

The newly developed PSS V techno-economic forecasting simulator is applied to analyse the selected case studies (also see deliverable D5.2). Full simulations are performed for the Balmatt, Turnhout-NW and Single Well cases. The Deep Mons case is operational but not sufficiently stable yet for presenting full results. Simulations were run for the different policy support scenarios, and a “Capacity” scenario where the full load time is increased from 50 to 90%.

The effect of the support measures is clear from the activation ratio (Table II; probability the project is activated in the simulation timeframe). Notable here is that increasing the full load time has a similar effect as the most effective support measures. The probability on a positive project value (NPV) paints a similar picture (Table III). Considering the selected input values, the Single Well case nearly always has a positive value when activated, while development probability lies around 40%. This reflects the limited variability that is generated in a non-interpolated lookup table, and can be considered as a limitation of this method. For all cases and scenarios, it is also observed that the lower the project value, the later it is activated.

Table II. Probability on activation or development in %.

Activation	Base	Heat-L	Heat-H	Invest-L	Invest-H	CO2Avoid	Insurance	Capacity	*Average*
Balmatt	34.6	33.5	59.4	41.4	61.0	39.1	31.3	63.0	*45.4*
Turhout	49.7	57.1	72.5	57.5	75.0	62.1	50.4	76.0	*62.5*
Single Well	37.1	40.4	44.6	34.1	36.9	31.4	38.3	39.6	*37.8*

Table III. Probability on positive project value (NPV) in %.

Pos NPV	Base	Heat-L	Heat-H	Invest-L	Invest-H	CO2Avoid	Insurance	Capacity	*Average*
Balmatt	65.8	69.9	69.4	54.5	79.4	66.3	60.6	77.7	*67.9*
Turhout	93.6	88.9	98.7	90.4	96.2	88.8	92.1	95.3	*93.0*
Single Well	100.0	100.0	100.0	100.0	99.2	100.0	100.0	100.0	*99.9*

A detailed analysis of the project value results for the Balmatt case (Figure 18) shows that average overall project value (5.4 M€) increases especially with a highly increased heat price (+4 M€), but also a high investment subsidy (+3.5 M€) and an increase in full load time (+8 M€). As support measure, a heat price subsidy has the largest effect, but can produce undesirable effects such as windfall profits because the operational phase of the project is targeted. An investment subsidy on the other hand targets the development phase, where the actual risk reduction is needed.

For the Turnhout-NW case (Figure 19), the average project value is higher due to more favourable geological circumstances, at 16.4 M€. A high heat price (+4.7 M€), and high full load time have similar effects. An investment subsidy has no significant effect on the average project value, likely because the project already has fairly good outlooks and a decrease in investment risk is compensated by a higher investment probability at lower heat prices.

Project value results of the single well case show a smaller range, due to the lower heat output (Figure 20). But, because project value is nearly always positive due to the limited and discrete options in the lookup table, average value is still 4 M€ without additional measures. With a high heat price subsidy, project value increases the most (+2.3 M€) of all measures. An investment subsidy has limited effect, also because risk is already small with nearly all projects having a positive economic value. An increase of the full load time from 50 to 90%, however, doubles the average value.

From the sensitivity analysis, the heat price appears as the main driver for project activation and value. This is expected because apart from avoided carbon taxes in the CO_2Avoid scenario, it is the sole source of revenues. From the geological and engineering parameters, flow (in direct relation with reservoir permeability) appears much more dominant for project value than production temperature (in direct relation with geothermal gradient and depth; Figure 21). Geological parameters in general have a significant influence on project timing, development probability and profitability.

As an extension of the Capacity scenario, the influence of a step-wise roll-out of a heat network on project profitably was investigated for a spreadsheet calculation (see also Meyvis et al., 2021). While initially income is lower and a an economic case is more difficult to build, it also introduces a flexibility to adjust to uncertain outlooks, reducing investment risk.

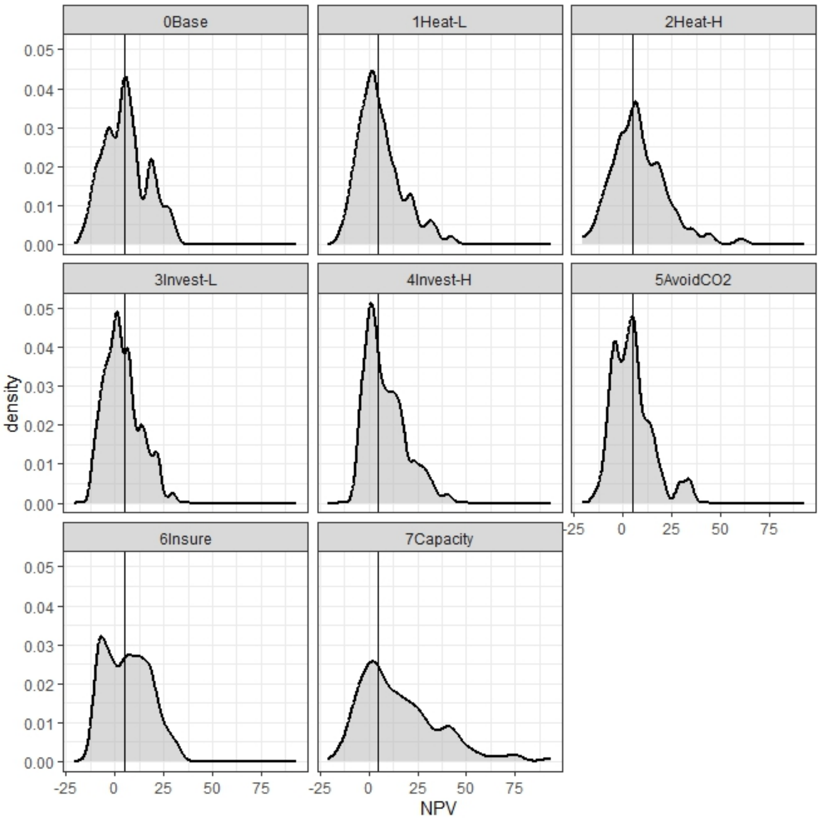

Figure 18. Project value of the Balmatt case for eight simulated scenarios, NPV in million €.

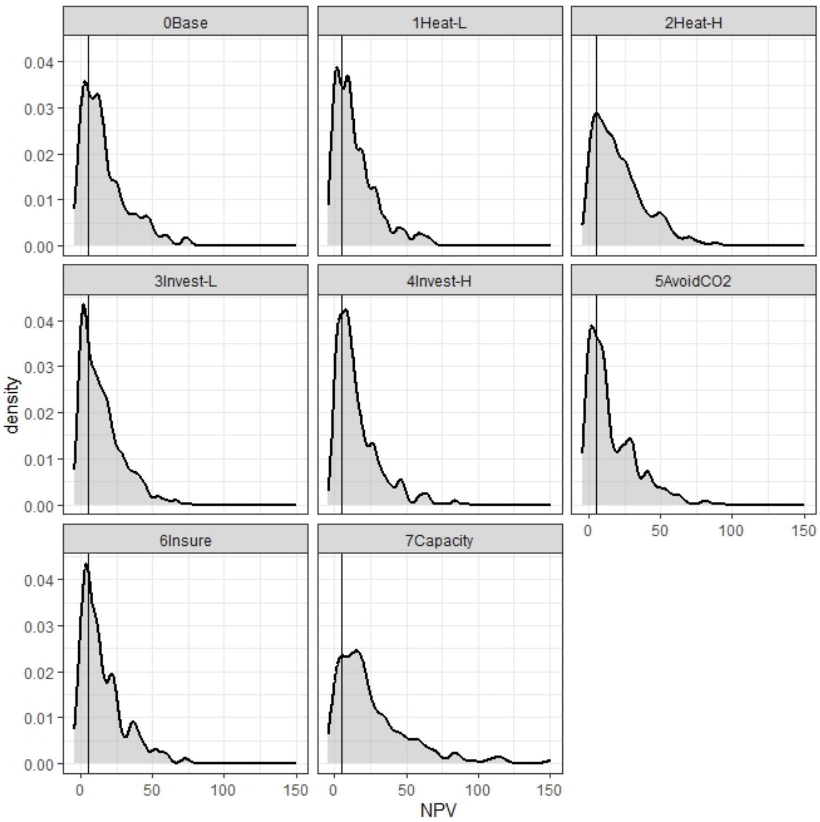

Figure 19. Project value of the Turnhout-NW case for eight simulated scenarios, NPV in million €.

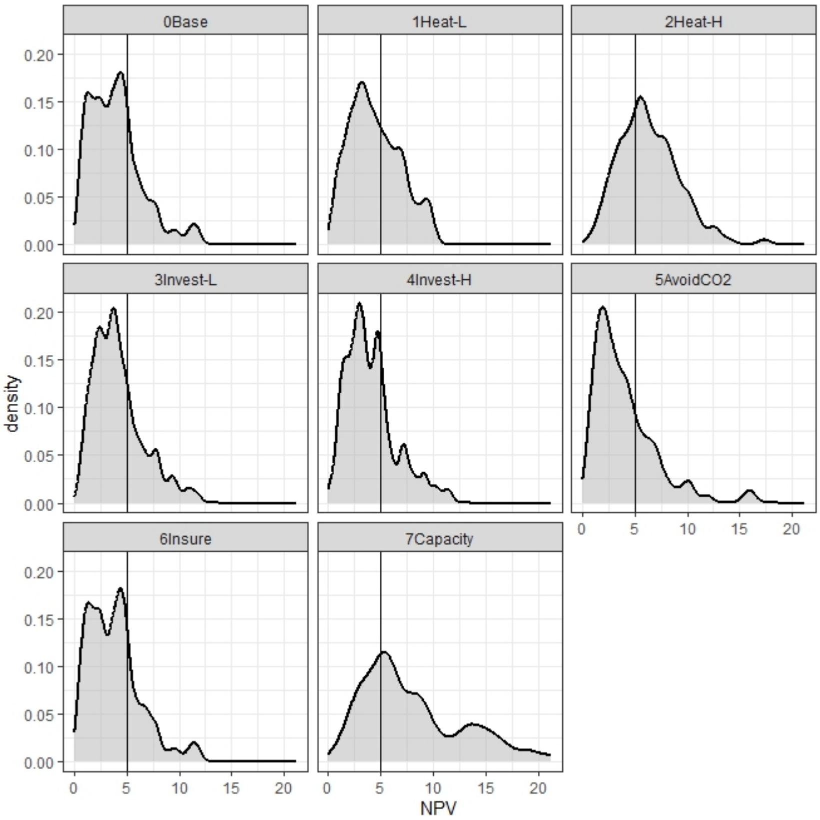

Figure 20. Project value of the Single Well case for eight simulated scenarios, NPV in million €.

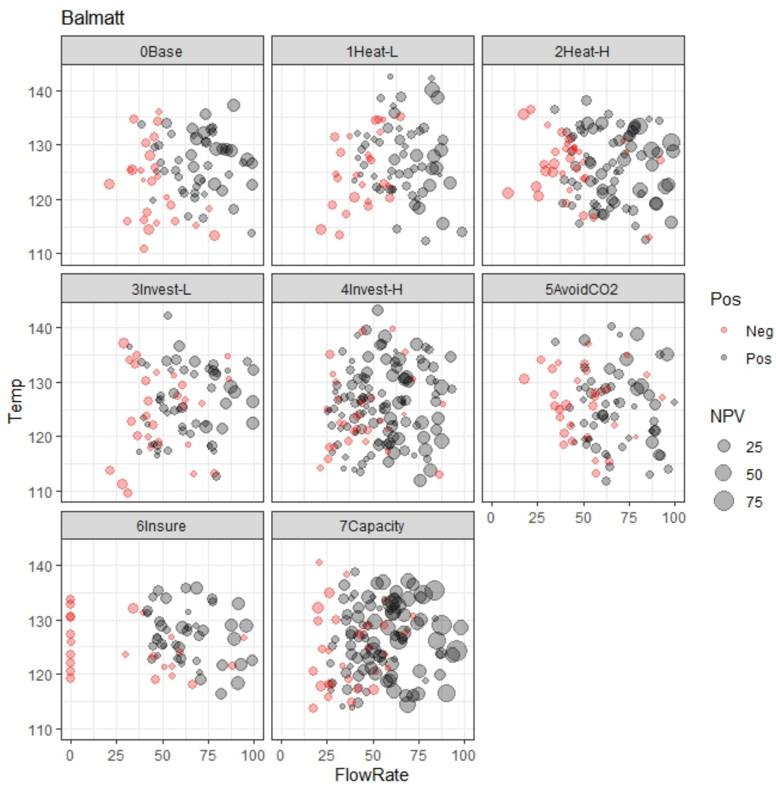

Figure 21. Sensitivity analysis of the production temperature and flow rate on project value for the Balmatt case.

4.5 Interferences

In collaboration with several other projects dealing with the management of the deep subsurface, a workflow was established for analysing potential pressure interference effects. A semi-analytical hydrogeological model for the Flemish Region is built (Figure 22), where the main geological building blocks are represented by "domains" (1A to 4A shown here). Projects that are chosen to be initiated by the PSS V simulations and their induced production/injection pressures over time are introduced in the regional model. A regional pressure calculation is able to reveal pressure influences at any given location (Figure 23), for example in between two deep geothermal projects, targeting the same reservoir.

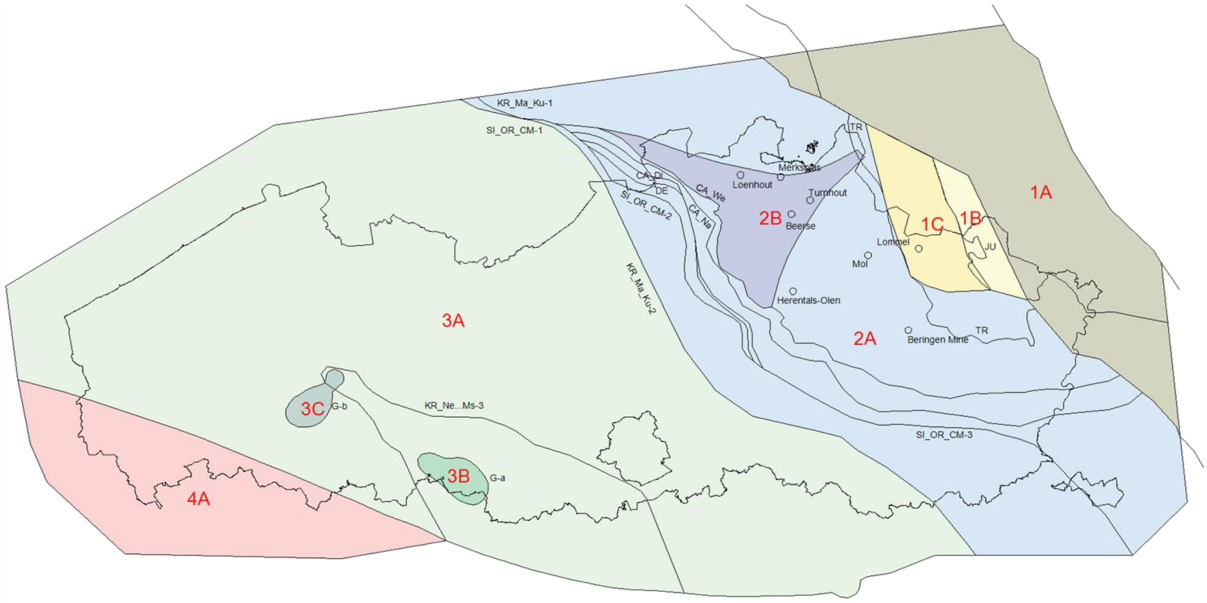

Figure 22. Building blocks or domains of a semi-analytical groundwater model for the Flemish Region in AnAqSim for investigating pressure interferences.

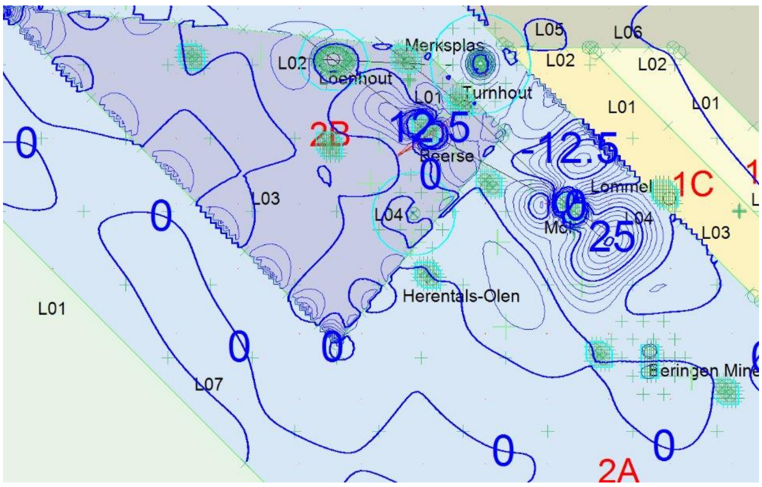

Figure 23. Detail of a preliminary AnAqSim model test result for the Campine area, with isobars and pressure differences indicated in blue. Geothermal activities in Mol and Beerse have clear pressure effects.

4.6 Recommendations

Several interdisciplinary tools and workflows are developed for assisting decision makers in planning deep geothermal projects. Their application is demonstrated with first analyses for multiple case studies and scenarios in Belgium.

Deep geothermal energy can have an important environmental benefit over alternative heating sources (natural gas or heat pumps). In the life cycle of a deep geothermal doublet project, (well) construction and pumping operation have highest the environmental impact. These phases are first targets to reduce environmental impact further.

Applying dynamic life cycle analysis (LCA) has major benefits over the industry-standard static LCA for accurately assessing environmental impact. The impacts are more accurately quantified and results are easier to communicate. It also allows to integrate flexible project decisions in Real Options Analysis (ROA), for environmental impact to weigh in as decision criterion. This method can also be useful for analysing other renewable technologies.

The consideration of flexibility to counter investment risk with for example Real Options Analysis is key when analysing economic performance of projects with large up-front investments and uncertainties such as deep geothermal projects. Including risk and flexibility is also important in designing support measures, to target the correct project phase at an appropriate level.

For increasing overall project value with government support schemes, both a heat subsidy and geothermal investment subsidy can achieve good results. However, an investment subsidy better targets the high-risk project development phase, with less excessive windfall profits for very successful projects. In addition, such investment support is easier to manage budget-wise in comparison with support in the operational phase. A drilling insurance also avoids windfall profits but its overall effect is smaller.

Geological conditions largely dictate project success, emphasizing the location-specific nature of the technology. Parameters that define flow, for example permeability, are most determining. Depth uncertainties (and thus temperature) can also be considerable in Belgium and need to be taken into account in reservoir modelling and project planning. Belgium has mixed geological conditions, and thorough site investigation is necessary. A government-led general exploration of the deep subsurface can de-risk the investment.

While heat demand is usually higher in winter, an optimization in the design of supply and demand, increasing the operational time, has a major influence on the business case, similar to high support measures. A phased roll-out of a geothermal project by increasing demand can also provide risk mitigation to adjust to unforeseen circumstances. It requires, however, different planning and surface circumstances at the demand side to succeed.

A number of recommendations for further research are also identified. The further development of fast reservoir simulations for various (geothermal) applications will expand possibilities for integrated assessment methods. As concrete example, a further development of simulation methods for geothermal applications in abandoned mines is suggested. It is also worth investigating the integration of assessment methods in a basin-wide approach, in view of project and policy planning.

Because of the site-specific nature of deep geothermal projects, a detailed analysis should consider project-specific conditions, in-depth investigating individual project decisions, an integration with transport and demand and potential interferences simulation with other activities.

The interdisciplinary analysis can be expanded in many ways to achieve a holistic overview of project impacts, for example by introducing the social context and impacts. Multi-criteria optimization decision-making principles in combination with Real Options Analysis can be applied for developing geothermal investment strategies.

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6. DISSEMINATION AND VALORISATION

6.1 PhD

For performing project work at the University of Antwerp, a PhD position was created. Spiros Gkousis was hired to start in September 2020, and finalized his PhD research at the public defense on 15/05/2024: Spyridon Gkousis, 2024. Deep geothermal energy investments under uncertainty - A techno-enviro-economic analysis. Universiteit Antwerpen. Supervisors: Tine Compernolle, Kris Welkenhuysen.

6.2 Website and social media

https://gsb.naturalsciences.be/portfolio/designate/

https://www.naturalsciences.be/en/science/research/geosciences-for-a-sustainable-society/projects/designate

https://vito.be/en/designate

https://www.uantwerpen.be/en/research-groups/engineering-management/mission-members/research-projects-enm/

https://www.linkedin.com/company/69234520/

https://www.researchgate.net/project/DESIGNATE-Decision-Support-under-Uncertainty-for-Geothermal-Applications

As part of a GSB social media campaign, the DESIGNATE project was presented in a post with the GSB's accounts for Twitter, Facebook and LinkedIn.

6.3 Meetings

- A plenary follow-up committee meeting was organized online on 05/05/2022 (see also deliverable D1.3).
- Several meetings were organized with HITA specifically concerning the Turnhout NW case study.
- Meeting with the cabinet of the Walloon minister of Energy Henry. Quelles mesures pour soutenir la géothermie profonde en Wallonie? Et pourquoi? Petitclerc, E. Vanbrabant, Y. & Welkenhuysen, K., 20/01/2020.
- Visit of Federal State Secretary of Science Policy Dermine at RBINS and GSB: presentation of ongoing research by Petitclerc, E., 26/10/2020.
- Public hearing on deep geothermal energy at the Flemish Parliament: Piessens, K, Petitclerc, E., & Welkenhuysen, K., 2021. Diepe geothermie. Hoorzitting diepe geothermie, Vlaams Parlement – C-LEE, 12/01/2021.
- Meeting with member of the Flemish Parliament on deep geothermal energy: Piessens, K., Welkenhuysen, K. & Heyvaert, V., 08/10/2021.
- Meeting of GSB Geo-Energy with EC DG GROW and DG ENER on geothermal energy: Petitclerc, E., Welkenhuysen, K., Piessens, K. & Vanbrabant, Y., 16/05/2022.

- Meeting with Virya Energy as follow-up committee member for discussing final project results, 21/11/2024.

6.4 Final event

On 16/09/2024, the final conference of the DESIGNATE and GeoCamb geothermal projects was organized at the RBINS, as a back-to-back event concluding both Belspo-funded geothermal projects (see also deliverable D1.3). It was a successful event with about 50 people attending, with stakeholders from science, industry, public services and policy from regional to EU level. The day was introduced by the RBINS general director Michel Van Camp, and by Belspo programme manager Koen Lefever.

6.5 Other

- The RBINS-GSB and UA are partners in a Flemish government assignment on the societal impact of deep subsurface uses. The DESIGNATE project results assist in building background, methodology and scenarios for the deep geothermal application.
- On 09/06/2022 the GSB organized a public celebration at the RBINS for its 125th birthday. At the Geo-energy booth, the DESIGNATE project was presented alongside other projects.
- The life cycle assessment results of the DESIGNATE project are used by the Hita geothermal development company in the environmental permit request for the GEO@Turnhout-NW geothermal project.
- The outcomes, specifically regarding developed methods, are integrated in ongoing follow-up projects on sustainable management of the deep subsurface in the Flemish Region:
    - FWO junior project MASSIF (Multidisciplinary assessment of subsurface interactions: the fundamentals)
    - FWO-SBO project DIAMONDS (Dynamic Integrated Assessment Methods for the sustainable Development of the Subsurface)
    - Flemish government assignment (Department Environment – VPO) on management of the deep subsurface

7. PUBLICATIONS

7.1 Scientific papers

Gkousis, S., Welkenhuysen, K. & Compernolle, T., 2022. Deep geothermal energy extraction, a review on environmental hotspots with focus on geo-technical site conditions. Renewable and Sustainable Energy Reviews, 162, 112430. https://doi.org/10.1016/j.rser.2022.112430

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7.2 Conference presentations

Dupont, N., Kaufmann O., Baele J.-M., 2021. Delineation of inferred high-transmittivity zones in the Dinantian geothermal reservoir of Hainaut (SW Belgium). Abstract book of the 7th International Geologica Belgica Meeting 2021, Tervuren, Belgium, 15-17/09/2021. (abstract & oral presentation)

Dupont N., Petitclerc E., Broothaers M., Kaufmann O., 2022. Geothermal Energy Use, Country Update for Belgium. European Geothermal Congress, 17-21/10/2022, Berlin, Germany. (conference paper)

Dupont, N. & Kaufmann, O., 2024. Development of a fast geothermal simulation tool designed to the Lower Carboniferous reservoir of Hainaut in the framework of the BRAIN-Be 2.0 DESIGNATE project. Abstract book of the 8th International Geologica Belgica Luxemburga Meeting 2024, Liège, Belgium, 11-13/09/2021, p.345-346. (abstract & oral presentation)

Gkousis, S., Compernolle, T. & Welkenhuysen, K., 2021. Deep geothermal energy extraction, a review on environmental hotspots with focus on geo-technical site conditions. Abstract book of the 7th International Geologica Belgica Meeting 2021, Tervuren, Belgium, 15-17/09/2021, p.335-336. (abstract & oral presentation)

Gkousis, S., Compernolle, T. & Welkenhuysen, K., 2021. Deep Geothermal Energy Extraction, a Review on Environmental Hotspots with Focus on Geo-technical Site Conditions. 16th Conference on

Sustainable Development of Energy, Water and Environmental Systems (SDEWES), 10-15/10/2021, Dubrovnik, Croatia. (full paper & oral presentation)

Gkousis, S., Harcouet-Menou, V., Damen, L., Welkenhuysen, K., Laenen, B., Compernolle, T., 2022. Life Cycle Assessment of Geothermal Plants Targeting the Lower Carboniferous Limestone Reservoir in Northern Belgium. Submitted to 17th Conference on Sustainable Development of Energy, Water and Environmental Systems (SDEWES), 6-10/11/2022, Paphos, Cyprus. (conference paper & oral presentation)

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Meyvis, B. & Welkenhuysen, K., 2024. Implementing geological and economic uncertainty in a techno-economic analysis of deep geothermal energy projects. Abstract book of the 8th International Geologica Belgica Luxemburga Meeting 2024, Liège, Belgium, 11-13/09/2021, p. 351-352. (abstract & poster presentation)

N'depo, Y., Dupont, N., Martin, T. & Kaufmann, O., 2024. Modelling the geometry of abandoned coal mines for inter-seasonal underground storage of heat and cold. Abstract book of the 8th International Geologica Belgica Luxemburga Meeting 2024, Liège, Belgium, 11-13/09/2021, p. 353. (abstract & poster presentation)

Pogacnick, J., Harcouët-Menou, V., Laenen, B., 2023. Analytical Estimation for the Production Temperature of a Geothermal Doublet. Geothermal Rising Conference (GRC) Transactions 47, Reno, Nevada, US, 1-4/10/2023. (conference paper & oral presentation)

Rodriguez, J., Piessens, K., Welkenhuysen, K., 2024. Building a regional telescoped model of the Campine Basin for subsurface management. Geologica Belgica Meeting 2024. Abstract book of the 8th International Geologica Belgica Luxemburga Meeting 2024, Liège, Belgium, 11-13/09/2021, p. 385-386. (abstract & oral presentation)

Welkenhuysen, K., Compernolle, T., Kaufmann, O., Laenen, B., Meyvis, B., Piessens, K., Gousis, S., Dupont, N., Harcouet-Menou, V., Pogacnik, J., 2021. Decision support under uncertainty for geothermal applications: case selection and concept development. Abstract book of the 7th International Geologica Belgica Meeting 2021, Tervuren, Belgium, 15-17/09/2021, p.350-351. (abstract & oral presentation)

Welkenhuysen, K., Meyvis, B., Rodriguez, J. & Piessens, K., 2024. PSS V, a modular techno-economic simulation tool for deep subsurface uses. Geologica Belgica Meeting 2024. Abstract book of the 8th International Geologica Belgica Luxemburga Meeting 2024, Liège, Belgium, 11-13/09/2021, p.392-393. (abstract & oral presentation)

8. ACKNOWLEDGEMENTS

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